

VEDLEGG 11

DIMENSJONERING AV SPENNARMERING, LENGDERETNING

Beregningene i vedlegget tar utgangspunkt i at vi ser per meter inn i planet.

Bruddgrensetilstand:

Maksimalt opptredende moment og skjærkraft:

$$M_{Ed} = 2497,98 \text{ kNm (Vedlegg 3, s. 9)}$$

$$M_{Ed,q} = 1720,54 \text{ kNm (Vedlegg 6, s. 8)}$$

$$V_{Ed} = 644,85 \text{ kN (Vedlegg 3, s. 12)}$$

Spennarmering:

For å finne nødvendig mengde spennarmering tas det kun utgangspunkt i moment pga. jevnt fordelte laster, $M_{Ed,q}$.

Overslagsberegninger ble gjort for å finne omtrentlig mengde nødvendig armering:

Velger 15-taus kabler $\Rightarrow \phi = 100\text{mm}$ (Statens Vegvesen, 2017, s.30)

Overdekning:

Velger dimensjonerende brukstid: 100 år

Eksponeeringsklasser: overkant og sidene av brua = XD3, underkant av brua = XC4 (Standard Norge, 2004, tabell 4.1)

$$c_{min,dur} = 60 \text{ mm (overkant og sidene) (Standard Norge, 2008, tabell NA.4.5N)}$$

$$c_{min,dur} = 45 \text{ mm (underkant) (Standard Norge, 2008, tabell NA.4.5N)}$$

$$\Delta c_{dev} = 10 \text{ mm (Standard Norge, 2008, pkt. NA.4.4.1.3(1))}$$

$$c_{min,b} = 1,5 * \varphi = 1,5 * 100 = 150 \text{ mm (Standard Norge, 2008, tabell NA.4.2)}$$

$$\Delta c_{dur,\gamma} = 0 \text{ mm (Standard Norge, 2008, pkt. NA.4.4.1.2(6))}$$

$$\Delta c_{dur,st} = 0 \text{ mm (Standard Norge, 2008, pkt. NA.4.4.1.2(7))}$$

$$\Delta c_{dur,add} = 0 \text{ mm (Standard Norge, 2008, pkt. NA.4.4.1.2(8))}$$

$$c_{min} = \max \left\{ c_{min,dur} + \Delta c_{dur,\gamma} - \frac{c_{min,b}}{10 \text{ mm}} - \Delta c_{dur,add} \right\} \text{ (Standard Norge, 2004, pkt. 4.4.1.2(2))}$$

$$c_{min} = \max \left\{ \begin{matrix} c_{min,b} \\ c_{min,dur} \\ 10 \text{ mm} \end{matrix} \right\} = \max \left\{ \begin{matrix} 150 \text{ mm} \\ 60 \text{ mm} \\ 10 \text{ mm} \end{matrix} \right\} = 150 \text{ mm}$$

$$c_{nom} = c_{min} + \Delta c_{dev} \text{ (Standard Norge, 2004, pkt. 4.4.1.1(1))}$$

$$c_{nom} = 150 \text{ mm} + 10 \text{ mm}$$

$$c_{nom} = 160,00 \text{ mm}$$

Krav til effektiv tverrsnittshøyde:

$$d_{krav} = \sqrt{\frac{M_{Ed,q}}{0,269 * f_{cd} * b}} \text{ (Sørensen, 2013, s.284)}$$

$$d_{krav} = \sqrt{\frac{1720,54 * 10^6}{0,269 * 31,17 * 1000}}$$

$$d_{krav} = 452,99 \text{ mm}$$

Tverrsnittets nødvendige effektive høyde:

$$d = h - c_{nom} - \frac{\phi_{kabel}}{2}$$

$$d = 800 - 160,00 - \frac{100}{2}$$

$$d = 590,00 \text{ mm} > d_{krav} = 452,99 \text{ mm} \Rightarrow OK$$

Eksentrisitet:

$$e = \frac{h}{2} - c_{nom} - \frac{\phi_{kabel}}{2}$$

$$e = \frac{800}{2} - 160,00 - \frac{100}{2}$$

$$e = 190,00 \text{ mm}$$

Indre momentarm:

$$z = (1 - 0,5 * \lambda * \alpha) * d \text{ (Sørensen, 2013, s.39)}$$

$$z = (1 - 0,5 * 0,79 * 0,383) * 590,00$$

$$z = 500,74 \text{ mm}$$

Nødvendig armeringsmengde mht. opptredende moment:

$$A_{p,nødvendig} \geq \frac{M_{Ed,q}}{f_{pd} * z} \text{ (Sørensen, 2013, s.285)}$$

$$A_{p,nødvendig} \geq \frac{1720,54 * 10^6}{1426,09 * 500,74}$$

$$A_{p,nødvendig} > 2409,38 \text{ mm}^2$$

Velger 15-taus kabler med tau som har tverrsnitt 140 mm^2 .

1 stk. 15-taus kabel $\Rightarrow A_{p,15} = 2100,00 \text{ mm}^2$ (Statens Vegvesen, 2017, s. 30)

Nødvendig antall kabler:

$$n \geq \frac{A_{p,n\ddot{o}dvendig}}{A_{p,15}} \text{ (Sørensen, 2013, s.41)}$$

$$n \geq \frac{2409,38}{2100,00}$$

$$n \geq 1,15 \Rightarrow n = 2 \text{ stk. 15-taus kabler}$$

Faktisk armeringsmengde:

$$A_p = 2 * A_{p,15}$$

$$A_p = 2 * 2100,00 \text{ mm}^2$$

$$A_p = 4200,00 \text{ mm}^2$$

Revidert verdi for α :

$$\alpha_{rev} = \frac{f_{pd} * A_p}{\lambda * f_{cd} * b * d} \text{ (Sørensen, 2013, s.280)}$$

$$\alpha_{rev} = \frac{1426,09 * 4200,00}{0,79 * 31,17 * 1000 * 590,00}$$

$$\alpha_{rev} = 0,41$$

Sjekker krav til armeringsmengde med den reviderte verdien for α :

$$z_{rev} = (1 - 0,5 * \lambda * \alpha) * d \text{ (Sørensen, 2013, s.39)}$$

$$z_{rev} = (1 - 0,5 * 0,79 * 0,41) * 590,00$$

$$z_{rev} = 494,45 \text{ mm}$$

$$A_{p,n\ddot{o}dvendig,rev} \geq \frac{M_{Ed,q}}{f_{pd} * z_{rev}} \text{ (Sørensen, 2013, s.285)}$$

$$A_{p,n\ddot{o}dvendig,rev} \geq \frac{1720,54 * 10^6}{1426,09 * 494,45}$$

$$A_{p,n\ddot{o}dvendig,rev} \geq 2440,03 \text{ mm}^2 < A_p = 4200 \text{ mm}^2 \Rightarrow OK$$

Største tillatte spenning i spennarmering ved oppspenning:

$$\sigma_{p,max} = \min \{0,8f_{pk}; 0,9f_{p0,1k}\} \text{ (Standard Norge, 2004, pkt. 5.10.2.1(1))}$$

$$\sigma_{p,max} = \min \{0,8 * 1860; 0,9 * 1640\}$$

$$\sigma_{p,max} = \min \{1488,00 ; 1476,00\} = 1476,00 \frac{\text{N}}{\text{mm}^2}$$

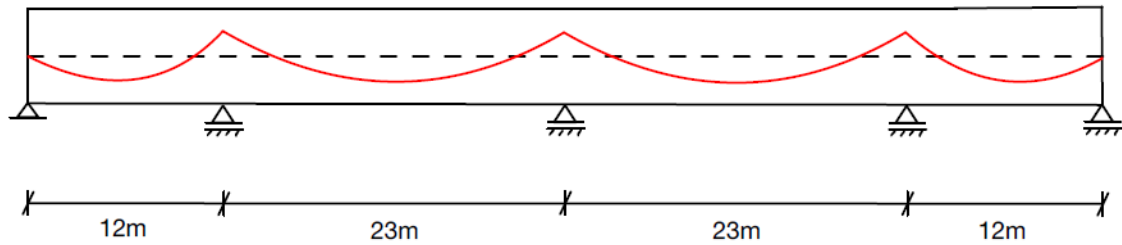
Største tillatte oppspenningskraft:

$$P_{max} = A_p * \sigma_{p,max} \text{ (Standard Norge, 2004, pkt. 5.10.2.1(1))}$$

$$P_{max} = 4200,00 * 1476,00$$

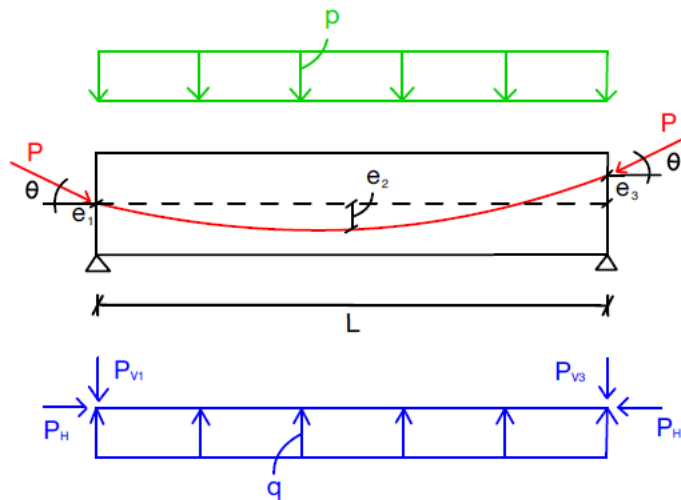
$$P_{max} = 6199,20 \text{ kN}$$

Beregning av nødvendig oppspenningskraft: (Formula list, TKT4220 Concrete Structures 2, s.2)



Figur 1: Skisse av spennarmering i lengderetning

Felt 1 og 4:



Figur 2: Skisse av lastbalansering for felt 1 og 4

$$e_1 = 0$$

$$e_2 = e$$

$$e_3 = e$$

$$e_m = \frac{e_1}{2} + e_2 + \frac{e_3}{2}$$

$$e_m = \frac{0}{2} + e + \frac{e}{2}$$

$$e_m = \frac{3}{2} * e$$

$$e = h - C_{nom} - \frac{\phi}{2} - \frac{h}{2}$$

$$e = 800 - 160,00 - \frac{100}{2} - \frac{800}{2}$$

$$e = 190,00 \text{ mm}$$

$$p = q = \frac{8 * P * e_m}{L^2}$$

$$p = \frac{8 * P * \frac{3}{2} * e}{L^2}$$

$$p = \frac{12 * P * e}{L^2}$$

$p = \text{maksimal jevnt fordelt last som forekommer på spennet}$

$$p = 26,1 + 8,1 \text{ (Vedlegg 3, s. 9)}$$

$$p = 34,2 \frac{\text{kN}}{\text{m}}$$

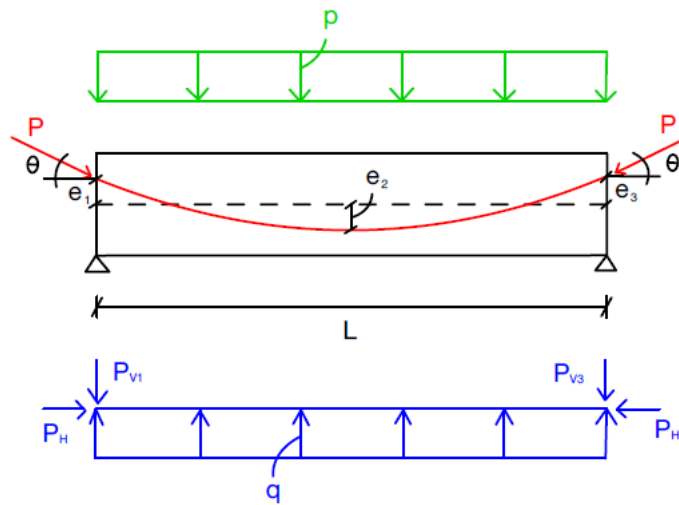
$$p = \frac{12 * P * e}{L^2} \Rightarrow P = \frac{p * L^2}{12 * e}$$

$$P = \frac{p * L^2}{12 * e}$$

$$P = \frac{34,2 * 12\,000^2}{12 * 190,00} * 10^{-3}$$

$$P_{n\ddot{o}dvendig} = 2160 \text{ kN} < P_{max} = 6199,20 \text{ kN} \Rightarrow OK$$

Felt 2 og 3:



Figur 3: Skisse av lastbalansering for felt 2 og 3

$$e_1 = e$$

$$e_2 = e$$

$$e_3 = e$$

$$e_m = \frac{e_1}{2} + e_2 + \frac{e_3}{2}$$

$$e_m = \frac{e}{2} + e + \frac{e}{2}$$

$$e_m = 2 * e$$

$$e = h - C_{nom} - \frac{\phi}{2} - \frac{h}{2}$$

$$e = 800 - 160,00 - \frac{100}{2} - \frac{800}{2}$$

$$e = 190,00 \text{ mm}$$

$$p = q = \frac{8 * P * e_m}{L^2}$$

$$p = \frac{8 * P * 2 * e}{L^2}$$

$$p = \frac{16 * P * e}{L^2}$$

p = maksimal jevnt fordelt last som forekommer på spennet

$$p = 26,1 + 8,1 \text{ (Vedlegg 3, s. 9)}$$

$$p = 34,2 \frac{\text{kN}}{\text{m}}$$

$$p = \frac{16 * P * e}{L^2} \Rightarrow P = \frac{p * L^2}{16 * e}$$

$$P = \frac{p * L^2}{16 * e}$$

$$P = \frac{34,2 * 23\,000^2}{16 * 190,00} * 10^{-3}$$

$$P_{n\ddot{o}dvendig} = 5951,25 \text{ kN} < P_{max} = 6199,20 \text{ kN} \Rightarrow OK$$

Strekkarmering:

Sjekker om spennarmeringen har tilstrekkelig kapasitet til å tåle maksimalt opptredende moment M_{Ed} , med både jevnt fordelte laster og punktlaster, eller om det er behov for strekkarmering i tillegg til spennarmeringen:

$$A_{p,n\ddot{o}dvendig} \geq \frac{M_{Ed}}{f_{pd} * z} \text{ (S\ddot{o}rensen, 2013, s.285)}$$

$$A_{p,n\ddot{o}dvendig} \geq \frac{2497,98 * 10^6}{1426,09 * 494,45}$$

$$A_{p,n\ddot{o}dvendig} > 3542,58 \text{ mm}^2 < A_p = 4200 \text{ mm}^2 \Rightarrow \text{Ikke behov for strekkarmering}$$

Trykkarmering:

$$M_{Rd} = K * f_{cd} * b * d^2 \text{ (Sørensen, 2013, s.38)}$$

$$M_{Rd} = 0,250 * 31,17 * 1000 * 590,00^2$$

$$M_{Rd} = 2712,57 \text{ kNm} > M_{Ed} = 2497,98 \text{ kNm} \Rightarrow \text{ikke behov for trykkarmering (Sørensen, 2013, s.46)}$$

Skjærarmering:

$$C_{Rd,c} = \frac{k_2}{\gamma_c} = \frac{0,18}{1,5} = 0,12 \text{ (Standard Norge, 2008, pkt. NA.6.2.2(1))}$$

$$k = 1 + \sqrt{\frac{200}{d}} \leq 2,0 \text{ (Standard Norge, 2004, pkt. 6.2.2(1))}$$

$$k = 1 + \sqrt{\frac{200}{590,00}} = 1,58 < 2,0 \Rightarrow OK$$

$$\rho_L = \frac{A_{sL}}{b_w * d} \leq 0,02 \text{ (Standard Norge, 2004, pkt. 6.2.2(1))}$$

$$\rho_L = \frac{4200,00}{1000 * 590,00} = 7,12 * 10^{-3} < 0,02 \Rightarrow OK$$

$$k_1 = 0,15 \text{ ved trykk (Standard Norge, 2008, pkt. NA6.2.2(1))}$$

Forenkler og setter $tap = 0$

$$N_{Ed} = -P * \gamma_p * (1 - tap) \text{ (Løsningsforslag øving 5, TKT4220 Concrete Structures, s.2)}$$

$$N_{Ed} = -(-5951,25) * 0,9 * (1 - 0)$$

$$N_{Ed} = 5356,13 \text{ kN}$$

$$\sigma_{cp} = \frac{N_{Ed}}{A_c} < 0,2f_{cd} \text{ (Standard Norge, 2004, pkt. 6.2.2(1))}$$

$$\sigma_{cp} = \frac{5356,13}{1000 * 800} < 0,2 * 31,17$$

$$\sigma_{cp} = 6,70 * 10^{-3} \frac{\text{N}}{\text{mm}^2} < 6,23 \frac{\text{N}}{\text{mm}^2} \Rightarrow OK$$

$$V_{Rd,c} = \left[c_{Rd,c} * k * (100 * \rho_L * f_{ck})^{\frac{1}{3}} + k_1 * \sigma_{cp} \right] * b_w * d \quad (\text{Standard Norge, 2004, pkt.}$$

6.2.2(1))

$$V_{Rd,c} = \left[0,12 * 1,58 * (100 * 7,12 * 10^{-3} * 55)^{\frac{1}{3}} + 0,15 * 6,70 * 10^{-3} \right] * 1000 * 590,00$$

$$V_{Rd,c} = 380,47 \text{ kN}$$

$$V_{Rd,c,min} = 0,035 * k^{\frac{3}{2}} * f_{ck}^{\frac{1}{2}} * b * d \quad (\text{Sørensen, 2013, s.62})$$

$$V_{Rd,c,min} = 0,035 * 1,58^{\frac{3}{2}} * 55^{\frac{1}{2}} * 1000 * 590,00$$

$$V_{Rd,c,min} = 307,39 \text{ kN}$$

Krav:

$$V_{Rd,c} \geq V_{Rd,c,min}$$

$$380,47 \text{ kN} > 307,39 \text{ kN} \Rightarrow OK$$

$$V_{Rd,c} < V_{Ed} \Rightarrow \text{Beregningsmessig behov for skjærarmering} \quad (\text{Sørensen, 2013, s.77})$$

$$380,47 \text{ kN} < 644,85 \text{ kN} \Rightarrow \text{Beregningsmessig behov for skjærarmering}$$

Nødvendig mengde skjærarmering per mm:

$$\frac{A_{s,w}}{s} \geq \frac{V_{Ed}}{f_{ywd} * z * \cot \theta} \quad (\text{Sørensen, 2013, s.77})$$

$$\frac{A_{s,w}}{s} \geq \frac{644,85 * 10^3}{434,78 * 494,45 * 1}$$

$$\frac{A_{s,w}}{s} \geq 3,00 \frac{\text{mm}^2}{\text{mm}}$$

Minimumskrav til skjærarmering per mm:

$$\frac{A_{sw,min}}{s} = 0,1 * \frac{\sqrt{f_{ck}}}{f_{yk}} * b_w \text{ (Sørensen, 2013, s.77)}$$

$$\frac{A_{sw,min}}{s} = 0,1 * \frac{\sqrt{55}}{500} * 1000$$

$$\frac{A_{sw,min}}{s} = 1,48 \frac{\text{mm}^2}{\text{mm}}$$

Krav:

$$\frac{A_{sw}}{s} > \frac{A_{sw,min}}{s}$$

$$3,00 \frac{\text{mm}^2}{\text{mm}} > 1,48 \frac{\text{mm}^2}{\text{mm}} \Rightarrow OK$$

Nødvendig senteravstand mellom skjærbøylene:

$$s \leq \frac{A_{s,w}}{V_{Ed}} * f_{ywd} * z * \cot\theta \text{ (Standard Norge, 2004, pkt. 6.2.3(3))}$$

$$s = \frac{2 * \pi * \left(\frac{10}{2}\right)^2}{644,85 * 10^3} * 434,78 * 494,45 * 1$$

$$s = 52,37 \text{ mm} \Rightarrow 50,00 \text{ mm}$$

Krav til minimum senteravstand:

$$s_{L,min} = \max \left\{ \begin{array}{l} k_1 * \phi \\ d_g + k_2 \\ 20 \text{ mm} \end{array} \right\} \text{ (Standard Norge, 2004, pkt. 8.2.(2); Standard Norge, 2008, pkt. NA.8.2(2))}$$

NA.8.2(2))

$$s_{L,min} = \max \left\{ \begin{array}{l} 1 * 10 \text{ mm} \\ 20 \text{ mm} + 5 \text{ mm} \\ 20 \text{ mm} \end{array} \right\} = \max \left\{ \begin{array}{l} 10 \text{ mm} \\ 25 \text{ mm} \\ 20 \text{ mm} \end{array} \right\}$$

$$s_{L,min} = 25,00 \text{ mm}$$

Krav til maksimum senteravstand:

$$s_{L,max} = 0,6 * z \text{ (Standard Norge, 2008, pkt. NA9.2.2(6))}$$

$$s_{L,max} = 0,6 * 494,45$$

$$s_{L,max} = 296,67 \text{ mm}$$

Krav til senteravstand:

$$s_{L,min} \leq s \leq s_{L,max}$$

$$25,00 \text{ mm} < 50,00 \text{ mm} < 296,67 \text{ mm} \Rightarrow OK$$

Skjærtrykkapasitet:

$$\alpha_{cw} = \left(1 + \frac{\sigma_{cp}}{f_{cd}}\right) \text{ for } 0 < \sigma_{cp} \leq 0,25 * f_{cd} \text{ (Standard Norge, 2008, pkt. NA.6.2.3(3))}$$

$$\alpha_{cw} = \left(1 + \frac{6,70 * 10^{-3}}{31,17}\right)$$

$$\alpha_{cw} = 1,00$$

$$v_1 = 0,6 \text{ gjelder for } f_{ck} \leq 60 \frac{\text{N}}{\text{mm}^2} \text{ (Standard Norge, 2008, pkt. NA.6.2.3(3))}$$

$$V_{Rd,max} = \frac{\alpha_{cw} * b_w * z * v_1 * f_{cd}}{\cot \theta + \tan \theta} \text{ (Standard Norge, 2004, pkt. 6.2.3(3))}$$

$$V_{Rd,max} = \frac{1 * 1000 * 494,45 * 0,6 * 31,17}{1 + 1}$$

$$V_{Rd,max} = 4623,60 \text{ kN}$$

Krav:

$$V_{Rd,max} > V_{Ed}$$

$$4623,60 \text{ kN} > 644,85 \text{ kN} \Rightarrow OK$$

Bruksgrensetilstand:

Maksimale spenninger pga. kryp (kun forspenning):

$$\eta = \frac{E_p}{E_{cm}} \text{ (Sørensen, 2013, s.252)}$$

$$\eta = \frac{195\,000}{38\,000}$$

$$\eta = 5,13$$

$$A_t = A_c + (\eta - 1) * A_p \text{ (Sørensen, 2013, s.252)}$$

$$A_t = 1000 * 800 + (5,13 - 1) * 4200,00$$

$$A_t = 817\,346,00 \text{ mm}^2$$

$$y_t = \frac{(\eta-1)*A_p*e}{A_t} \text{ (Sørensen, 2013, s.252)}$$

$$y_t = \frac{(5,13-1)*4200,00*190,00}{817\,346,00}$$

$$y_t = 4,03 \text{ mm}$$

$$I_t = \frac{1}{12} * b * h^3 + b * h * y_t^2 + (\eta - 1) * A_p * (e - y_t)^2 \text{ (Sørensen, 2013, s. 252)}$$

$$I_t = \frac{1}{12} * 1000 * 800^3 + 1000 * 800 * 4,03^2 + (5,13 - 1) * 4200,00 * (190,00 - 4,03)^2$$

$$I_t = 4,33 * 10^{10} \text{ mm}^4$$

$$N = -P_0 \text{ (Sørensen, 2013, s.252)}$$

$$N = -5951,25 \text{ kN}$$

$$M_t = -P_0 * (e - y_t) \text{ (Sørensen, 2013, s.253)}$$

$$M_t = -5951,25 * 10^3 * (190,00 - 4,03)$$

$$M_t = -1106,75 \text{ kNm}$$

Betongspenninger i underkant av tverrsnitt ($y = \frac{800}{2} \text{ mm}$):

$$\sigma_c^u = \frac{N}{A_t} + \frac{M_t * (y - y_t)}{I_t} \text{ (Sørensen, 2013, s.253)}$$

$$\sigma_c^u = -\frac{5951,25 * 10^3}{817 \ 346,00} - \frac{1106,75 * 10^6 * \left(\frac{800}{2} - 4,03\right)}{4,33 * 10^{10}}$$

$$\sigma_c^u = -17,40 \frac{\text{N}}{\text{mm}^2} \text{ (trykk)}$$

Betongspenninger i overkant av tverrsnitt ($y = -\frac{800}{2} \text{ mm}$):

$$\sigma_c^o = \frac{N}{A_t} + \frac{M_t * (y - y_t)}{I_t} \text{ (Sørensen, 2013, s.253)}$$

$$\sigma_c^o = -\frac{5951,25 * 10^3}{817 \ 346,00} - \frac{1106,75 * 10^6 * \left(-\frac{800}{2} - 4,03\right)}{4,33 * 10^{10}}$$

$$\sigma_c^o = 3,05 \frac{\text{N}}{\text{mm}^2} \text{ (strek)}$$

Betongspenninger ved spennarmeringen i tverrsnittet ($y = e = 190,00 \text{ mm}$):

$$\sigma_c^t = \frac{N}{A_t} + \frac{M_t * (y - y_t)}{I_t} \text{ (Sørensen, 2013, s.253)}$$

$$\sigma_c^t = -\frac{5951,25 * 10^3}{817 \ 346,00} - \frac{1106,75 * 10^6 * (190,00 - 4,03)}{4,33 * 10^{10}}$$

$$\sigma_c^t = -12,03 \frac{\text{N}}{\text{mm}^2} \text{ (trykk)}$$

Kontroll av trykkspenninger:

$$\sigma_{c,tillatt} = -0,6 * f_{ck} \text{ (Standard Norge, 2004, pkt. 5.10.2.2(5))}$$

$$\sigma_{c,tillatt} = -0,6 * 55$$

$$\sigma_{c,tillatt} = -33,00 \frac{\text{N}}{\text{mm}^2} > \sigma_c^u = -17,40 \frac{\text{N}}{\text{mm}^2} \Rightarrow OK$$

Kontroll av strekkspenninger:

$$f_{ctm} = 4,2 \frac{\text{N}}{\text{mm}^2} \text{ (Standard Norge, 2004, tabell 3.1)}$$

$$f_{ctm} = 4,2 \frac{\text{N}}{\text{mm}^2} > \sigma_c^o = 3,05 \frac{\text{N}}{\text{mm}^2} \Rightarrow OK$$

Spenninger pga. kryp (forspenning og egenlast):

Beregnete verdier, likt som for kun forspenning:

$$\eta = 5,13$$

$$A_t = 817\,346,00 \text{ mm}^2$$

$$y_t = 4,03 \text{ mm}$$

$$I_t = 4,33 * 10^{10} \text{ mm}^4$$

$$N = -5951,25 \text{ kN}$$

Felt 1 og 4:

$$g = 21,75 \frac{\text{kN}}{\text{m}} \text{ (Vedlegg 5, s.7)}$$

$$M_g = \frac{9}{128} * g * L^2 \text{ (Aalberg, Clausen og Larsen, 2003, tabell 3.2)}$$

$$M_g = \frac{9}{128} * 21,75 * 12\,000^2$$

$$M_g = 220,22 \text{ kNm}$$

$$M_t = -P_0 * (e - y_t) + M_g \text{ (Sørensen, 2013, s.253)}$$

$$M_t = -5951,25 * 10^3 * (190,00 - 4,03) + 220,22 * 10^6$$

$$M_t = -886,53 \text{ kNm}$$

Betongspenninger i underkant av tverrsnitt ($y = \frac{800}{2}$ mm):

$$\sigma_c^u = \frac{N}{A_t} + \frac{M_t * (y - y_t)}{I_t} \text{ (Sørensen, 2013, s.253)}$$

$$\sigma_c^u = -\frac{5951,25 * 10^3}{817\,346,00} - \frac{886,53 * 10^6 * \left(\frac{800}{2} - 4,03\right)}{4,33 * 10^{10}}$$

$$\sigma_c^u = -15,39 \frac{\text{N}}{\text{mm}^2} \text{ (trykk)}$$

Betongspenninger i overkant av tverrsnitt ($y = -\frac{800}{2}$ mm):

$$\sigma_c^o = \frac{N}{A_t} + \frac{M_t * (y - y_t)}{I_t} \text{ (Sørensen, 2013, s.253)}$$

$$\sigma_c^o = -\frac{5951,25 * 10^3}{817\,346,00} - \frac{886,53 * 10^6 * \left(-\frac{800}{2} - 4,03\right)}{4,33 * 10^{10}}$$

$$\sigma_c^o = 0,99 \frac{\text{N}}{\text{mm}^2} \text{ (strekk)}$$

Betongspenninger ved spennarmeringen i tverrsnittet ($y = e = 190,00$ mm):

$$\sigma_c^t = \frac{N}{A_t} + \frac{M_t * (y - y_t)}{I_t} \text{ (Sørensen, 2013, s.253)}$$

$$\sigma_c^t = -\frac{5951,25 * 10^3}{817\,346,00} - \frac{886,53 * 10^6 * (190,00 - 4,03)}{4,33 * 10^{10}}$$

$$\sigma_c^t = -11,09 \frac{\text{N}}{\text{mm}^2} \text{ (trykk)}$$

Felt 2 og 3:

$$g = 21,75 \frac{\text{kN}}{\text{m}} \text{ (Vedlegg 5, s. 9)}$$

$$M_g = \frac{g \cdot L^2}{24} \text{ (Aalberg, Clausen og Larsen, 2003, tabell 3.2)}$$

$$M_g = \frac{21,75 \cdot 23\,000^2}{24}$$

$$M_g = 479,41 \text{ kNm}$$

$$M_t = -P_0 \cdot (e - y_t) + M_g \text{ (Sørensen, 2013, s.253)}$$

$$M_t = -5951,25 \cdot 10^3 \cdot (190,00 - 4,03) + 479,41 \cdot 10^6$$

$$M_t = -627,34 \text{ kNm}$$

Betongspenninger i underkant av tverrsnitt $(y = \frac{800}{2} \text{ mm})$:

$$\sigma_c^u = \frac{N}{A_t} + \frac{M_t \cdot (y - y_t)}{I_t} \text{ (Sørensen, 2013, s.253)}$$

$$\sigma_c^u = -\frac{5951,25 \cdot 10^3}{817\,346,00} - \frac{627,34 \cdot 10^6 \cdot \left(\frac{800}{2} - 4,03\right)}{4,33 \cdot 10^{10}}$$

$$\sigma_c^u = -13,02 \frac{\text{N}}{\text{mm}^2} \text{ (trykk)}$$

Betongspenninger i overkant av tverrsnitt ($y = -\frac{800}{2}$ mm):

$$\sigma_c^o = \frac{N}{A_t} + \frac{M_t * (y - y_t)}{I_t} \text{ (Sørensen, 2013, s.253)}$$

$$\sigma_c^o = -\frac{5951,25 * 10^3}{817\,346,00} - \frac{627,34 * 10^6 * \left(-\frac{800}{2} - 4,03\right)}{4,33 * 10^{10}}$$

$$\sigma_c^o = -1,43 \frac{\text{N}}{\text{mm}^2} \text{ (trykk)}$$

Betongspenninger ved spennarmeringen i tverrsnittet ($y = e = 190,00$ mm):

$$\sigma_c^t = \frac{N}{A_t} + \frac{M_t * (y - y_t)}{I_t} \text{ (Sørensen, 2013, s.253)}$$

$$\sigma_c^t = -\frac{5951,25 * 10^3}{817\,346,00} - \frac{627,34 * 10^6 * (190,00 - 4,03)}{4,33 * 10^{10}}$$

$$\sigma_c^t = -9,98 \frac{\text{N}}{\text{mm}^2} \text{ (trykk)}$$

Spenninger pga. kryp (forspenning, egenlast og trafikklast):

$$\eta = \frac{E_p}{E_{middel}} \text{ (Sørensen, 2013, s.252)}$$

$$\eta = \frac{195\,000}{15\,161,47}$$

$$\eta = 12,86$$

$$A_t = A_c + (\eta - 1) * A_p \text{ (Sørensen, 2013, s.252)}$$

$$A_t = 1000 * 800 + (12,86 - 1) * 4200,00$$

$$A_t = 849\,812,00 \text{ mm}^2$$

$$y_t = \frac{(\eta-1)*A_p*e}{A_t} \text{ (Sørensen, 2013, s.252)}$$

$$y_t = \frac{(12,86-1)*4200,00*190,00}{849\,812,00}$$

$$y_t = 11,14 \text{ mm}$$

$$I_t = \frac{1}{12} * b * h^3 + b * h * y_t^2 + (\eta - 1) * A_p * (e - y_t)^2 \text{ (Sørensen, 2013, s.252)}$$

$$I_t = \frac{1}{12} * 1000 * 800^3 + 1000 * 800 * 11,14^2 + (12,86 - 1) * 4200,00 * (190,00 - 11,14)^2$$

$$I_t = 4,44 * 10^{10} \text{ mm}^4$$

$$N = -P_0 \text{ (Sørensen, 2013, s.252)}$$

$$N = -5951,25 \text{ kN}$$

Felt 1 og 4:

$$g = 21,75 \frac{\text{kN}}{\text{m}} \text{ (Vedlegg 5, s. 7)}$$

$$p = 5,4 \frac{\text{kN}}{\text{m}} \text{ (Vedlegg 5, s. 7)}$$

$$M_{g+p} = \frac{9}{128} * (g + p) * L^2 \text{ (Aalberg, Clausen og Larsen, 2003, tabell 3.2)}$$

$$M_{g+p} = \frac{9}{128} * (21,75 + 5,4) * 12\,000^2$$

$$M_{g+p} = 274,89 \text{ kNm}$$

$$M_t = -P_0 * (e - y_t) + M_{g+p} \text{ (Sørensen, 2013, s.253)}$$

$$M_t = -5951,25 * 10^3 * (190,00 - 11,14) + 274,89 * 10^6$$

$$M_t = -789,55 \text{ kNm}$$

Betongspenninger i underkant av tverrsnitt ($y = \frac{800}{2} \text{ mm}$):

$$\sigma_c^u = \frac{N}{A_t} + \frac{M_t * (y - y_t)}{I_t} \text{ (Sørensen, 2013, s.253)}$$

$$\sigma_c^u = -\frac{5951,25 * 10^3}{849\,812,00} - \frac{789,55 * 10^6 * \left(\frac{800}{2} - 11,14\right)}{4,44 * 10^{10}}$$

$$\sigma_c^u = -16,92 \frac{\text{N}}{\text{mm}^2} \text{ (trykk)}$$

Betongspenninger i overkant av tverrsnitt ($y = -\frac{800}{2}$ mm):

$$\sigma_c^o = \frac{N}{A_t} + \frac{M_t * (y - y_t)}{I_t} \text{ (Sørensen, 2013, s.253)}$$

$$\sigma_c^o = -\frac{5951,25 * 10^3}{849\,812,00} - \frac{789,55 * 10^6 * \left(-\frac{800}{2} - 11,14\right)}{4,44 * 10^{10}}$$

$$\sigma_c^o = 0,31 \frac{\text{N}}{\text{mm}^2} \text{ (strek)}$$

Betongspenninger ved spennarmeringen i tverrsnittet ($y = e = 190,00$ mm):

$$\sigma_c^t = \frac{N}{A_t} + \frac{M_t * (y - y_t)}{I_t} \text{ (Sørensen, 2013, s.253)}$$

$$\sigma_c^t = -\frac{5951,25 * 10^3}{849\,812,00} - \frac{789,55 * 10^6 * (190,00 - 11,14)}{4,44 * 10^{10}}$$

$$\sigma_c^t = -10,18 \frac{\text{N}}{\text{mm}^2} \text{ (trykk)}$$

Spenningsendring:

$$\varepsilon_{ck}^t = \Delta \varepsilon_{pk} = \frac{\sigma_c^t(korttid)}{E_{cm}} \text{ (Sørensen, 2013, s.259)}$$

$$\Delta \varepsilon_{pk} = -\frac{11,09}{38\,000}$$

$$\Delta \varepsilon_{pk} = -2,92 * 10^{-4}$$

$$\varepsilon_{cL}^t = \Delta \varepsilon_{pL} = \frac{\sigma_c^t(langtid)}{E_{middel}} \text{ (Sørensen, 2013, s.259)}$$

$$\Delta \varepsilon_{pL} = -\frac{10,18}{15\,161,47}$$

$$\Delta \varepsilon_{pL} = -6,71 * 10^{-4}$$

$$\Delta\sigma_{pk} = \Delta\varepsilon_{pk} * E_p \text{ (Sørensen, 2013, s.259)}$$

$$\Delta\sigma_{pk} = -2,92 * 10^{-4} * 195\,000$$

$$\Delta\sigma_{pk} = -56,94 \frac{\text{N}}{\text{mm}^2}$$

$$\Delta\sigma_{pL} = \Delta\varepsilon_{pL} * E_p \text{ (Sørensen, 2013, s.259)}$$

$$\Delta\sigma_{pL} = -6,71 * 10^{-4} * 195\,000$$

$$\Delta\sigma_{pL} = -130,85 \frac{\text{N}}{\text{mm}^2}$$

$$\Delta\sigma_{p,kryp} = \Delta\sigma_{pL} - \Delta\sigma_{pk} \text{ (Sørensen, 2013, s.259)}$$

$$\Delta\sigma_{p,kryp} = -130,85 - (-56,94)$$

$$\Delta\sigma_{p,kryp} = -73,91 \frac{\text{N}}{\text{mm}^2}$$

Prosentvis reduksjon av kraft i spennarmering pga. kryp:

$$\frac{|\Delta\sigma_{p,kryp}|}{\sigma_{p,max}} * 100\% \text{ (Sørensen, 2013, s.259)}$$

$$\frac{73,91}{1476,00} * 100\% = 5,01\%$$

Felt 2 og 3:

$$g = 21,75 \frac{\text{kN}}{\text{m}} \text{ (Vedlegg 5, s. 9)}$$

$$p = 5,4 \frac{\text{kN}}{\text{m}} \text{ (Vedlegg 5, s. 9)}$$

$$M_{g+p} = \frac{(g+p)*L^2}{24} \text{ (Aalberg, Clausen og Larsen, 2003, tabell 3.2)}$$

$$M_{g+p} = \frac{(21,75+5,4)*23\,000^2}{24}$$

$$M_{g+p} = 598,43 \text{ kNm}$$

$$M_t = -P_0 * (e - y_t) + M_{g+p} \text{ (Sørensen, 2013, s.253)}$$

$$M_t = -5951,25 * 10^3 * (190,00 - 11,14) + 598,43 * 10^6$$

$$M_t = -466,01 \text{ kNm}$$

Betongspenninger i underkant av tverrsnitt $(y = \frac{800}{2} \text{ mm})$:

$$\sigma_c^u = \frac{N}{A_t} + \frac{M_t*(y-y_t)}{I_t} \text{ (Sørensen, 2013, s.253)}$$

$$\sigma_c^u = -\frac{5951,25*10^3}{849\,812,00} - \frac{466,01*10^6*\left(\frac{800}{2}-11,14\right)}{4,44*10^{10}}$$

$$\sigma_c^u = -11,08 \frac{\text{N}}{\text{mm}^2} \text{ (trykk)}$$

Betongspenninger i overkant av tverrsnitt ($y = -\frac{800}{2}$ mm):

$$\sigma_c^o = \frac{N}{A_t} + \frac{M_t * (y - y_t)}{I_t} \text{ (Sørensen, 2013, s.253)}$$

$$\sigma_c^o = -\frac{5951,25 * 10^3}{849\,812,00,00} - \frac{466,01 * 10^6 * \left(-\frac{800}{2} - 11,14\right)}{4,44 * 10^{10}}$$

$$\sigma_c^o = -2,69 \frac{\text{N}}{\text{mm}^2} \text{ (trykk)}$$

Betongspenninger ved spennarmeringen i tverrsnittet ($y = e = 190,00$ mm):

$$\sigma_c^t = \frac{N}{A_t} + \frac{M_t * (y - y_t)}{I_t} \text{ (Sørensen, 2013, s.253)}$$

$$\sigma_c^t = -\frac{5951,25 * 10^3}{849\,812,00} - \frac{466,01 * 10^6 * (190,00 - 11,14)}{4,44 * 10^{10}}$$

$$\sigma_c^t = -8,88 \frac{\text{N}}{\text{mm}^2} \text{ (trykk)}$$

Spenningsendring:

$$\varepsilon_{ck}^t = \Delta \varepsilon_{pk} = \frac{\sigma_c^t(korttid)}{E_{cm}} \text{ (Sørensen, 2013, s.259)}$$

$$\Delta \varepsilon_{pk} = -\frac{9,98}{38\,000}$$

$$\Delta \varepsilon_{pk} = -2,63 * 10^{-4}$$

$$\varepsilon_{cL}^t = \Delta \varepsilon_{pL} = \frac{\sigma_c^t(langtid)}{E_{middel}} \text{ (Sørensen, 2013, s.259)}$$

$$\Delta \varepsilon_{pL} = -\frac{8,88}{15\,161,47}$$

$$\Delta \varepsilon_{pL} = -5,86 * 10^{-4}$$

$$\Delta\sigma_{pk} = \Delta\varepsilon_{pk} * E_p \text{ (Sørensen, 2013, s.259)}$$

$$\Delta\sigma_{pk} = -2,63 * 10^{-4} * 195\,000$$

$$\Delta\sigma_{pk} = -51,29 \frac{\text{N}}{\text{mm}^2}$$

$$\Delta\sigma_{pL} = \Delta\varepsilon_{pL} * E_p \text{ (Sørensen, 2013, s.259)}$$

$$\Delta\sigma_{pL} = -5,86 * 10^{-4} * 195\,000$$

$$\Delta\sigma_{pL} = -114,27 \frac{\text{N}}{\text{mm}^2}$$

$$\Delta\sigma_{p,kryp} = \Delta\sigma_{pL} - \Delta\sigma_{pk} \text{ (Sørensen, 2013, s.259)}$$

$$\Delta\sigma_{p,kryp} = -114,27 - (-51,29)$$

$$\Delta\sigma_{p,kryp} = -62,98 \frac{\text{N}}{\text{mm}^2}$$

Prosentvis reduksjon av kraft i spennarmering pga. kryp:

$$\frac{|\Delta\sigma_{p,kryp}|}{\sigma_{p,max}} * 100\% \text{ (Sørensen, 2013, s.259)}$$

$$\frac{62,98}{1476,00} * 100\% = 4,27\%$$

Spenningsendring pga. svinn:

Tidligere beregnede verdier:

$$A_t = 849\,812,00 \text{ mm}^2$$

$$A_p = 4200,00 \text{ mm}^2$$

$$y_t = 11,14 \text{ mm}$$

$$I_t = 4,44 * 10^{10} \text{ mm}^4$$

$$e = 190,00 \text{ mm}$$

$$\varepsilon_{cs} = -2,55 * 10^{-4} \text{ (Vedlegg 9, s. 20)}$$

$$E_{middel} = 15\,161,47 \frac{\text{N}}{\text{mm}^2} \text{ (Vedlegg 9, s. 15)}$$

$$N_s = |\varepsilon_{sc}| * E_p * A_p \text{ (Sørensen, 2013, s.260)}$$

$$N_s = 2,55 * 10^{-4} * 195\,000 * 4200,00$$

$$N_s = 208,85 \text{ kN}$$

$$\Delta\varepsilon_{p,svinn} = \varepsilon_{cs} + \frac{N_s}{E_{middel} * A_t} + \frac{N_s * (e - y_t)^2}{E_{middel} * I_t} \text{ (Sørensen, 2013, s.260)}$$

$$\Delta\varepsilon_{p,svinn} = -2,55 * 10^{-4} + \frac{208,85 * 10^3}{15\,161,47 * 849\,812,00} + \frac{208,85 * 10^3 * (190,00 - 11,14)^2}{15\,161,47 * 4,44 * 10^{10}}$$

$$\Delta\varepsilon_{p,svinn} = -2,29 * 10^{-4}$$

Spenningsendring i spennarmeringen pga. svinn:

$$\Delta\sigma_{p,svinn} = \Delta\varepsilon_{p,svinn} * E_p \text{ (Sørensen, 2013, s.261)}$$

$$\Delta\sigma_{p,svinn} = -2,29 * 10^{-4} * 195\,000$$

$$\Delta\sigma_{p,svinn} = -44,66 \frac{\text{N}}{\text{mm}^2}$$

Prosentvis reduksjon av kraft i spennarmering pga. svinn:

$$\frac{|\Delta\sigma_{p,svinn}|}{\sigma_{p,max}} * 100\% \text{ (Sørensen, 2013, s.261)}$$

$$\frac{44,66}{1476,00} * 100\% = 3,03\%$$

Spenningsendring pga. relaksasjon:

$$\rho_{1000} = 2,5\% \text{ (Standard Norge, 2004, pkt. 3.3.2(6))}$$

$$\sigma_{pi} = \sigma_{pm0} \text{ (Standard Norge, 2004, pkt. 3.3.2(7))}$$

$$\sigma_{pm0} = \min \{0,75f_{pk}; 0,85f_{p0,1k}\} \text{ (Standard Norge, 2004, pkt. 5.10.3(2))}$$

$$\sigma_{pm0} = \min \{0,75 * 1860; 0,85 * 1640\}$$

$$\sigma_{pm0} = \min\{1395,00; 1394,00\}$$

$$\sigma_{pm0} = 1394,00 \frac{\text{N}}{\text{mm}^2}$$

$$\mu = \frac{\sigma_{pi}}{f_{pk}} \text{ (Sørensen, 2013, s.263)}$$

$$\mu = \frac{1394,00}{1860}$$

$$\mu = 0,75$$

$$\frac{\Delta\sigma_{pr}}{\sigma_{pi}} = 0,66 * \rho_{1000} * e^{9,1\mu} \left(\frac{t}{1000}\right)^{0,75(1-\mu)} * 10^{-5} \text{ (Standard Norge, 2004, pkt. 3.3.2(7))}$$

Omformulert:

$$\Delta\sigma_{pr} = \left(0,66 * \rho_{1000} * e^{9,1\mu} \left(\frac{t}{1000}\right)^{0,75(1-\mu)} * 10^{-5}\right) * \sigma_{pi}$$

$$\Delta\sigma_{pr} = \left(0,66 * 2,5 * e^{9,1*0,75} * \left(\frac{500\ 000}{1000}\right)^{0,75*(1-0,75)} * 10^{-5}\right) * 1394,00$$

$$\Delta\sigma_{pr} = 67,90 \frac{\text{N}}{\text{mm}^2}$$

Prosentvis reduksjon av kraft i spennarmeringen pga. relaksasjon:

$$\frac{|\Delta\sigma_{pr}|}{\sigma_{p,max}} * 100\% \text{ (Sørensen, 2013, s.264)}$$

$$\frac{67,90}{1476,00} * 100\% = 4,60\%$$

Total prosentvis reduksjon av kraft i spennarmeringen:

Felt 1 og 4:

$$5,01\% + 3,03\% + 4,60\% = 12,64\%$$

Felt 2 og 3:

$$4,27\% + 3,03\% + 4,60\% = 11,90\%$$

Nedbøying:

Krav til maksimum nedbøying:

$$\delta_{tillatt} = \frac{L}{500} \text{ (Standard Norge, 2004, pkt. 7.4.1(5))}$$

Felt 1 og 4:

$$\delta_{tillatt} = \frac{12\,000}{500}$$

$$\delta_{tillatt} = 24,00 \text{ mm}$$

Felt 2 og 3:

$$\delta_{tillatt} = \frac{23\,000}{500}$$

$$\delta_{tillatt} = 46,00 \text{ mm}$$

Oppbøying av bjelke:

$$\delta_b = \frac{P \cdot e}{EI} * \frac{L^2}{12} \text{ (Sørensen, 2013, s.226)}$$

Felt 1 og 4:

$$\delta_{b,start} = \frac{5951,25 \cdot 10^3 \cdot 190,00}{15\,161,47 \cdot \frac{1}{12} \cdot 1000 \cdot 800^3} \cdot \frac{12\,000^2}{12}$$

$$\delta_{b,start} = 20,98 \text{ mm}$$

$$\delta_{b,langtid} = \frac{5951,25 \cdot 10^3 \cdot (100\% - 12,64\%) \cdot 190,00}{15\,161,47 \cdot \frac{1}{12} \cdot 1000 \cdot 800^3} \cdot \frac{12\,000^2}{12}$$

$$\delta_{b,langtid} = 18,32 \text{ mm}$$

Nedbøying pga. kryp, svinn og relaksasjon:

$$\delta_{total} = \delta_{b,start} - \delta_{b,langtid}$$

$$\delta_{total} = 20,98 - 18,32$$

$$\delta_{total} = 2,66 \text{ mm} < \delta_{tillatt} = 24,00 \text{ mm} \Rightarrow OK$$

Felt 2 og 3:

$$\delta_{b,start} = \frac{5951,25 \cdot 10^3 \cdot 190,00}{15\,161,47 \cdot \frac{1}{12} \cdot 1000 \cdot 800^3} \cdot \frac{23\,000^2}{12}$$

$$\delta_{b,start} = 77,06 \text{ mm}$$

$$\delta_{b,langtid} = \frac{5951,25 \cdot 10^3 \cdot (100\% - 11,90\%) \cdot 190,00}{15\,161,47 \cdot \frac{1}{12} \cdot 1000 \cdot 800^3} \cdot \frac{23\,000^2}{12}$$

$$\delta_{b,langtid} = 67,89 \text{ mm}$$

Nedbøying pga. kryp, svinn og relaksasjon:

$$\delta_{total} = \delta_{b,start} - \delta_{b,langtid}$$

$$\delta_{total} = 77,06 - 67,89$$

$$\delta_{total} = 9,17 \text{ mm} < \delta_{tillatt} = 46,00 \text{ mm} \Rightarrow OK$$