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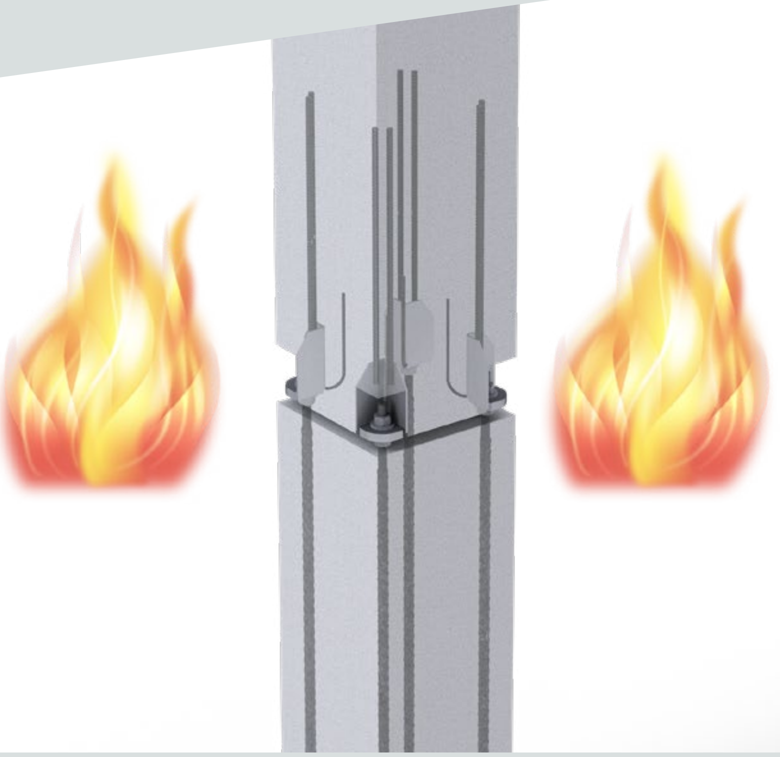

FIRE RESISTANCE AND DESIGN OF COLUMN CONNECTION

PEIKKO DESIGNER® CALCULATION PROCEDURE

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SUMMARY

This White Paper describes the calculation method used by Peikko Designer®, that enables resistance verification of fire exposed column connection. It also explains fire design procedure, calculation flow, and used calculation parameters in accordance with Eurocodes.

INTRODUCTION

Fire resistance is defined in terms of time as follows: Relevant time of fire exposure during which the corresponding fire resistance function of a structure is maintained despite fire action.

According to European standard there are 3 criteria to define the fire resistance:

- R = load bearing function (**checked by Peikko Designer®**)
- E = integrity separating function (not applicable for column connection)
- I = thermal insulation separating function (not applicable for column connection)

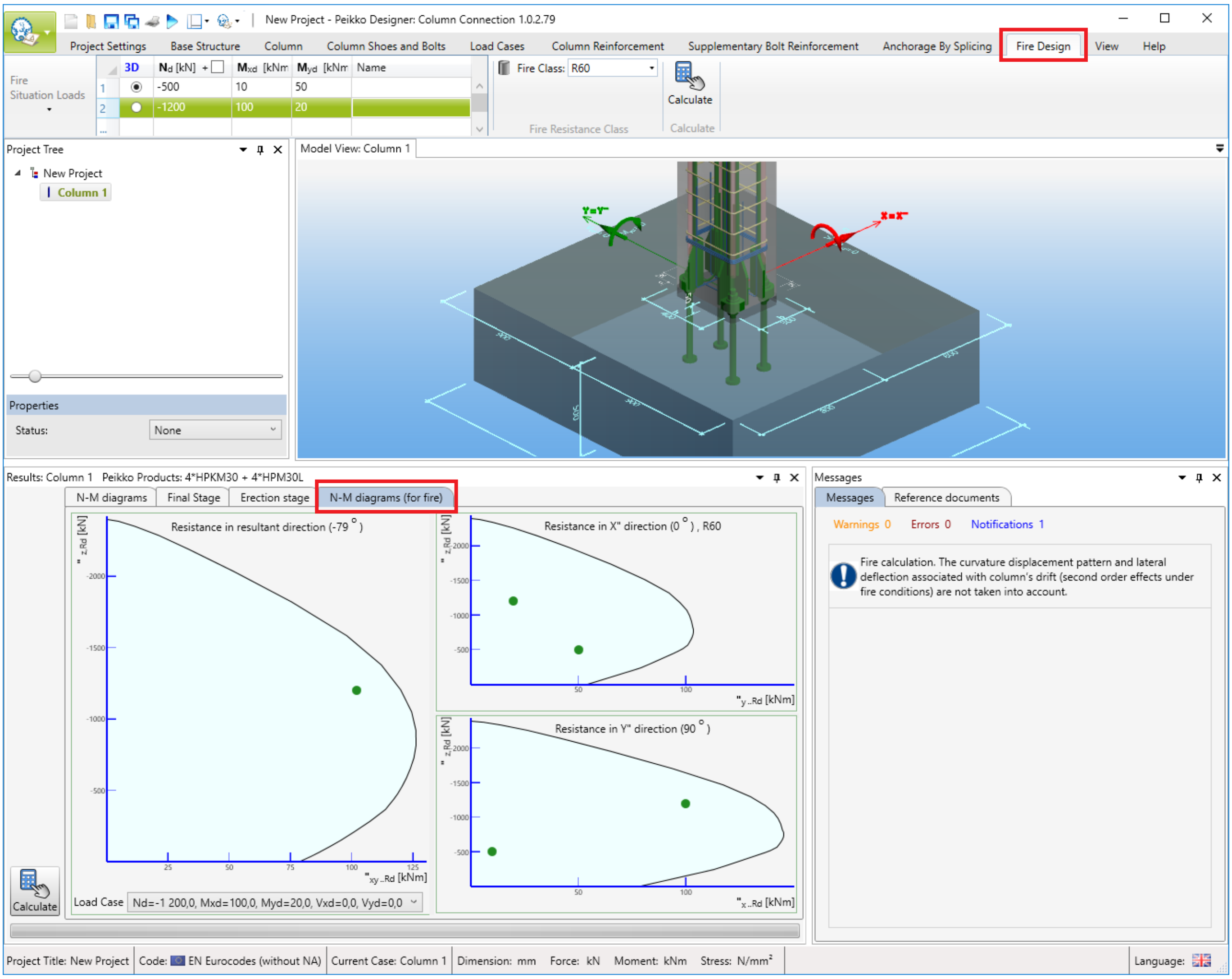


FIGURE 1. FIRE DESIGN INTERFACE OF PEIKKO DESIGNER®.

Chain of events in case of fire:

- Ignition
- Thermal action
- Mechanical actions
- Thermal responses
- Mechanical response
- Possible collapse, if fire resistance of structure not sufficient
- Cooling phase

Fire design is performed according to EN 1992-1-2 (Eurocode 2: Design of concrete structures. Part 1-2: General rules. Structural fire design). Resistance to fire is verified to the relevant duration of fire exposure t and defined with expression:

$$E_{d,fi} \leq R_{d,t,fi} \quad (1)$$

Where:

$E_{d,fi}$ is the design effect of actions for the fire situation, determined in accordance with EN 1991-1-2, including effects of thermal expansion and deformations.

$R_{d,t,fi}$ is the corresponding design resistance in the fire situation.

The temperature data used for fire design of Peikko Designer® is obtained by a finite element analysis. The FEA was validated by comparing the results against the fire tests carried out by VTT. The tests and analysis were necessary as EN 1992-1-2 does not give any temperature contours for precast column connections.

SCOPE OF PEIKKO DESIGNER®

In Peikko Designer® fire resistance can be calculated under design code section:

⇨ *Design based on connection performance and resistance (EN Eurocodes + ETA 18/0037)*
  - Respecting available National Annexes.

FIGURE 2. CODE SELECTION THAT SUPPORTS FIRE DESIGN.

Design is applicable:

- for concrete columns with HPM® + HPKM® and PPM® + BOLDA®.
- for calculating axial force-bending moment (N-M) resistance interaction curves.
- for final stage.
- for rectangular and circular cross-sections.
- for connections with 4 or more bolts.
- shear force is not checked.
- arrangements with 2 bolts can’t be checked.
- cross-section’s width and height shall be equal or greater than 200 mm.

THERMAL ACTIONS

Column shoes are exposed to standard fire according to EN 1363-1.

$$T = 20 + 345 \cdot log_{10}(8 \cdot Time + 1) \quad (2)$$

Where:

T is gas temperature in the fire compartment

$Time$ is input value in minute [min] and corresponds to fire class.

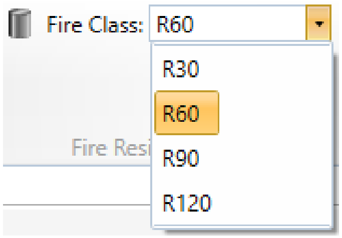


FIGURE 3. SELECTION OF FIRE CLASS, PEIKKO DESIGNER®

Fire design with Peikko Designer® can be verified up to 120 minutes (R120).

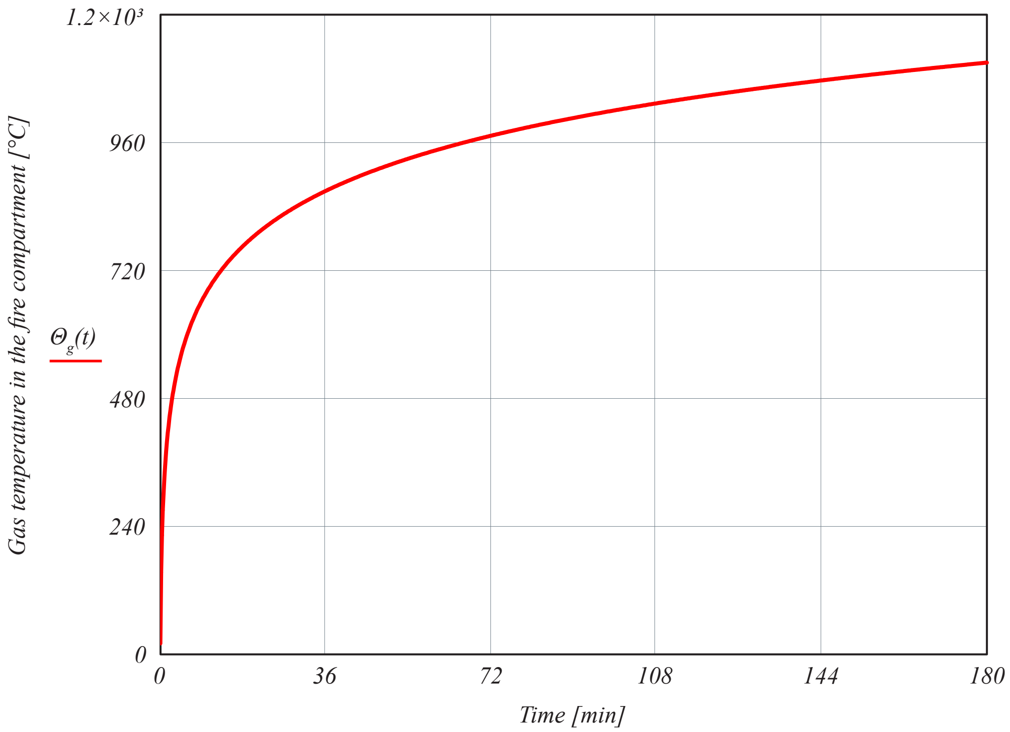


FIGURE 4. STANDARD TEMPERATURE-TIME CURVE.

THERMAL RESPONSE

To analyze temperature distribution in connection temperature dependent material properties are used:

- Specific heat c_p *(θ)* [*J/(kg K)*] (amount of heat per unit mass required to raise the temperature by one degree Celsius)
- Thermal conductivity *λ (θ)* [*W/(m K)*] (property of material to conduct heat)

As a simplification for material density *ρ (θ)* [kg/m^3] constant value was used.

CONCRETE

In the FEA model the moisture content of concrete was set to 3% which gave the best agreement with the fire test results. The moisture content has an effect on the peak value on the specific heat of concrete. The peak value appears between 100°C and 200°C.

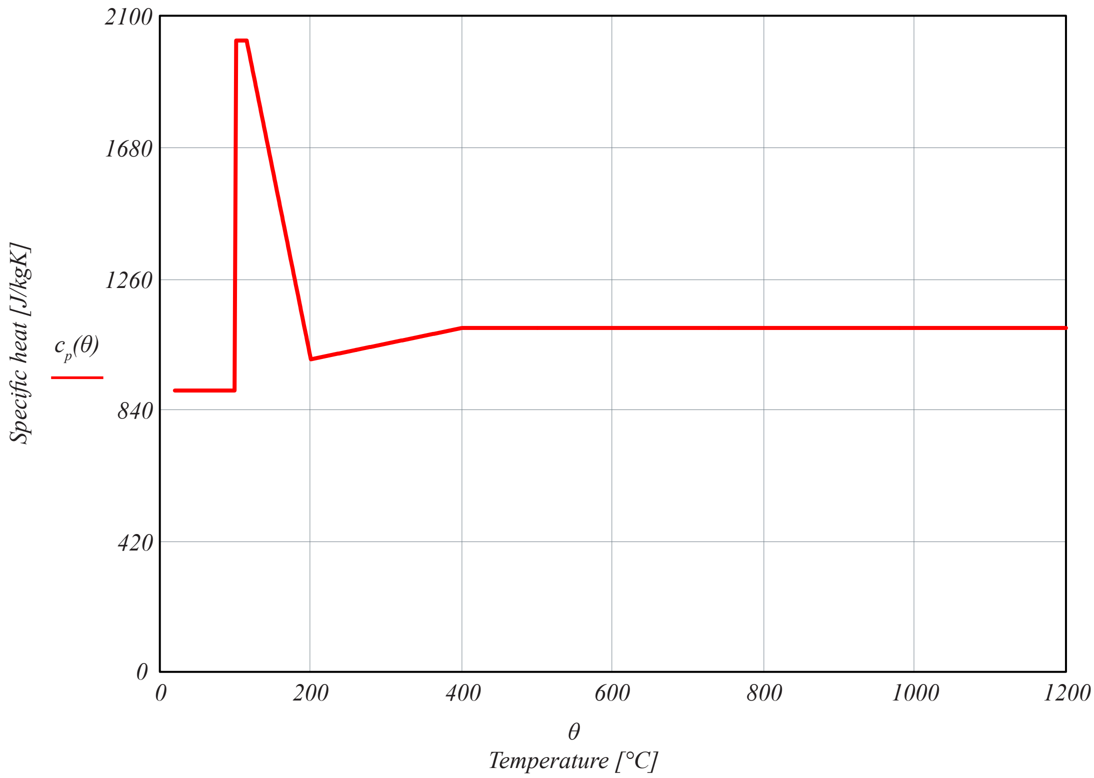


FIGURE 5. SPECIFIC HEAT OF CONCRETE.

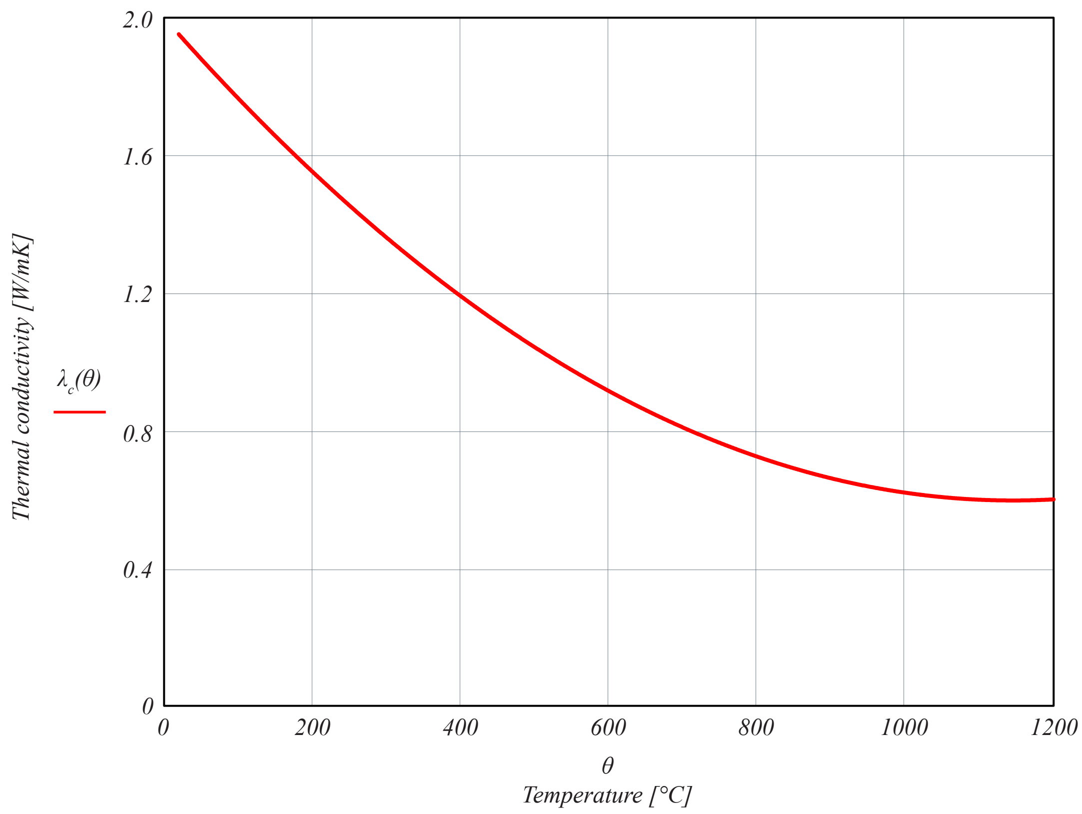


FIGURE 6. THERMAL CONDUCTIVITY OF CONCRETE.

STRUCTURAL AND REINFORCING STEEL (ANCHOR BOLTS)

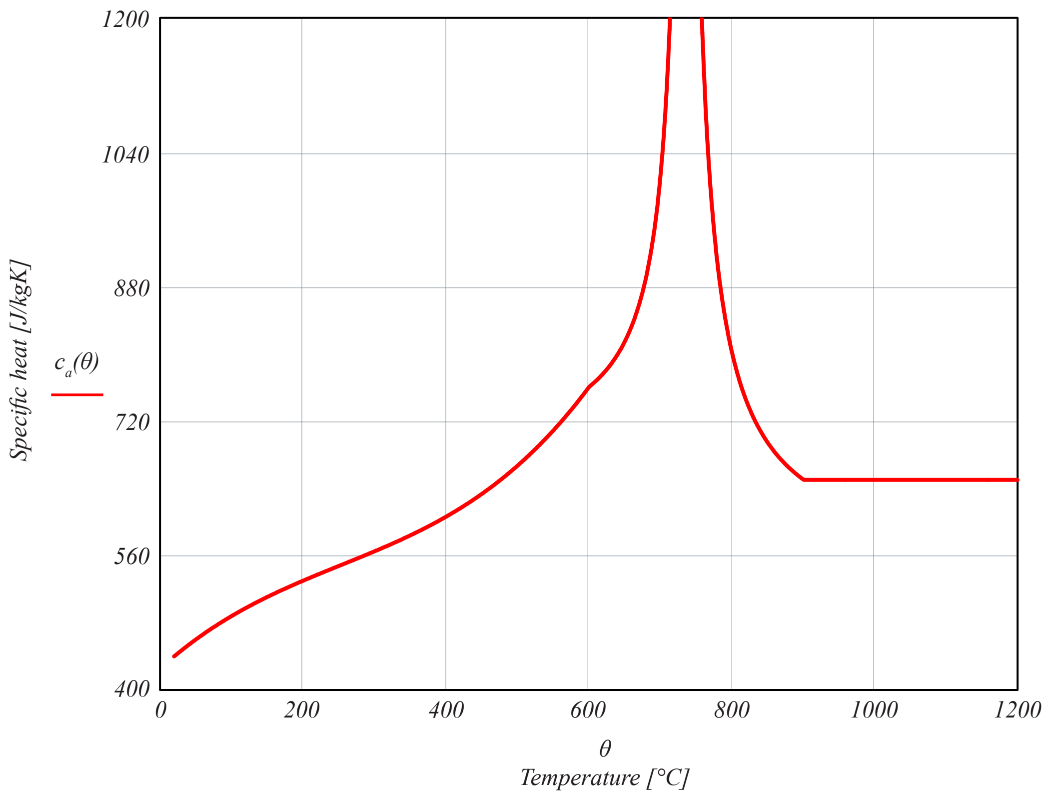


FIGURE 7. SPECIFIC HEAT OF STEEL.

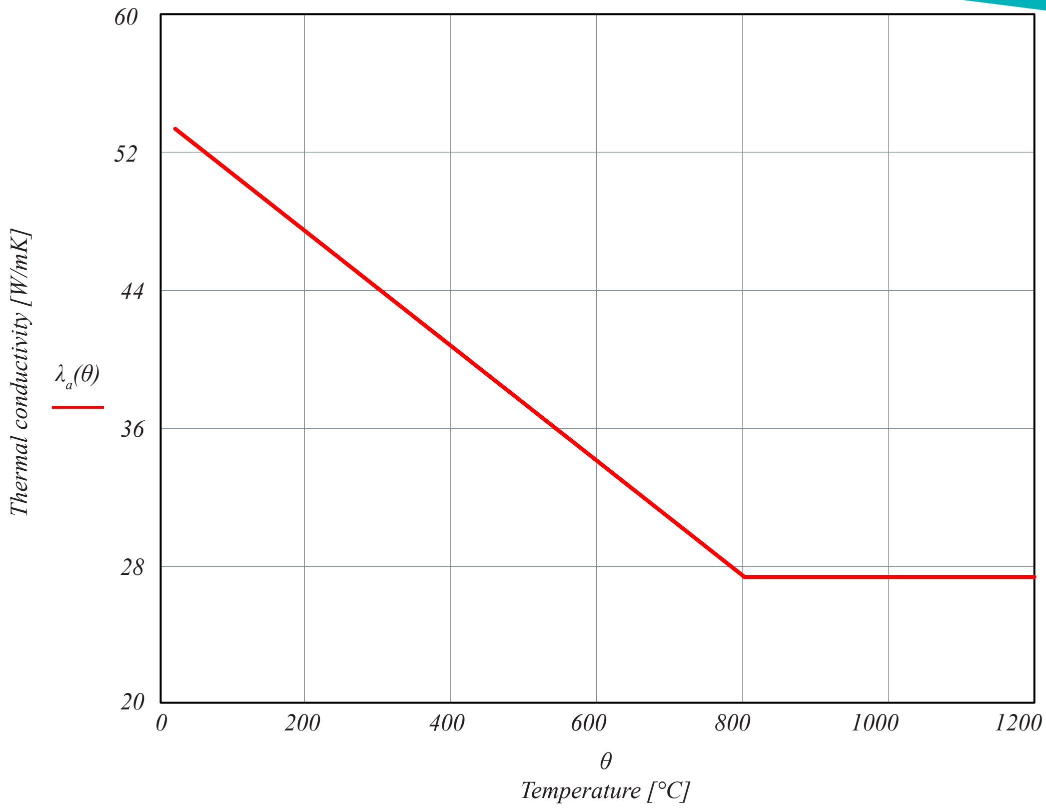


FIGURE 8. THERMAL CONDUCTIVITY OF STEEL.

TEMPERATURE DATA

Column connection is exposed to fire from four sides. Software COMSOL was used to solve temperature distribution in connection and to generate temperature contours. To cover Peikko Designer®'s freely definable dimensions of connection, column width or diameter were altered from 200 to 1000 mm with steps of 100 mm. In addition, ratio of cross-sections (h/b) were altered from 1.0 to 3.0 with steps of 0.25. Analysis were performed to cover all Peikko column shoe sizes. Derived data is hardcoded in Peikko Designer® and depending on the input variables selected for the fire design.

CONCRETE TEMPERATURES

The values in database are already temperatures integrated over the elementary surface and the element distribution corresponds the system used in Peikko Designer®.

Concrete temperatures are determined by ignoring the middle shoes.
Simulations which account for only corner shoes provide conservative results.
Steel from middle shoes would increase heat flow inside the concrete reducing the temperatures close to the edge.

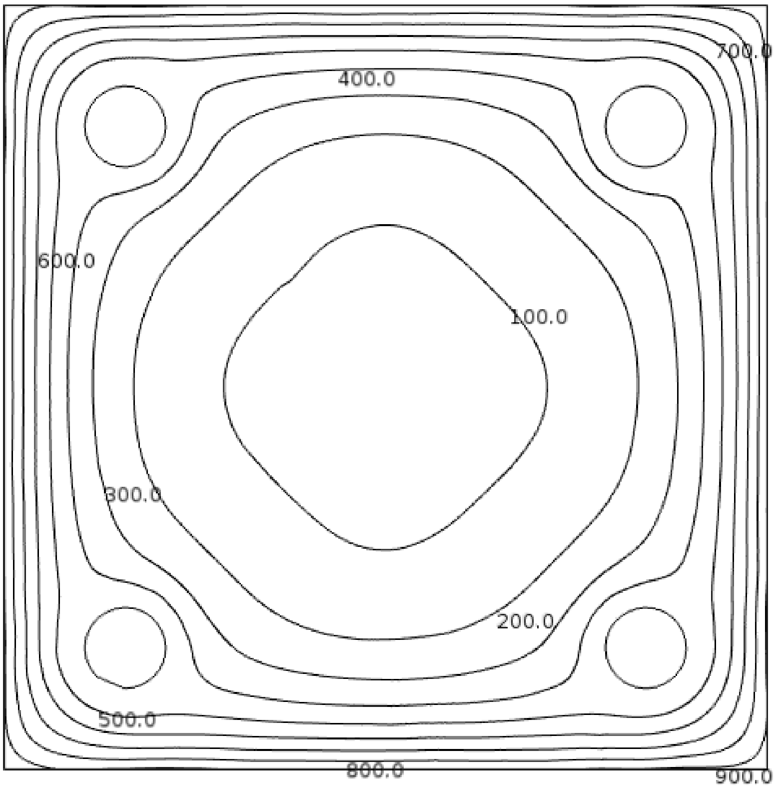


FIGURE 9. EXAMPLE OF TEMPERATURE PROFILE (°C). MIDDLE OF THE JOINT $H \times B = 380 \times 380$ MM^2, R60.

In case of rectangular column one corner of cross-section are processed. Temperatures in remaining elements are assigned symmetrically. In case of circular column, it is one sector.

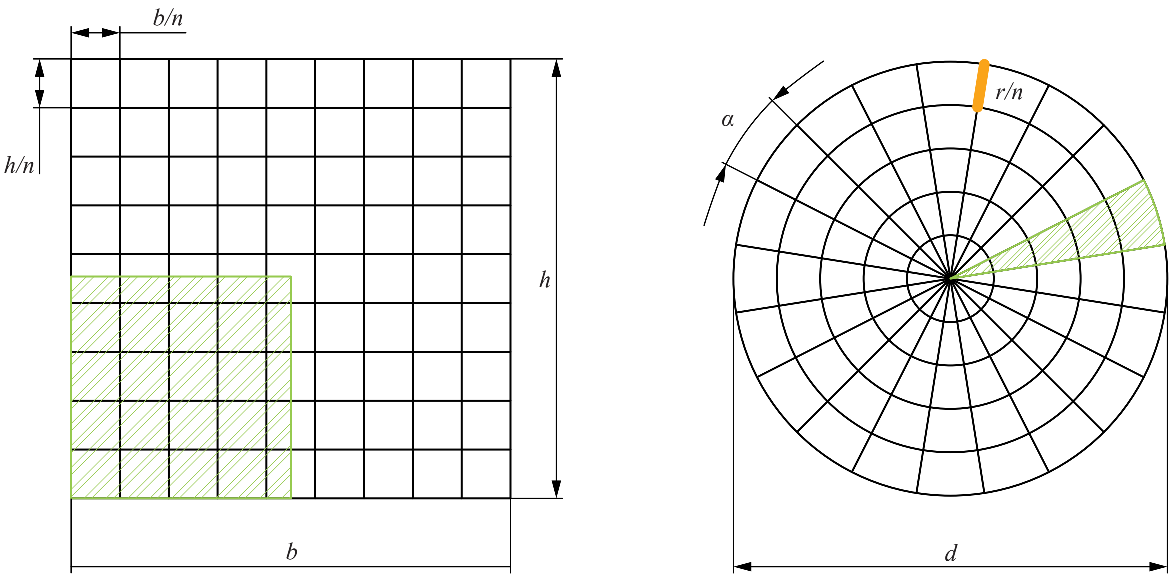


FIGURE 10. PEIKKO DESIGNER®'S GRID (ELEMENT DISTRIBUTION)

Data contains the average temperature in each element depending on

- fire class (R30, R60, R90, R120)
- size of column shoe (HPKM16, HPKM20, HPKM24, HPKM30, HPKM39, BOLDA30, BOLDA36, BOLDA39, BOLDA45, BOLDA52)
- column shape (rectangular or circular)
- column width or diameter that is altered between 200...1000 [mm] with 100 [mm] steps
- cross-section's ratio between height and width h/b that is altered between 1 and 3 with steps of 0.25

Linear interpolation is used when cross-section dimensions are set between the steps.

			Element $A_{i,j}$								
Fire Class	**Shoe**	h/b	b_1 (width)	b_2 (width)	b_3 (width)	b_4 (width)	b_5 (width)	b_6 (width)	b_7 (width)	b_8 (width)	b_9 (width)
			200	**300**	**400**	**500**	**600**	**700**	**800**	**900**	**1000**
R30	**HPKM16**	1	$^{o}t_{1}$	$^{o}t_{10}$	$^{o}t_{19}$	$^{o}t_{28}$	$^{o}t_{37}$	$^{o}t_{46}$	$^{o}t_{55}$	$^{o}t_{64}$	$^{o}t_{73}$
R30	**HPKM16**	1.25	$^{o}t_{2}$	$^{o}t_{11}$	$^{o}t_{20}$	$^{o}t_{29}$	$^{o}t_{38}$	$^{o}t_{47}$	$^{o}t_{56}$	$^{o}t_{65}$	$^{o}t_{74}$
R30	**HPKM16**	1.5	$^{o}t_{3}$	$^{o}t_{12}$	$^{o}t_{21}$	$^{o}t_{30}$	$^{o}t_{39}$	$^{o}t_{48}$	$^{o}t_{57}$	$^{o}t_{65}$	$^{o}t_{75}$
R30	**HPKM16**	1.75	$^{o}t_{4}$	$^{o}t_{13}$	$^{o}t_{22}$	$^{o}t_{31}$	$^{o}t_{40}$	$^{o}t_{49}$	$^{o}t_{58}$	$^{o}t_{67}$	$^{o}t_{76}$
R30	**HPKM16**	2	$^{o}t_{5}$	$^{o}t_{14}$	$^{o}t_{23}$	$^{o}t_{32}$	$^{o}t_{41}$	$^{o}t_{50}$	$^{o}t_{59}$	$^{o}t_{68}$	$^{o}t_{77}$
R30	**HPKM16**	2.25	$^{o}t_{6}$	$^{o}t_{15}$	$^{o}t_{24}$	$^{o}t_{33}$	$^{o}t_{42}$	$^{o}t_{51}$	$^{o}t_{60}$	$^{o}t_{69}$	$^{o}t_{78}$
R30	**HPKM16**	2.5	$^{o}t_{7}$	$^{o}t_{16}$	$^{o}t_{25}$	$^{o}t_{34}$	$^{o}t_{43}$	$^{o}t_{52}$	$^{o}t_{61}$	$^{o}t_{70}$	$^{o}t_{79}$
R30	**HPKM16**	2.75	$^{o}t_{8}$	$^{o}t_{17}$	$^{o}t_{26}$	$^{o}t_{35}$	$^{o}t_{44}$	$^{o}t_{53}$	$^{o}t_{62}$	$^{o}t_{71}$	$^{o}t_{80}$
R30	**HPKM16**	3	$^{o}t_{9}$	$^{o}t_{18}$	$^{o}t_{27}$	$^{o}t_{36}$	$^{o}t_{45}$	$^{o}t_{54}$	$^{o}t_{63}$	$^{o}t_{72}$	$^{o}t_{81}$

FIGURE 11. EXAMPLE. CONCRETE TEMPERATURE ATTRIBUTE FOR RECTANGULAR COLUMN, ELEMENT $A_{I,J}$.

Similar tables are saved for each element of the grid.

BOLT TEMPERATURES

Thermal analysis with FEM software provided temperatures along the axis of anchor bolt. To calibrate the numerical results, a fire tests on three connections (HPKM16, HPKM24, HPKM39, BOLDA30, BOLDA39, and BOLDA52), each with minimum cross-section, has been carried out. Both fire tests and FEA models showed that the critical temperatures were in the anchor bolts on both sides of the base plate. The resulting average temperatures in the warmest section of the anchor bolt have been determined and used in fire design in accordance with relevant Eurocodes.

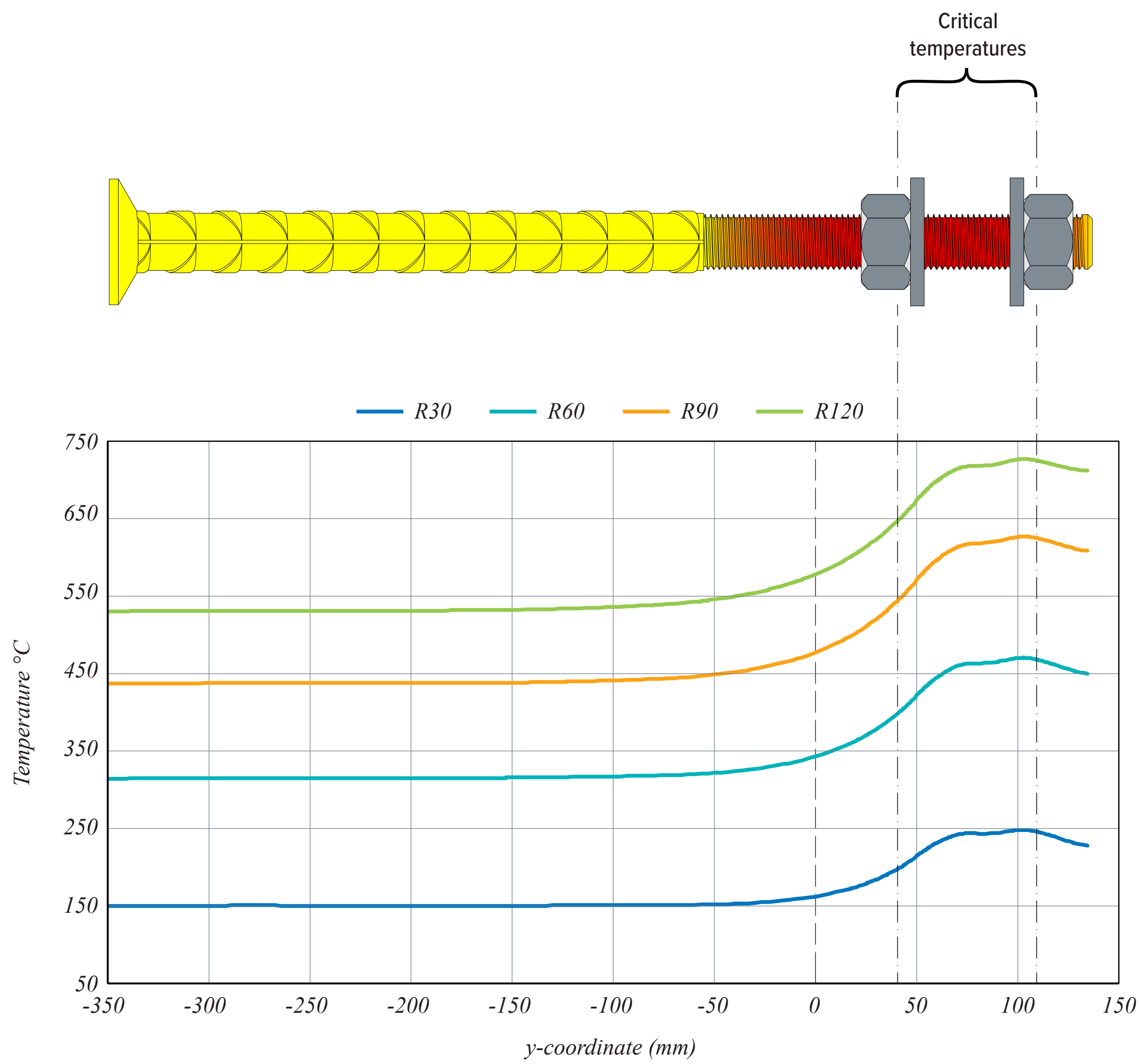


FIGURE 12. EXAMPLE OF ANCHOR BOLT TEMPERATURES. FIRE TEST SETUP AND GRAPH FROM FEA.

It has been also checked that under fire exposure column shoe doesn't become the weakest link and the connection's fire resistance is governed by bolt's critical temperature. Resistance can be increased by embedding column shoes deeper inside cross-section, what reduces temperature in anchor bolt.

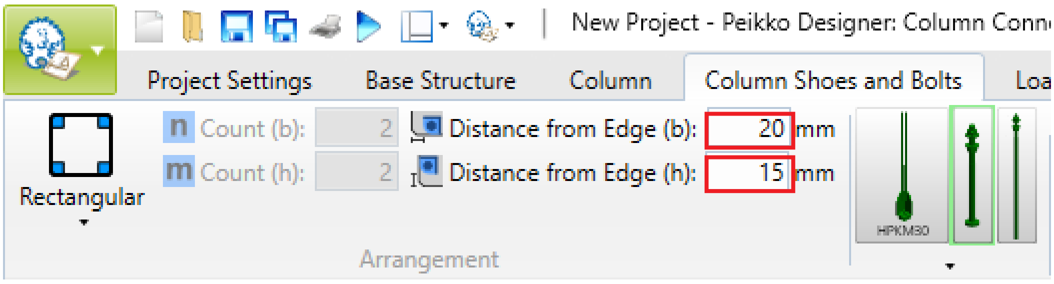


FIGURE 13. MOVING COLUMN SHOES INWARDS.

Data saved into Peikko Designer® contains max temperature along axis depending on:

- bolt size (HPM16, HPM20, HPM24, HPM30, HPM39, PPM30, PPM36, PPM39, PPM45, PPM52)
- fire class (R30, R60, R90, R120)
- positioning; is the bolt in the middle or corner of cross-section
- concrete cover of column shoe $c_{nom} = 0...100\ mm$ with steps of 10 mm.

Fire Class	Bolt	Location	Concrete cover of column shoe 0 [mm]	10 [mm]	20 [mm]	30 [mm]	40 [mm]	...	100 [mm]
R30	**HPM16**	Corner bolt	^{o}t	^{o}t	^{o}t	^{o}t	^{o}t	...	^{o}t
R30	**HPM20**	Corner bolt	^{o}t	^{o}t	^{o}t	^{o}t	^{o}t	...	^{o}t
R30	**HPM24**	Corner bolt	^{o}t	^{o}t	^{o}t	^{o}t	^{o}t	...	^{o}t
R30	**HPM30**	Corner bolt	^{o}t	^{o}t	^{o}t	^{o}t	^{o}t	...	^{o}t
R30	**HPM39**	Corner bolt	^{o}t	^{o}t	^{o}t	^{o}t	^{o}t	...	^{o}t

FIGURE 14. EXAMPLE. CORNER BOLT TEMPERATURE ATTRIBUTE FOR FIRE CLASS R30.

MECHANICAL ACTIONS

Fire situation loads (under Fire Design tab) are input values in **Peikko Designer**® determined for time $t = 0\ [min]$ using combination factors $\psi_{1,1}$ or $\psi_{1,2}$ according to EN 1991-1-2 Section 4.

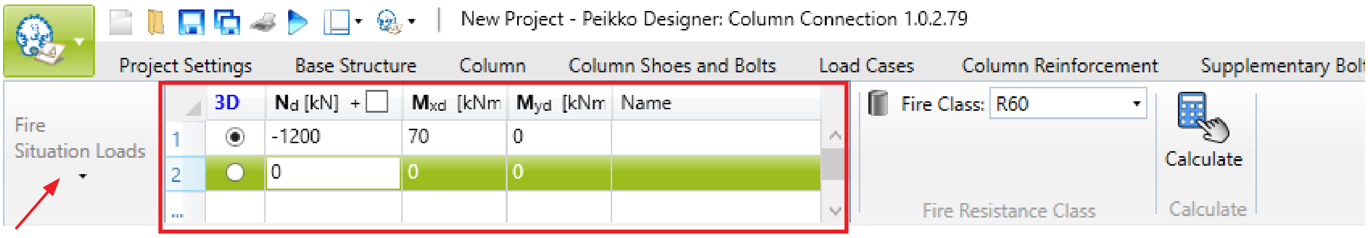


FIGURE 15. FIRE LOAD INPUT IN PEIKKO DESIGNER®.

As a simplification the effects of actions may be obtained from a structural analysis for normal temperature design as:

$$E_{d,fi} = \eta_{fi} E_d \tag{3}$$

Where:

E_d is the design value of the corresponding force or moment for normal temperature design, for a fundamental combination of actions (see EN 1990).

η_{fi} is the reduction factor for the design load level for the fire situation.

The reduction factor η_{fi} for load combination (6.10) in EN 1990 should be taken as:

$$\eta_{fi} = \frac{G_k + \psi_{fi} Q_{k,1}}{\gamma_G G_k + \gamma_{Q,1} Q_{k,1}} \tag{4}$$

Or for load combination (6.10a) and (6.10b) in EN 1990 as the smaller value given by the two following expressions:

$$\eta_{fi} = \frac{G_k + \psi_{fi} Q_{k,1}}{\gamma_G G_k + \gamma_{Q,1} \psi_{0,1} Q_{k,1}} \tag{5}$$

$$\eta_{fi} = \frac{G_k + \psi_{fi} Q_{k,1}}{\xi \gamma_G G_k + \gamma_{Q,1} Q_{k,1}} \tag{6}$$

NOTE: As a simplification a recommended value of $\eta_{fi} = 0.7$ may be used.

Regarding equation (4), examples of the variation of the reduction factor η_{fi} versus the load ratio $Q_{k,1}/G_k$ with different values of the combination factor $\psi_{1,1}$ are shown in Figure 16.

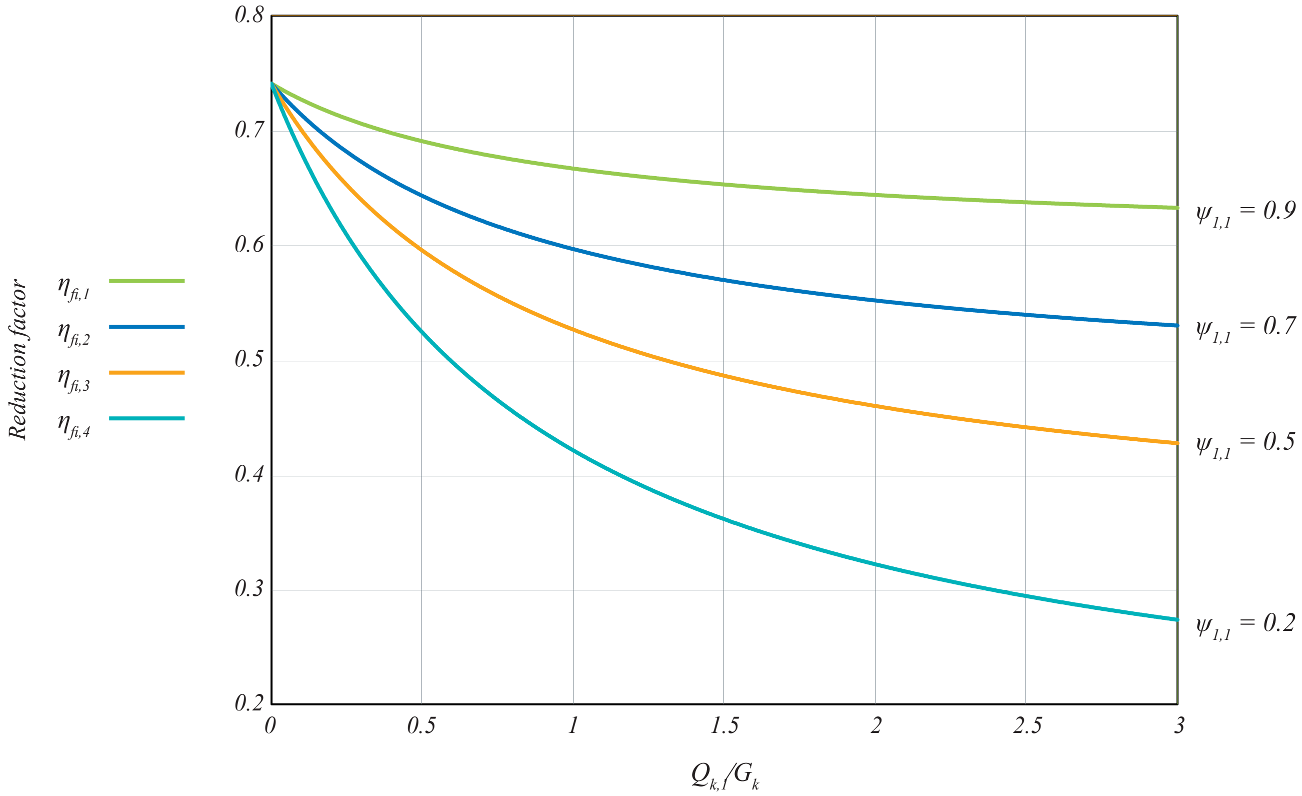


FIGURE 16. VARIATIONS OF THE REDUCTION FACTOR H_{FI}, ARGUMENT THE LOAD RATIO $Q_{K,1}/G_K$. FOR LOAD COMBINATION (6.10) ACCORDING TO EN 1990.

Where:

$Q_{k,1}$ is the principal variable load

G_k is the characteristic value of a permanent action

ψ_{fi} is the combination factor for frequent or quasi-permanent values given either by $\psi_{1,1}$ or $\psi_{2,1}$, see EN 1991-1-2

MECHANICAL RESPONSE

Strength and deformation properties at elevated temperature are defined according to EN 1992-1-2. High temperatures will weaken the mechanical properties of steel and concrete and reduce mechanical resistance of column connection.

CONCRETE UNDER COMPRESSION

The strength and deformation properties of concrete at elevated temperature shall be obtained from the stress-strain relationships as presented in Figures 17 and 26. The stress-strain curve is defined by

- the compressive strength $f_{c,\theta}$
- the strain $\varepsilon_{c1,\theta}$ corresponding to $f_{c,\theta}$
- ultimate compressive strain $\varepsilon_{c1,\theta}$ under fire exposure.

Values of each of these parameters are given in Table 1 as a function of concrete temperature. For the intermediate values of the temperature, linear interpolation is used.

Concrete temperature	Siliceous aggregates		
	$f_{c,\theta}/f_{ck}$	$\varepsilon_{c1,\theta}$	$\varepsilon_{cu1,\theta}$
[°C]	[-]	[-]	[-]
20	1.00	0.0025	0.0200
100	1.00	0.0040	0.0225
200	0.95	0.0055	0.0250
300	0.85	0.0070	0.0275
400	0.75	0.0100	0.0300
500	0.60	0.0150	0.0325
600	0.45	0.0250	0.0350
700	0.30	0.0250	0.0375
800	0.15	0.0250	0.0400
900	0.08	0.0250	0.0425
1000	0.04	0.0250	0.0450
1100	0.01	0.0250	0.0475
1120	0.00	-	-

TABLE 1. VALUES OF THE MAIN PARAMETERS OF THE STRESS-STRAIN CURVE AT ELEVATED TEMPERATURE IN ACCORDANCE TO EN 1992-1-2, SECTION 3.2.2.

Peikko Designer® for fire calculation uses strength reduction factors $k_c(\theta)$ according to the properties of normal weight concrete with siliceous aggregates.

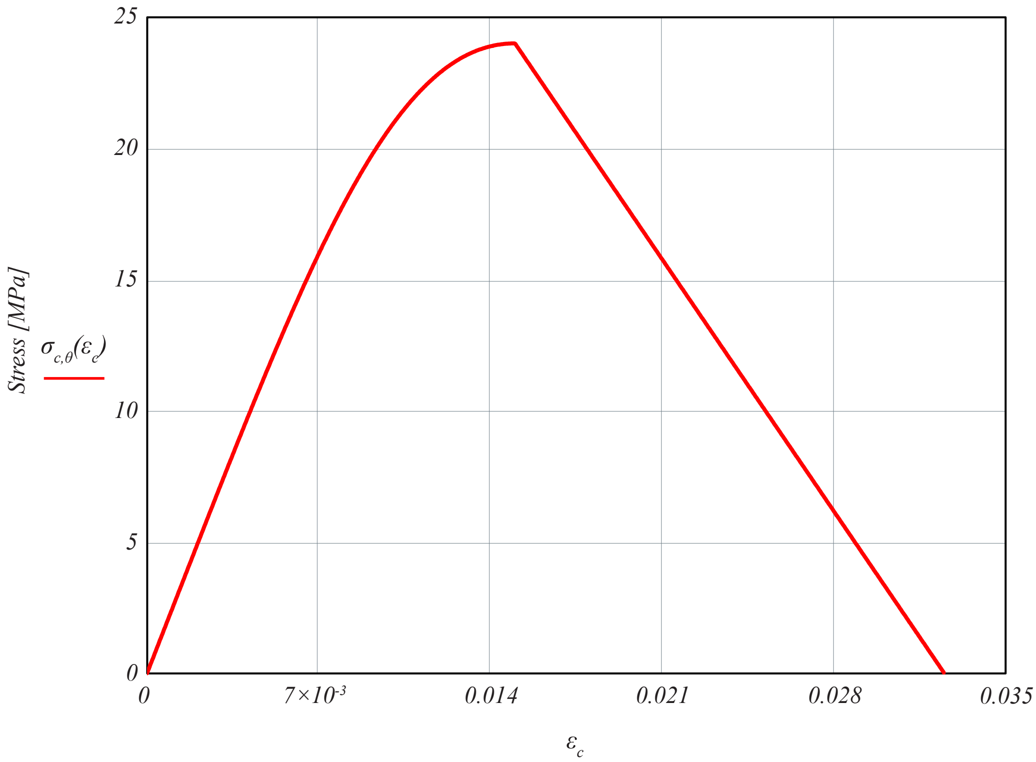


FIGURE 17. EXAMPLE OF STRESS-STRAIN CURVE. CONCRETE CLASS C40/50, TEMPERATURE 500°C.

REINFORCING STEEL (ANCHOR BOLTS)

The strength and deformation properties of reinforcement steel at elevated temperature shall be obtained from the stress-strain relationships as presented in Figures 18 and 26.

The stress-strain curve are defined by parameters:

- the slope of the linear elastic range E_s
- the proportional limit $f_{sp,\theta}$
- the maximum stress level $f_{sy,\theta}$.

Values for the parameters at elevated temperature are given in Table 2. For the intermediate values of the temperature, linear interpolation is used. The same mathematical model of stress-strain relationships is also applied for anchor bolts in tension and compression.

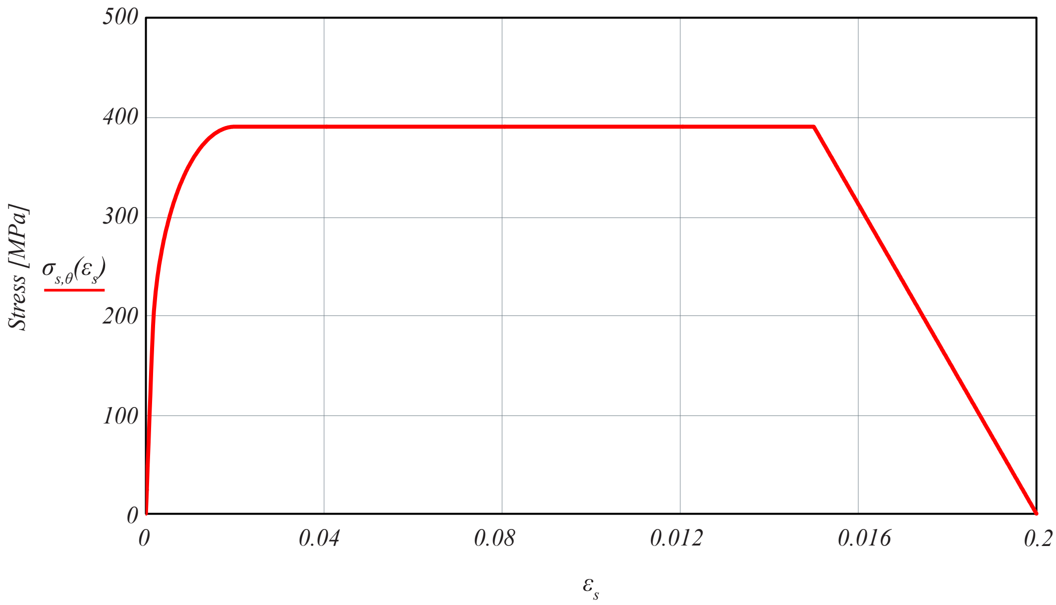


FIGURE 18. EXAMPLE OF STRESS-STRAIN CURVE. REINFORCEMENT B500B, TEMPERATURE 500°C.

Steel Temperature θ[°C]	$f_{sy,\theta}/f_{yk}$		$f_{sp,\theta}/f_{yk}$		$E_{s,\theta}/E_s$	
	Hot Rolled	Cold worked	**Hot Rolled**	Cold worked	**Hot Rolled**	Cold worked
20	**1.00**	1.00	**1.00**	1.00	**1.00**	1.00
100	**1.00**	1.00	**1.00**	0.96	**1.00**	1.00
200	**1.00**	1.00	**0.81**	0.92	**0.90**	0.87
300	**1.00**	1.00	**0.61**	0.81	**0.80**	0.72
400	**1.00**	0.94	**0.42**	0.63	**0.70**	0.56
500	**0.78**	0.67	**0.36**	0.44	**0.60**	0.40
600	**0.47**	0.40	**0.18**	0.26	**0.31**	0.24
700	**0.23**	0.12	**0.07**	0.08	**0.13**	0.08
800	**0.11**	0.11	**0.05**	0.06	**0.09**	0.06
900	**0.06**	0.08	**0.04**	0.05	**0.07**	0.05
1000	**0.04**	0.05	**0.02**	0.03	**0.04**	0.03
1100	**0.02**	0.03	**0.01**	0.02	**0.02**	0.02
1200	**0.00**	0.00	**0.00**	0.00	**0.00**	0.00

TABLE 2. VALUES OF THE MAIN PARAMETERS OF THE STRESS-STRAIN CURVE AT ELEVATED TEMPERATURE IN ACCORDANCE TO EN 1992-1-2, SECTION 3.2.3.

Peikko Designer® for fire calculation uses strength reduction factors $k_c(\theta)$ according to the properties of hot rolled reinforcing steel as seen in Table 3.

DESIGN PROCEDURE TO VERIFY FIRE RESISTANCE

SUMMARY OF ALTERNATIVE METHODS OF EN 1992-1-2

There are two possibilities in the Eurocodes to design braced reinforced concrete columns under fire conditions with tabulated data: methods A and B. Method A is suitable exclusively for short columns whereas method B is complicated to use and cannot be applied for the most slender columns.

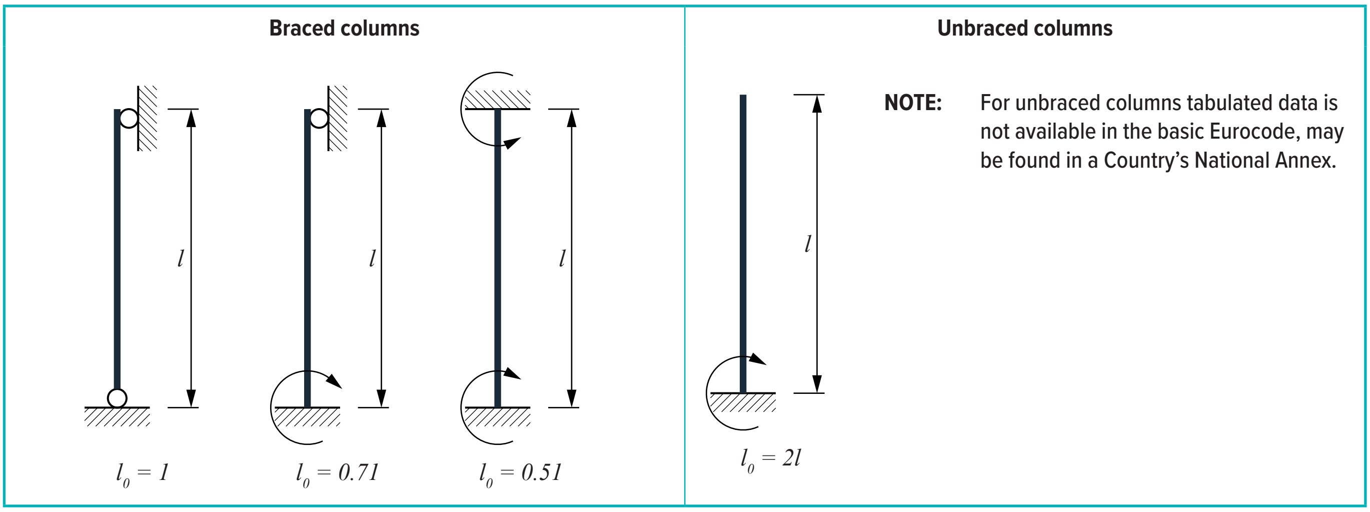
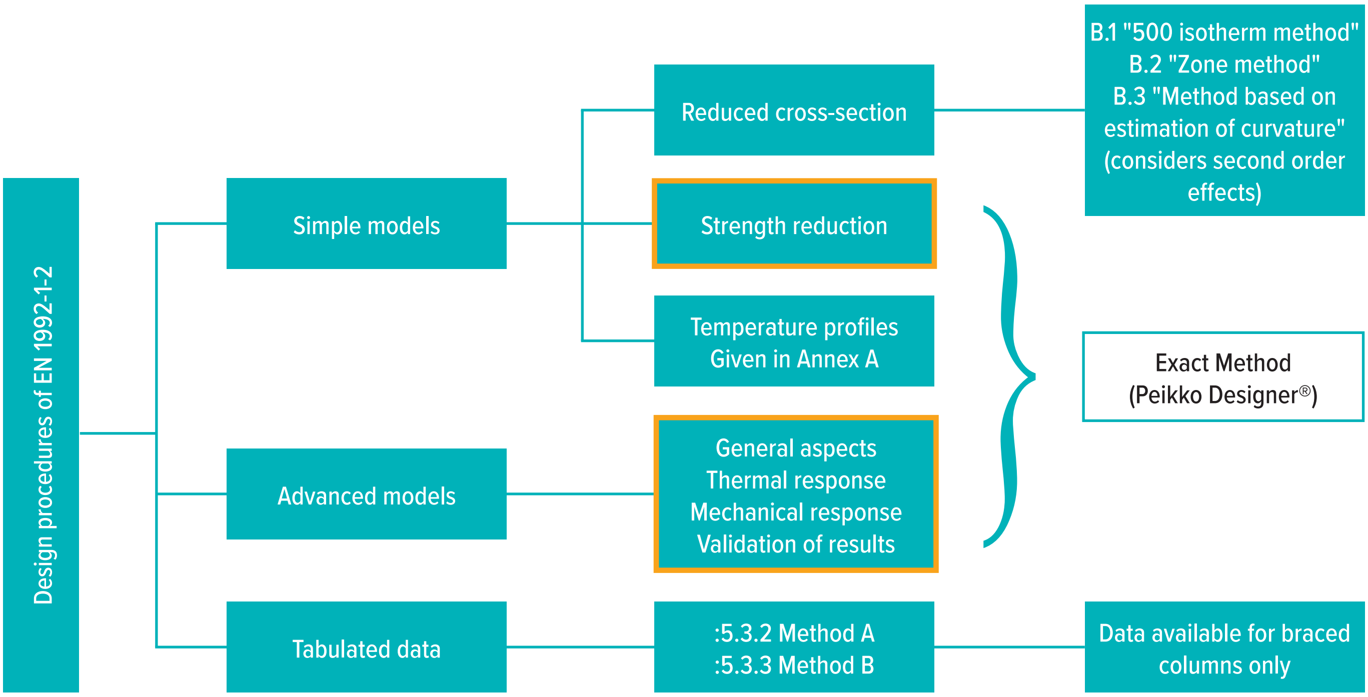


FIGURE 19. STRUCTURAL MODEL OF COLUMNS.



Peikko Designer® utilizes principles of simplified and advanced calculation models resulting in so called Exact Method to obtain fire resistance of fire exposed column connection. See following chapter.

Principles of advanced model regarding Peikko Designer® approach:

- General aspects ⇨ *Behavior of the column connection under fire exposure assessed*
- Thermal response ⇨ *Taken from corresponding finite element analysis*
- Mechanical response ⇨ *Taken according to EN 1992-1-2, material strength and deformation properties at elevated temperature*
- Validation ⇨ *Executed fire tests and Peikko Designer® result verification*

FIRE DESIGN IN PEIKKO DESIGNER®. EXACT METHOD

Using stress-strain temperature dependent laws Exact Method is utilized by Peikko Designer®. Exact Method is incremental/iterative procedure according to ***fib Bulletin 46: Fire design of concrete structures – structural behavior and assessment.***

In general, the fire design implemented in Peikko Designer® follows the logic of conventional calculation for reinforced concrete column in normal temperature.

The axial force-bending moment (N-M) resistance diagrams for the given cross-section are produced by variating strain distribution.

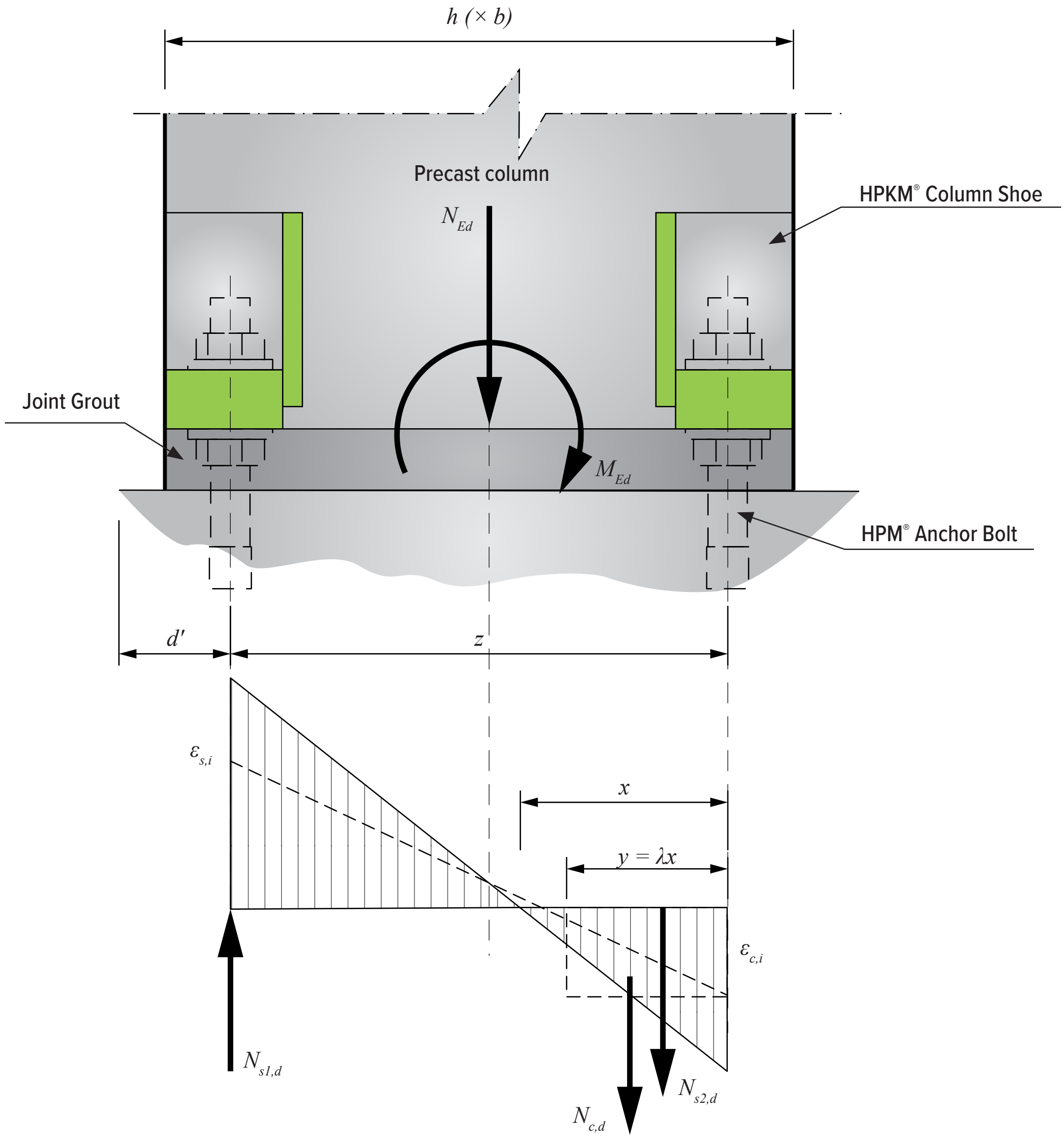


FIGURE 20. DESIGN PRINCIPLE ACCORDING TO EC 2, NORMAL TEMPERATURE DESIGN.

2D MESHING

Cross-section element grid example.

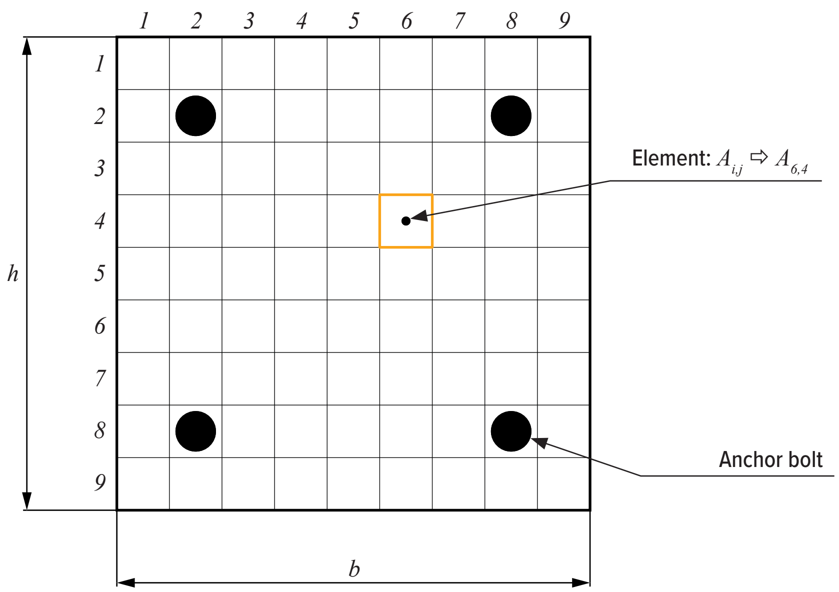


FIGURE 21. GRID OF RECTANGULAR CROSS-SECTION.

TEMPERATURE PROFILES

Average temperature for each concrete element in grid ($°t_{c,i,j}$) and for bolts ($°t_{b,n}$) calculated based on obtained temperature data.

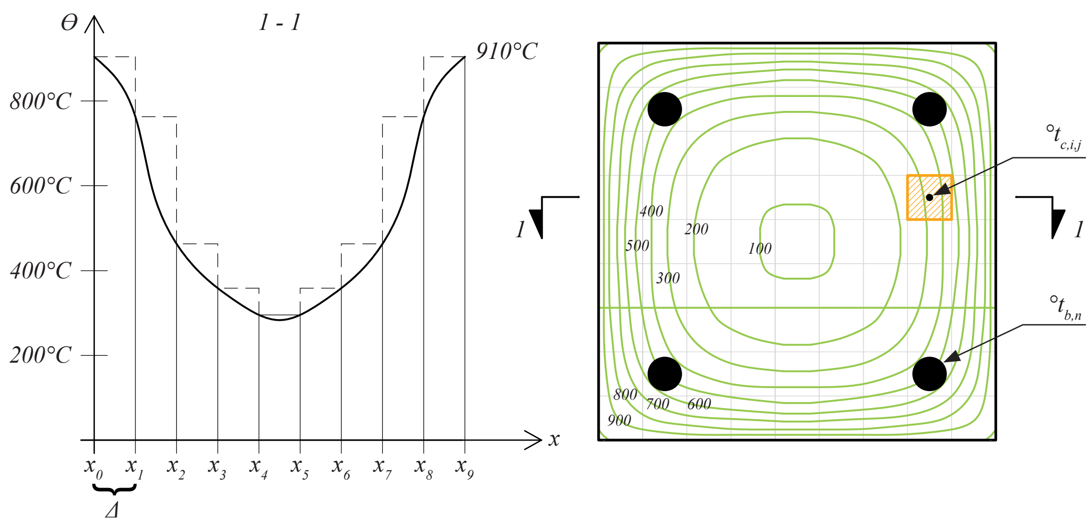


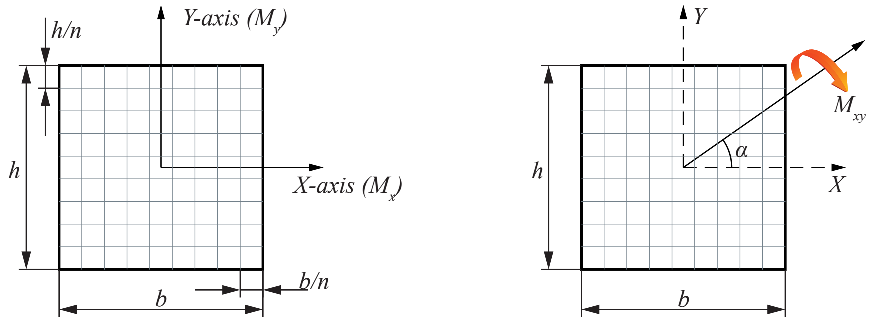
FIGURE 22. EXAMPLE ISOTHERM CURVES FOR RECTANGULAR CROSS-SECTION WITH 4 BOLTS.

Average temperature in each concrete element is calculated as follows.
As an example, expression for first element looks like:

$$^{\circ}t_{c,1,1} = \frac{1}{x_1 - x_0} \cdot \int_{x_0}^{x_1} \theta(x)\,dx \qquad (7)$$

COORDINATE SYSTEM

Origin of the coordinate system is placed in the center of gravity of the cross-section.
Depending on the direction of bending the corresponding axis is selected for the resistance domain.



Bending around X or Y axis

Bending around resultant direction

FIGURE 23. AXES OF COORDINATE SYSTEM.

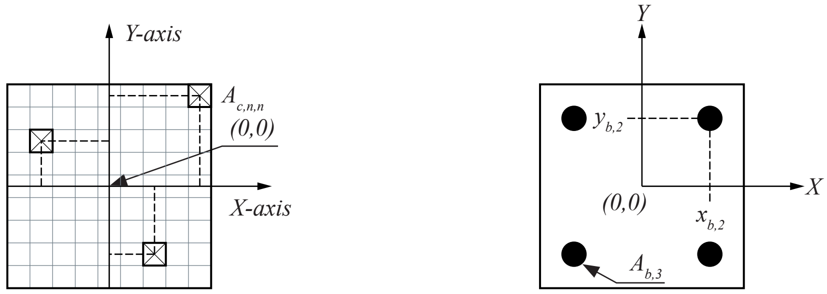
GEOMETRICAL CHARACTERISTICS

For each concrete element; calculate area $A_{c,i,j}$ and coordinates $\{x_{c,i,j};y_{c,i,j}\}$
For each bolt; calculate area $A_{b,n}$ and coordinates $\{x_{b,n};y_{b,n}\}$

Example:

$$\begin{matrix} concrete\,elements \\ (rectangular\,column) \end{matrix} = \begin{bmatrix} \{x_{c,1,1};y_{c,1,1}\}\,and\,A_{c,1,1} & \cdots & \{x_{c,1,n};y_{c,1,n}\}\,and\,A_{c,1,n} \\ \vdots & & \vdots \\ \{x_{c,n,1};y_{c,n,1}\}\,and\,A_{c,n,1} & \cdots & \{x_{c,n,n};y_{c,n,n}\}\,and\,A_{c,n,n} \end{bmatrix}$$

$$anchor\,bolts = \begin{bmatrix} \{x_{b,1};Y_{b,1}\}\,and\,A_{b,1} \\ \vdots \\ \{x_{b,n};Y_{b,n}\}\,and\,A_{b,n} \end{bmatrix}$$



Concrete elements

Anchor bolts

FIGURE 24. GEOMETRICAL CHARACTERISTICS OF COMPONENTS, RECTANGULAR CROSS-SECTION.

The force on each bolt and concrete element will be obtained from their area, material properties and the strain to which they are subjected. The coordinates of each bolt and concrete element represents the lever arms from which moments in the X and Y directions will be calculated.

STRENGTH AND DEFORMATION PROPERTIES AT ELEVATED TEMPERATURE

Depending on temperature at each point (calculated from thermal field over the cross-section) for each concrete element and bolt the strength and deformation properties are assigned, what then defines unique stress-strain relationship curve for each component. In this way, the cross-section is considered as a composite section, consisting of many different materials, whose properties are related to the maximum temperature reached locally.

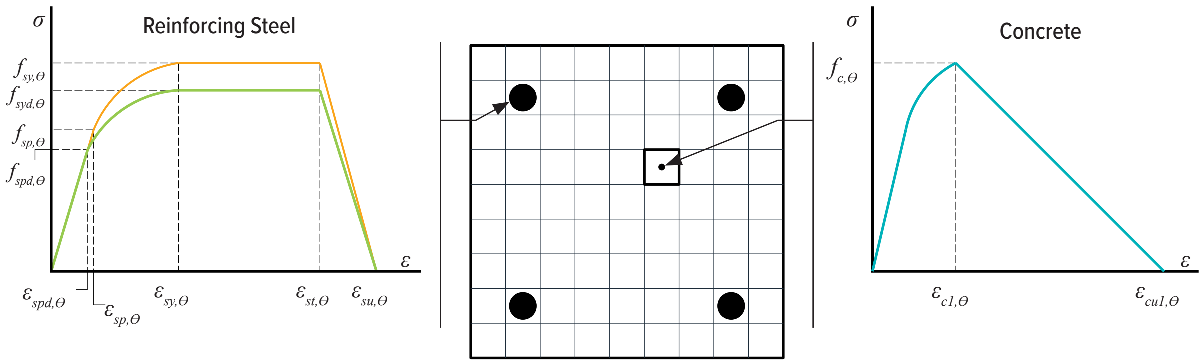


FIGURE 25. MATHEMATICAL MODEL FOR STRESS-STRAIN RELATIONSHIPS FOR EACH COMPONENT OF CROSS-SECTION.

CONCRETE

1. The design compressive strength $f_{cd,\theta}$ of concrete at temperature θ.

$$f_{cd,\theta} = k_{\theta,1} \cdot \frac{f_{ck}}{\gamma_{c,M,fi}} \qquad (8)$$

Where:

f_{ck} is the characteristic compressive strength for normal temperature design.
$k_{\theta,1}$ is the reduction factor for strength depending on element temperature, EN 1992-1-2: Table 3.1.
$\gamma_{c,M,fi}$ is the partial safety factor for the concrete, for the fire situation = 1.0 according to basic Eurocode.

2. The strain $\varepsilon_{c1,\theta}$ corresponding to $f_{c,\theta}$ (EN 1992-1-2: Table 3.1)

3. Ultimate compressive strain $\varepsilon_{cu1,\theta}$ under fire exposure (EN 1992-1-2: Table 3.1)

REINFORCING STEEL (ANCHOR BOLTS)

1. The design value of yield stress level $f_{syd,\theta}$ at temperature θ.

$$f_{syd,\theta} = k_{\theta,2} \cdot \frac{f_{yk}}{\gamma_{s,M,fi}} \cdot \eta_d \tag{9}$$

Where:

f_{yk} is the characteristic yield strength for normal temperature design.
$k_{\theta,2}$ is the reduction factor for yield strength depending on element temperature, EN 1992-1-2: Table 3.2a.
$\gamma_{s,M,fi}$ is the partial safety factor for the reinforcing steel, for the fire situation = 1.0 according to basic Eurocode.
η_d is the reduction factor to ensure stiffness of connection according to ETA 18/0037.

2. Design value of proportional stress limit $f_{spd,\theta}$ at temperature θ.

$$f_{spd,\theta} = k_{\theta,3} \cdot \frac{f_{yk}}{\gamma_{s,M,i}} \cdot \eta_d \tag{10}$$

Where:

f_{yk} is the characteristic yield strength for normal temperature design.
$k_{\theta,3}$ is the reduction factor for proportional strength limit depending on element temperature, EN 1992-1-2: Table 3.2a.
$\gamma_{s,M,fi}$ is the partial safety factor for the reinforcing steel, for the fire situation = 1.0 according to basic Eurocode.
η_d is the reduction factor according to ETA 18/0037.

3. The slope of the linear elastic range $E_{s,\theta}$ at temperature θ.

$$E_{s,\theta} = k_{\theta,4} \cdot E_s \tag{11}$$

Where:

E_s is Young's modulus of reinforcing steel for normal temperature design.
$k_{\theta,4}$ is the reduction factor for deformation property depending on element temperature, EN 1992-1-2: Table 3.2a.

4. Strain $\varepsilon_{spd,\theta}$ describing end of the proportional stress-strain range at temperature θ.

$$\varepsilon_{spd,\theta} = \frac{f_{spd,\theta}}{E_{s,\theta}} \tag{12}$$

5. Strain $\varepsilon_{sy,\theta} = 0.02$ corresponding to yield strength at temperature θ.

6. Strain $\varepsilon_{st,\theta} = 0.15$ describing end of yielding plateau at temperature θ.

7. Ultimate strain $\varepsilon_{su,\theta} = 0.20$ at temperature θ.

STRAIN DISTRIBUTION

When strain values ε_{sup} and ε_{inf} at edges are fixed the strain in each concrete element and bolt is calculated.

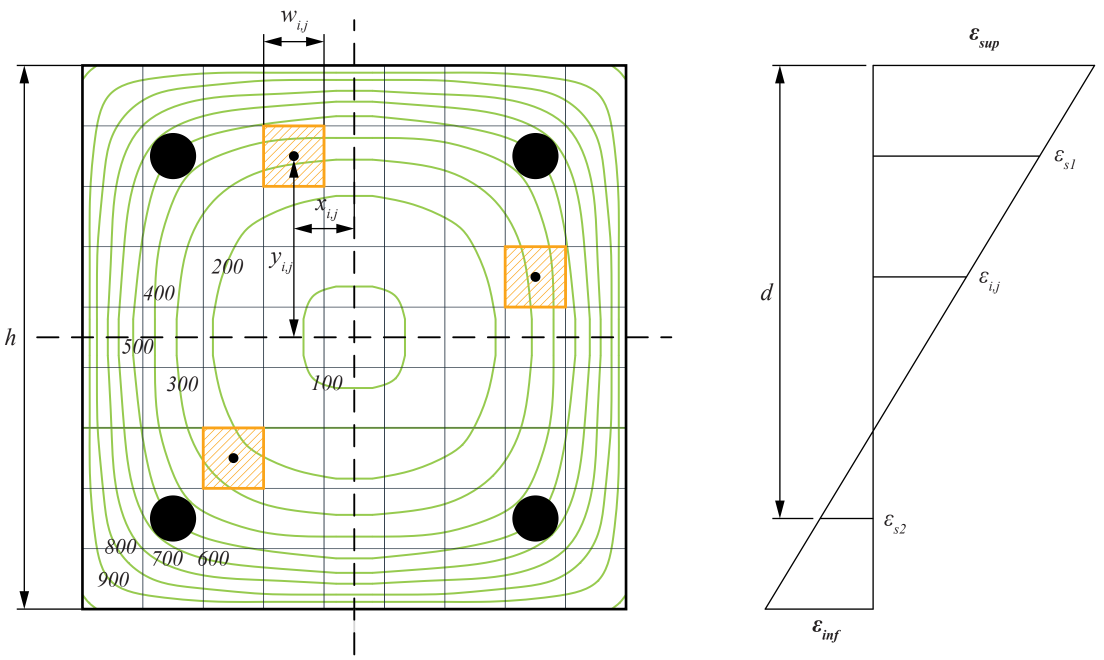


FIGURE 26. STRAIN DIAGRAM OF CROSS-SECTION.

Symbols

ε_{sup}	is set strain at the top edge of cross-section
ε_{inf}	is set strain at the bottom edge of cross-section
$\varepsilon_{i,j}$	is strain in concrete element
$\varepsilon_{s,i}$	is strain in the bolts
$w_{i,j}$	is width of concrete element
$x_{i,j}$	is x coordinate of concrete element
$y_{i,j}$	is y coordinate of concrete element
h	is length cross-section
d	is effective depth on tension bolts

INTERNAL STRESSES

When strain is known temperature dependent stress value in each concrete element and bolt is then calculated from corresponding functions.

STRESS FUNCTION FOR CONCRETE

Stress	Range
$\sigma_c(\theta) = \dfrac{3 \cdot \varepsilon \cdot f_{c,\theta}}{\varepsilon_{c1,\theta}\left(2 + \left(\dfrac{\varepsilon}{\varepsilon_{c1,\theta}}\right)^3\right)}$	$\varepsilon \leq \varepsilon_{c1,\theta}$
$\sigma_c(\theta) = \dfrac{f_{c,\theta}}{\varepsilon_{c1,\theta} - \varepsilon_{cu1,\theta}} \cdot (\varepsilon - \varepsilon_{cu1,\theta})$	$\varepsilon_{c1,\theta} < \varepsilon \leq \varepsilon_{cu1,\theta}$

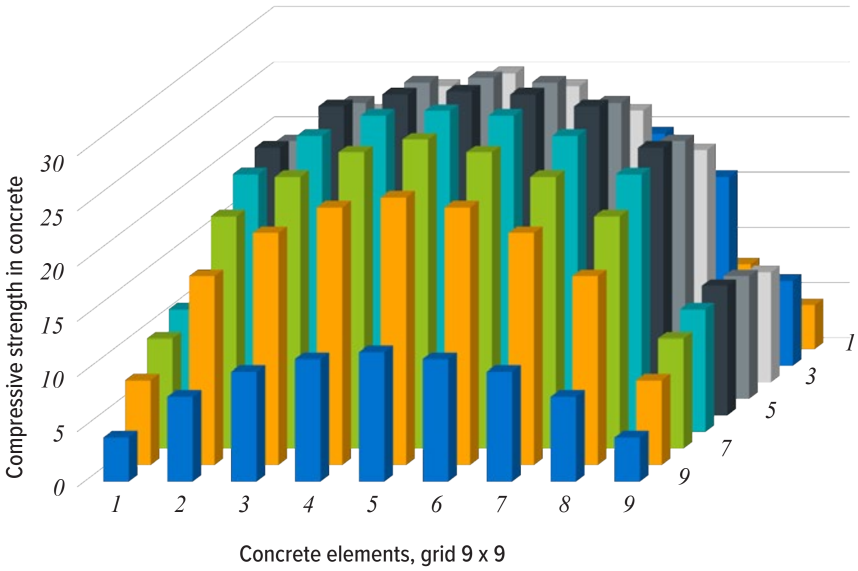


FIGURE 27. REACTION IN EACH CONCRETE ELEMENT. COLUMN 280 MM × 280 MM, CONCRETE C30/37, BOLT HPM 30, FIRE CLASS R60. CROSS-SECTION RECTANGULAR.

STRESS FUNCTION FOR REINFORCING STEEL (ANCHOR BOLTS)

Stress	Range
$\sigma_s(\theta) = \varepsilon \cdot E_{s,\theta}$	$\varepsilon < \varepsilon_{sp,\theta}$
$\sigma_s(\theta) = f_{sp,\theta} - c + \left(\frac{b}{a}\right) \cdot \left(a^2 - \left(\varepsilon_{sy,\theta} - \varepsilon\right)^2\right)^{0.5}$	$\varepsilon_{sp,\theta} \le \varepsilon \le \varepsilon_{sy,\theta}$
$\sigma_s(\theta) = f_{sy,\theta}$	$\varepsilon_{sy,\theta} \le \varepsilon \le \varepsilon_{st,\theta}$
$\sigma_s(\theta) = f_{sy,\theta} \cdot \left[1 - \frac{\varepsilon - \varepsilon_{st,\theta}}{\varepsilon_{su,\theta} - \varepsilon_{st,\theta}}\right]$	$\varepsilon_{st,\theta} \le \varepsilon \le \varepsilon_{su,\theta}$
$\sigma_s(\theta) = 0,0$	$\varepsilon = \varepsilon_{su,\theta}$
Intermediate parameters used in expressions: $a^2 = \left(\varepsilon_{sy,\theta} - \varepsilon_{sp,\theta}\right)\left(\varepsilon_{sy,\theta} - \varepsilon_{sp,\theta} + \frac{c}{E_{s,\theta}}\right)$ $b^2 = c\left(\varepsilon_{sy,\theta} - \varepsilon_{sp,\theta}\right)E_{s,\theta} + c^2$ $c = \frac{\left(f_{sy,\theta} - f_{sp,\theta}\right)^2}{\left(\varepsilon_{sy,\theta} - \varepsilon_{sp,\theta}\right)E_{s,\theta} - 2\left(f_{sy,\theta} - f_{sp,\theta}\right)}$	

INTERNAL FORCES IN CONCRETE

From known stress value internal force in each concrete element is calculated:

$$F_{c,i,j} = A_{c,i,j} \cdot \sigma_{c,\theta,i,j} \tag{13}$$

Where:

$A_{c,i,j}$ is area of concrete element.

$\sigma_{c,\theta,i,j}$ is stress value over the element.

Resultant force in concrete:

Rectangular cross-section

$$F_c = \sum_{i=1}^{n} \sum_{j=1}^{n} A_{c,i,j} \cdot \sigma_{c,\theta,i,j} \tag{14}$$

Circular cross-section

$$F_c = \sum_{i=1}^{n} A_{c,i} \cdot \sigma_{c,\theta,i} \tag{15}$$

INTERNAL FORCES IN BOLTS

From known stress value internal force in each bolt is calculated:

$$F_{b,n} = A_{b,n} \cdot \sigma_{s,\theta,n} \quad (16)$$

Where:

$A_{b,n}$ is stress area in bolt's thread.
$\sigma_{s,\theta,n}$ is stress in a bolt.

Resultant force from anchor bolts:

$$F_b = \sum_{n=1}^{number\ of\ bolts} A_{b,n} \cdot \sigma_{s,\theta,n} \quad (17)$$

BENDING RESISTANCE PART RESULTING FROM EACH CONCRETE ELEMENT

Bending resistance of each element in relation to X and Y axis:

$$M_{xc,i,j} = F_{c,i,j} \cdot y_{c,i,j} \quad (18)$$

$$M_{yc,i,j} = F_{c,i,j} \cdot x_{c,i,j} \quad (19)$$

Where:

$f_{c,i,j}$ is force in concrete element.
$x_{c,i,j}$ is lever arm of concrete element in relation to Y-axis.
$y_{c,i,j}$ is lever arm of concrete element in relation to X-axis.

Bending resistance from concrete in relation to X and Y axis:

Rectangular cross-section

$$M_{xc} = \sum_{i=1}^{n}\sum_{j=1}^{n} F_{c,i,j} \cdot y_{c,i,j} \quad (20)$$

$$M_{yc} = \sum_{i=1}^{n}\sum_{j=1}^{n} F_{c,i,j} \cdot x_{c,i,j} \quad (21)$$

Circular cross-section

$$Mx_c = \sum_{i=1}^{n} F_{c,i} \cdot y_{c,i} \quad (22)$$

$$My_c = \sum_{i=1}^{n} F_{c,i} \cdot x_{c,i} \quad (23)$$

Resultant bending resistance from concrete:

$$M_c = \sqrt{M_{xc}^{\ 2} + M_{yc}^{\ 2}} \quad (24)$$

BENDING RESISTANCE RESULTING FROM ANCHOR BOLTS

Bending resistance of each bolt in relation to X and Y axis:

$$M_{xb,n} = F_{b,n} \cdot y_{b,n} \tag{25}$$

$$M_{yb,n} = F_{b,n} \cdot x_{b,n} \tag{26}$$

Where:

$F_{b,n}$ is force in the anchor bolt.

$x_{b,n}$ is lever arm of anchor bolt in relation to Y-axis.

$y_{b,n}$ is lever arm of anchor bolt in relation to X-axis.

Bending resistance from anchor bolts:

$$M_{xb} = \sum_{n=1}^{number\ of\ bolts} F_{b,n} \cdot y_{b,n} \tag{27}$$

$$M_{yb} = \sum_{n=1}^{number\ of\ bolts} F_{b,n} \cdot x_{b,n} \tag{28}$$

Resultant bending resistance from anchor bolts:

$$M_b = \sqrt{M_{xb}^2 + M_{yb}^2} \tag{29}$$

RESISTANCE OF CROSS-SECTION (N-M DIAGRAMS)

$$N_{Rd,fi} = F_c + F_b \tag{30}$$

$$M_{Rd,fi} = M_c + M_b \tag{31}$$

The interaction design curve is obtained through an iterative process. Each point of the curve is defined by setting a N_{Rd} value and varying the bending moment until its maximum value M_{Rd} is reached.

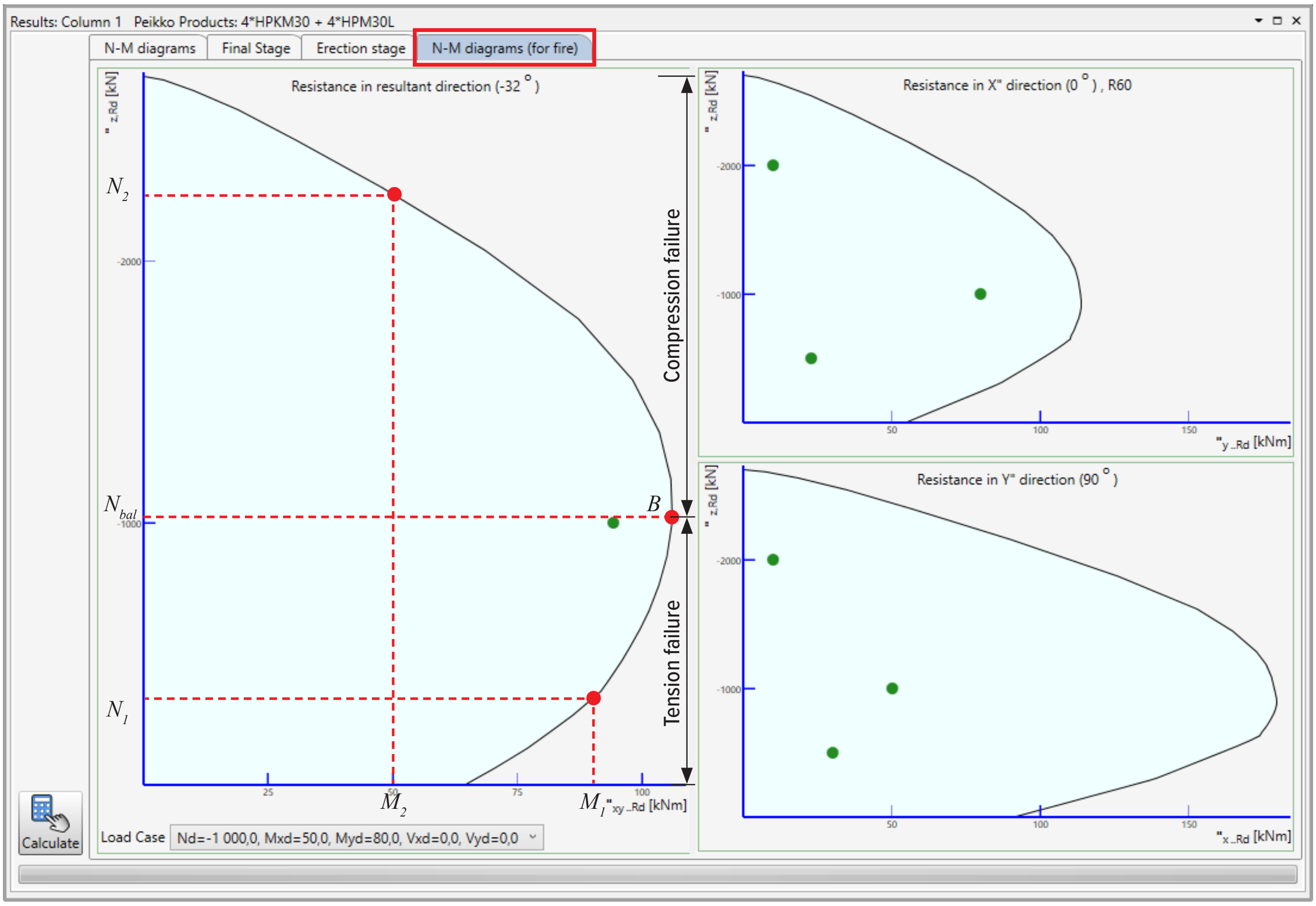


FIGURE 28. N-M FIRE RESISTANCE DIAGRAMS.

Modes of failure

Tension failure: failure begins with yielding of the tensile reinforcement, followed by crushing of the concrete as the tensile strains rapidly increases. Limiting factor is anchor bolt steel strength.

Balance failure, Point B: when failure occurs with yielding of the tension steel and crushing of the concrete at the same instant. Balance failure represents the biggest bending moment resistance M_{bal} corresponding to axial load N_{bal}.

Compression failure: when the load $N_{Ed} > N_{bal}$ the section will fail in compression. Primary limiting factor concrete compression strength.

NOTE ON SECOND ORDER EFFECTS

$M_{Rd,fi}$ in Peikko Designer® is ultimate moment capacity for $N_{Ed,fi}$.

$$M_{Rd,fi} = M_{0Rd,fi} + M_{2,fi} \tag{32}$$

Where:

$M_{0Rd,fi}$ is first order moment capacity.

$M_{2,fi}$ is second order moment.

Hence input bending moment load $M_{Ed,fi}$ shall already include second order effects.

$$M_{Ed,fi} = M_{0Ed,fi} + M_{2,fi} \tag{33}$$

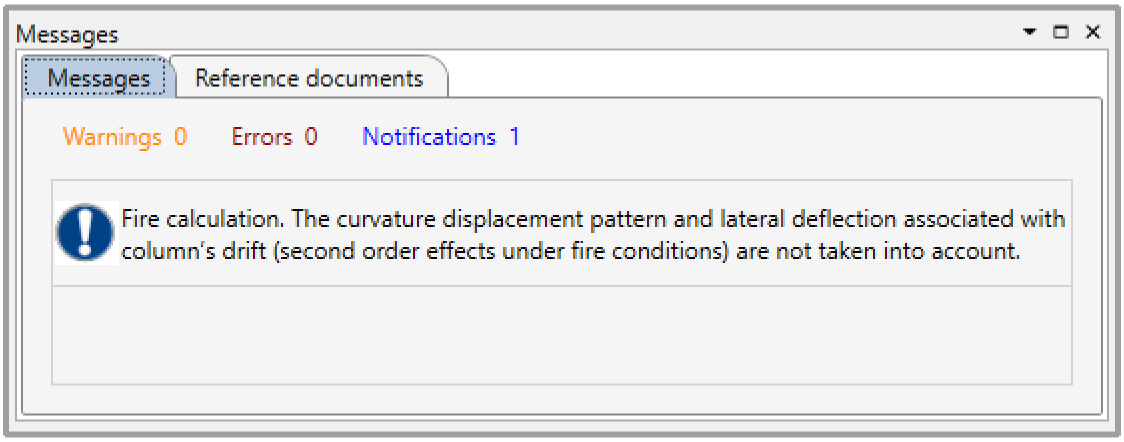


FIGURE 29. NOTIFICATION REGARDING FIRE DESIGN DISPLAYED IN PEIKKO DESIGNER®.

Also note that Peikko Designer® doesn't check critical load $P_{cr,fi}$ for column's **buckling failure mode** as design is done specifically for the connection. Under fire conditions, the damage of the outer layers of the column due to high temperatures, combined with drop of the elasticity modulus at the inner layers, results in a decrease of the stiffness of structural member. Because of this, second order effects can be significant for columns in the fire situation.

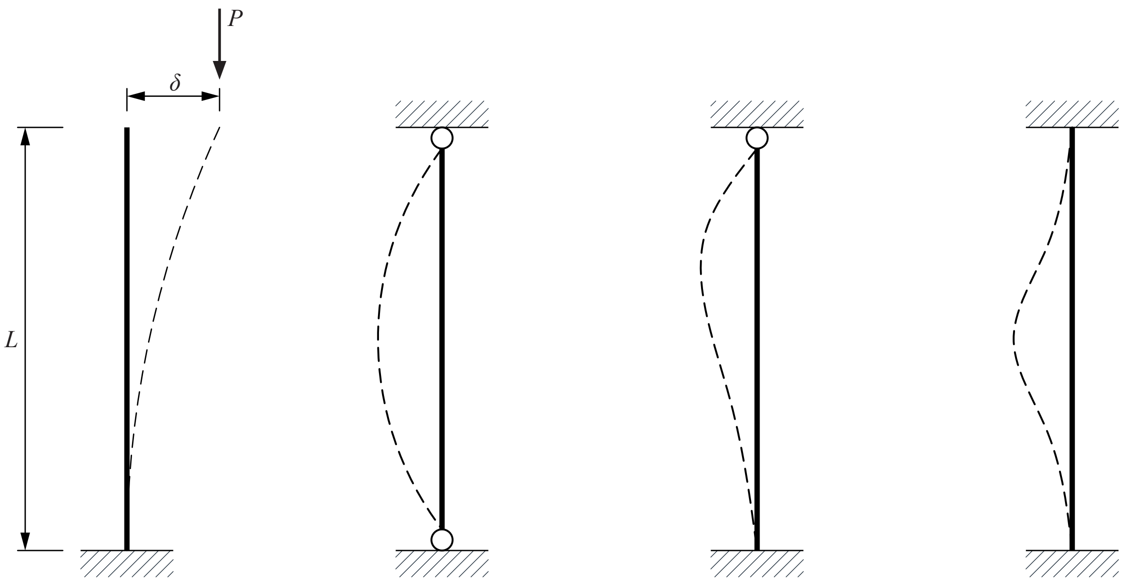


FIGURE 30. EXAMPLES OF DIFFERENT BUCKLING MODES.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