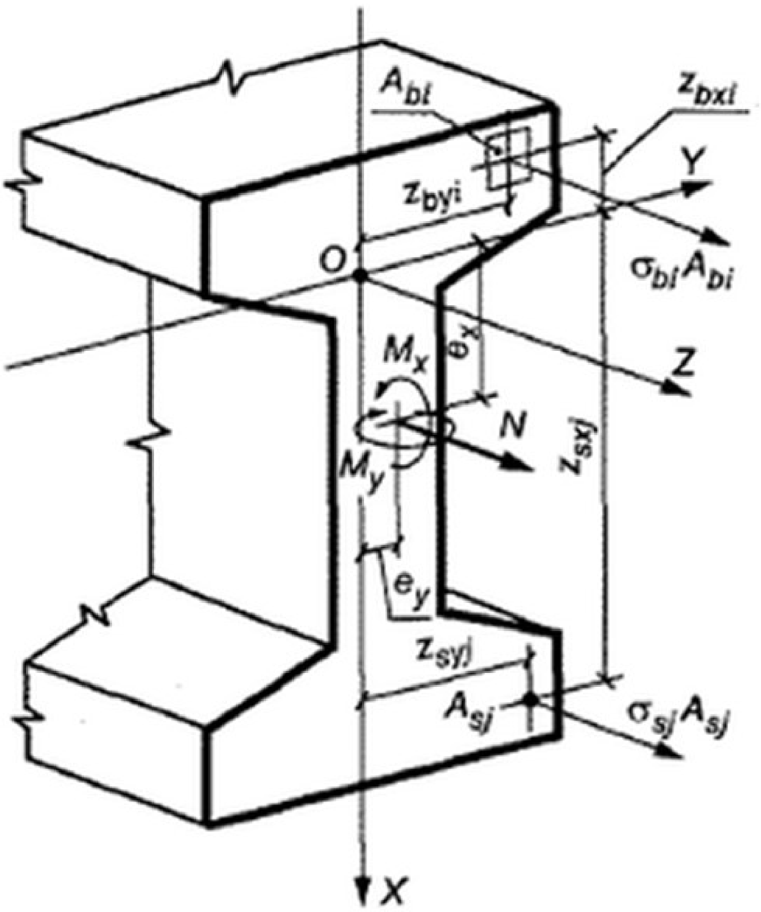
Strength calculation of normal sections based on a nonlinear deformation model



1. Rectangular section

$B := 400\ mm$ $H := 600\ mm$ $n_b := 8$ $n_h := 12$

$A_c := B \cdot H = 0.24\ m^2$ $\Delta B := \frac{B}{n_b} = 0.05\ m$ $\Delta H := \frac{H}{n_h} = 0.05\ m$ $A_{bi} := \Delta B \cdot \Delta H = 0.0025\ m^2$

Reinforcing bars

X_s (mm)	Y_s (mm)	d_s (mm)
250	−150	32
250	150	32
−250	−150	32
−250	150	32
0	−150	18
0	150	18

$ns := \text{rows}(X_s) = 6$

Concrete elements

$$Sec := \left\| \begin{array}{l} \text{for } i \in 0..n_b-1 \\ \quad \left\| \begin{array}{l} \text{for } j \in 0..n_h-1 \\ \quad \left\| \begin{array}{l} Sec_{j+i\cdot n_h,0} \leftarrow -\frac{H}{2}+\Delta H\cdot j+\frac{\Delta H}{2} \\ Sec_{j+i\cdot n_h,1} \leftarrow -\frac{B}{2}+\Delta B\cdot i+\frac{\Delta B}{2} \end{array} \right. \end{array} \right. \\ Sec \end{array} \right.$$

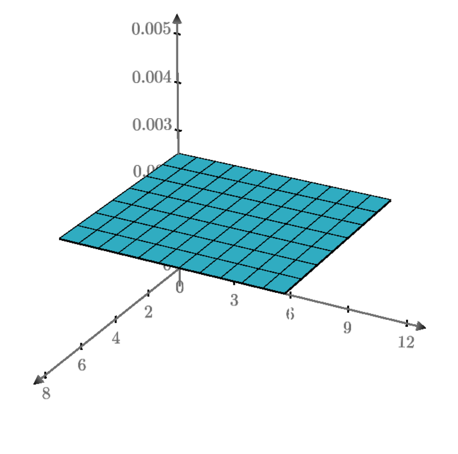
$$nb := \text{rows}(Sec) = 96$$

$$A_b := \left\| \begin{array}{l} \text{for } i \in 0..nb-1 \\ \quad \left\| A_{b_i} \leftarrow A_{bi} \right. \\ A_b \end{array} \right.$$

$$Ab := \left\| \begin{array}{l} \text{for } i \in 0..n_b-1 \\ \quad \left\| \begin{array}{l} \text{for } j \in 0..n_h-1 \\ \quad \left\| Ab_{i,j} \leftarrow A_{bi} \right. \end{array} \right. \\ Ab \end{array} \right.$$

$$X_b := Sec^{\langle 0 \rangle}$$

$$Y_b := Sec^{\langle 1 \rangle}$$



$Ab \ (m^2)$

Loads

N (kN)	M_x $(kN\cdot m)$	M_y $(kN\cdot m)$
−2600	250	−200

$$kM_x := \frac{M_x}{|M_x|} = 1 \qquad kM_y := \frac{M_y}{|M_y|} = -1$$

$$L := \begin{bmatrix} N \\ M_x \\ M_y \end{bmatrix} = \begin{bmatrix} -2600000\ N \\ 250000\ J \\ -200000\ J \end{bmatrix}$$

Включить << D:\Programs\MathCAD_Prime\Column\Concrete.mcdx

$$rb := \text{match}(\text{“B25”}, Grade\_b)_0 = 2 \qquad R_b := R\_b_{rb} = -14.5\ MPa \qquad k_{bt} := 0 \qquad R_{bt} := R\_bt_{rb} \cdot k_{bt} = 0\ MPa$$

$$\varepsilon_{b2} := \varepsilon_{b\_2_{rb}} = -0.004 \qquad \varepsilon_{b0} := \varepsilon_{b\_0_{rb}} = -0.002 \qquad \varepsilon_{bt0} := \varepsilon_{b\_t0_{rb}} = 1\cdot 10^{-4} \qquad \varepsilon_{bt2} := \varepsilon_{b\_t2_{rb}} = 1.5\cdot 10^{-4}$$

$$E_{bi} := E\_b_{rb} = (3\cdot 10^4)\ MPa \qquad \sigma_{b1} := 0.6\cdot R_b = -8.7\ MPa \qquad \sigma_{bt1} := 0.6\cdot R_{bt} = 0\ MPa$$

$$\varepsilon_{b1} := \frac{\sigma_{b1}}{E_{bi}} = -2.9\cdot 10^{-4} \qquad \varepsilon_{bt1} := \frac{\sigma_{bt1}}{E_{bi}} = 0$$

Включить << D:\Programs\MathCAD_Prime\Column\Effective_length.mcdx

$l_c = 6\ m$ $\mu_x = 0.7$ $\mu_y = 0.7$ $st_x = \text{“indef”}$ $st_y = \text{“indef”}$

$l_{0x} := \mu_x \cdot l_c = 4.2\ m$

Случайный эксцентриситет

$l_{0y} := \mu_y \cdot l_c = 4.2\ m$

$$e_{ax} := \max\left(\frac{l_c}{600}, \frac{H}{30}, 10\ mm\right) = 2\ cm \qquad e_{ay} := \max\left(\frac{l_c}{600}, \frac{B}{30}, 10\ mm\right) = 1.333\ cm$$

Эксцентриситет продольной силы

$$e_{0x} := \left\| \begin{array}{l} \text{if } st_x = \text{“indef”} \\ \quad \left\| \begin{array}{l} \text{if } e_{ax} > \left|\dfrac{M_x}{N}\right| \\ \quad \| e \leftarrow e_{ax} \\ \text{else} \\ \quad \| e \leftarrow 0\ m \end{array} \right. \\ \text{else} \\ \quad \| e \leftarrow e_{ax} \\ e \end{array} \right. = 0\ cm \qquad e_{0y} := \left\| \begin{array}{l} \text{if } st_y = \text{“indef”} \\ \quad \left\| \begin{array}{l} \text{if } e_{ay} > \left|\dfrac{M_y}{N}\right| \\ \quad \| e \leftarrow e_{ay} \\ \text{else} \\ \quad \| e \leftarrow 0\ m \end{array} \right. \\ \text{else} \\ \quad \| e \leftarrow e_{ay} \\ e \end{array} \right. = 0\ cm$$

Коэффициент длительности нагрузки

$M_{1x} := M_x = 250\ kN \cdot m$ $M_{1y} := M_y = -200\ kN \cdot m$

$k_{dx} := 0.5$ $k_{dy} := 0.5$

$M_{1lx} := k_{dx} \cdot M_{1x} = 125\ kN \cdot m$ $M_{1ly} := k_{dy} \cdot M_{1y} = -100\ kN \cdot m$

$$\varphi_{lx} := \left\| \begin{array}{l} \varphi \leftarrow 1 + \dfrac{M_{1lx}}{M_{1x}} \\ \text{if } \varphi > 2 \\ \quad \| \varphi \leftarrow 2 \\ \text{else} \\ \quad \| \varphi \\ \varphi \end{array} \right. = 1.5 \qquad \varphi_{ly} := \left\| \begin{array}{l} \varphi \leftarrow 1 + \dfrac{M_{1ly}}{M_{1y}} \\ \text{if } \varphi > 2 \\ \quad \| \varphi \leftarrow 2 \\ \text{else} \\ \quad \| \varphi \\ \varphi \end{array} \right. = 1.5$$

$$h_{0x} := \max\left(X_s\right) + \frac{H}{2} = 0.55\ m \qquad h_{0y} := \max\left(Y_s\right) + \frac{B}{2} = 0.35\ m$$

Момент инерции площади сечения бетона

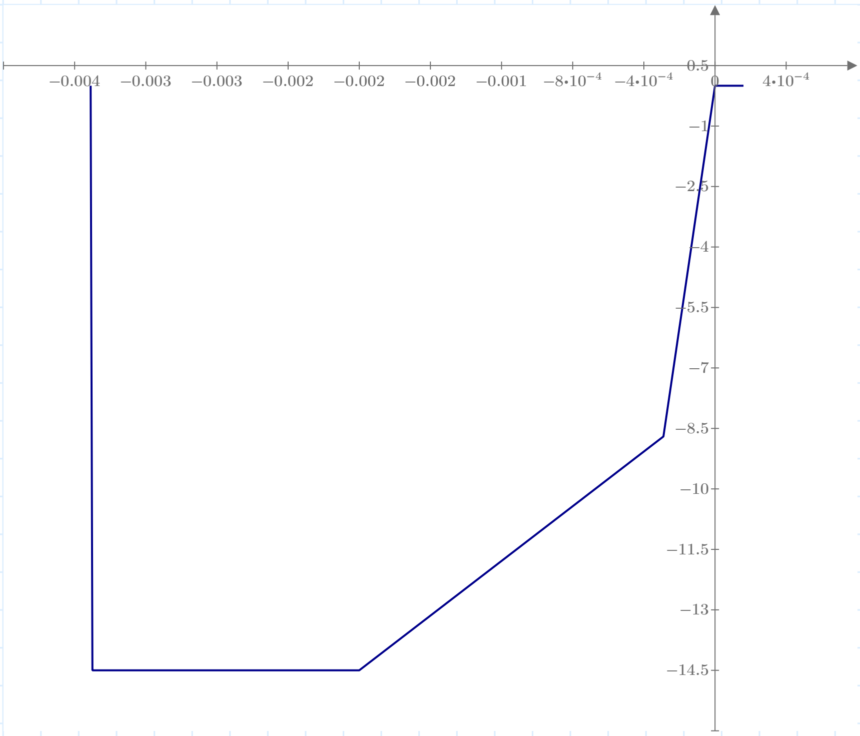
$$I_{by} := \frac{B \cdot H^3}{12} = 0.007\ m^4 \quad \lambda_x := \frac{l_{0x}}{\sqrt{\dfrac{I_{by}}{A_c}}} = 24.249 \qquad I_{bx} := \frac{H \cdot B^3}{12} = 0.003\ m^4 \quad \lambda_y := \frac{l_{0x}}{\sqrt{\dfrac{I_{bx}}{A_c}}} = 36.373$$

$$\sigma b(\varepsilon) := \left\| \begin{array}{l} \text{if } \varepsilon \ge \varepsilon_{b2} \wedge \varepsilon \le \varepsilon_{b0} \\ \quad \| \ \sigma_b \leftarrow R_b \\ \text{else if } \varepsilon > \varepsilon_{b0} \wedge \varepsilon < \varepsilon_{b1} \\ \quad \left\| \ \sigma_b \leftarrow R_b + (\varepsilon - \varepsilon_{b0}) \cdot \dfrac{\sigma_{b1} - R_b}{\varepsilon_{b1} - \varepsilon_{b0}} \right. \\ \text{else if } \varepsilon \ge \varepsilon_{b1} \wedge \varepsilon \le \varepsilon_{bt1} \\ \quad \left\| \ \sigma_b \leftarrow \sigma_{b1} + (\varepsilon - \varepsilon_{b1}) \cdot \dfrac{\sigma_{b1}}{\varepsilon_{b1}} \right. \\ \text{else if } \varepsilon > \varepsilon_{bt1} \wedge \varepsilon < \varepsilon_{bt0} \\ \quad \left\| \ \sigma_b \leftarrow R_{bt} + (\varepsilon - \varepsilon_{bt0}) \cdot \dfrac{\sigma_{bt1} - R_{bt}}{\varepsilon_{bt1} - \varepsilon_{bt0}} \right. \\ \text{else if } \varepsilon \ge \varepsilon_{bt0} \wedge \varepsilon \le \varepsilon_{bt2} \\ \quad \| \ \sigma_b \leftarrow R_{bt} \\ \text{else} \\ \quad \| \ \sigma_b \leftarrow 0 \\ \sigma_b \end{array} \right.$$

$$E_b := \left\| \begin{array}{l} \text{for } i \in 0 \,..\, nb-1 \\ \quad \| \ E_{b_i} \leftarrow E_{bi} \\ E_b \end{array} \right.$$

$$\varepsilon_{bi} := \varepsilon_{b2} - 0.00001, \varepsilon_{b2} \,..\, \varepsilon_{bt2} + 0.00001$$

Concrete strain-stress diagram



$\sigma b(\varepsilon_{bi})$ (MPa)

ε_{bi}

Включить << D:\Programs\MathCAD_Prime\Column\Rebar.mcdx

$rs := \text{match}(\text{“A400”}, Grade\_s)_0 = 1$ $\varepsilon_{sc2} := \varepsilon_{s\_c2_{rs}} = -0.025$ $\varepsilon_{s2} := \varepsilon_{s\_2_{rs}} = 0.025$

$R_{sc} := R_{s\_c_{rs}} = -350\ MPa$ $R_s := R\_s_{rs} = 350\ MPa$ $E_{sj} := E\_s_{rs} = (2 \cdot 10^5)\ MPa$

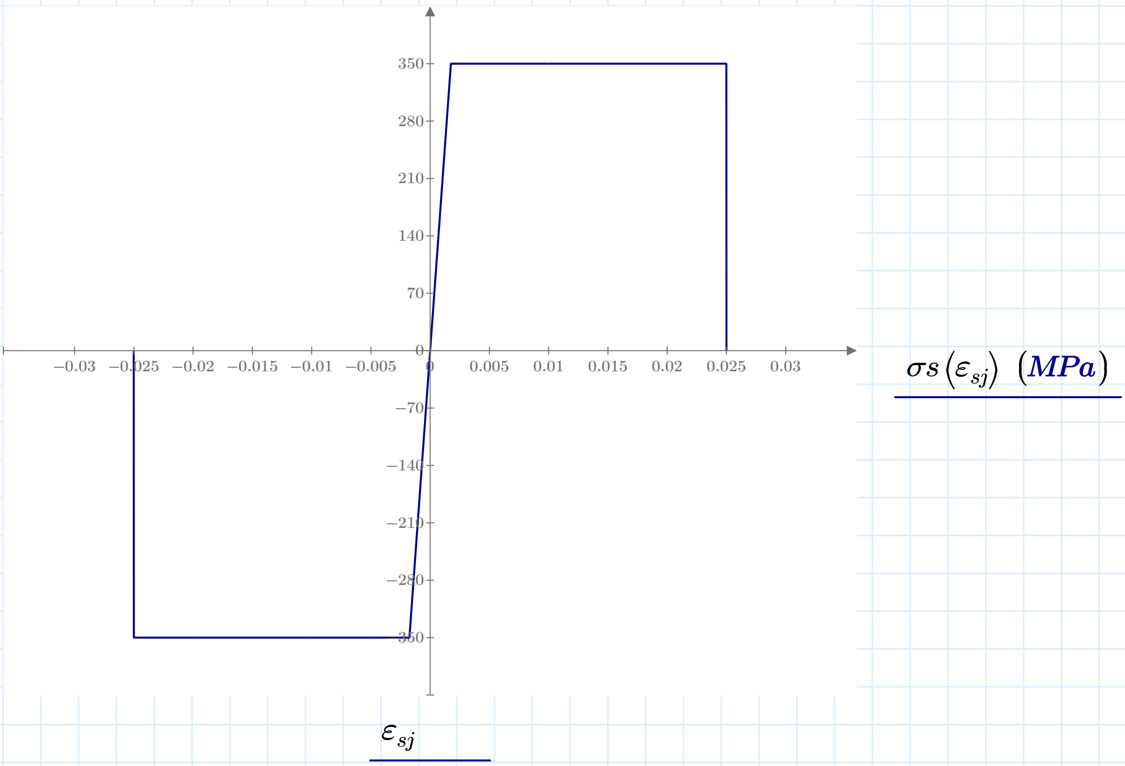
$\varepsilon_{sc0} := \frac{R_{sc}}{E_{sj}} = -0.00175$ $\varepsilon_{s0} := \frac{R_s}{E_{sj}} = 0.00175$

$$E_s := \begin{Vmatrix} \text{for } j \in 0..ns-1 \\ \quad \Vert\ E_{s_j} \leftarrow E_{sj} \\ E_s \end{Vmatrix}$$

$$\sigma s(\varepsilon) := \begin{Vmatrix} \text{if } \varepsilon \ge \varepsilon_{sc2} \wedge \varepsilon \le \varepsilon_{sc0} \\ \quad \Vert\ \sigma_s \leftarrow R_{sc} \\ \text{else if } \varepsilon > \varepsilon_{sc0} \wedge \varepsilon < \varepsilon_{s0} \\ \quad \Vert\ \sigma_s \leftarrow R_{sc} + (\varepsilon - \varepsilon_{sc0}) \cdot E_{sj} \\ \text{else if } \varepsilon \ge \varepsilon_{s0} \wedge \varepsilon \le \varepsilon_{s2} \\ \quad \Vert\ \sigma_s \leftarrow R_s \\ \text{else} \\ \quad \Vert\ \sigma_s \leftarrow 0 \\ \sigma_s \end{Vmatrix}$$

$$\varepsilon_{sj} := \varepsilon_{sc2} - 0.00001, \varepsilon_{sc2} .. \varepsilon_{s2} + 0.00001$$

Rebar steel strain-stress diagram



$$X_s=\begin{bmatrix}0.25\\0.25\\-0.25\\-0.25\\0\\0\end{bmatrix} m \qquad Y_s=\begin{bmatrix}-0.15\\0.15\\-0.15\\0.15\\-0.15\\0.15\end{bmatrix} m \qquad A_s:=\frac{\pi\cdot d_s^{\,2}}{4}=\begin{bmatrix}8.042\\8.042\\8.042\\8.042\\2.545\\2.545\end{bmatrix} cm^2$$

Момент инерции площадей всей продольной арматуры

$$I_{sy}:=\overrightarrow{\left(A_s\cdot X_s^{\,2}\right)}=20106.193\ cm^4 \qquad I_{sx}:=\overrightarrow{\left(A_s\cdot Y_s^{\,2}\right)}=8383.34\ cm^4$$

$$k_s:=0.7$$

Относительное значение эксцентриситета продольной силы

$$\delta_{ex}:=\left\|\begin{array}{l}\delta\leftarrow\left|\dfrac{e_{0x}}{H}\right|\\ \text{if } \delta<0.15\\ \quad\left\|\ \delta\leftarrow0.15\right.\\ \text{else if } \delta>1.5\\ \quad\left\|\ \delta\leftarrow1.5\right.\\ \text{else}\\ \quad\left\|\ \delta\right.\\ \delta\end{array}\right.=0.15 \qquad \delta_{ey}:=\left\|\begin{array}{l}\delta\leftarrow\left|\dfrac{e_{0y}}{B}\right|\\ \text{if } \delta<0.15\\ \quad\left\|\ \delta\leftarrow0.15\right.\\ \text{else if } \delta>1.5\\ \quad\left\|\ \delta\leftarrow1.5\right.\\ \text{else}\\ \quad\left\|\ \delta\right.\\ \delta\end{array}\right.=0.15$$

$$k_{bx}:=\frac{0.15}{\varphi_{lx}\cdot\left(0.3+\delta_{ex}\right)}=0.222 \qquad k_{by}:=\frac{0.15}{\varphi_{ly}\cdot\left(0.3+\delta_{ey}\right)}=0.222$$

Жесткость железобетонного элемента в предельной по прочности стадии

$$D_x:=k_{bx}\cdot E_{bi}\cdot I_{by}+k_s\cdot E_{sj}\cdot I_{sy}=76148.67\ m^2\cdot kN$$

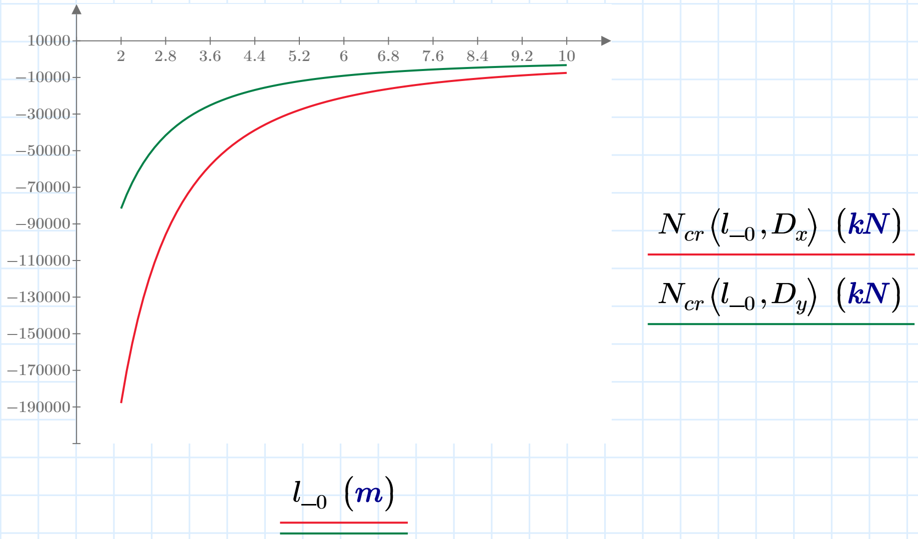
$$D_y:=k_{by}\cdot E_{bi}\cdot I_{bx}+k_s\cdot E_{sj}\cdot I_{sx}=33070.009\ m^2\cdot kN$$

Условная критическая сила

$$N_{cr}\left(l_0,D\right):=-\frac{\pi^2\cdot D}{l_0^{\,2}} \qquad N_{crx}:=N_{cr}\left(l_{0x},D_x\right)=-42605.286\ kN$$

$$N_{cry}:=N_{cr}\left(l_{0y},D_y\right)=-18502.716\ kN$$

$$l\_0 := 2\ m, 2.1\ m..10\ m$$



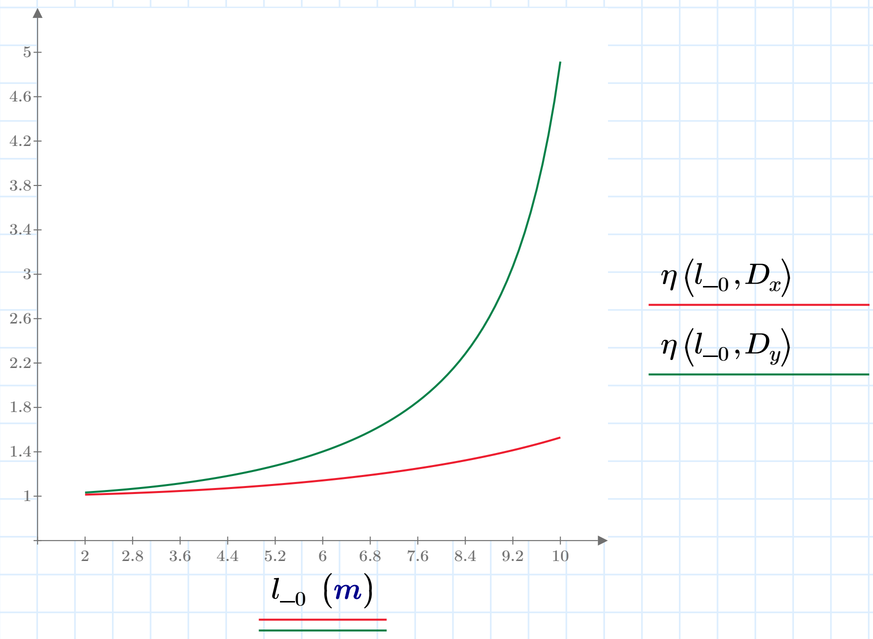
Коэффициент, учитывающий влияние продольного изгиба (прогиба) элемента на его несущую способность

$$\eta(l_0, D) := \begin{array}{|l} N_{cr} \leftarrow N_{cr}(l_0, D) \\ \text{if } N_{cr} < N \\ \quad \eta \leftarrow \dfrac{1}{1 - \dfrac{N}{N_{cr}}} \\ \text{else} \\ \quad \eta \leftarrow 100000 \\ \eta \end{array}$$

$$N = -2600\ kN$$

$$\eta_x := \eta(l_{0x}, D_x) = 1.065$$

$$\eta_y := \eta(l_{0y}, D_y) = 1.163$$



$e_x := e_{0x} \cdot \eta_x = 0\ cm$ $\qquad$ $e_y := e_{0y} \cdot \eta_y = 0\ cm$

$$Load := \begin{bmatrix} N \\ M_x + |N| \cdot e_x \cdot kM_x \\ M_y + |N| \cdot e_y \cdot kM_y \end{bmatrix} = \begin{bmatrix} -2600000\ N \\ 250000\ J \\ -200000\ J \end{bmatrix}$$

$$D00(v_b, v_s) := \sum_{i=0}^{nb-1} \overrightarrow{A_{b_i} \cdot E_{b_i} \cdot v_{b_i}} + \sum_{j=0}^{ns-1} \overrightarrow{A_{s_j} \cdot E_{s_j} \cdot v_{s_j}}$$

$$D11(v_b, v_s) := \sum_{i=0}^{nb-1} \overrightarrow{A_{b_i} \cdot X_{b_i}^{\ 2} \cdot E_{b_i} \cdot v_{b_i}} + \sum_{j=0}^{ns-1} \overrightarrow{A_{s_j} \cdot X_{s_j}^{\ 2} \cdot E_{s_j} \cdot v_{s_j}}$$

$$D22(v_b, v_s) := \sum_{i=0}^{nb-1} \overrightarrow{A_{b_i} \cdot Y_{b_i}^{\ 2} \cdot E_{b_i} \cdot v_{b_i}} + \sum_{j=0}^{ns-1} \overrightarrow{A_{s_j} \cdot Y_{s_j}^{\ 2} \cdot E_{s_j} \cdot v_{s_j}}$$

$$D01(v_b, v_s) := \sum_{i=0}^{nb-1} \overrightarrow{A_{b_i} \cdot X_{b_i} \cdot E_{b_i} \cdot v_{b_i}} + \sum_{j=0}^{ns-1} \overrightarrow{A_{s_j} \cdot X_{s_j} \cdot E_{s_j} \cdot v_{s_j}}$$

$$D02(v_b, v_s) := \sum_{i=0}^{nb-1} \overrightarrow{A_{b_i} \cdot Y_{b_i} \cdot E_{b_i} \cdot v_{b_i}} + \sum_{j=0}^{ns-1} \overrightarrow{A_{s_j} \cdot Y_{s_j} \cdot E_{s_j} \cdot v_{s_j}}$$

$$D12(v_b, v_s) := \sum_{i=0}^{nb-1} \overrightarrow{A_{b_i} \cdot X_{b_i} \cdot Y_{b_i} \cdot E_{b_i} \cdot v_{b_i}} + \sum_{j=0}^{ns-1} \overrightarrow{A_{s_j} \cdot X_{s_j} \cdot Y_{s_j} \cdot E_{s_j} \cdot v_{s_j}}$$

Stiffness matrix

$$Di(v_b, v_s) := \left\| \begin{array}{l} Di_{0,0} \leftarrow D00(v_b, v_s) \\ Di_{1,1} \leftarrow D11(v_b, v_s) \\ Di_{2,2} \leftarrow D22(v_b, v_s) \\ Di_{0,1} \leftarrow D01(v_b, v_s) \\ Di_{1,0} \leftarrow D01(v_b, v_s) \\ Di_{0,2} \leftarrow D02(v_b, v_s) \\ Di_{2,0} \leftarrow D02(v_b, v_s) \\ Di_{1,2} \leftarrow D12(v_b, v_s) \\ Di_{2,1} \leftarrow D12(v_b, v_s) \\ Di \end{array} \right.$$

Linear solution

$$v_b := \left\| \begin{array}{l} \text{for } i \in 0..nb-1 \\ \quad \left\| v_{b_i} \leftarrow 1 \right. \\ v_b \end{array} \right.$$

$$v_s := \left\| \begin{array}{l} \text{for } j \in 0..ns-1 \\ \quad \left\| v_{s_j} \leftarrow 1 \right. \\ v_s \end{array} \right.$$

$$D := Di\left(v_b, v_s\right) \qquad R := \text{lsolve}\left(D, Load\right)$$

$$\varepsilon_b := \left\| \begin{array}{l} \text{for } i \in 0..nb-1 \\ \quad \left\| \varepsilon_{b_i} \leftarrow R_0 + R_1 \cdot X_{b_i} + R_2 \cdot Y_{b_i} \right. \\ \varepsilon_b \end{array} \right.$$

$$\varepsilon_s := \left\| \begin{array}{l} \text{for } j \in 0..ns-1 \\ \quad \left\| \varepsilon_{s_j} \leftarrow R_0 + R_1 \cdot X_{s_j} + R_2 \cdot Y_{s_j} \right. \\ \varepsilon_s \end{array} \right.$$

$$\sigma_b := \left\| \begin{array}{l} \text{for } i \in 0..nb-1 \\ \quad \left\| \sigma_{b_i} \leftarrow \sigma b\left(\varepsilon_{b_i}\right) \right. \\ \sigma_b \end{array} \right.$$

$$\sigma_s := \left\| \begin{array}{l} \text{for } j \in 0..ns-1 \\ \quad \left\| \sigma_{s_j} \leftarrow \sigma s\left(\varepsilon_{s_j}\right) \right. \\ \sigma_s \end{array} \right.$$

Stiffness matrix

$$D = \begin{bmatrix} \left(7.945 \cdot 10^{9}\right) \mathbf{N} & -1.08 \cdot 10^{-7} \mathbf{J} & -5.588 \cdot 10^{-8} \mathbf{J} \\ -1.08 \cdot 10^{-7} \mathbf{J} & \left(2.547 \cdot 10^{8}\right) \dfrac{\mathbf{kg} \cdot \mathbf{m}^3}{\mathbf{s}^2} & -4.657 \cdot 10^{-10} \dfrac{\mathbf{kg} \cdot \mathbf{m}^3}{\mathbf{s}^2} \\ -5.588 \cdot 10^{-8} \mathbf{J} & -4.657 \cdot 10^{-10} \dfrac{\mathbf{kg} \cdot \mathbf{m}^3}{\mathbf{s}^2} & \left(1.113 \cdot 10^{8}\right) \dfrac{\mathbf{kg} \cdot \mathbf{m}^3}{\mathbf{s}^2} \end{bmatrix}$$

Strain vector

$$R = \begin{bmatrix} -0.000327 \\ 0.000981 \dfrac{1}{\mathbf{m}} \\ -0.001797 \dfrac{1}{\mathbf{m}} \end{bmatrix}$$

Number of iterations $ni := 20$

Nonlinear solution

$$
\begin{aligned}
Result := & \text{for } k \in 0..ni-1 \\
& \quad \text{for } i \in 0..nb-1 \\
& \quad\quad v_{b_i} \leftarrow \frac{\sigma_{b_i}}{E_{b_i} \cdot \varepsilon_{b_i}} \\
& \quad \text{for } j \in 0..ns-1 \\
& \quad\quad v_{s_j} \leftarrow \frac{\sigma_{s_j}}{E_{s_j} \cdot \varepsilon_{s_j}} \\
& \quad D \leftarrow Di\left(v_b, v_s\right) \\
& \quad R \leftarrow \text{lsolve}\left(D, Load\right) \\
& \quad \text{for } i \in 0..nb-1 \\
& \quad\quad \varepsilon_{b_i} \leftarrow R_0 + R_1 \cdot X_{b_i} + R_2 \cdot Y_{b_i} \\
& \quad \text{for } i \in 0..nb-1 \\
& \quad\quad \sigma_{b_i} \leftarrow \sigma b\left(\varepsilon_{b_i}\right) \\
& \quad \text{for } j \in 0..ns-1 \\
& \quad\quad \varepsilon_{s_j} \leftarrow R_0 + R_1 \cdot X_{s_j} + R_2 \cdot Y_{s_j} \\
& \quad \text{for } j \in 0..ns-1 \\
& \quad\quad \sigma_{s_j} \leftarrow \sigma s\left(\varepsilon_{s_j}\right) \\
& \quad \begin{bmatrix} \sigma_b \\ \sigma_s \\ \varepsilon_b \\ \varepsilon_s \\ D \\ R \end{bmatrix}
\end{aligned}
$$

Strain vector

$$
Result_5 = \begin{bmatrix} -9.334 \cdot 10^{-4} \\ 0.004 \ \dfrac{1}{m} \\ -0.008 \ \dfrac{1}{m} \end{bmatrix}
$$

Stiffness matrix

$$
Result_4 = \begin{bmatrix} \left(2.934 \cdot 10^{9}\right) N & -5.562 \cdot 10^{6} \ J & -2.097 \cdot 10^{7} \ J \\ -5.562 \cdot 10^{6} \ J & \left(9.428 \cdot 10^{7}\right) \dfrac{kg \cdot m^3}{s^2} & \left(2.103 \cdot 10^{7}\right) \dfrac{kg \cdot m^3}{s^2} \\ -2.097 \cdot 10^{7} \ J & \left(2.103 \cdot 10^{7}\right) \dfrac{kg \cdot m^3}{s^2} & \left(4.012 \cdot 10^{7}\right) \dfrac{kg \cdot m^3}{s^2} \end{bmatrix}
$$

Convergence check

$$N_c := \sum_{i=0}^{nb-1} \overrightarrow{A_{b_i} \cdot \left(Result_0\right)_i} + \sum_{j=0}^{ns-1} \overrightarrow{A_{s_j} \cdot \left(Result_1\right)_j} = -2597.985 \ kN$$

$$M_{xc} := \sum_{i=0}^{nb-1} \overrightarrow{A_{b_i} \cdot \left(Result_0\right)_i \cdot X_{b_i}} + \sum_{j=0}^{ns-1} \overrightarrow{A_{s_j} \cdot \left(Result_1\right)_j \cdot X_{s_j}} = 249.801 \ kN \cdot m$$

$$M_{yc} := \sum_{i=0}^{nb-1} \overrightarrow{A_{b_i} \cdot \left(Result_0\right)_i \cdot Y_{b_i}} + \sum_{j=0}^{ns-1} \overrightarrow{A_{s_j} \cdot \left(Result_1\right)_j \cdot Y_{s_j}} = -199.846 \ kN \cdot m$$

Rebars stress

$$X_s = \begin{bmatrix} 0.25 \\ 0.25 \\ -0.25 \\ -0.25 \\ 0 \\ 0 \end{bmatrix} m \qquad Y_s = \begin{bmatrix} -0.15 \\ 0.15 \\ -0.15 \\ 0.15 \\ -0.15 \\ 0.15 \end{bmatrix} m \qquad Result_1 = \begin{bmatrix} 261.613 \\ -202.71 \\ -170.637 \\ -350 \\ 45.488 \\ -350 \end{bmatrix} MPa$$

Rebars strain

$$X_s = \begin{bmatrix} 0.25 \\ 0.25 \\ -0.25 \\ -0.25 \\ 0 \\ 0 \end{bmatrix} m \qquad Y_s = \begin{bmatrix} -0.15 \\ 0.15 \\ -0.15 \\ 0.15 \\ -0.15 \\ 0.15 \end{bmatrix} m \qquad Result_3 = \begin{bmatrix} 0.00131 \\ -0.00101 \\ -0.00085 \\ -0.00317 \\ 0.00023 \\ -0.00209 \end{bmatrix}$$

$$\sigma_0 := \text{submatrix}\left(Result_0, 0, n_h - 1, 0, 0\right)$$

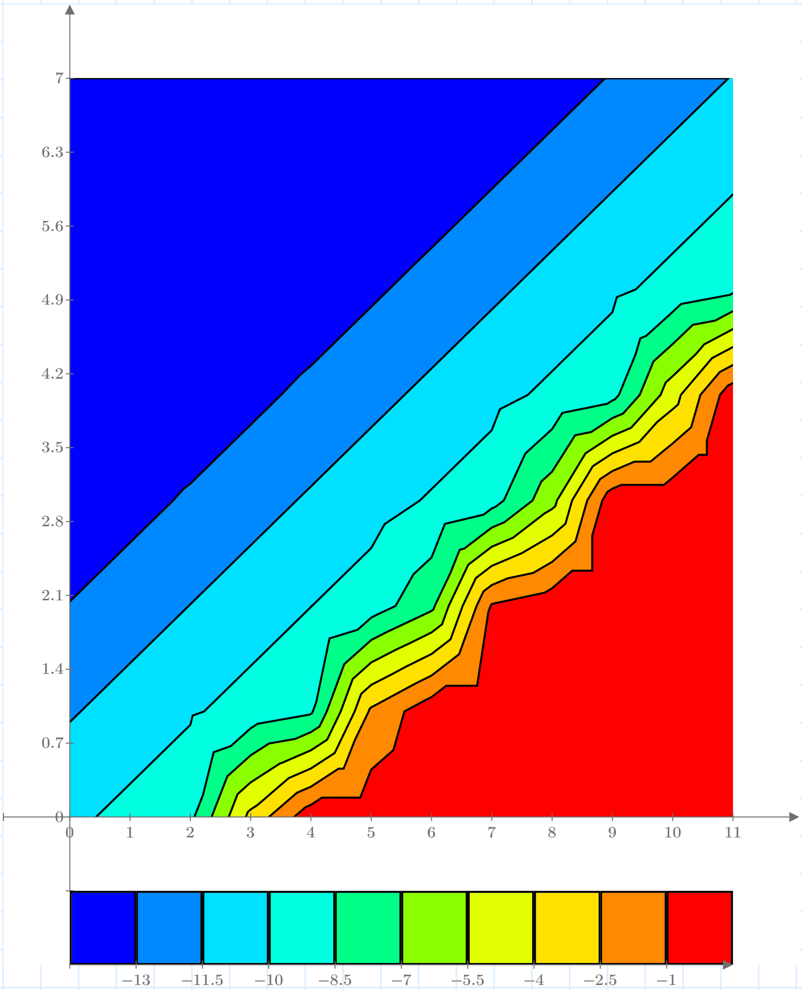
$$\varepsilon_0 := \text{submatrix}\left(Result_2, 0, n_h - 1, 0, 0\right)$$

$$\sigma\varepsilon_b := \left\| \begin{array}{l} \text{for } i \in 2 .. n_b \\ \quad \left\| \begin{array}{l} \sigma \leftarrow \text{submatrix}\left(Result_0, n_h \cdot i - n_h, n_h \cdot i - 1, 0, 0\right) \\ \varepsilon \leftarrow \text{submatrix}\left(Result_2, n_h \cdot i - n_h, n_h \cdot i - 1, 0, 0\right) \\ \sigma_0 \leftarrow \text{augment}\left(\sigma_0, \sigma\right) \\ \varepsilon_0 \leftarrow \text{augment}\left(\varepsilon_0, \varepsilon\right) \end{array} \right. \\ \begin{bmatrix} \sigma_0 \\ \varepsilon_0 \end{bmatrix} \end{array} \right.$$

Concrete stress

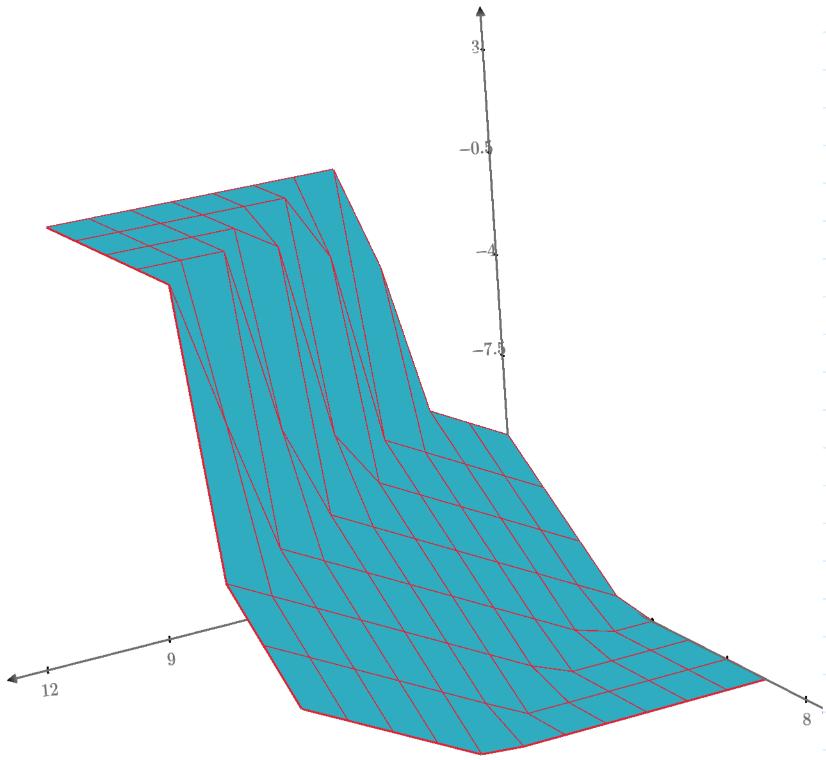
$$\sigma\varepsilon_{b_0} = \begin{bmatrix} -10.321 & -11.633 & -12.945 & -14.258 & -14.5 & -14.5 & -14.5 & -14.5 \\ -9.587 & -10.9 & -12.212 & -13.525 & -14.5 & -14.5 & -14.5 & -14.5 \\ -8.854 & -10.167 & -11.479 & -12.792 & -14.104 & -14.5 & -14.5 & -14.5 \\ -3.582 & -9.434 & -10.746 & -12.059 & -13.371 & -14.5 & -14.5 & -14.5 \\ 0 & -8.701 & -10.013 & -11.326 & -12.638 & -13.95 & -14.5 & -14.5 \\ 0 & -2.223 & -9.28 & -10.593 & -11.905 & -13.217 & -14.5 & -14.5 \\ 0 & 0 & -7.347 & -9.859 & -11.172 & -12.484 & -13.797 & -14.5 \\ 0 & 0 & -0.863 & -9.126 & -10.439 & -11.751 & -13.064 & -14.376 \\ 0 & 0 & 0 & -5.988 & -9.706 & -11.018 & -12.331 & -13.643 \\ 0 & 0 & 0 & 0 & -8.973 & -10.285 & -11.598 & -12.91 \\ 0 & 0 & 0 & 0 & -4.628 & -9.552 & -10.864 & -12.177 \\ 0 & 0 & 0 & 0 & 0 & -8.819 & -10.131 & -11.444 \end{bmatrix} \; MPa$$

Concrete stress



$\sigma\varepsilon_{b_0}$ (MPa)

Concrete stress

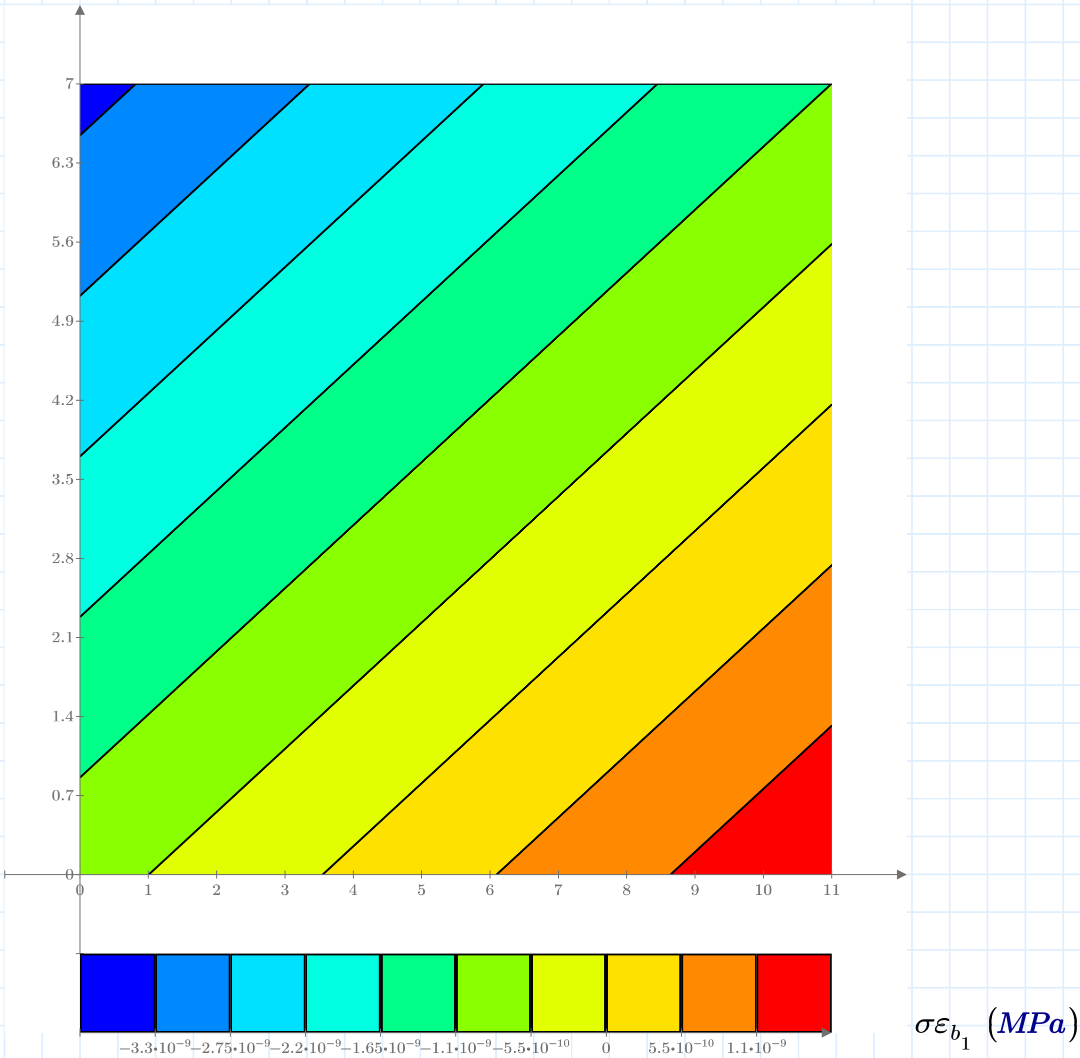


$\sigma\varepsilon_{b_0}$ (MPa)

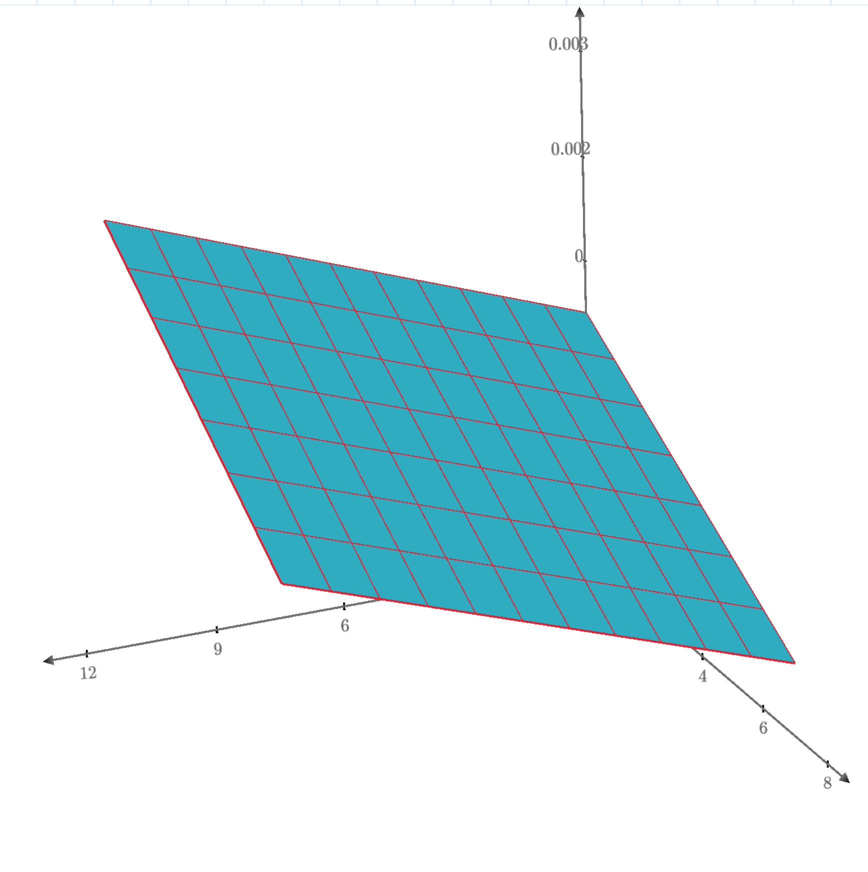
Concrete strain

$$\sigma\varepsilon_{b_1}=\begin{bmatrix} -0.00077 & -0.00115 & -0.00154 & -0.00193 & -0.00232 & -0.0027 & -0.00309 & -0.00348 \\ -0.00055 & -0.00094 & -0.00133 & -0.00171 & -0.0021 & -0.00249 & -0.00287 & -0.00326 \\ -0.00034 & -0.00072 & -0.00111 & -0.0015 & -0.00188 & -0.00227 & -0.00266 & -0.00304 \\ -0.00012 & -0.00051 & -0.00089 & -0.00128 & -0.00167 & -0.00205 & -0.00244 & -0.00283 \\ 0.0001 & -0.00029 & -0.00068 & -0.00106 & -0.00145 & -0.00184 & -0.00222 & -0.00261 \\ 0.00031 & -0.00007 & -0.00046 & -0.00085 & -0.00123 & -0.00162 & -0.00201 & -0.0024 \\ 0.00053 & 0.00014 & -0.00024 & -0.00063 & -0.00102 & -0.00141 & -0.00179 & -0.00218 \\ 0.00075 & 0.00036 & -0.00003 & -0.00042 & -0.0008 & -0.00119 & -0.00158 & -0.00196 \\ 0.00096 & 0.00057 & 0.00019 & -0.0002 & -0.00059 & -0.00097 & -0.00136 & -0.00175 \\ 0.00118 & 0.00079 & 0.0004 & 0.00002 & -0.00037 & -0.00076 & -0.00114 & -0.00153 \\ 0.00139 & 0.00101 & 0.00062 & 0.00023 & -0.00015 & -0.00054 & -0.00093 & -0.00132 \\ 0.00161 & 0.00122 & 0.00084 & 0.00045 & 0.00006 & -0.00033 & -0.00071 & -0.0011 \end{bmatrix}$$

Concrete strain



Concrete strain



$\sigma\varepsilon_{b_1}$