

Univerza v Ljubljani, Fakulteta za gradbeništvo in geodezijo
Katedra za metalne konstrukcije

Projektiranje rezervoarjev po evropskih standardih

delovno gradivo - II

December 2008

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Mejna stanja nosilnosti

- **LS1: Plastična nosilnost**
 - običajno polni rezervoarji
 - predvsem zadnji pas ob dnu rezervoarja (robna motnja)
- **LS2: Nizko-ciklično utrujanje**
 - akumuliranje plastičnih deformacij
 - polnjenje – praznjenje rezervoarja, temperaturne spremembe
- **LS3: Stabilnost**
 - običajno prazni rezervoarji (veter, vertikalna obtežba – streha)
- **LS4: Visoko-ciklično utrujanje**
 - $\Delta\sigma$ (polnjenje – praznjenje rezervoarja, temperaturne spremembe)
 - nominalno elastično obnašanje

LS1: Plastična nosilnost

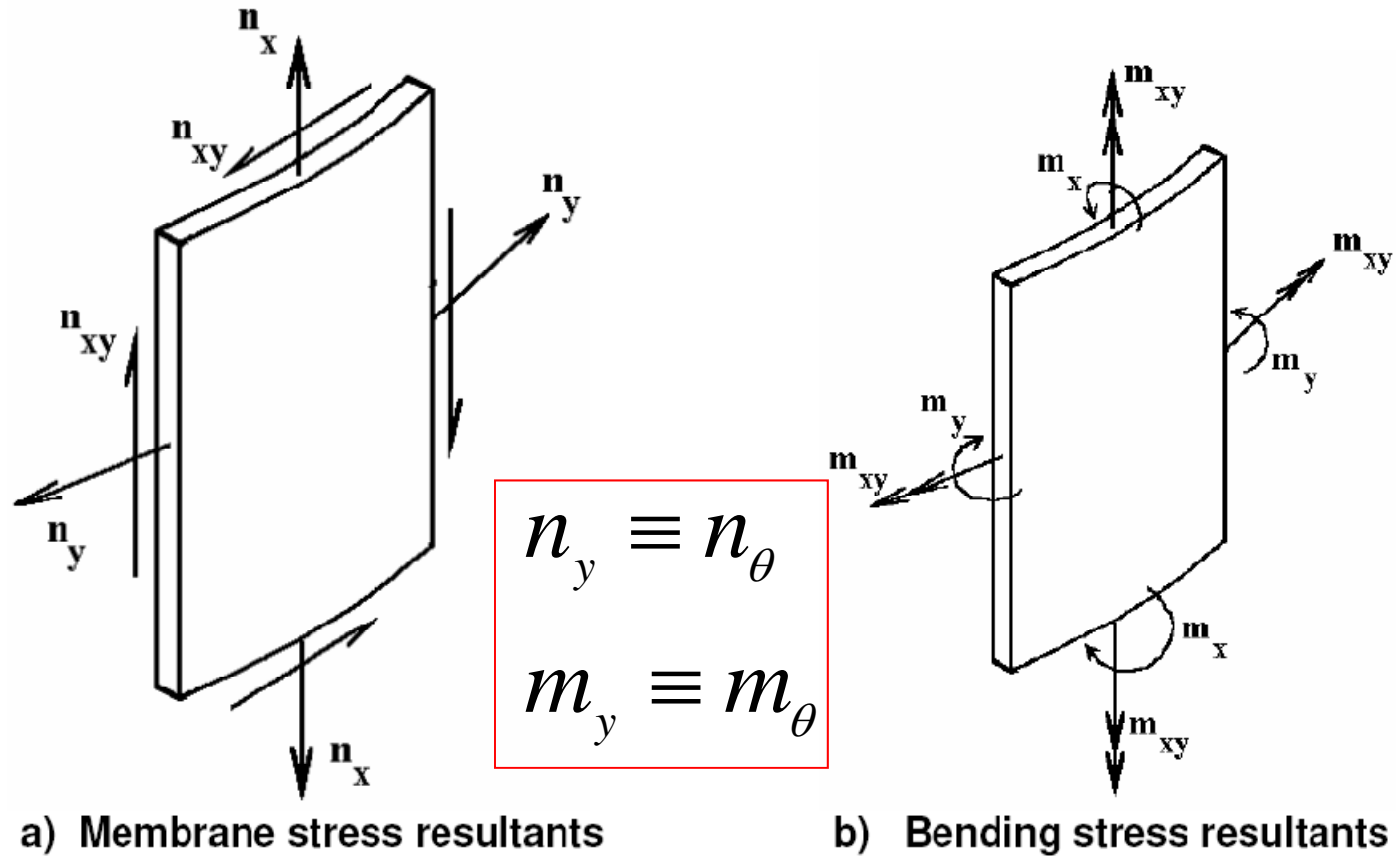


Figure 1.5: Stress resultants in the tank wall (shells and boxes)

LS1: Plastična nosilnost

- Napetostna metoda

Membransko stanje

$$\sigma_{eq,Ed} = \frac{1}{t} \sqrt{n_{x,Ed}^2 + n_{\theta,Ed}^2 - n_{x,Ed} \cdot n_{\theta,Ed} + 3n_{x\theta,Ed}^2}$$

Upogibno stanje

$$\sigma_{eq,Ed} = \sqrt{\sigma_{x,Ed}^2 + \sigma_{\theta,Ed}^2 - \sigma_{x,Ed} \cdot \sigma_{\theta,Ed} + 3(\tau_{x\theta,Ed}^2 + \tau_{xn,Ed}^2 + \tau_{\theta n,Ed}^2)}$$

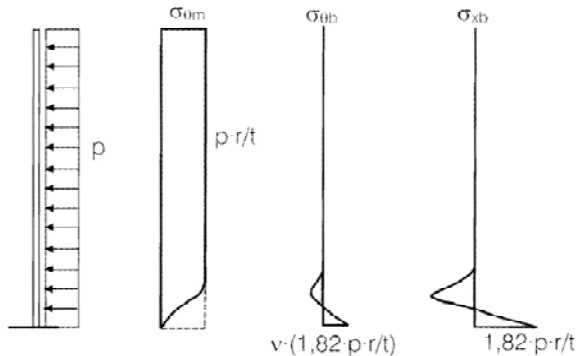
$$\sigma_{x,Ed} = \frac{n_{x,Ed}}{t} \pm \frac{m_{x,Ed}}{(t^2 / 4)} \quad \sigma_{\theta,Ed} = \frac{n_{\theta,Ed}}{t} \pm \frac{m_{\theta,Ed}}{(t^2 / 4)} \quad \tau_{x\theta,Ed} = \frac{n_{x\theta,Ed}}{t} \pm \frac{m_{x\theta,Ed}}{(t^2 / 4)}$$

$$\tau_{xn,Ed} = \frac{q_{xn,Ed}}{t} \quad \tau_{\theta n,Ed} = \frac{q_{\theta n,Ed}}{t}$$

$$\sigma_{eq,Ed} \leq f_{eq,Ed} = f_{yk} / \gamma_{M0}$$

LS1: Plastična nosilnost

- Direktna metoda



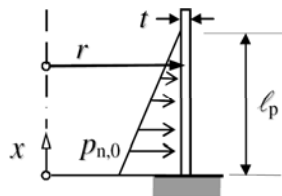
$$\sigma_{eq.Ed} = 1,614 p \frac{r}{t} \leq \frac{f_y}{\gamma_{M0}}$$

$$\gamma_G = 1,35$$

$$\gamma_Q = 1,50$$

Bild 6. Membran- und Biegespannungsanteile

C.2.4 Cylinder, clamped: hydrostatic internal pressure



$$\sigma_{MT\theta} = p_{n,0} \frac{r}{t}$$

BC1r

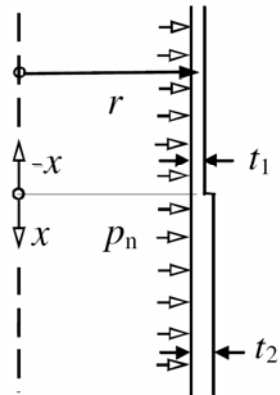
Ostale vplive običajno lahko zanemarimo (veter, streha ...)

Maximum σ_{sx}	Maximum $\sigma_{s\theta}$	Maximum τ_{xn}	Maximum $\sigma_{eq,s}$	Maximum $\sigma_{eq,m}$
$k_x \sigma_{MT\theta}$	$k_\theta \sigma_{MT\theta}$	$k_\tau \sqrt{t/r} \sigma_{MT\theta}$	$k_{eq,s} \sigma_{MT\theta}$	$k_{eq,m} \sigma_{MT\theta}$

$\left(\frac{\sqrt{rt}}{\ell_p}\right)$	k_x	k_θ	k_τ	$k_{eq,s}$	$k_{eq,m}$
0	1,816	1,080	1,169	1,614	1,043
0,2	1,533	0,733	1,076	1,363	0,647

Direktna metoda

C.4.3 Cylinder: step change of thickness



$$\sigma_{MT\theta} = p_n \frac{r}{t_1}$$

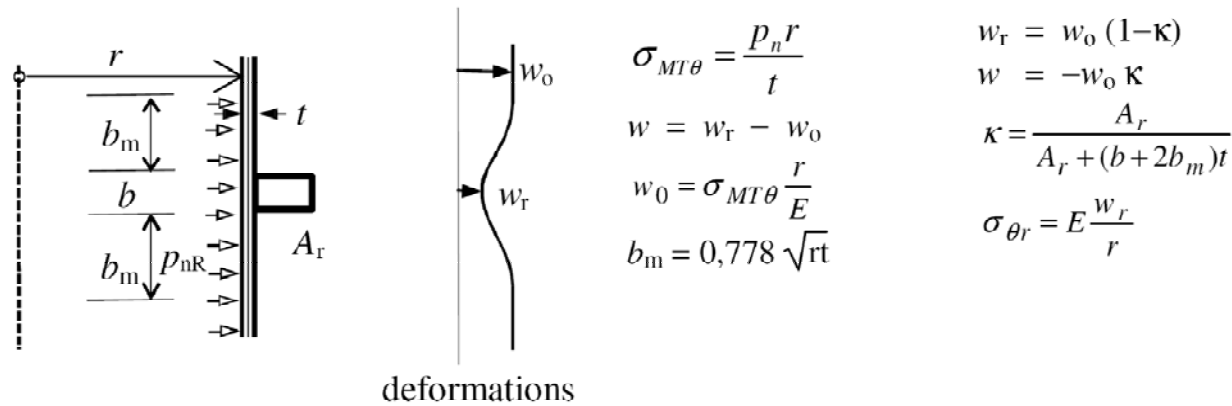
Maximum σ_{sx}	Maximum $\sigma_{s\theta}$	Maximum τ_{xn}	Maximum $\sigma_{eq,s}$	Maximum $\sigma_{eq,m}$
$k_x \sigma_{MT\theta}$	$k_\theta \sigma_{MT\theta}$	$k_\tau \sqrt{t/r} \sigma_{MT\theta}$	$k_{eq,s} \sigma_{MT\theta}$	$k_{eq,m} \sigma_{MT\theta}$

$\left(\frac{t_1}{t_2}\right)$	k_x	k_θ	k_τ	$k_{eq,s}$	$k_{eq,m}$
1,0	0,0	1,0	0,0	1,0	1,0
0,8	0,0256	1,010	0,179	1,009	0,895
0,667	0,0862	1,019	0,349	1,015	0,815
0,571	0,168	1,023	0,514	1,019	0,750
0,5	0,260	1,027	0,673	1,023	0,694

Direktna metoda

C.5.3 Ring stiffened cylinder: uniform internal pressure

The stresses in the shell should be determined using the calculated value of w from this clause introduced into the expressions given in C.2.5 and C.2.1.

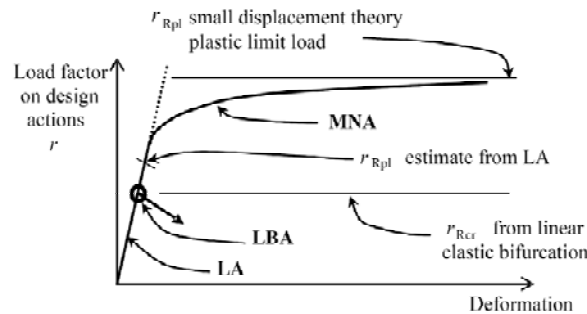


Maximum σ_{sx}	Maximum $\sigma_{s\theta}$	Maximum τ_{xn}	Maximum $\sigma_{eq,s}$	Maximum $\sigma_{eq,m}$
$k_x \sigma_{MT\theta}$	$k_\theta \sigma_{MT\theta}$	$k_\tau \sqrt{t/r} \sigma_{MT\theta}$	$k_{eq,s} \sigma_{MT\theta}$	$k_{eq,m} \sigma_{MT\theta}$

κ	k_x	k_θ	k_τ	$k_{eq,s}$	$k_{eq,m}$
1,0	1,816	1,080	1,169	1,614	1,043
0,75	1,312	1,060	0,877	1,290	1,032
0,50	0,908	1,040	0,585	1,014	1,021
0,0	0,0	1,000	0,0	1,000	1,000

LS1: Plastična nosilnost

- Nelinearna globalna analiza
 - Metoda končnih elementov: **materialno nelinearna** analiza brez geometrijskih nepopolnosti
 - Kriteriji
 - Najvišji nivo obtežne poti



$$F_{Ed} \leq F_{Rd}$$

Figure 8.5: Definition of plastic reference resistance ratio r_{Rpl} and critical buckling resistance ratio r_{Rcr} derived from global MNA and LBA analyses

- Misesova ekvivalentna plastična deformacija

$$\varepsilon_{p.eq.Ed} \leq 50 \left(\frac{f_y}{E} \right) \approx 50 \cdot 0,001 = 0,05 \quad (\text{za } S235)$$

LS2: Nizko-ciklično utrujanje

- Napetostna metoda
 - merodajna sprememba obtežbe, ki povzroča ponavljajoče se plastične deformacije
 - pri rezervoarjih običajno kontrola ni kritična (polnjenje – praznjenje: $\Delta\sigma$ - od 0 do σ_{\max} , ni večjih obtežb v drugo smer!)

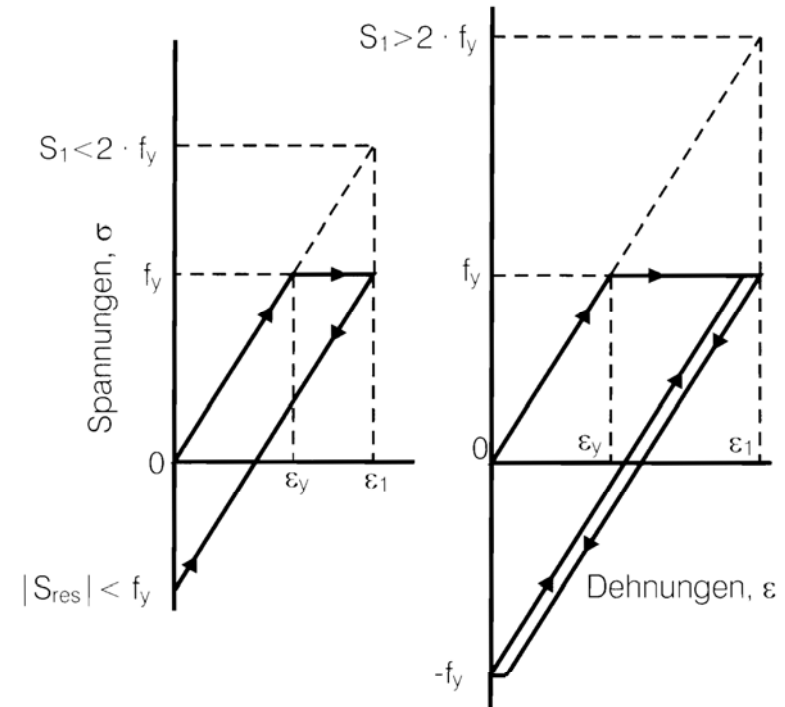


Bild 4. Dehnungsverlauf bei Überschreitung der Fließgrenze

- kontrola utrujanja:

$$\Delta\sigma_{eq.Ed} = \sqrt{\Delta\sigma_{x.Ed}^2 - \Delta\sigma_{x.Ed}\Delta\sigma_{\theta.Ed} + \Delta\sigma_{\theta.Ed}^2 - 3\Delta\tau_{x\theta.Ed}}$$

$$\Delta\sigma_{eq.Ed} \leq \Delta f_{eq.Rd} = 2f_y$$

$$\gamma_G = 1,00$$

$$\gamma_Q = 1,00$$

LS2: Nizko-ciklično utrujanje

- Direktna metoda
 - $\Delta\sigma$ določena s formulami iz aneksa C – SIST EN 1993-1-6
- Nelinearna globalna analiza
 - Materialno nelinearna analiza brez nepopolnosti
 - akumulirana Misesova plastična deformacija:

$$\varepsilon_{p.eq.Ed} = n\Delta\varepsilon_{p.eq.Ed} \leq 25 \left(\frac{f_{yd}}{E} \right)$$

n = število ciklov

LS3: Stabilnost

- Upoštevamo samo membranske napetosti
- Prazen rezervoar – streha, veter
- Vertikalni uklon – notranji pritisk (elast., plast.)
- Robni pogoji
- Tolerance izdelave – trije razredi
- Napetostna metoda: dodatek D – SIST EN 1993-1-6
- Nelinearna globalna analiza
 - MNA + LBA
 - GMNIA (nepopolnosti)
- Direktna metoda – ne obstaja

$$\gamma_G = 1,35$$

$$\gamma_Q = 1,50$$

LS3: Stabilnost

- Robni pogoji

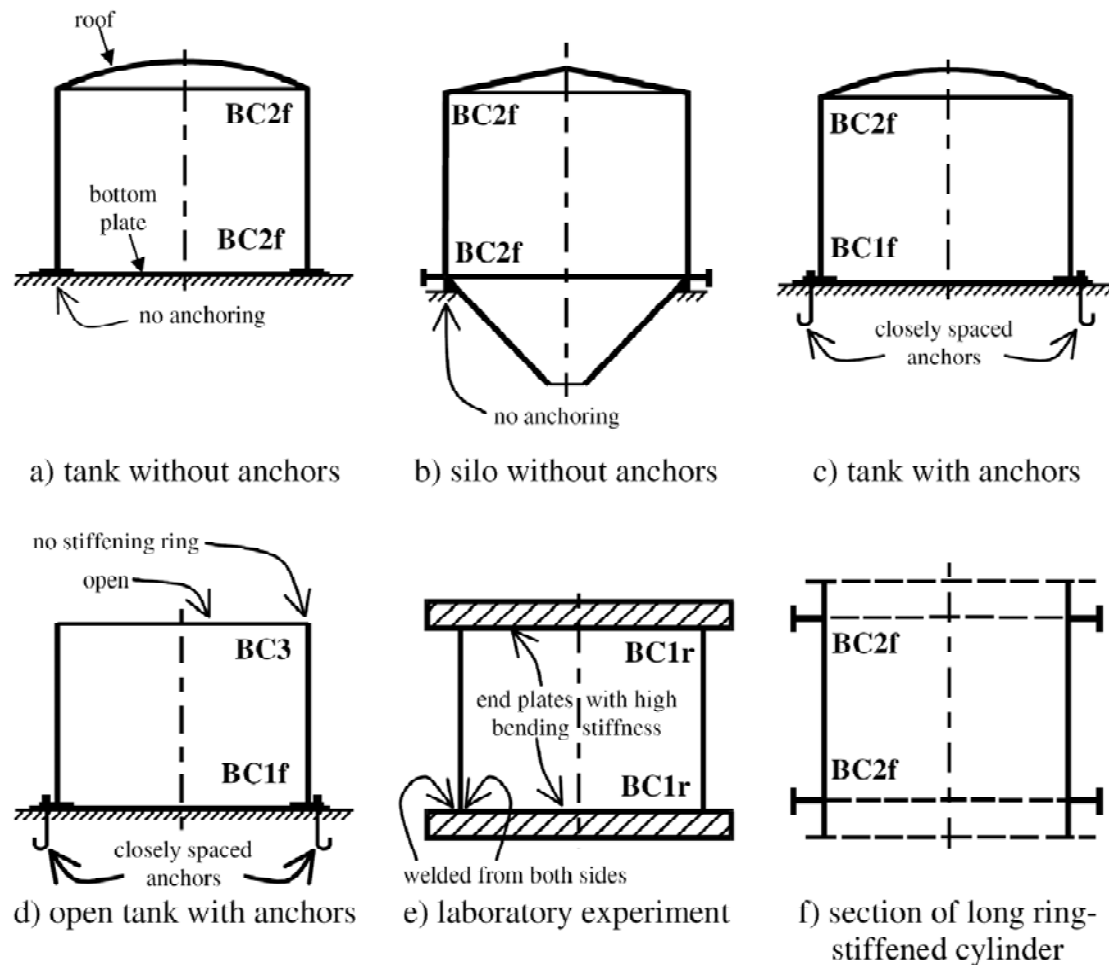
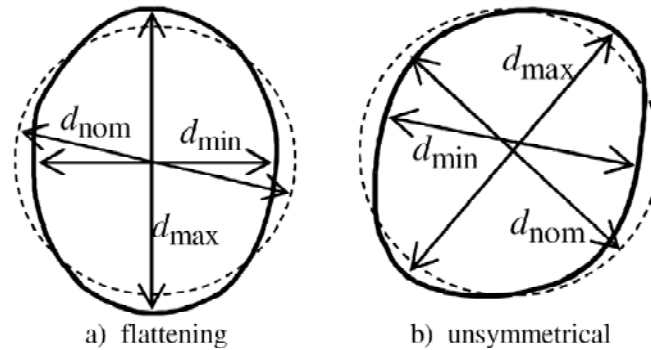


Figure 8.1: Schematic examples of boundary conditions for limit state LS3

LS3: Stabilnost

- Tolerance izdelave – trije razredi: A, B in C
 - Plašč: ostopanje od kroga



a) flattening

b) unsymmetrical

$$U_r = \frac{d_{\max} - d_{\min}}{d_{\text{nom}}} \leq U_{r.\max}$$

Table 8.1: Recommended values for out-of-roundness tolerance parameter $U_{r,\max}$

	Diameter range	d [m] \leq 0,50m	0,50m < d [m] < 1,25m	1,25m \leq d [m]
Fabrication tolerance quality class	Description	Recommended value of $U_{r,\max}$		
Class A	Excellent	0,014	$0,007 + 0,0093(1,25-d)$	0,007
Class B	High	0,020	$0,010 + 0,0133(1,25-d)$	0,010
Class C	Normal	0,030	$0,015 + 0,0200(1,25-d)$	0,015

LS3: Stabilnost

- Plašč: slučajna ekscentričnost pri stikovanju pločevin

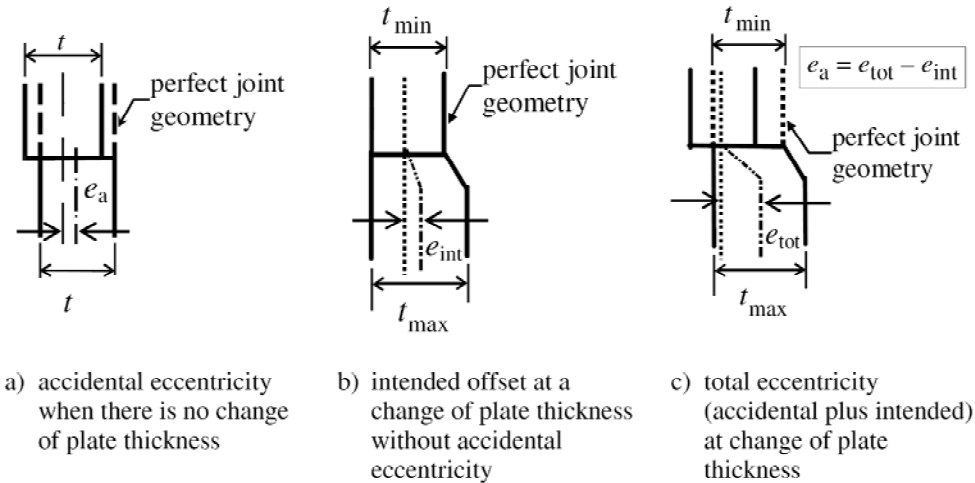


Figure 8.3: Accidental eccentricity and intended offset at a joint

Table 8.2: Recommended values for maximum permitted accidental eccentricities

Fabrication tolerance quality class	Description	Recommended values for maximum permitted accidental eccentricity $e_{a,max}$
Class A	Excellent	2 mm
Class B	High	3 mm
Class C	Normal	4 mm

LS3: Stabilnost

- Plašč: slučajna ekscentričnost pri stikovanju pločevin

$$U_e = \frac{e_a}{t} \text{ ali } \frac{e_a}{t_{av}} \leq U_{e.\max}$$

- (4) The accidental eccentricity parameter U_e should satisfy the condition:

$$U_e \leq U_{e,\max} \quad \dots (8.5)$$

where:

$U_{e,\max}$ is the accidental eccentricity tolerance parameter for the relevant fabrication tolerance quality class.

NOTE 1: Values for the accidental eccentricity tolerance parameter $U_{e,\max}$ may be obtained from the National Annex. The recommended values are given in Table 8.3.

Table 8.3: Recommended values for accidental eccentricity tolerances

Fabrication tolerance quality class	Description	Recommended value of $U_{e,\max}$
Class A	Excellent	0,14
Class B	High	0,20
Class C	Normal	0,30

NOTE 2: Intended offsets are treated within D.2.1.2 and lapped joints are treated within D.3. These two cases are not treated as imperfections within this standard.

LS3: Stabilnost

– Plašč: lokalne nepopolnosti

$$l_{gx} = 4\sqrt{rt}$$

$$l_{g\theta} = 2,3(l^2 rt)^{0,25} \leq r$$

$$l_{gw} = 25t_{\min} \leq 500\text{mm}$$

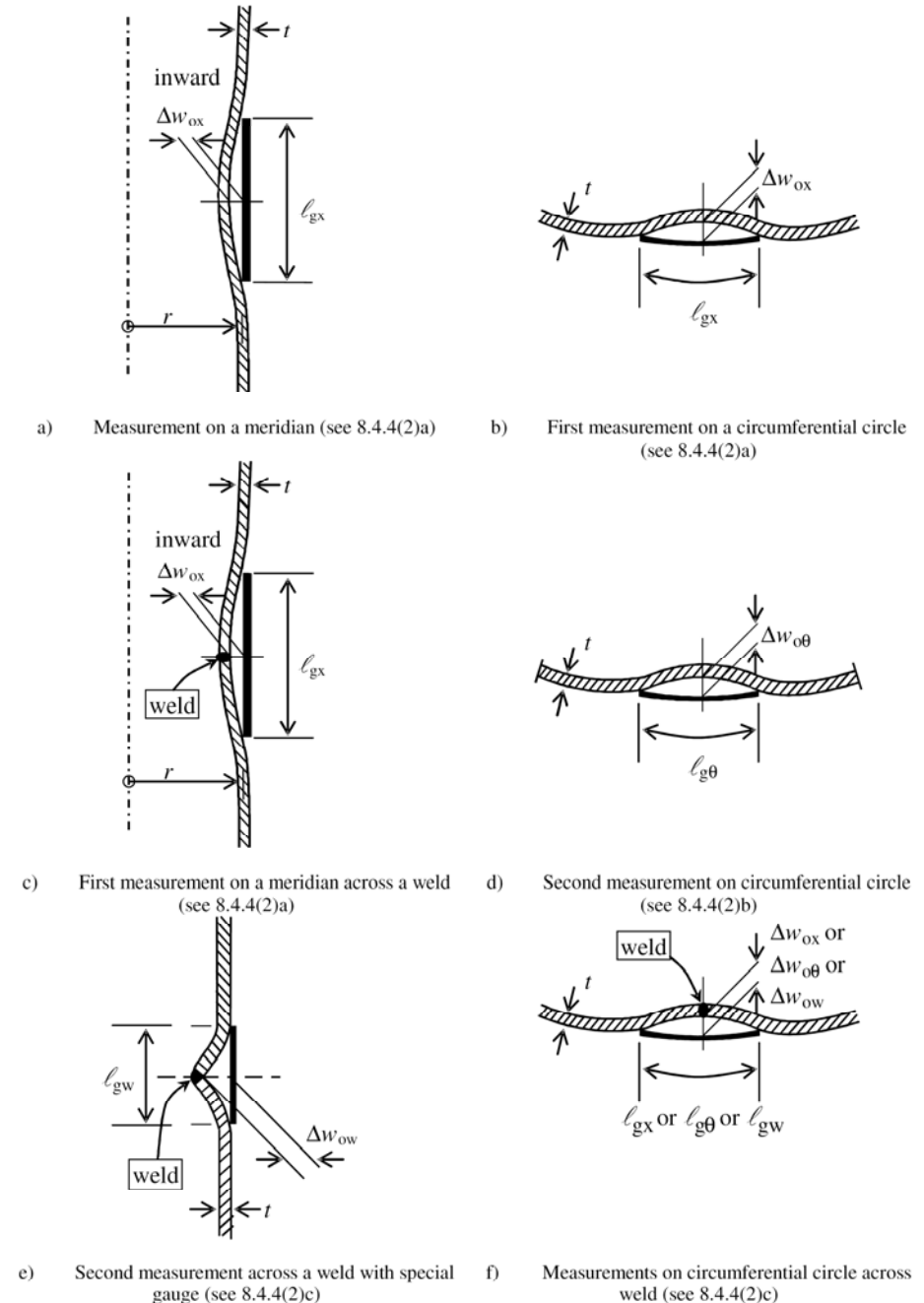


Figure 8.4: Measurement of depths Δw_0 of initial dimples

LS3: Stabilnost

- Plašč: lokalne nepopolnosti

$$U_{0i} = \frac{\Delta w_{0i}}{l_{gi}} \leq U_{0.\max} \quad , \quad i = x, \theta, w$$

Table 8.4: Recommended values for dimple tolerance parameter $U_{0,\max}$

Fabrication tolerance quality class	Description	Recommended value of $U_{0,\max}$
Class A	Excellent	0,006
Class B	High	0,010
Class C	Normal	0,016

LS3: Stabilnost

- Napetostna metoda: dodatek D – SIST EN 1993-1-6

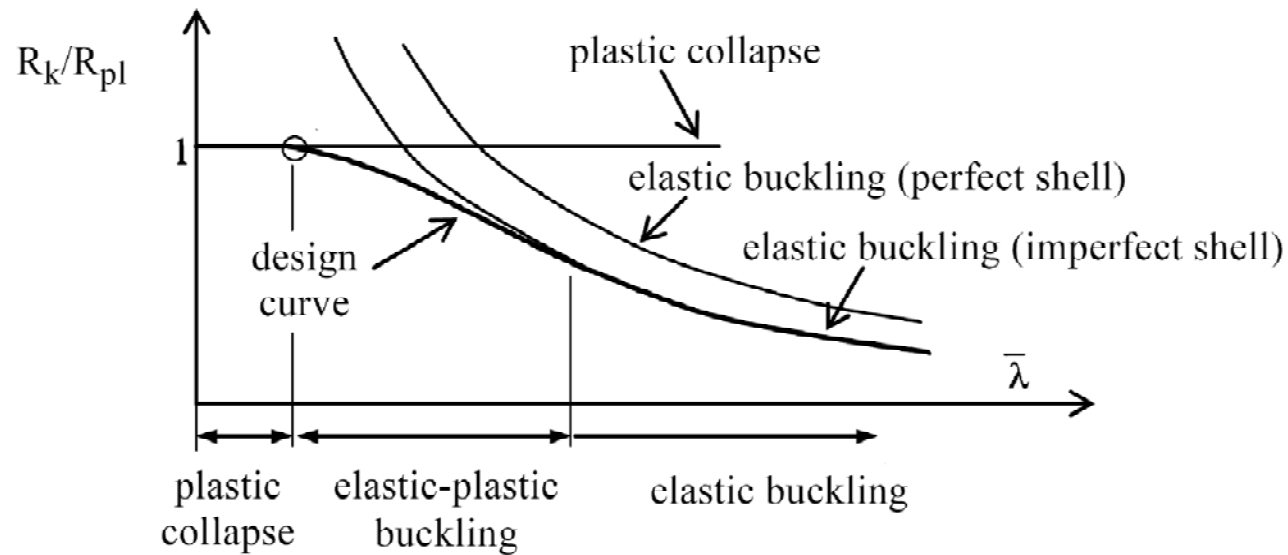


Figure 2.6 Typical curve of buckling load factor against slenderness for a shell

Vertikalni uklon

$$\sigma_{x,Rd} = \chi_x f_y / \gamma_{M1}$$

Redukcijski faktor uklona χ_x se določi v odvisnosti od vrednosti λ

$$\chi_x = 1 \quad \text{za} \quad \bar{\lambda}_x \leq \bar{\lambda}_0$$

$$\chi_x = 1 - \beta_x \left(\frac{\bar{\lambda}_x - \bar{\lambda}_0}{\bar{\lambda}_p - \bar{\lambda}_0} \right)^{\eta_x} \quad \text{za} \quad \bar{\lambda}_0 \leq \bar{\lambda}_x < \bar{\lambda}_{p,x}$$

$$\chi_x = \frac{\alpha_x}{\bar{\lambda}_x^2} \quad \text{za} \quad \bar{\lambda}_{p,x} \leq \bar{\lambda}_x$$

Vrednost mejne plastične vitkosti:

$$\bar{\lambda}_{p,x} = \sqrt{\frac{\alpha_x}{1 - \beta_x}}$$

Relativna vitkosti:

$$\bar{\lambda}_x = \sqrt{f_{yk} / \sigma_{x,Rcr}}$$

$\sigma_{x,Rcr}$ določimo skladno z dodatkom D.

$$\sigma_{x,Rcr} = 0,605 E C_x \frac{t}{r}$$

Brezdimenzionalni dolžinski parameter ω

$$\omega = \frac{l}{r} \sqrt{\frac{r}{t}} = \frac{l}{\sqrt{rt}}$$

Elastični redukcijski faktor nepopolnosti

$$\alpha_x = \frac{0,62}{1 + 1,91(\Delta w_k / t)^{1,44}} \quad \Delta w_k = \frac{1}{Q} \sqrt{\frac{r}{t}} \cdot t$$

Preglednica D.2: Vrednosti faktorja kvalitete izdelave Q

Fabrication tolerance quality class	Description	Q
Class A	Excellent	40
Class B	High	25
Class C	Normal	16

Vrednosti ostalih parametrov:

$$\bar{\lambda}_{x0} = 0,20 \qquad \beta_x = 0,60 \qquad \eta_x = 1,0$$

Za dolge cilindre, kjer velja:

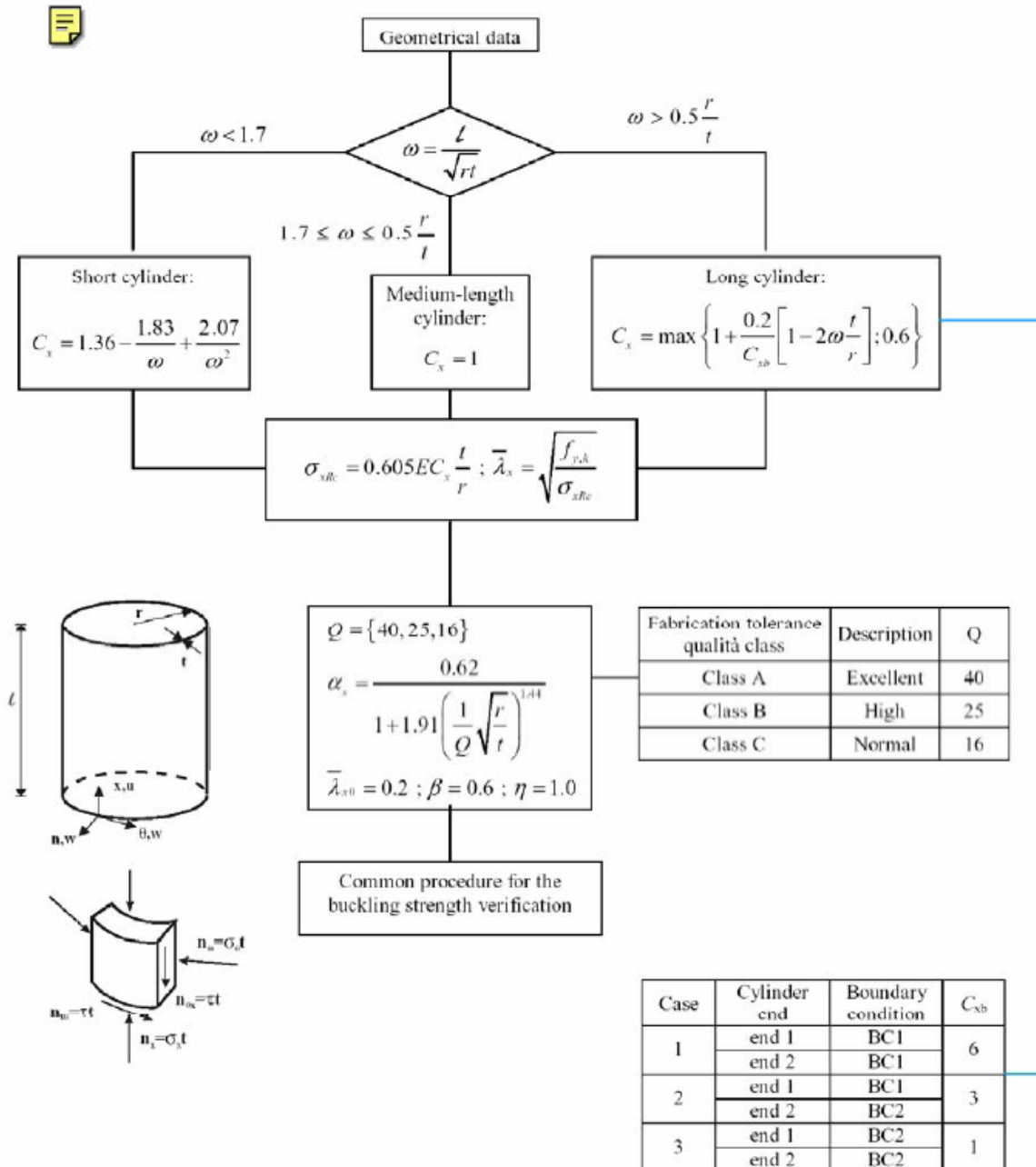
$$\frac{r}{t} \leq 150 \quad \text{in} \quad \omega \leq 6 \left(\frac{r}{t} \right) \quad \text{in} \quad 500 \leq \frac{E}{f_{y,k}} \leq 1000, \text{ je:}$$

$$\bar{\lambda}_{x0} = 0,20 + 0,10 \left(\frac{\sigma_{xE,M}}{\sigma_{xE}} \right)$$

Uklonska kontrola ni potrebna, kadar je:

$$\frac{r}{t} \leq 0,03 \frac{E}{f_{yk}}$$

PROCEDURE FOR THE DESIGN CHECK OF CYLINDRICAL SHELLS SUBJECT TO AXIAL COMPRESSION



Uklon v obodni smeri

$$\sigma_{\theta,Rd} = \chi_{\theta} f_y / \gamma_{M1}$$

Redukcijski faktor uklona χ_{θ} se določi v odvisnosti od vrednosti λ

$$\chi_{\theta} = 1 \quad \text{za} \quad \bar{\lambda}_{\theta} \leq \bar{\lambda}_0$$

$$\chi_{\theta} = 1 - \beta_{\theta} \left(\frac{\bar{\lambda}_{\theta} - \bar{\lambda}_0}{\bar{\lambda}_p - \bar{\lambda}_0} \right)^{\eta} \quad \text{za} \quad \bar{\lambda}_0 \leq \bar{\lambda}_{\theta} < \bar{\lambda}_{p,\theta}$$

$$\chi_{\theta} = \frac{\alpha_{\theta}}{\bar{\lambda}_{\theta}^2} \quad \text{za} \quad \bar{\lambda}_{p,\theta} \leq \bar{\lambda}_{\theta}$$

Vrednost mejne plastične vitkosti:

$$\bar{\lambda}_{p,\theta} = \sqrt{\frac{\alpha_{\theta}}{1 - \beta_{\theta}}}$$

Relativna vitkost:

$$\bar{\lambda}_{\theta} = \sqrt{f_{yk} / \sigma_{\theta,Rcr}}$$

$\sigma_{\theta,Rcr}$ določimo skladno z dodatkom D.

$$\sigma_{\theta,Rcr} = 0,92E \frac{C_{\theta} t}{\omega r}$$

Preglednica D.5: Vrednosti faktorja kvalitete izdelave α_θ

Fabrication tolerance quality class	Description	α_θ
Class A	Excellent	0,75
Class B	High	0,65
Class C	Normal	0,50

Vrednosti ostalih parametrov:

$$\bar{\lambda}_{\theta 0} = 0,40 \quad \beta_\theta = 0,60 \quad \eta_\theta = 1,0$$

Uklonska kontrola ni potrebna, kadar je :

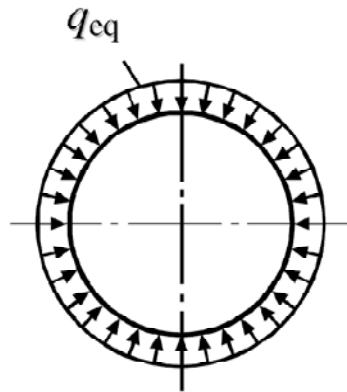
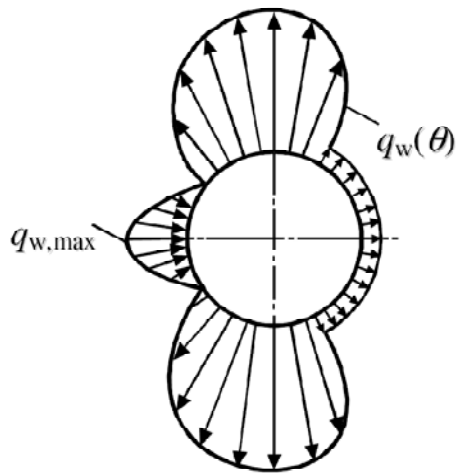
$$\frac{r}{t} \leq 0,21 \sqrt{\frac{E}{f_{yk}}}$$

Ekvivalentni zunanji pritisk vetra:

$$q_{eq} = k_w q_{w,max}$$

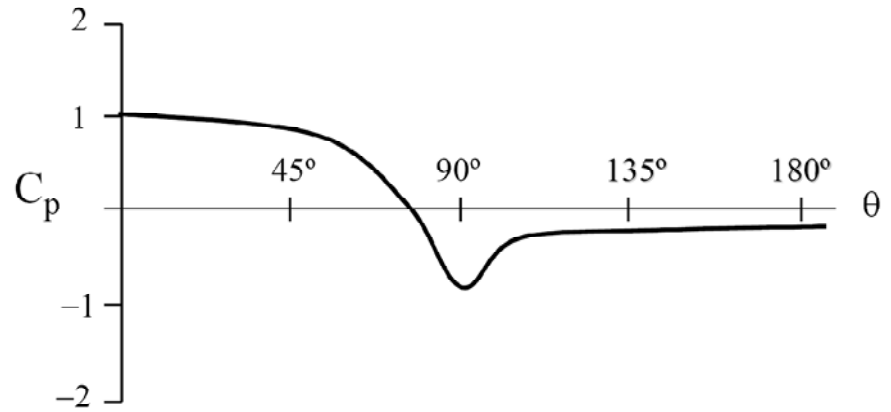
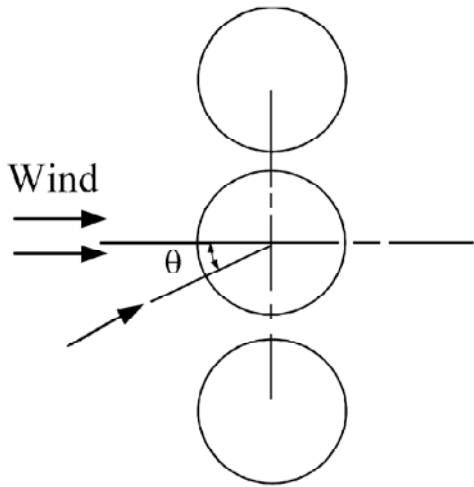
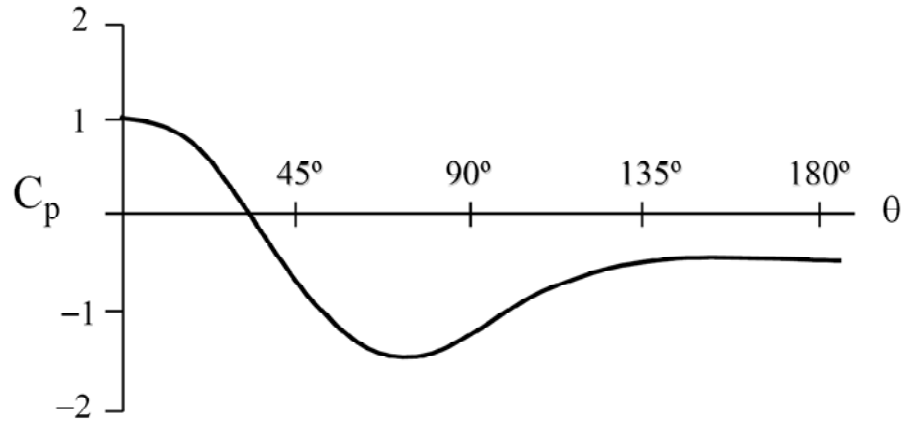
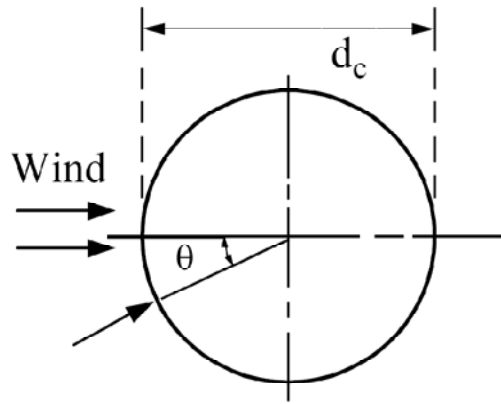
$$k_w = 0,46 \left(1 + 0,1 \sqrt{\frac{C_\theta r}{\omega t}} \right) \quad 0,65 \leq k_w \leq 1$$

C_θ se določi po preglednici D.3 v skladu z robnimi pogoji cilindra.

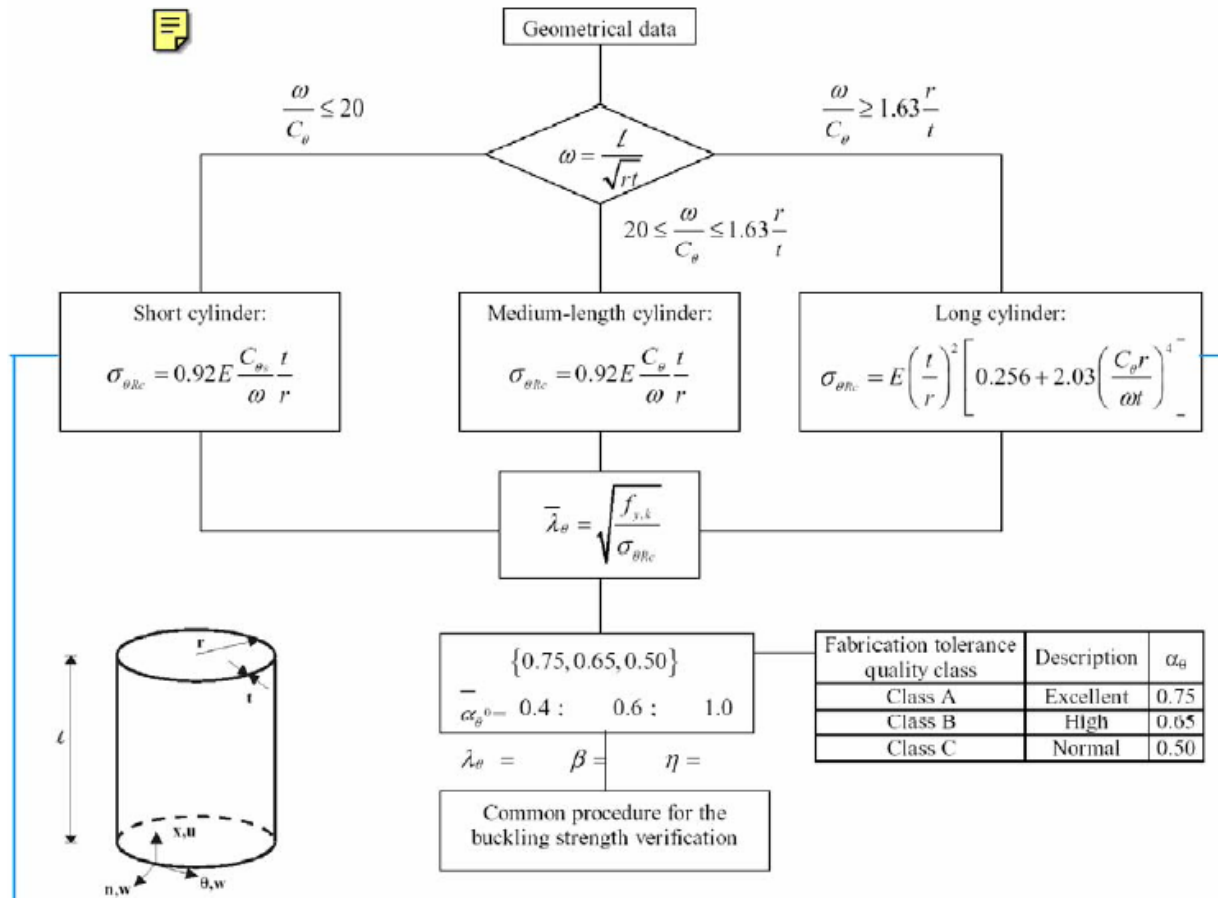


$$\sigma_{\theta,Ed} = \left(q_{eq} + 0,4(0,6) q_{w,max} \right) \left(\frac{r}{t} \right)$$

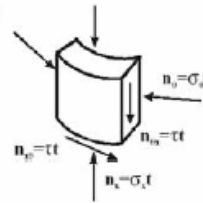
Pritisk vetra



PROCEDURE FOR THE DESIGN CHECK OF CYLINDRICAL SHELLS SUBJECT TO CIRCUMFERENTIAL COMPRESSION

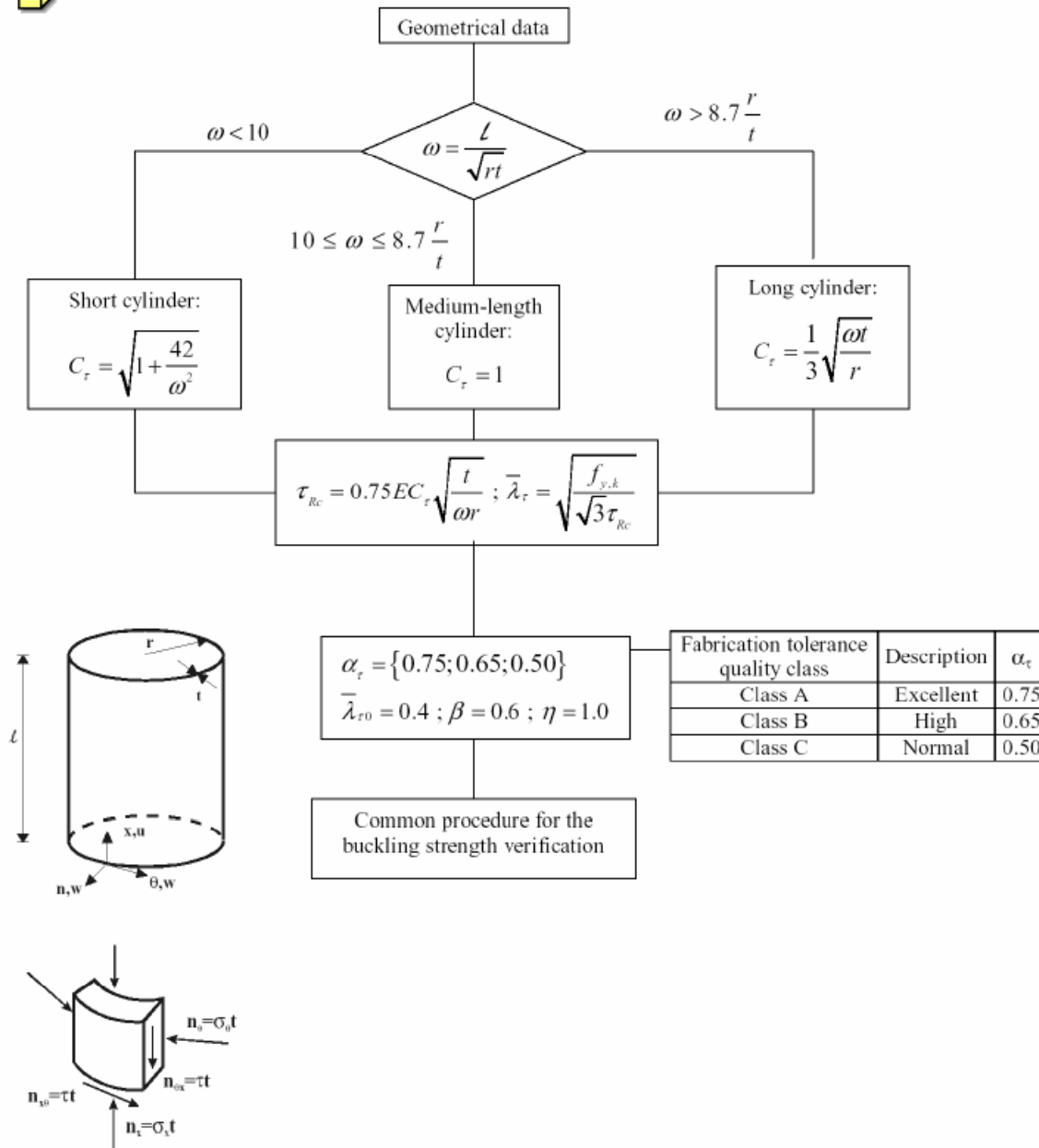


Case	Cylinder end	Boundary condition	C_{θ}
1	end 1	BC1	$1.5 + \frac{10}{\omega^2} - \frac{5}{\omega^3}$
	end 2	BC1	
2	end 1	BC1	$1.5 + \frac{8}{\omega^2} - \frac{4}{\omega^3}$
	end 2	BC2	
3	end 1	BC2	$1.5 + \frac{3}{\omega^{1.35}}$
	end 2	BC2	
4	end 1	BC1	$0.6 + \frac{1}{\omega^2} - \frac{0.3}{\omega^3}$
	end 2	BC3	



Case	Cylinder end	Boundary condition	C_{θ}
1	end 1	BC1	1.50
	end 2	BC1	
2	end 1	BC1	1.25
	end 2	BC2	
3	end 1	BC2	1.00
	end 2	BC2	
4	end 1	BC1	0.60
	end 2	BC3	
5	end 1	BC2	0
	end 2	BC3	
6	end 1	BC3	0
	end 2	BC3	

PROCEDURE FOR THE DESIGN CHECK OF CYLINDRICAL SHELLS SUBJECT TO SHEAR¹



Elastični vertikalni uklon ob upoštevanju notranjega pritiska

Elastični redukcijski faktor za imperfektnost α_x je potrebno nadomestiti z elastičnim redukcijskim faktorjem za imperfektnost v primeru notranjega pritiska α_{xp} :

$$\alpha_x \rightarrow \alpha_{xp} = \min \begin{cases} \alpha_{xpe} \\ \alpha_{xpp} \end{cases}$$

$$\alpha_{xpe} = \alpha_x + (1 - \alpha_x) \left[\frac{\bar{p}_s}{\bar{p}_s + 0,3 / \alpha_x^{0,5}} \right]$$

$$\bar{p}_s = \left(\frac{p_s}{\sigma_{x,Rcr}} \right) \left(\frac{r}{t} \right)$$

p_s **najmanjša** računsko vrednost notranjega pritiska v obravnavani točki, ki sodeluje v kombinaciji s tlakom v smeri osi cilindra.

Elastoplastičen vertikalni uklon ob prisotnosti notranjega pritiska – slonova noga

$$\alpha_{xpp} = \left\{ 1 - \left(\frac{\bar{p}_g}{\bar{\lambda}_x} \right)^2 \right\} \left[1 - \frac{1}{1,12 + s^{3/2}} \right] \left[\frac{s^2 + 1,21\bar{\lambda}_x^2}{s(s+1)} \right]$$

$$\bar{p}_g = \left(\frac{p_g}{\sigma_{x,Rcr}} \right) \left(\frac{r}{t} \right)$$

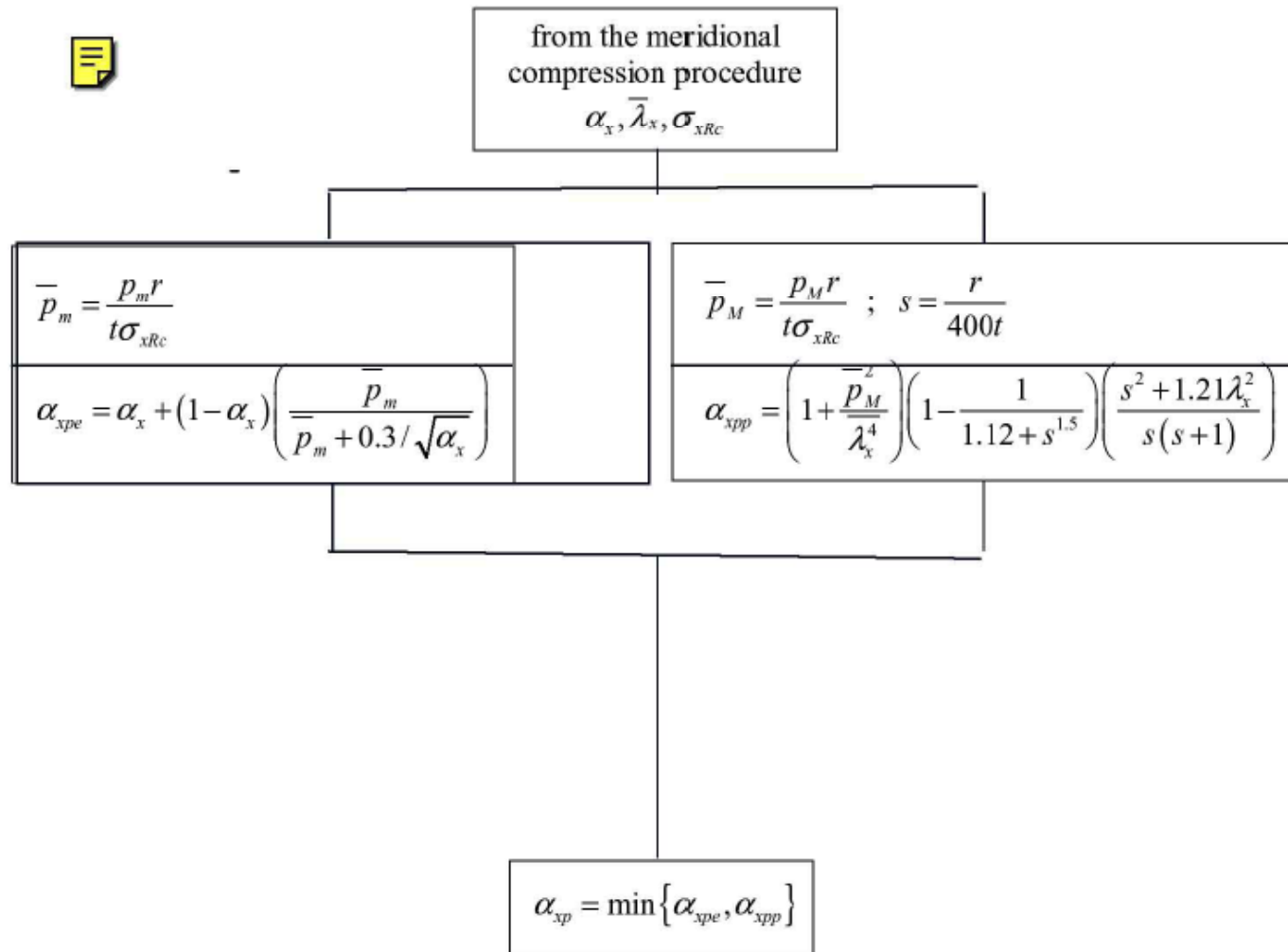
$$s = \frac{1}{400} \cdot \frac{r}{t}$$

p_g **največja** računaska vrednost notranjega pritiska v obravnavani točki, ki lahko sodeluje v kombinaciji s tlakom v smeri osi cilindra.

Vertikalni uklon – notranji pritisk

PROCEDURE FOR THE DESIGN CHECK OF CYLINDRICAL SHELLS SUBJECT TO MERIDIONAL COMPRESSION AND INTERNAL PRESSURE

The pressurized meridional buckling strength should be verified analogously to the unpressurised meridional buckling strength. However the unpressurised elastic imperfection factor α_x may be replaced by the pressurized elastic imperfection factor α_{xp} ²



Kontrola stabilnosti - interakcija

V odvisnosti od obtežbe in napetostnega stanja je potrebno opraviti eno ali več izmed spodaj navedenih kontrol za največje vrednosti posameznih membranskih napetosti:

$$\sigma_{x,Ed} \leq \sigma_{x,Rd} \qquad \sigma_{\theta,Ed} \leq \sigma_{\theta,Rd} \qquad \tau_{x\theta,Ed} \leq \tau_{x\theta,Rd}$$

V primeru, ko je v obravnavanem obtežnem stanju prisotna kombinacija membranskih napetosti, je potrebno upoštevati kontrolo interakcije napetosti:

$$\left(\frac{\sigma_{x,Ed}}{\sigma_{x,Rd}} \right)^{k_x} - k_i \left(\frac{\sigma_{x,Ed}}{\sigma_{x,Rd}} \right) \left(\frac{\sigma_{\theta,Ed}}{\sigma_{\theta,Rd}} \right) + \left(\frac{\sigma_{\theta,Ed}}{\sigma_{\theta,Rd}} \right)^{k_\theta} + \left(\frac{\tau_{x\theta,Ed}}{\tau_{x\theta,Rd}} \right)^{k_\tau} \leq 1$$

k_x , k_θ , k_τ so interakcijski faktorji uklona, definirani v aneksu D.

V primeru, ko sta $\sigma_{x,Ed}$ ali $\sigma_{\theta,Ed}$ **natezni** za njuno vrednost vzamemo vrednost nič.

Kontrola stabilnosti - interakcija

Interakcijski faktorji uklona:

$$k_x = 1,25 + 0,75 \chi_x$$

$$k_\theta = 1,25 + 0,75 \chi_\theta$$

$$k_\tau = 1,75 + 0,25 \chi_\tau$$

$$k_i = (\chi_x \chi_\theta)^2$$

$\chi_x, \chi_\theta, \chi_\tau$ so uklonski redukcijski faktorji

Kontrola stabilnosti - interakcija

$$l_{\text{int}} = 1,3 r \sqrt{r/t} \quad \dots \text{(D.53)}$$

... (D.53)

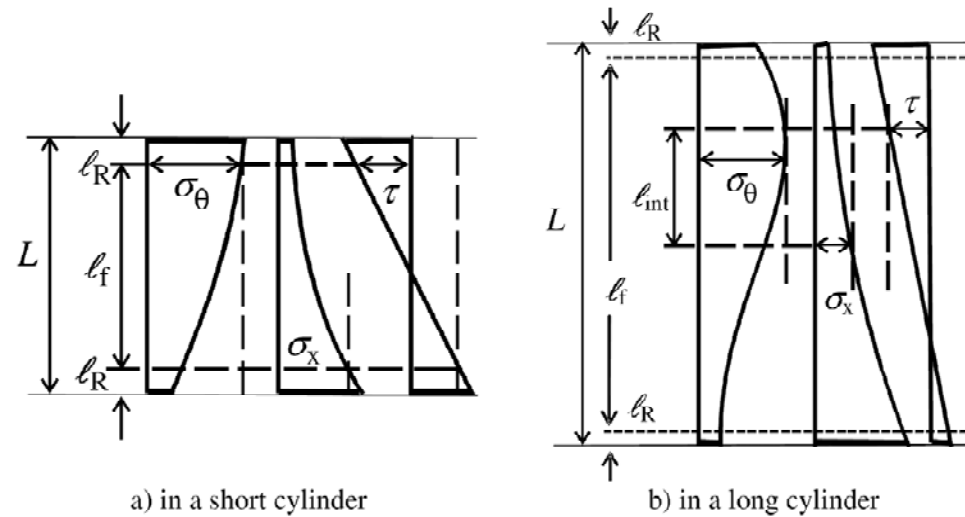


Figure D.3: Examples of interaction-relevant groups of membrane stress components

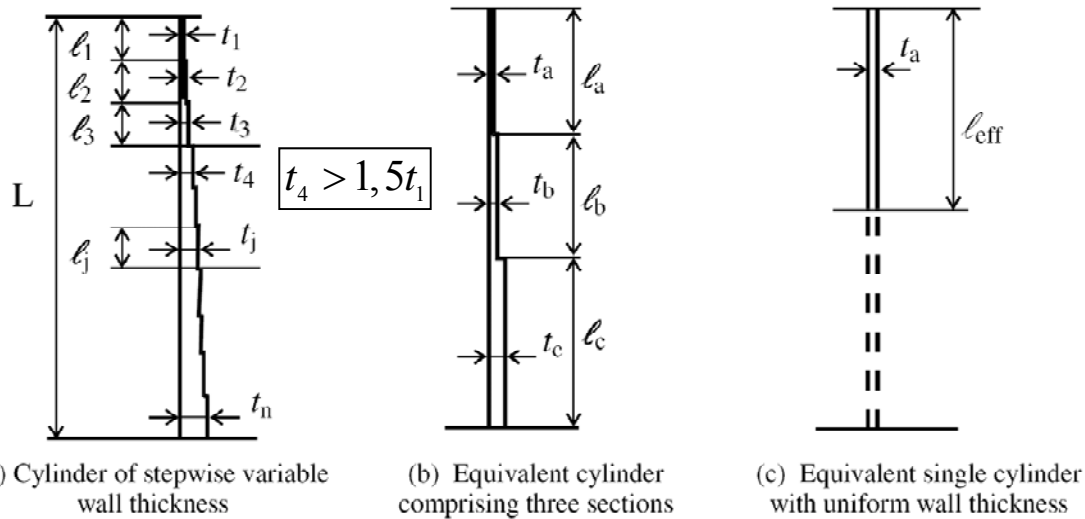
$$l_R = 0,1L \rightarrow \text{ni interakcije}$$

Nekonstantna debelina stene plašča

$$l_b = l_a \text{ and } l_c = L - 2l_a, \text{ if } l_a \leq L/3 \quad \dots (D.56)$$

$$l_b = l_c = 0,5(L - l_a), \text{ if } L/3 < l_a \leq L/2 \quad \dots (D.57)$$

**Uklon v
obodni smeri**



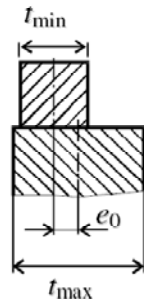
$$t_a = \frac{1}{l_a} \sum_a l_j t_j$$

$$t_b = \frac{1}{l_b} \sum_b l_j t_j$$

$$t_c = \frac{1}{l_c} \sum_c l_j t_j$$

Figure D.5: Transformation of stepped cylinder into equivalent cylinder

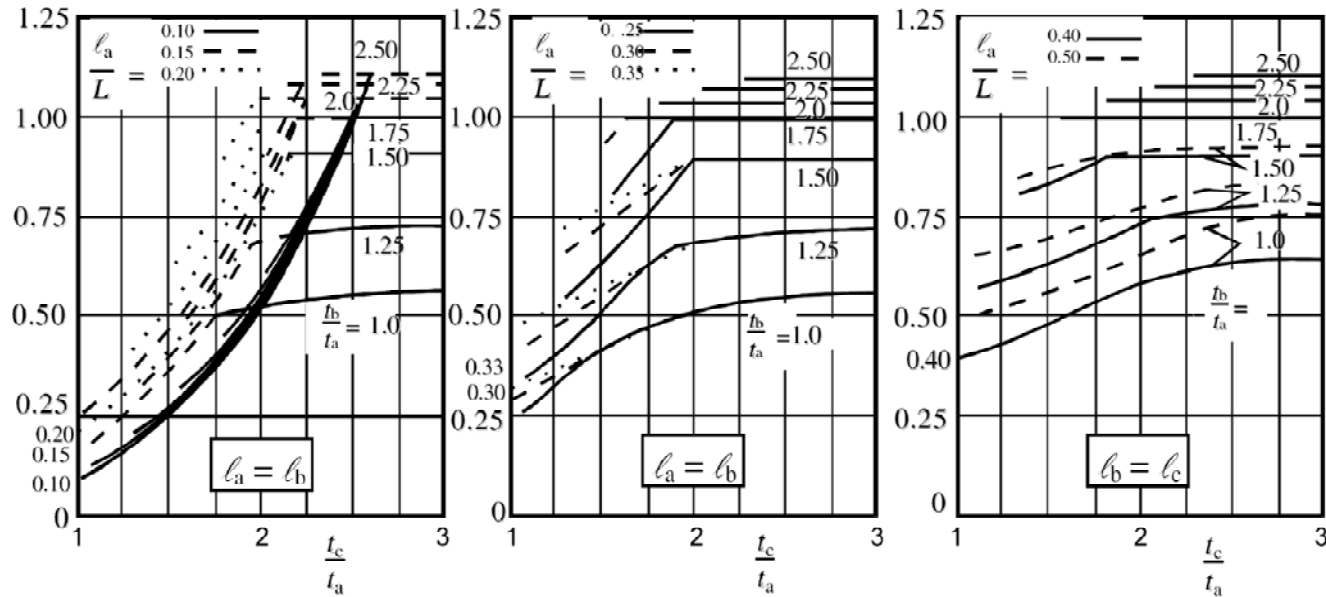
$$l_{eff} = \frac{l_a}{K}$$



$$e_0 \leq \min(0,5(t_{max} - t_{min}), 0,5t_{min})$$

Figure D.4: Intended offset e_0 in a butt-jointed shell

Nekonstantna debelina stene plašča



Za vsak pas j:

$$\sigma_{\theta, Rcr, j} = \left(\frac{t_a}{t_j} \right) \sigma_{\theta, Rcr, eff}$$

$$\sigma_{\theta, Rcr, Eff} \rightarrow l_{eff}, t_a, C_{\theta} = 1, 0, \omega_j$$

**Uklon v
obodni smeri**

Nekonstantna debelina stene plašča

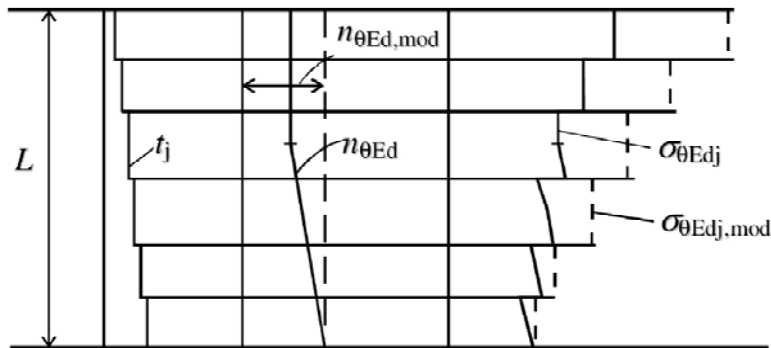
$$\sigma_{\theta,Ed,j} \leq \sigma_{\theta,Rd,j}$$

$$\sigma_{\theta,Ed,j} = n_{\theta,Ed} / t_j$$

$$\sigma_{\theta,Ed,j,mod} = \max(n_{\theta,Ed}) / t_j$$

**Uklon v
obodni smeri**

... (D.68)



Nekonstantna debelina stene plašča

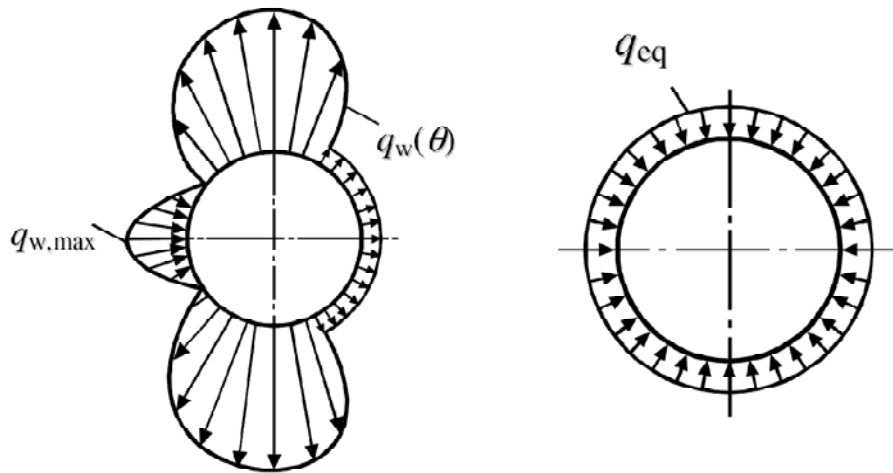
Ekvivalentni zunanji pritisk vetra:

$$q_{eq} = k_w q_{w,max}$$

$$k_w = 0,46(1 + 0,037m_{cr}) \leq 1,0$$

$$m_{cr} \geq 10, m_{cr} = \dots$$

C_θ se določi po preglednici D.3 v skladu z robnimi pogoji cilindra.



$$\sigma_{\theta,Ed} = \left(q_{eq} + 0,4(0,6) q_{w,max} \right) \left(\frac{r}{t} \right)$$

Nekonstantna debelina stene plašča

$$\ell_b = \ell_a \text{ and } \ell_c = L - 2\ell_a, \text{ if } \ell_a \leq L/3 \quad \dots (D.56)$$

$$\ell_b = \ell_c = 0,5(L - \ell_a), \text{ if } L/3 < \ell_a \leq L/2 \quad \dots (D.57)$$

Uklon v vertikalni smeri

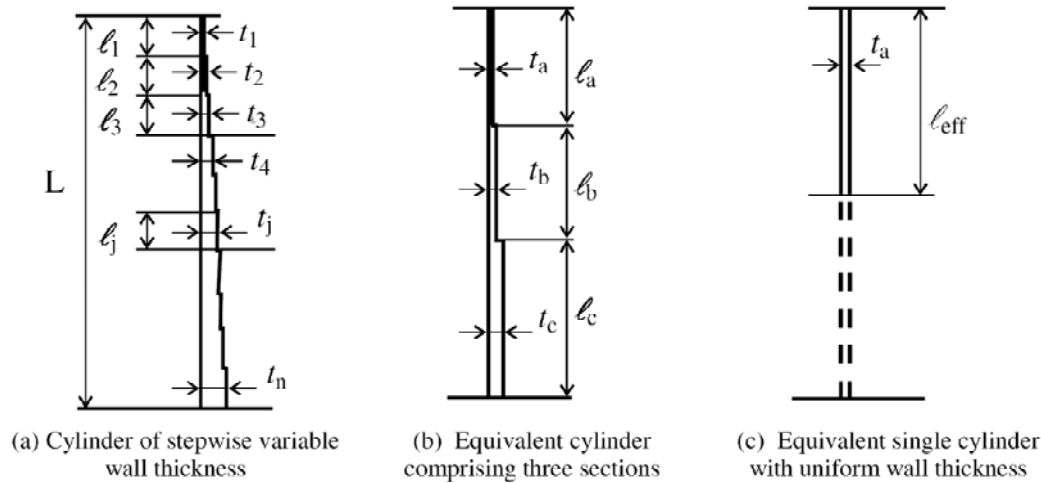


Figure D.5: Transformation of stepped cylinder into equivalent cylinder

Vsak pas j z dolžino l_j se obravnava kot nadomestna cilindrična lupina dolžine $l = L$ in debeline $t = t_j$.

L = višina celotnega rezervoarja ali razdalja med ojačilnimi obroči

Dimenzioniranje obročev

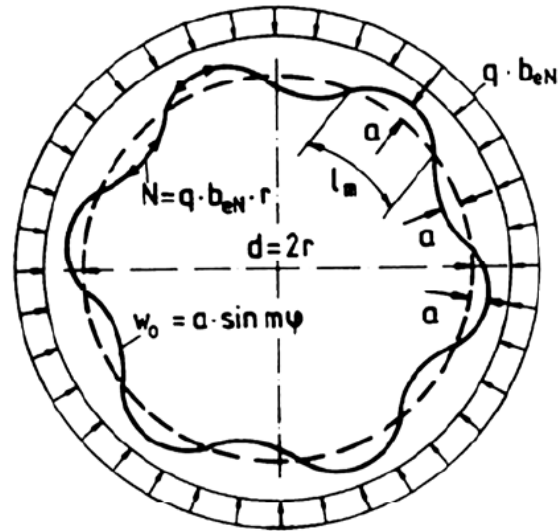


Figure 17.8 Example of a ring stiffener, designed with an equivalent imperfection shape of $m = m_{cr} = 6$

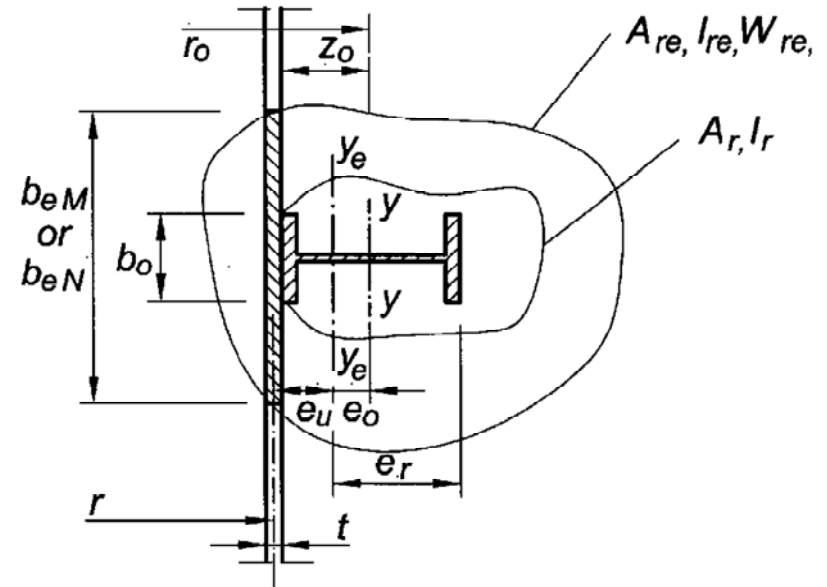
$$q_{cr} b_{ef} = \frac{3EI_o}{r^3} \quad m = 2$$

Dimenzioniranje obročev

$$q_{h,Rcr} = \frac{3EI_{he}}{r^3 l_h} \xrightarrow{\text{minimalna togost}} I_{he} \geq q \frac{r^3 l_h}{3E}$$

Kontrola obroča ob upoštevanju uklona z upogibom po teoriji drugega reda:

$$\sigma_{\theta h} = \frac{N_h}{A_{he}} + \frac{M_h}{W_{he}} \leq f_{y,k} / \gamma_M$$



$$M_h = \frac{EI_{he}}{r} \left(\frac{\eta_2}{67} \right) \left(\frac{q / q_{h,Rcr}}{1 - q / q_{h,Rcr}} \right) \quad N_h = q r b_{eN}$$

$$\eta_2 = \begin{cases} 1,5 & \text{hladno oblikovane ojačitve} \\ 1,3 & \text{vroče valjane ali varjene ojačitve} \end{cases}$$

LS3: Stabilnost

- Materialno nelinearna analiza (r_{pl}) + uklonska analiza (r_{cr})

$$\bar{\lambda} = \sqrt{\frac{r_{pl}}{r_{cr}}} \rightarrow \chi \rightarrow r_{Rd} = \frac{\chi r_{pl}}{\gamma_{M1}}$$

- Geometrijsko in materialno nelinearna analiza z nepopolnostmi
 - določitev nepopolnosti (lastne uklonske oblike + lokalne nepopolnosti)
 - Kalibracija orodja

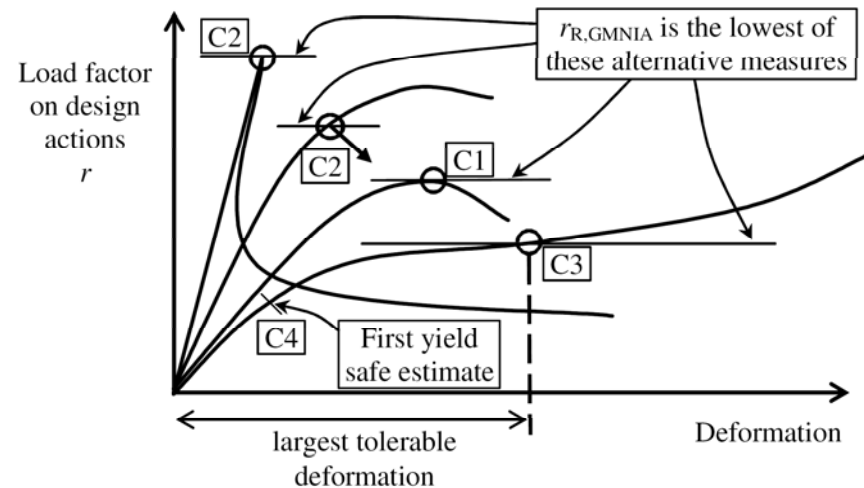


Figure 8.6: Definition of buckling resistance from global GMNIA analysis

LS4: Visoko-ciklično utrujanje

- Običajno ni merodajno mejno stanje za rezervoarje
- Elastična analiza za določanje $\Delta\sigma$
- Upoštevaj SIST EN1993-1-9 in SIST EN1993-3-2

$$\gamma_{Ff} \Delta\sigma_E \leq \frac{\Delta\sigma_R}{\gamma_{Mf}}$$

$$\gamma_{Ff} = 1,0$$

$$\gamma_{Mf} = 1,1$$

- **P** - Potresni vplivi ($\gamma = 1,0$)

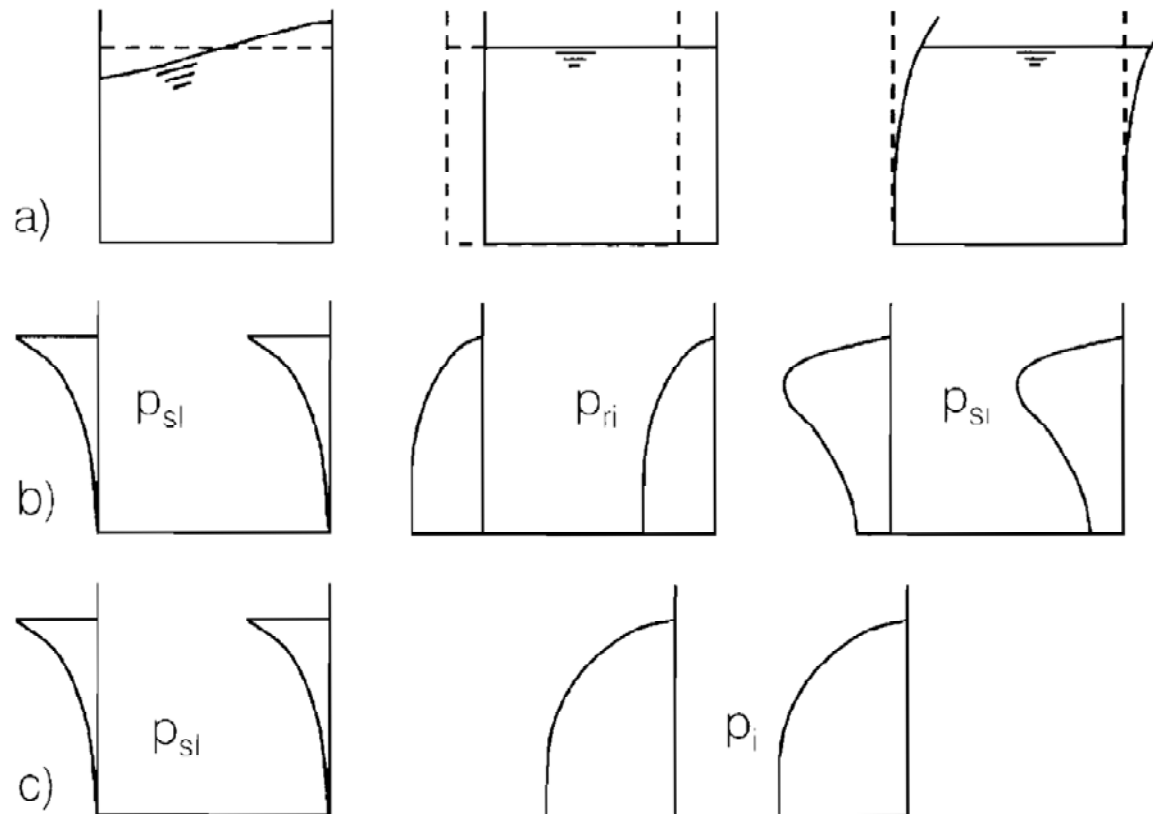


Bild 15. Verformungen (a) und Druckverteilungen entsprechend EC 8-4 [26] (b) und den neuseeländischen Empfehlungen [29] (c)

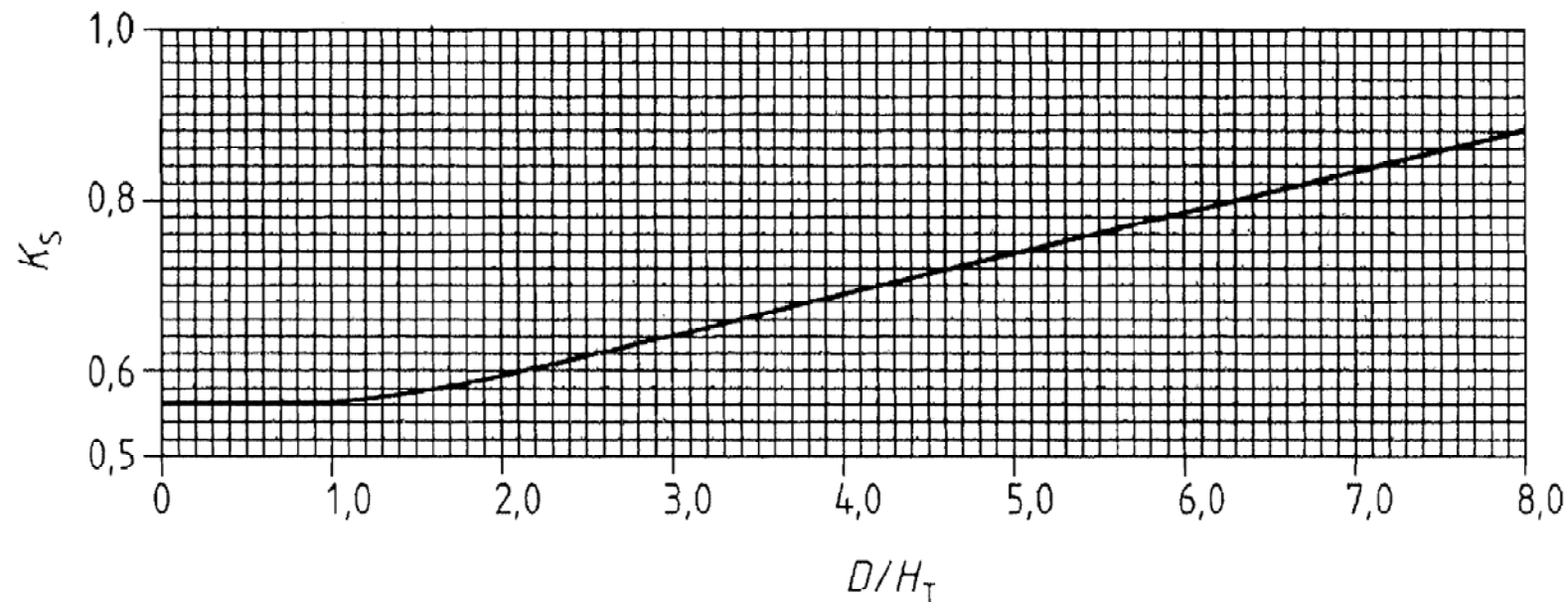
Potresna analiza rezervoarjev

Nihajni čas

Nihajni čas (valovanja) T_s se določi kot:

$$T_s = 1,8 K_s D^{1/2}$$

Faktor K_s se določi iz spodnje slike na podlagi razmerja D/H_T



D premer rezervoarja v m;

H_T maksimalna višina polnjenja rezervoarja v m.

Koeficient pospeška G_2

G_1 koeficient pospeška določen iz seizmološke karte;

$$G_2 = \begin{cases} \frac{1,25 G_1 j}{T_S} & \text{za } T_S \leq 4,5 \\ \frac{5,625 G_1 j}{T_S^2} & \text{za } 4,5 < T_S \end{cases}$$

j amplifikacijski faktor določen iz spodnje tabele.

Site amplification factor	Soil profile type		
	A ¹⁾	B ²⁾	C ³⁾
j	1,0	1,2	1,5

¹⁾ Soil profile type A is either of two profiles as follows.

a) Rock of any characteristic, either shale-like or crystalline in nature. Such material may be characterized by a shear wave velocity greater than 760 m/s

or

b) Stiff soil conditions where the soil depth is less than 60 m and the soil types overlying rock are stable deposits of sands, gravels, or stiff clays.

²⁾ Soil profile type B is a profile with deep cohesionless or stiff clay conditions, including sites where the soil depth exceeds 60 m and the soil types overlying rock are stable deposits of sands, gravels, or stiff clays.

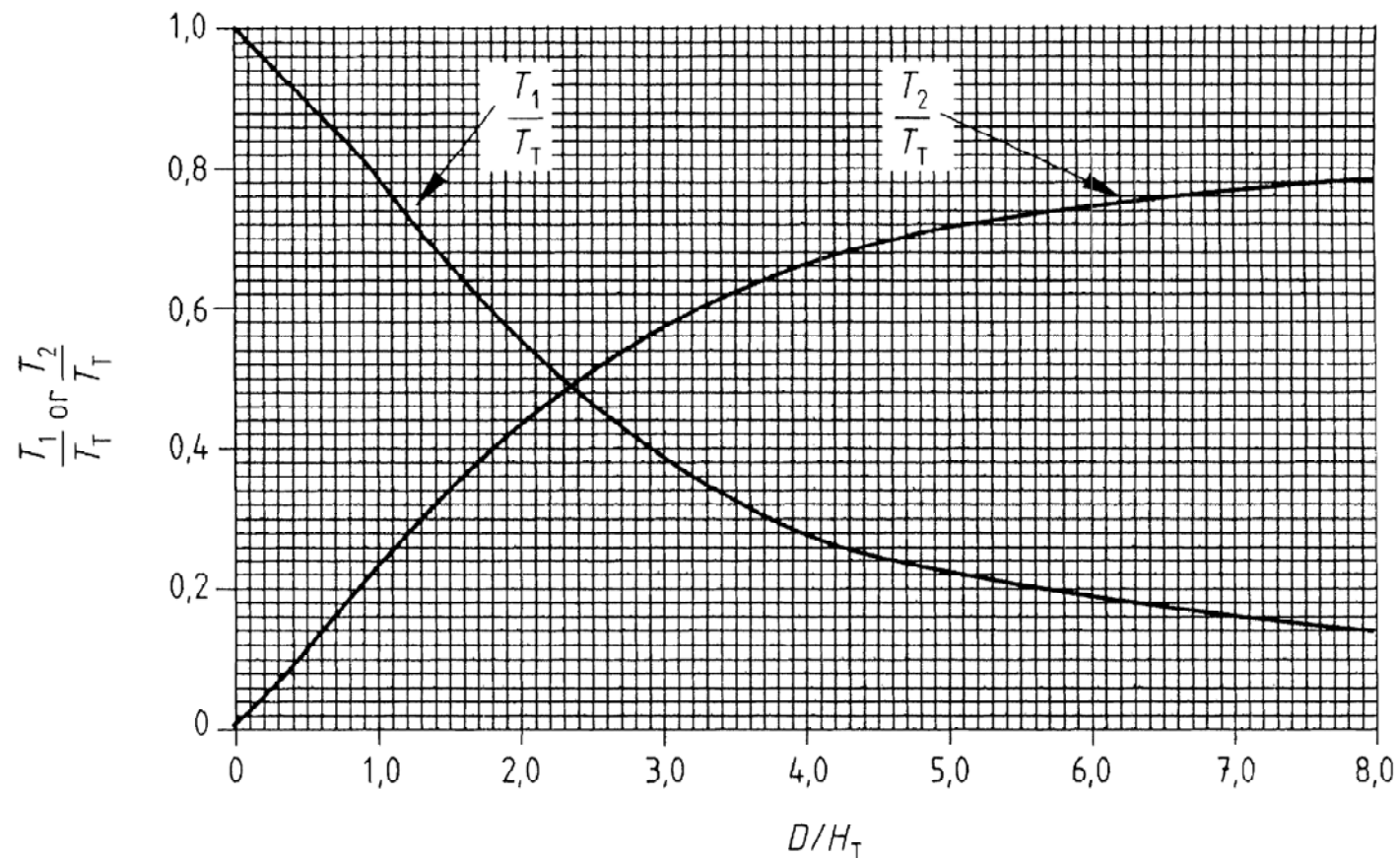
³⁾ Soil profile type C is a profile with soft-to-medium-stiff clays and sands, characterized by 10 m or more of soft-to-medium-stiff clay with or without intervening layers of sand or other cohesionless soils.

NOTE In locations where the soil profile is not known in sufficient detail to determine the site amplification factor, j , the soil profile, C, should be assumed.

Določitev sodelujočih mas vsebine rezervoarja

- T_1 teža vsebine rezervoarja, ki niha skupaj z rezervoarjem, v kg;
 T_2 teža vsebine rezervoarja, ki niha z valovanjem tekočine, v kg;
 T_T celotna teža vsebine rezervoarja.

Sodelujoči masi T_1 in T_2 določimo na podlagi spodnjega diagrama.

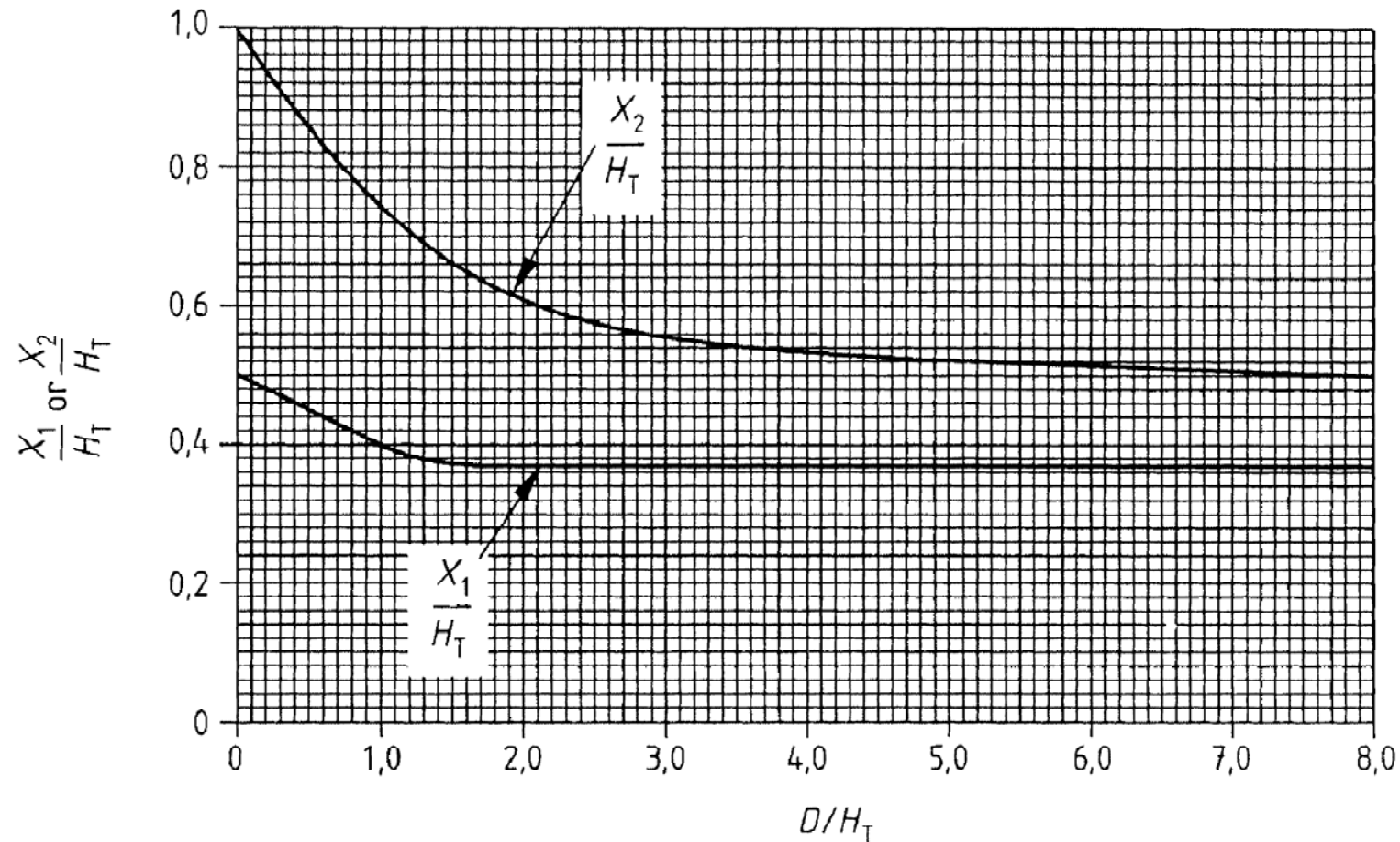


Določitev ročic do težišč sodelujočih mas T_1 in T_2

X_1 višina od dna rezervoarja do težišča sodelujoče mase T_1 ;

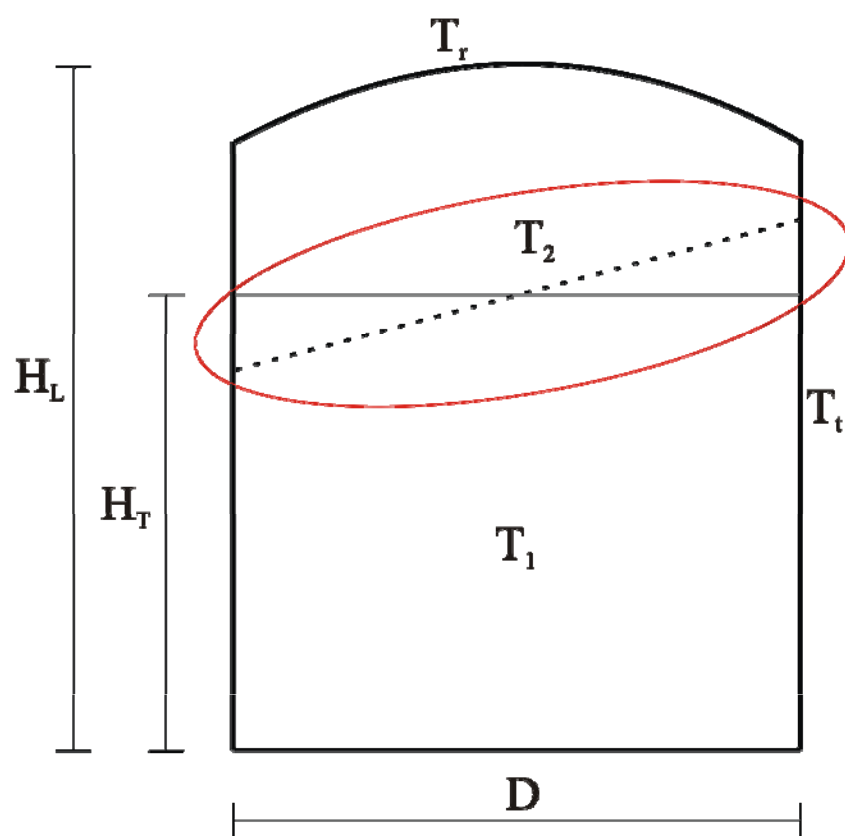
X_2 višina od dna rezervoarja do težišča sodelujoče mase T_2 .

Ročici X_1 in X_2 določimo na podlagi spodnjega diagrma.



Prevrnitveni moment

- H_L celotna višina rezervoarja v m;
 T_r teža strehe rezervoarja v kg;
 T_t teža valja rezervoarja v kg;
 X_S višina od dna rezervoarja do težišča valja rezervoarja



$$M = \frac{G_1 (T_t X_S + T_r H_L + T_1 X_1) + G_2 T_2 X_2}{102}$$

