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

Projektiranje rezervoarjev po evropskih standardih

delovno gradivo

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Ključni standardi

- SIST EN 1990 : principi projektiranja
- SIST EN 1991-1-1 : lastne teže in koristne obtežbe
- SIST EN 1991-1-3 : obtežba s snegom
- SIST EN 1991-1-4 : obtežba z vetrom
- SIST EN 1991-4 : obtežbe rezervoarjev in silosov
- SIST EN 1993-1-1 : jeklene konstrukcije (osnovna pravila)
- SIST EN 1993-1-6 : lupinaste konstrukcije
- SIST EN 1993-1-8 : spoji
- SIST EN 1993-1-10 : izbira materiala
- SIST EN 1993-4-2 : rezervoarji
- SIST EN 1998-4 : potresna analiza rezervoarjev?
- SIST EN 14015 : nadzemni rezervoarji z ravnim dnom

Območje uporabe

- Pritisk nad tekočino:
  - -100mbar do +500mbar

- Temperaturno območje:
  - -50°C do +300°C   (za običajna jekla)
  - -165°C do +300°C (za austenitna nerjavna jekla)

- Višina tekočine ne presega vrha plašča

Glavne koordinatne osi pri cilindričnih lupinah

(1)   Geometrical quantities

ℓ cylinder length between defined boundaries
r radius of cylinder middle surface
t thickness of shell
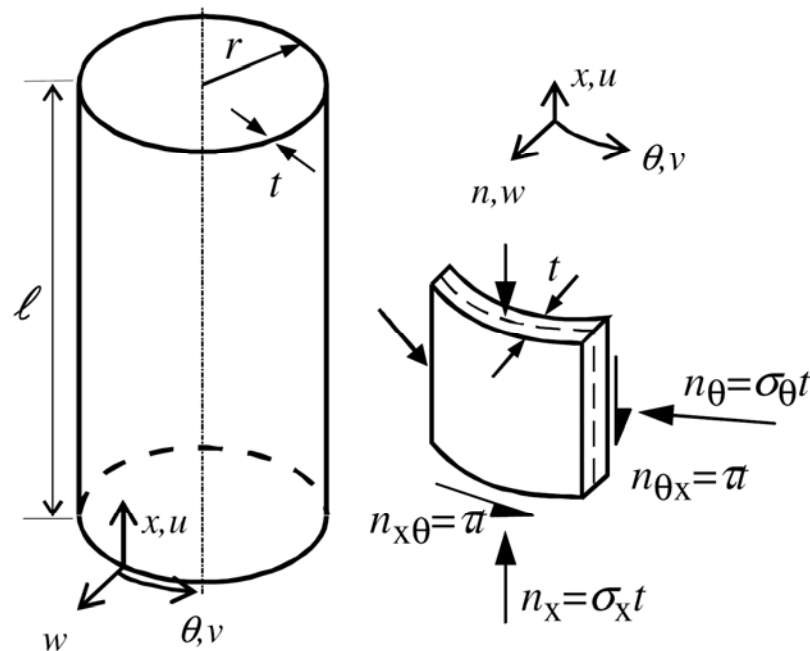Δw_k characteristic imperfection amplitude

Figure D.1: Cylinder geometry, membrane stresses and stress resultants

Napetosti in rezultante napetosti pri cilindričnih lupinah

$$n_y \equiv n_\theta$$

$$m_y \equiv m_\theta$$

a) Membrane stress resultants
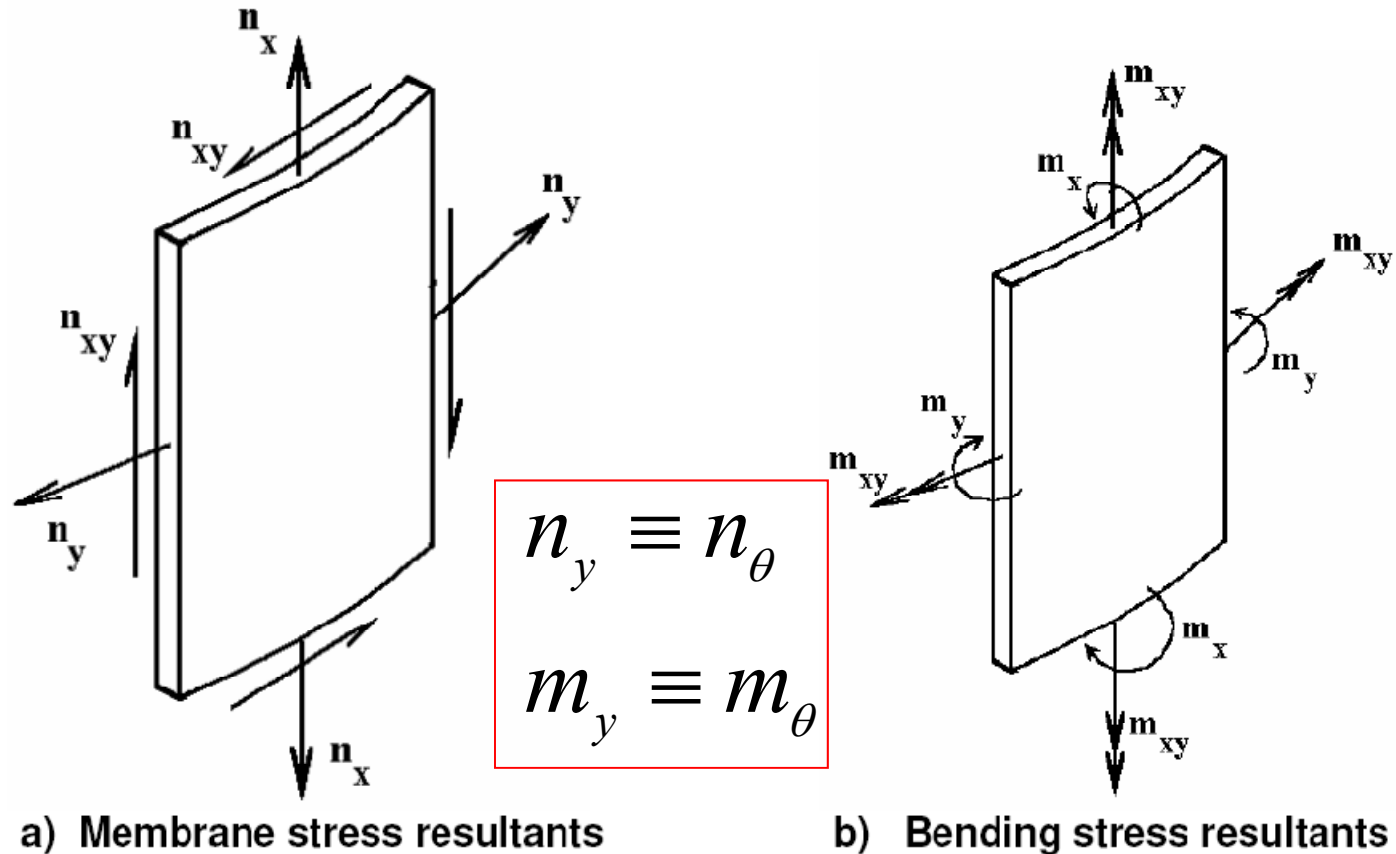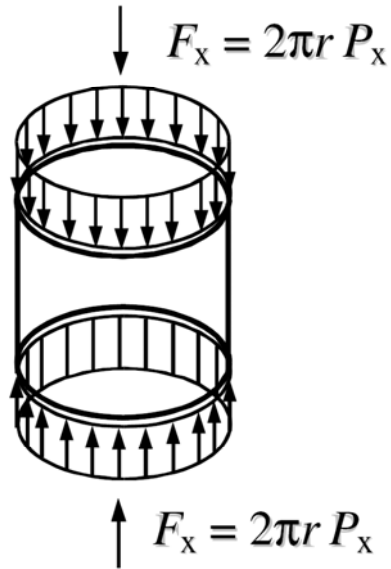
b) Bending stress resultants

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

Osnovne enačbe

Membransko napetostno stanje:

A.2.1 Uniform axial load
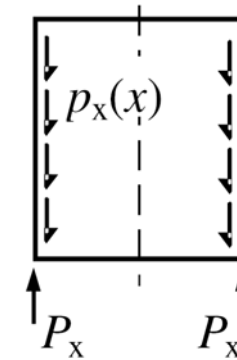
$$F_x = 2\pi r\, P_x$$

$$F_x = 2\pi r\, P_x$$

$$\sigma_x = -\frac{F_x}{2\pi r t}$$

A.2.2 Axial load from global bending

$$M = \pi r^2 P_{x,max}$$

$$P_{x,max}$$

$$P_{x,max}$$

$$M = \pi r^2 P_{x,max}$$
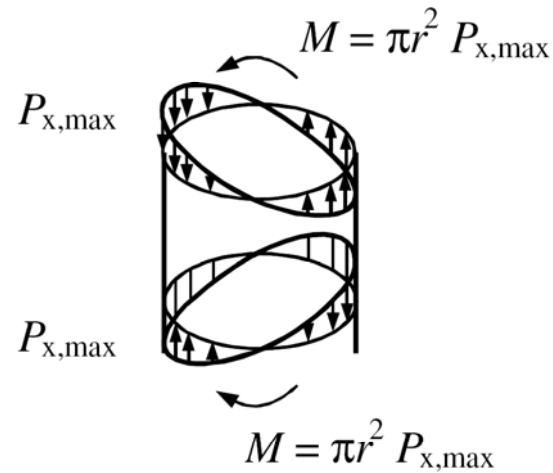
$$\sigma_x = \pm\frac{M}{\pi r^2 t}$$

A.2.3 Friction load

$$p_x(x)$$

$$P_x \qquad P_x$$
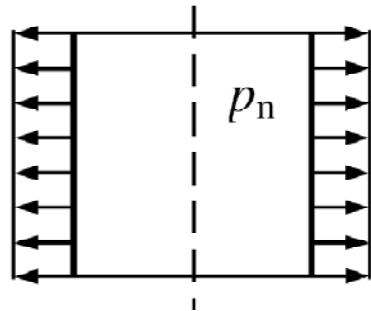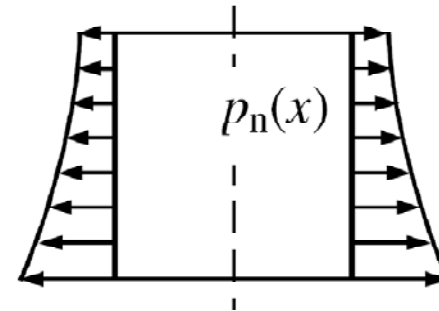
$$\sigma_x = -\frac{1}{t}\int_0^l p_x \cdot dx$$

Mebransko napetostno stanje

A.2.4 Uniform internal pressure

$$\sigma_\theta = p_n \cdot \frac{r}{t}$$

A.2.5 Variable internal pressure

$$\sigma_\theta(x) = p_n(x) \cdot \frac{r}{t}$$
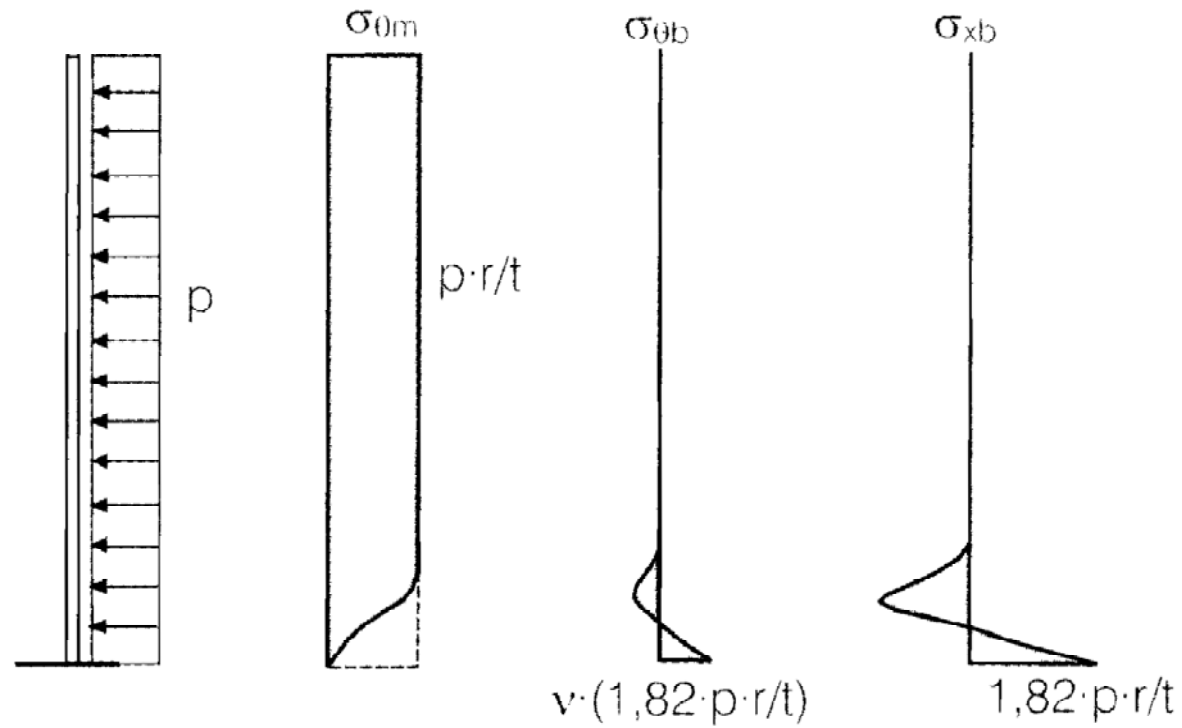
Robna motnja – upogibni momenti

Bild 6. Membran- und Biegespannungsanteile nach linear-elastischer Berechnung

Stabilnost – uvod

(a) (a1) Unloaded member

Load P induces compressive stresses

(a2) Primary path condition "pre-buckling"

Load P

u_1

w_b

(a3) Secondary path condition "post-buckling"

Load P

Primary path

P_{bif}

Secondary path

Typical displacement u, v or w

(b) (b1) Any typical displacement in structure

Load P

Continu

Primary

Bifurcation point

Take on ne

Secondary p

Post-buckling displacement w_b

(b2) Displacement in buckling mo

P

Deflection

w

w

w

P

w

(a)

Snap through point: "limit point"

Structure jumps across

Load P

P_{lim}

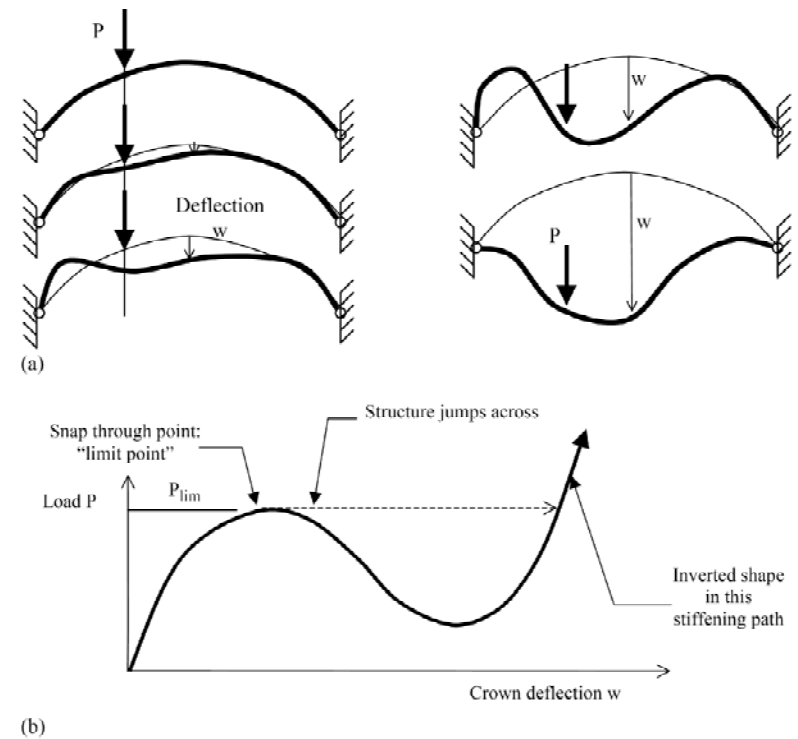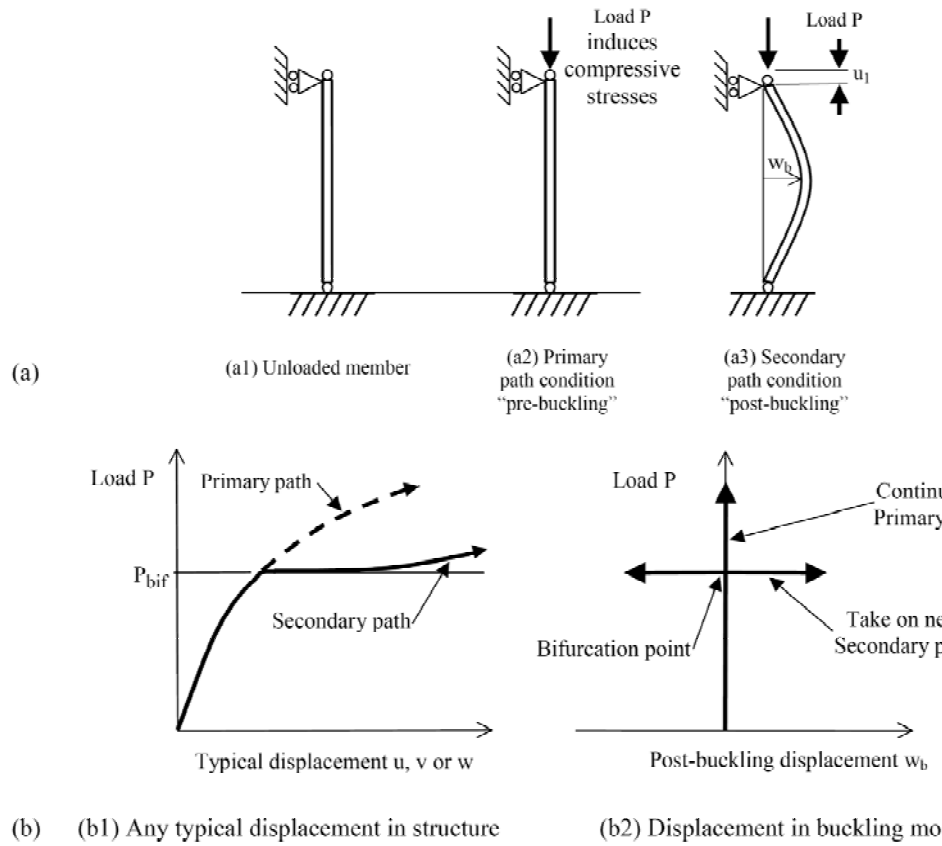Inverted shape in this stiffening path

Crown deflection w

(b)

Figure 2.1 Snap-through buckling: (a) changing geometry of the structure, (b) load displacement response

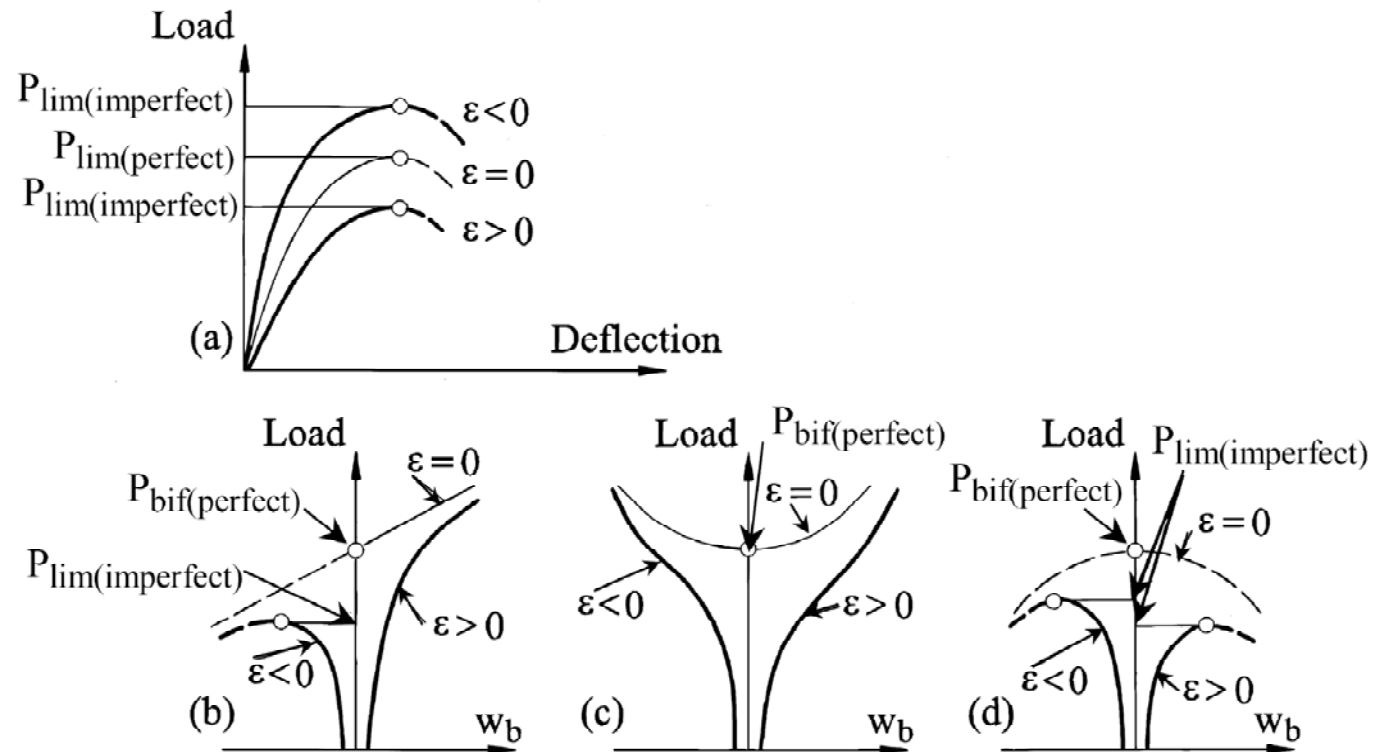# Stabilnost – občutljivost na nepopolnosti

Figure 2.5   The effect of geometric imperfections for: (a) snap-through instability in a perfect structure, (b)-(d) bifurcation instabilities in a perfect structure

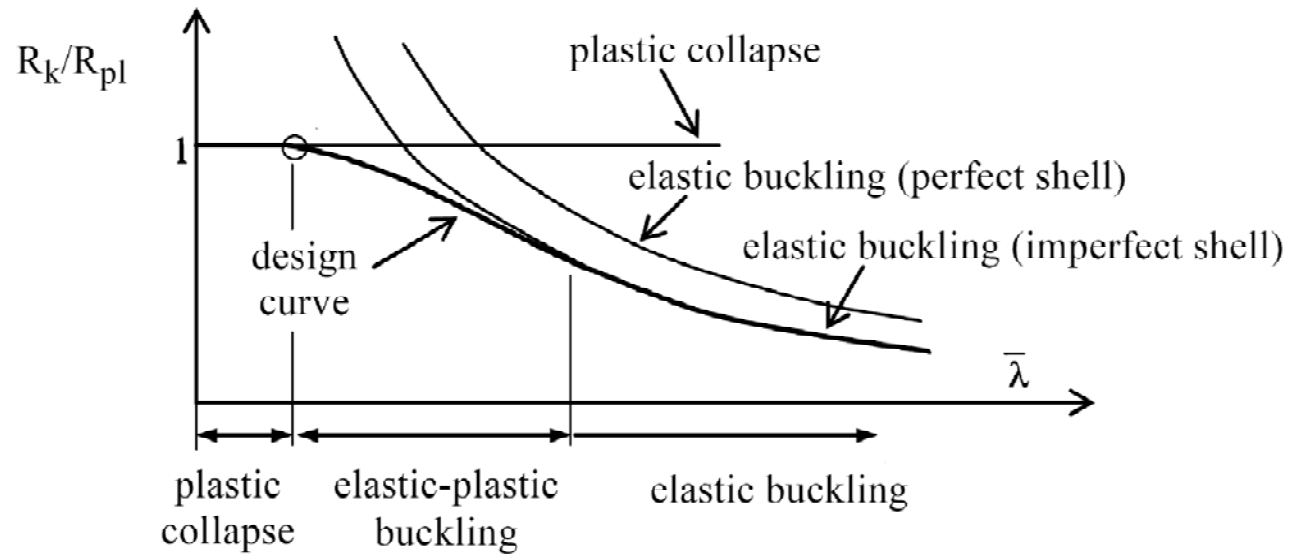# Stabilnost – občutljivost na nepopolnosti

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

Stabilnost – kritične napetosti

- Kratke, srednje dolge in dolge cilindrične lupine
  - Parameter ω:

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

Wind

a) stocky cylinder   b) intermediate aspect   c) slender cylinder
ratio cylinder
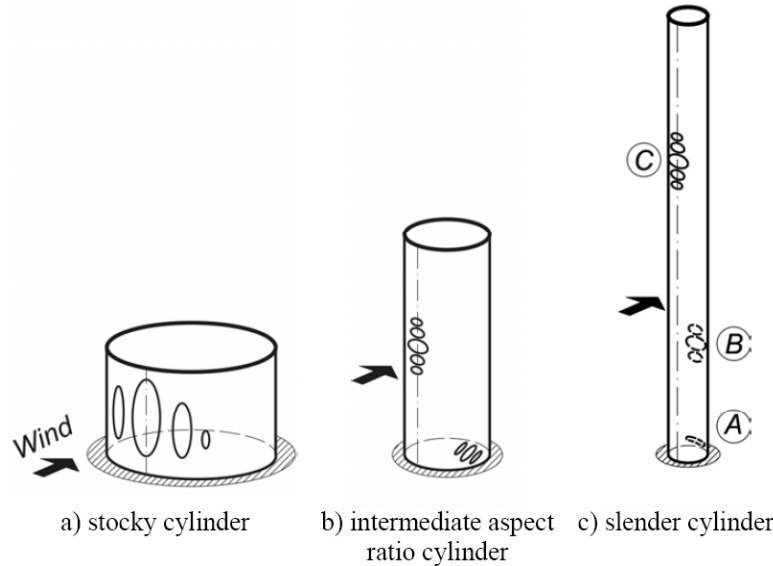
Stabilnost – robni pogoji

a) tank without anchors
b) silo without anchors
c) tank with anchors
d) open tank with anchors
e) laboratory experiment
f) section of long ring-stiffened cylinder

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

Uklon v vertikalni smeri x

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

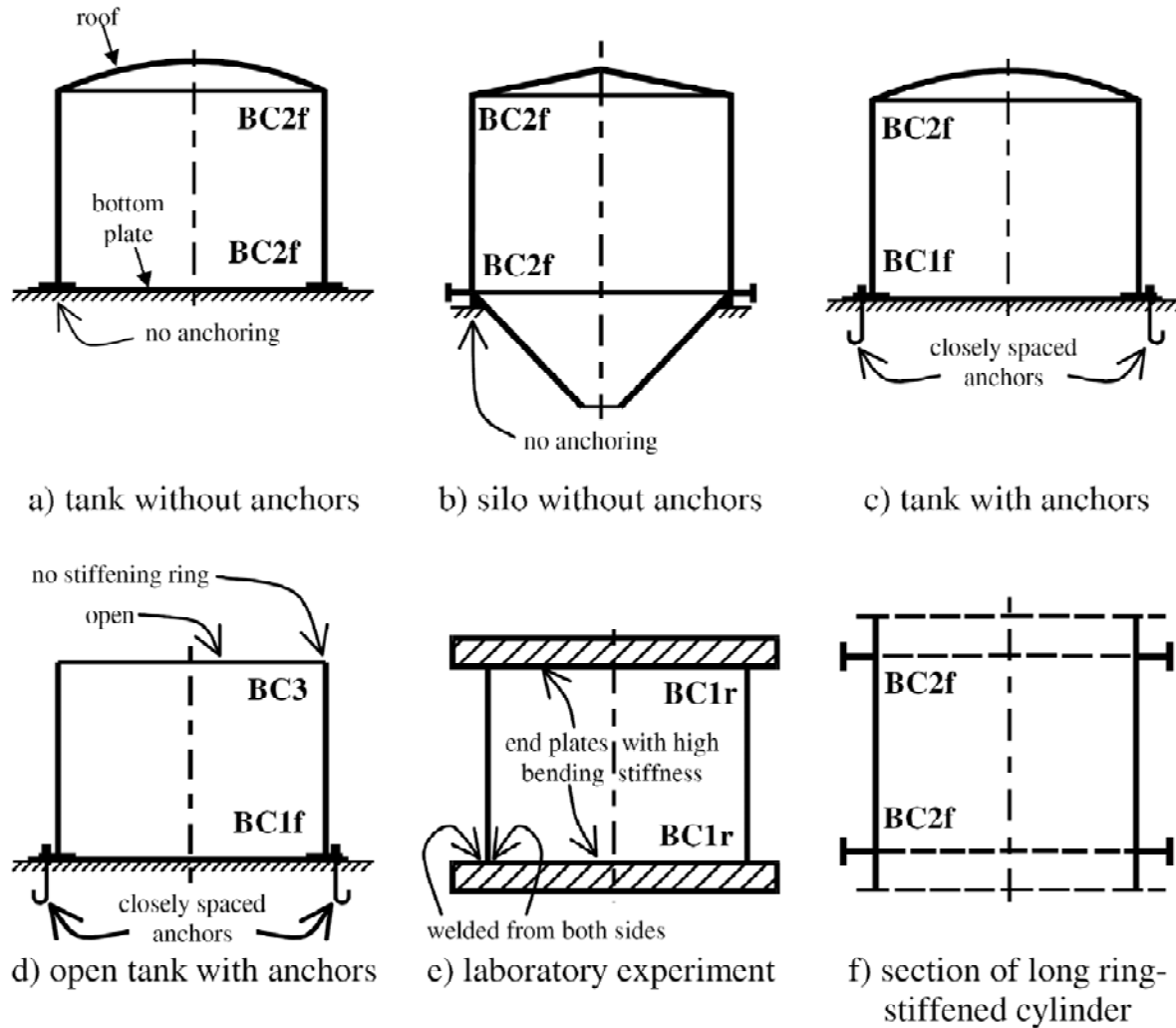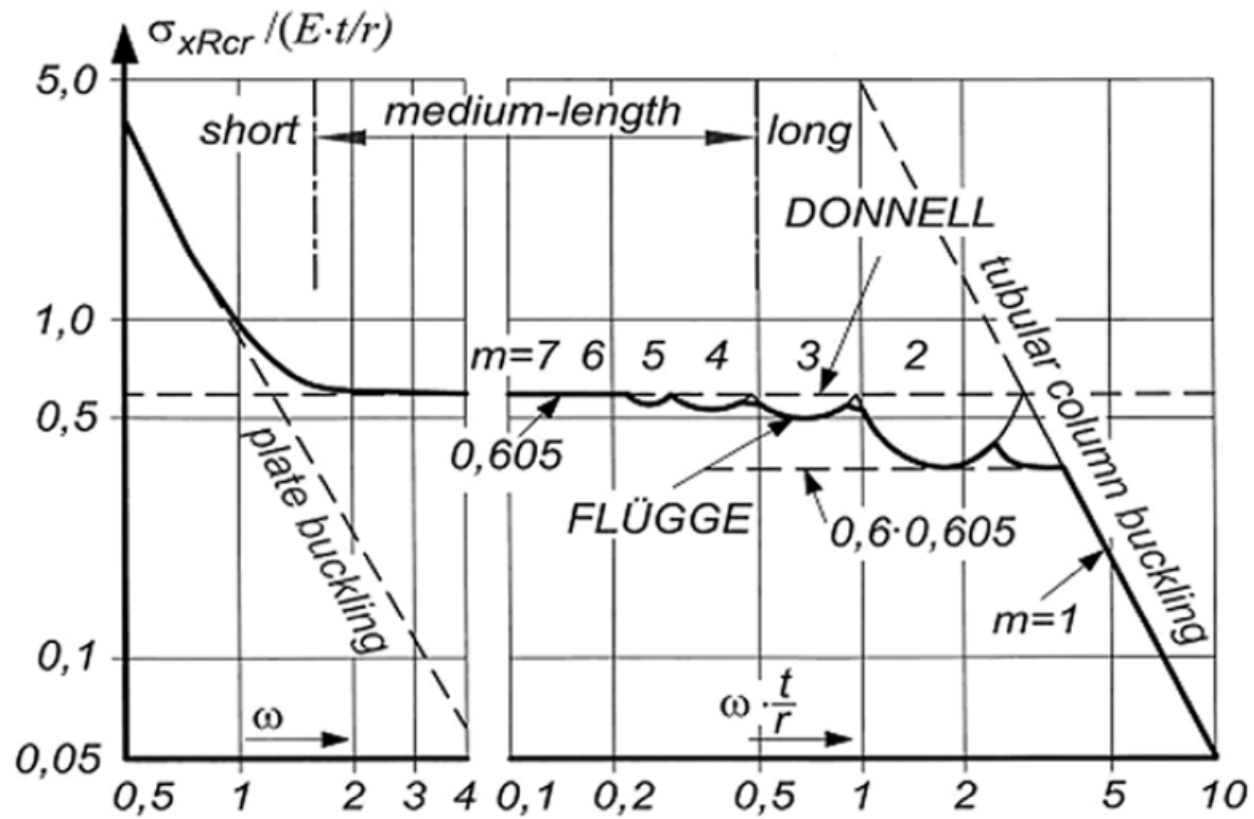Figure 10.2 Critical meridional buckling stresses according to classical linear buckling theory

Uklon v vertikalni smeri x

Case	Cylinder end	Boundary condition	C_{xb}
1	end 1	BC 1	6
	end 2	BC 1	
2	end 1	BC 1	3
	end 2	BC 2	
3	end 1	BC 2	1
	end 2	BC 2	

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

- Kratke cilindrične lupine:

  $$\omega \leq 1,7 \qquad C_x = 1,36 - \frac{1,83}{\omega} + \frac{2,07}{\omega^2}$$

- Srednje dolge lupine:

  $$1,7 \leq \omega \leq 0,5\frac{r}{t} \qquad C_x = 1,0$$

- Dolge lupine:

  $$\omega > 0,5\frac{r}{t} \qquad C_x = \max\left(0,6 \; ; 1+\frac{0,2}{C_{xb}}\left[1-2\omega\frac{t}{r}\right]\right)$$
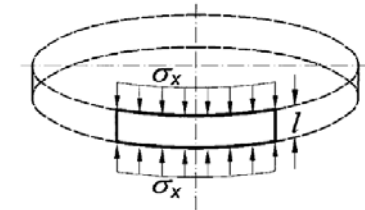
Figure 10.3 Plate buckling as limiting case of a short cylindrical shell under axial compression

Uklon v obodni smeri θ
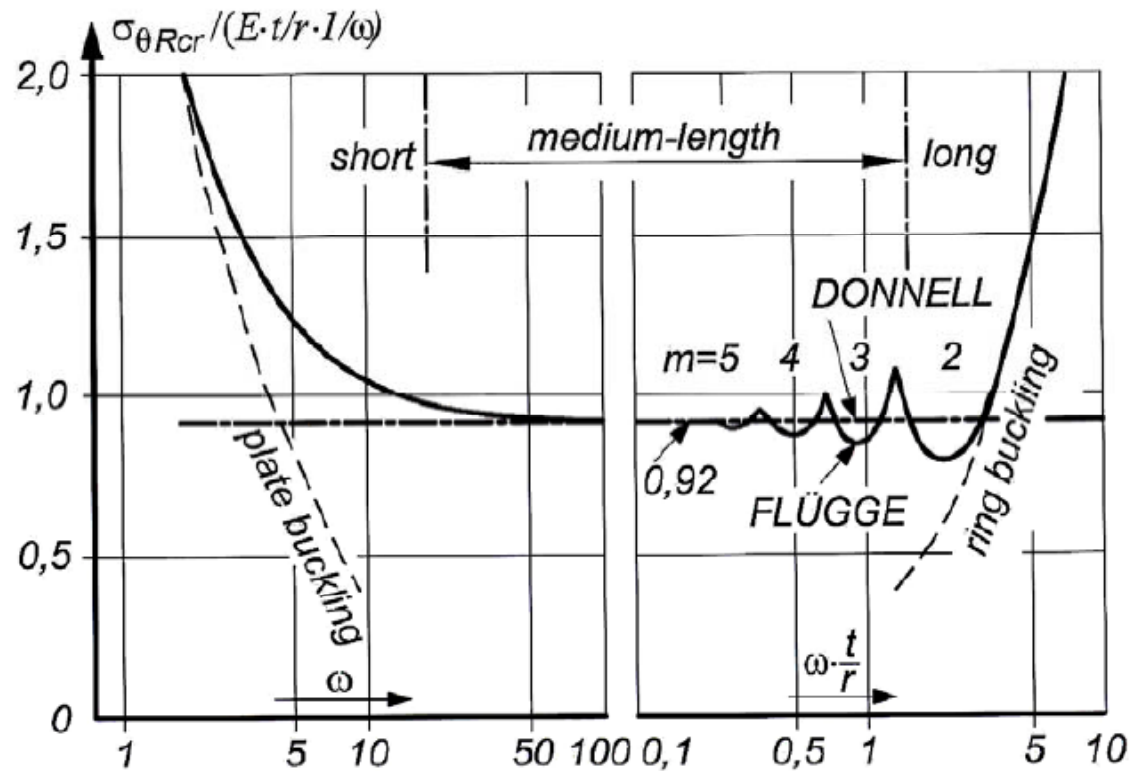
$$\sigma_{\theta,Rcr} = 0{,}92E \frac{C_\theta}{\omega} \frac{t}{r}$$

Figure 10.5 Critical circumferential buckling stresses according to classical linear buckling theory (BC2)

Uklon v obodni smeri θ

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

- Kratke cilindrične lupine:

$$\frac{\omega}{C_\theta} \leq 20 \qquad\qquad C_\theta = C_{\theta s}$$

Figure 10.6 Plate buckling as limiting case of a short cylindrical shell under circumferential compression

- Srednje dolge lupine:

$$20 \leq \frac{\omega}{C_\theta} \leq 1,63 \frac{r}{t} \qquad\qquad C_\theta \leq 1,5$$

- Dolge lupine:

$$\omega > 1,63 \frac{r}{t} \qquad\qquad \sigma_{\theta Rcr} = E \left(\frac{t}{r}\right)^2 \left(0,275 + 2,03 \left[\frac{C_\theta r}{\omega t}\right]^4\right)$$

Uklon v obodni smeri θ

Table 10.3   External pressure buckling factors for medium-length cylinders C_θ

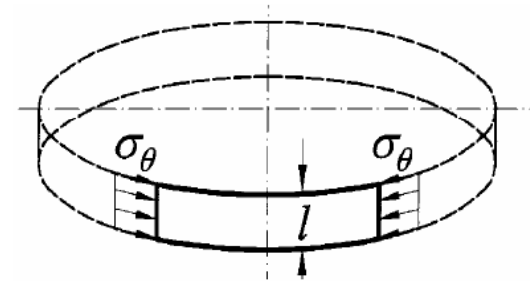| Case	Cylinder end	Boundary condition	Value of C_θ
1	end 1	BC 1	1,5
	end 2	BC 1	
2	end 1	BC 1	1,25
	end 2	BC 2	
3	end 1	BC 2	1,0
	end 2	BC 2	
4	end 1	BC 1	0,6
	end 2	BC 3	
5	end 1	BC2	0
	end 2	BC3	
6	end 1	BC 3	0
	end 2	BC 3	

Table 10.4   External pressure buckling factors for short cylinders $C_{\theta s}$

Case	Cylinder end	Boundary condition	$C_{\theta s}$
1	end 1	BC 1	$1,5 + \dfrac{10}{\omega^2} - \dfrac{5}{\omega^3}$
	end 2	BC 1	
2	end 1	BC 1	$1,25 + \dfrac{8}{\omega^2} - \dfrac{4}{\omega^3}$
	end 2	BC 2	
3	end 1	BC 2	$1,0 + \dfrac{3}{\omega^{1,35}}$
	end 2	BC 2	
4	end 1	BC 1	$0,6 + \dfrac{1}{\omega^2} - \dfrac{0,3}{\omega^3}$
	end 2	BC 3	

$$\text{where} \quad \omega = \frac{\ell}{\sqrt{rt}}$$

Uklon obroča v obodni smeri θ
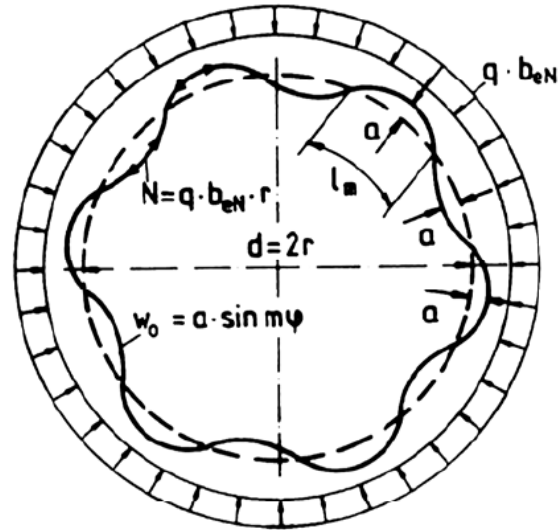
Figure 17.8 Example of a ring stiffener, designed with an equivalent imperfection shape of $m = m_{cr} = 6$

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

m = 2

Pristopi k računu lupin

- **Napetostna metoda** – račun napetosti z elastično analizo brez nepopolnosti (membranska ali upogibna teorija)

- **Direktna metoda** – uporaba formul iz dodatkov k SIST EN1993-1-6: predvsem za osno-simetrične primere, s katerimi pokrijemo večini relevantnih obtežb

- **Nelinearna globalna analiza z MKE** – geometrijska in materialna nelinearnost, začetne geometrijske nepopolnosti.

Direktna metoda

C.2.4 Cylinder, clamped: hydrostatic internal pressure

$$\sigma_{MT\theta} = p_{n0} \frac{r}{t}$$

BC1r

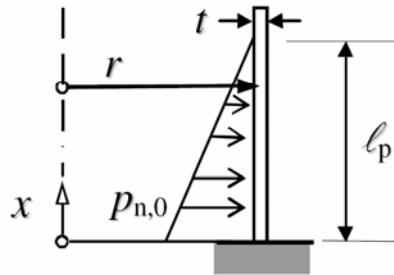| Maximum σ_{sx}	Maximum $\sigma_{s\theta}$	Maximum τ_{xn}	Maximum $\sigma_{eq,s}$	Maximum $\sigma_{eq,m}$
$k_x \, \sigma_{MT\theta}$	$k_\theta \, \sigma_{MT\theta}$	$k_\tau \sqrt{t/r} \, \sigma_{MT\theta}$	$k_{eq,s} \, \sigma_{MT\theta}$	$k_{eq,m} \, \sigma_{MT\theta}$

$\left(\dfrac{\sqrt{rt}}{\ell_p} \right)$	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
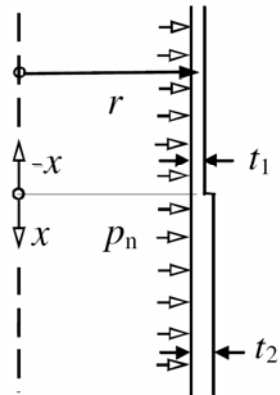
$$\sigma_{MT\theta} = p_n \frac{r}{t_1}$$

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

$\left(\dfrac{t_1}{t_2}\right)$	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

B.3.1 Ring stiffened Cylinder: Radial line load
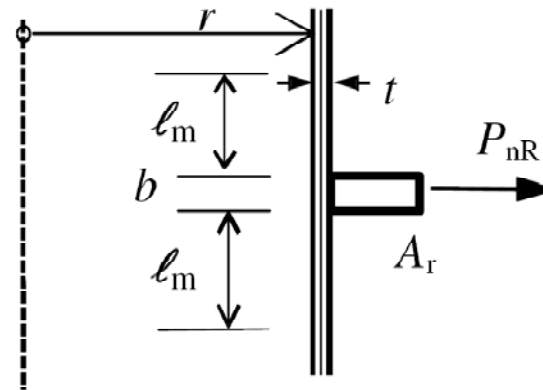
The plastic resistance P_{nR} (force per unit circumference) is given by:

$$P_{nR} = f_y \left(\frac{A_r + (b + 2\ell_m)t}{r} \right)$$
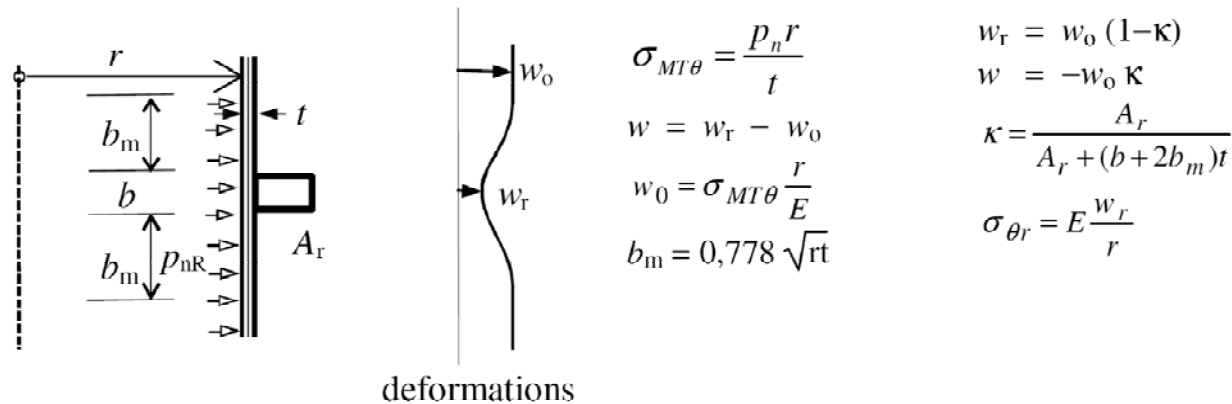
$$\ell_m = \ell_0 = 0.975 \sqrt{rt}$$

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 claus introduced into the expressions given in C.2.5 and C.2.1.

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

$$w = w_r - w_o$$

$$w_0 = \sigma_{MT\theta}\frac{r}{E}$$

$$b_m = 0{,}778\sqrt{rt}$$

$$w_r = w_o(1-\kappa)$$

$$w = -w_o\,\kappa$$

$$\kappa = \frac{A_r}{A_r + (b + 2b_m)t}$$

$$\sigma_{\theta r} = E\frac{w_r}{r}$$

deformations

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

Globalna analiza z MKE

Table 5.2: Types of shell analysis

| Type of analysis	Shell theory	Material law	Shell geometry
Membrane theory of shells	membrane equilibrium	not applicable	perfect
Linear elastic shell analysis (LA)	linear bending and stretching	linear	perfect
Linear elastic bifurcation analysis (LBA)	linear bending and stretching	linear	perfect
Geometrically non-linear elastic analysis (GNA)	non-linear	linear	perfect
Materially non-linear analysis (MNA)	linear	non-linear	perfect
Geometrically and materially non-linear analysis (GMNA)	non-linear	non-linear	perfect
Geometrically non-linear elastic analysis with imperfections (GNIA)	non-linear	linear	imperfect
Geometrically and materially non-linear analysis with imperfections (GMNIA)	non-linear	non-linear	imperfect

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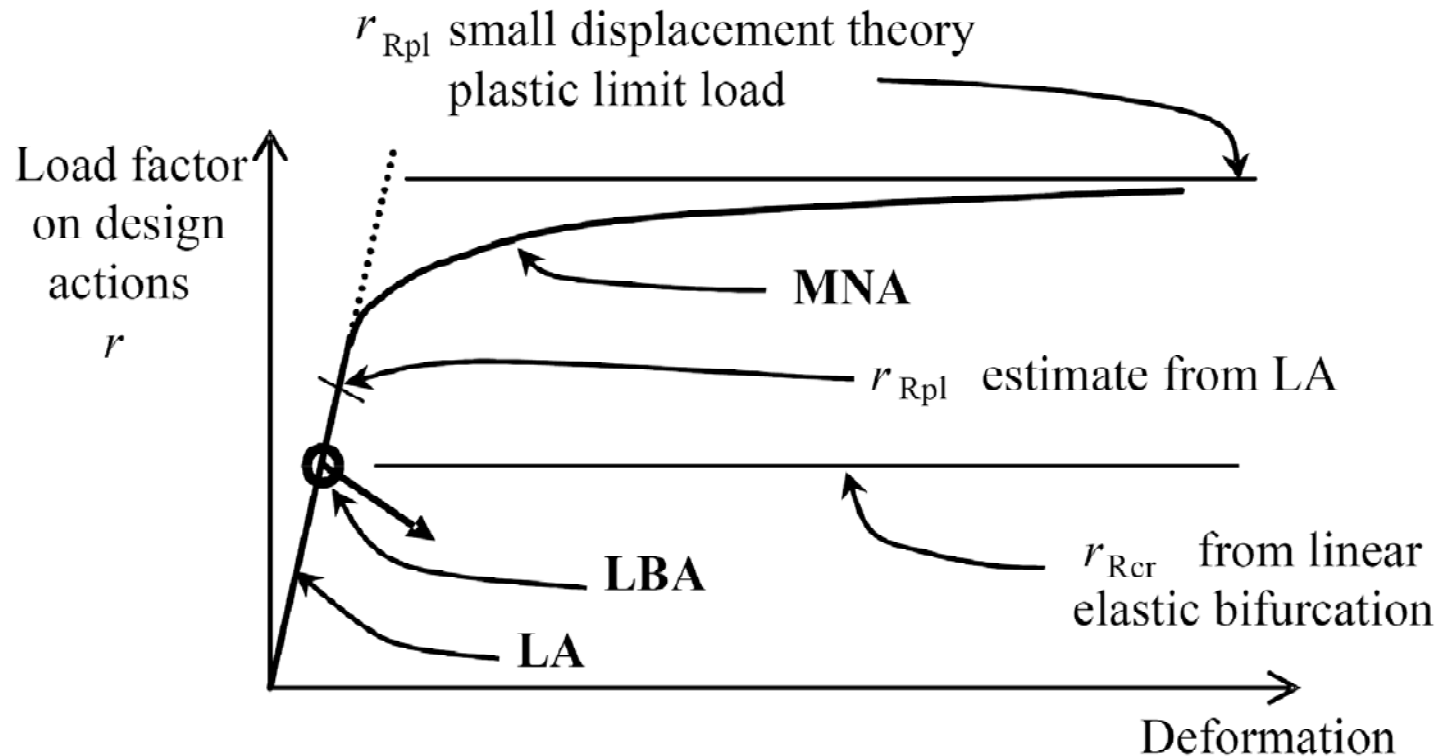
Figure 8.5: Definition of plastic reference resistance ratio r_{Rpl} and critical buckling resistance ratio r_{Rcr} derived from global MNA and LBA analyses
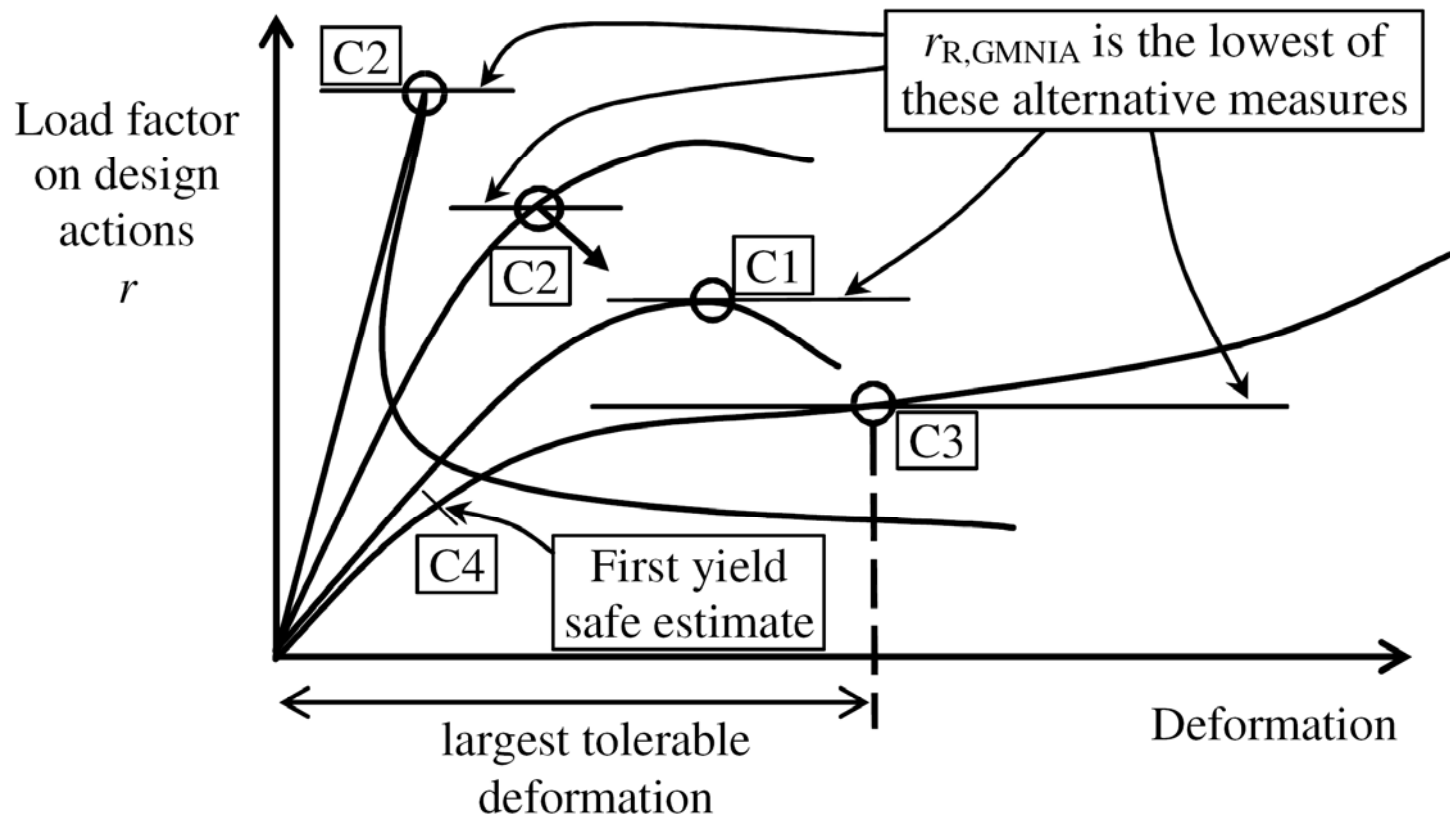
Globalna analiza z MKE

Figure 8.6: Definition of buckling resistance from global GMNIA analysis

Obtežbe (vplivi) na rezervoarje

- **L** - Teža tekočine : projektna višina in specifična teža

$$p = h\gamma$$
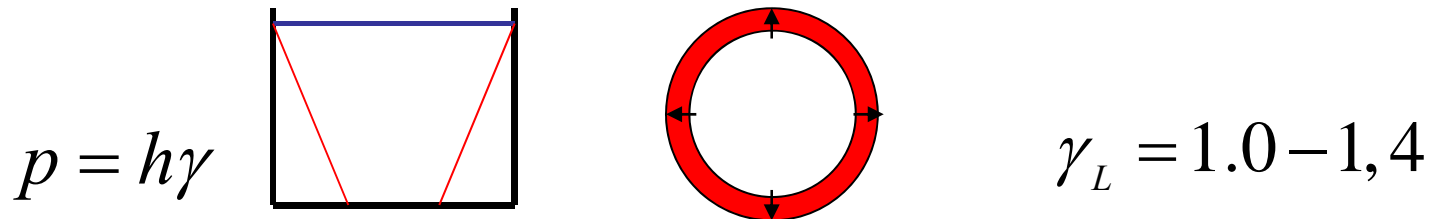

$$\gamma_L = 1.0 - 1,4$$

Table 2.1: Recommended values for the partial factors for actions on tanks for persistent and transient design situations and for accidental design situation

| design situation	liquid type	recommended values for γ_F in case of variable actions from liquids	recommended values for γ_F in case of permanent actions
liquid induced loads during operation	toxic, explosive or dangerous liquids	1,40	1,35
	flammable liquids	1,30	1,35
	other liquids	1,20	1,35
liquid induced loads during test	all liquids	1,00	1,35
accidental actions	all liquids	1,00	

Obtežbe (vplivi) na rezervoarje

- **NP** -Notranji pritisk ali podtlak : iz tehnologije ($\gamma = 1{,}5$)
- **T** - Toplotni vplivi : toplotne vplive se lahko zanemari, če ni nevarnosti utrujanja ($\gamma = 1{,}5$)
- **G** - Lastna teža in stalna oprema ($\gamma = 1{,}35$)
- **I** - Izolacija ($\gamma = 1{,}35$)

Obtežbe (vplivi) na rezervoarje

- **Q** - Koristna obtežba na strehi (zvezna, koncentrirana – SIST EN1991-1-1) (γ = 1,5)
  - q_k = 0,4 kN/m^2 na 10m^2
  - Q_k = 1,0 kN
- **S** - Sneg (SIST EN1991-1-3) – ne skupaj s koristno (γ = 1,5)
- **V** - Veter (SIST EN1991-1-4) (γ = 1,5)
  - Notranji srk zaradi vetra (c_p = -0,6 za odprte in c_p = -0,4 za zaprte rezervoarje z majhnimi odprtinami) - VN
  - Zunanji srk na strehi (redko pritisk) - VN
  - Zunanji pritisk na plašč (poenostavimo: zunanji pritisk po celem obodu in zanemarjen globalni upogib)

Vplivi vetra

$c_p = 0,4$ [1]

$c_p = 0,6$

D_T

D_C
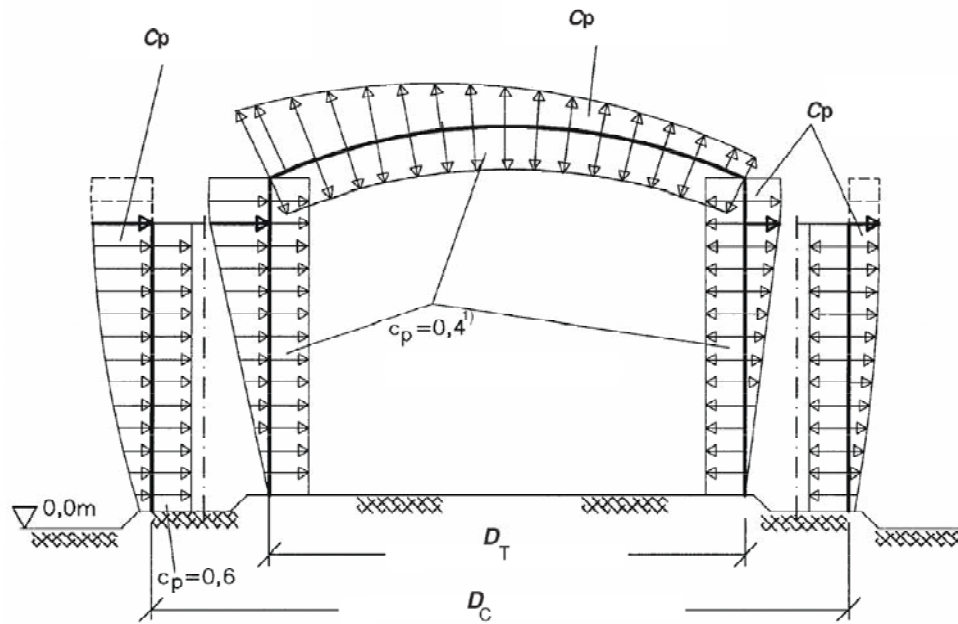
a) Tank with catch basin

$c_p = 0,4$ [1]

D_T
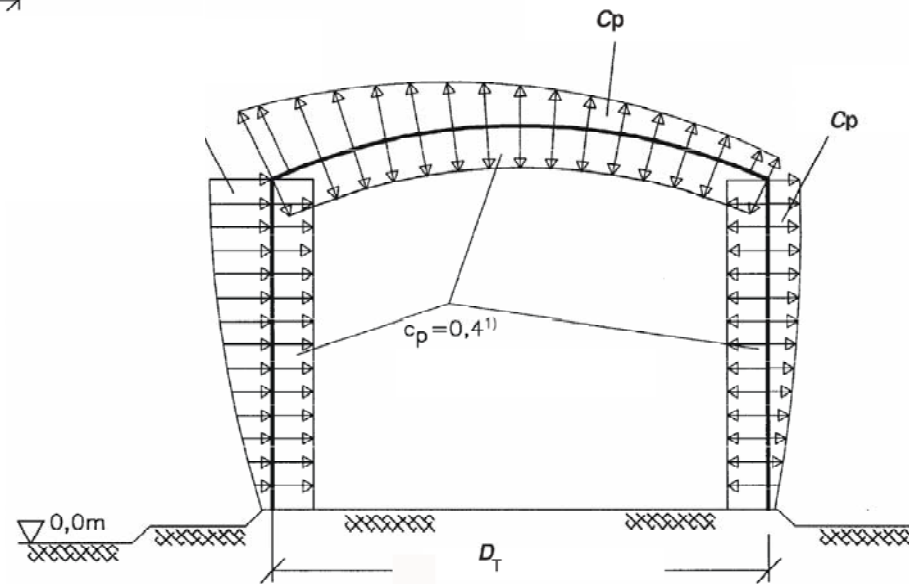
b) Tank without catch basin

D_T= Diameter of tank; D_c= Diameter of catch-basin;
1) C_p= 0,4 applies only for the vented tank; where no numerical values are given with C_p they have to be obtained from EN 1991-1-4.

Vplivi vetra

a) wind pressure distribution around shell circumference

b) equivalent axisymmetric pressure distribution
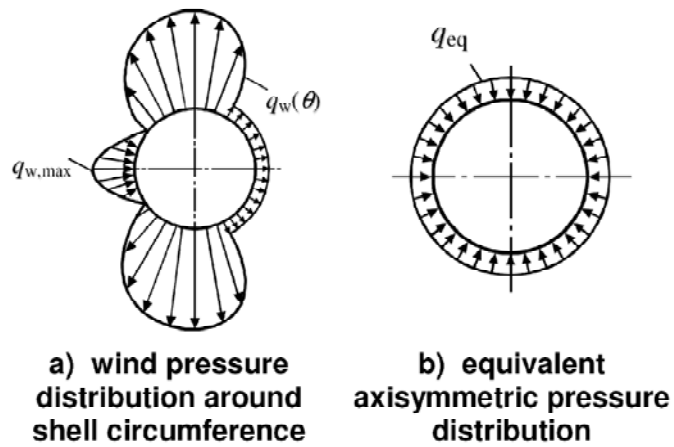
Figure D.2: Transformation of typical wind external pressure load distribution

a) stocky cylinder

b) intermediate aspect ratio cylinder

c) slender cylinder
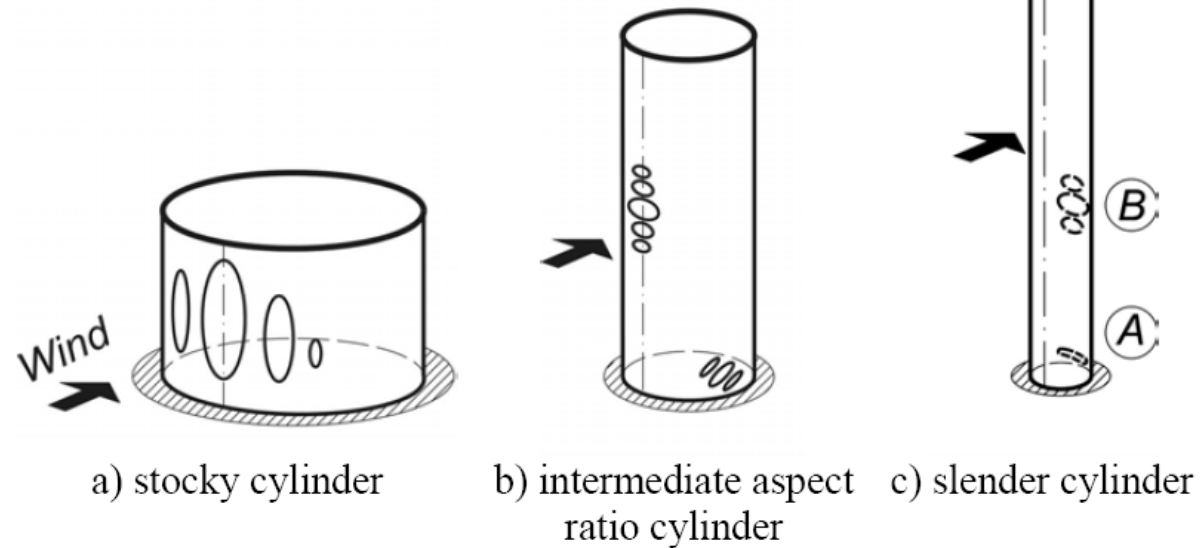
Figure 12.1 Buckling modes in cylinders with different aspect ratios under wind pressure when empty

Obtežbe (vplivi) na rezervoarje

- **NS** - Notranji srk zaradi neustreznega ventiliranja (projektna naloga) – hitro praznjenje ($\gamma = 1{,}5$)
- **O** -Obtežbe od delovanja cevovodov in druge opreme ($\gamma = 1{,}5$)
- **PO** - Obtežbe od neenakomernega posedanja ($\gamma = 1{,}5$)
- **A** - Nezgodne obtežbe (projektna naloga) ($\gamma = 1{,}0$)

Obtežbe (vplivi) na rezervoarje

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

Bild 15. Verformungen (a) und Druckverteilungen entsprechend EC 8-4 [26] (b) und den neuseeländischen Empfehlungen [29] (c)
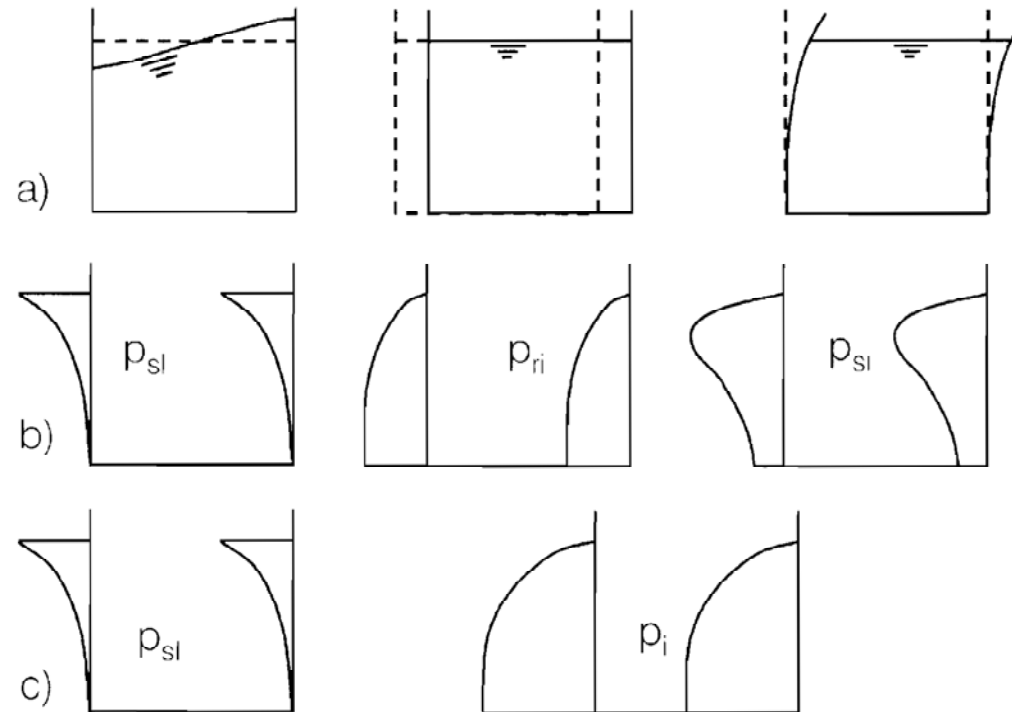
Preglednica A.1.1: Priporočene vrednosti faktorjev ψ za stavbe

Vpliv	ψ_0	ψ_1	ψ_2
Koristna obtežba v stavbah (glej EN 1991-1-1)			
Kategorija A: bivalni prostori	0,7	0,5	0,3
Kategorija B: pisarne	0,7	0,5	0,3
Kategorija C: stavbe, kjer se zbirajo ljudje	0,7	0,7	0,6
Kategorija D: trgovine	0,7	0,7	0,6
Kategorija E: skladišča	1,0	0,9	0,8
Kategorija F: prometne površine vozilo s težo $\leq$ 30 kN	0,7	0,7	0,6
Kategorija G: prometne površine 30 kN < teža vozila $\leq$ 160 kN	0,7	0,5	0,3
Kategorija H: strehe	0	0	0
Obtežba snega na stavbah (glej EN 1991-1-3)*			
Finska, Islandija, Norveška, Švedska	0,7	0,5	0,2
Druge članice CEN, za kraje z nadmorsko višino nad 1.000 m	0,7	0,5	0,2
Druge članice CEN, za kraje z nadmorsko višino pod 1.000 m	0,5	0,2	0
Obtežba vetra na stavbah (glej EN 1991-1-4)	0,6	0,2	0
Spremembe temperature (ne pri požaru) v stavbah (glej EN 1991-1-5)	0,6	0,5	0

Obtežne kombinacije

- Ventiliran rezervoar s streho (ali brez strehe) - prazen

$$VN = 0,4V\,(0,6V)$$

   – Največja vertikalna obtežba (σ_x – tlak)

$$1,35G + 1,5Q(S) + \left[0,6 \cdot 1,5(VN - 0,5V)\right] \qquad streha, plašč$$

$$1,35G + 1,5Q(S) + 0,6 \cdot 1,5(VN + V) \qquad plašč$$

   – Največja vertikalna obtežba (σ_x – nateg) – dvig streha (rez.)

$$1,00G - 1,5(V - \left[0,5V\right])$$

   – Največja prečna obtežba (σ_θ - tlak)

$$1,35G + 1,5(V + VN) + 0,7(0,5) \cdot 1,5Q(S)$$

Obtežne kombinacije

- Zaprt rezervoar s streho – nadpritisk $\pm$NP - prazen

  - Največja vertikalna obtežba (σ_x – tlak)

    $$1,35G + 1,5Q(S) + 0,6 \cdot 1,5(VP)$$

    $$1,35G + 1,5(VP) + 0,7(0,5) \cdot 1,5Q(S)$$

  - Največja vertikalna obtežba (σ_x – nateg) – dvig streha (rez.)

    $$1,00G - 1,5VP$$

  - Največja prečna obtežba (σ_θ - tlak)

    $$1,35G + 1,5VP + 0,6 \cdot 1,5V + 0,7(0,5) \cdot 1,5Q(S)$$

    $$1,35G + 1,5V + 0,6 \cdot 1,5VP + 0,7(0,5) \cdot 1,5Q(S)$$

Obtežne kombinacije

- Zaprt rezervoar s streho – srk NS - prazen

  - Največja vertikalna obtežba (σ_x – tlak)

    $$1,35G + 1,5Q(S) + 0,6 \cdot 1,5(VS)$$

    $$1,35G + 1,5(VS) + 0,7(0,5) \cdot 1,5Q(S)$$

  - Največja vertikalna obtežba (σ_x – nateg) – dvig streha (rez.)
    - Ni relevantno

  - Največja prečna obtežba (σ_θ - tlak)

    $$1,35G + 1,5VS + 0,6 \cdot 1,5V + 0,7(0,5) \cdot 1,5Q(S)$$

    $$1,35G + 1,5V + 0,6 \cdot 1,5VS + 0,7(0,5) \cdot 1,5Q(S)$$

Obtežne kombinacije

- Ventiliran rezervoar s streho (ali brez strehe) - poln

$$VN = 0,4V(0,6V)$$

- Največja vertikalna obtežba (σ_x – tlak)

$$1,35G + 1,5Q(S) + 1,3L + \left[0,6 \cdot 1,5(VN - 0,5V)\right]$$

- Največja vertikalna obtežba (σ_x – nateg) – dvig streha

$$1,00G - 1,5(V - \left[0,5V\right])$$

- Največja prečna obtežba (σ_θ) – veter samo vertikalno

$$1,35G + 1,3L + \left[0,6 \cdot 1,5(VN - 0,5V)\right] + 0,7(0,5) \cdot 1,5Q(S)$$

Material - žilavost

Table 3.1: Minimum design metal temperature MDMT based on LODMAT

Lowest one day mean ambient temperature LODMAT	Minimum design metal temperature MDMT	
	10 years data	30 years data
−10°C ≤ LODMAT	LODMAT +5°C	LODMAT +10°C
−25°C ≤ LODMAT ≤ −10°C	LODMAT	LODMAT +5°C
LODMAT ≤ −25°C	LODMAT −5°C	LODMAT

Projektne dimenzije

- Računska debelina pločevin

$$t_d = t_{nom} - \max(-toleranca) - \Delta t_{cor}$$

nabavna

debelina

SIS EN 10029

če je potrebno

(projektna naloga

Delni varnostni faktorji odpornosti

Table 2.2: Partial factors for resistance

Resistance to failure mode	Relevant γ
Resistance of welded or bolted shell wall to plastic limit state, cross-sectional resistance	γ_{M0}
Resistance of shell wall to stability	γ_{M1}
Resistance of welded or bolted shell wall to rupture	γ_{M2}
Resistance of shell wall to cyclic plasticity	γ_{M4}
Resistance of welded or bolted connections or joints	γ_{M5}
Resistance of shell wall to fatigue	γ_{M6}

$\gamma_{M0} = 1{,}00$	$\gamma_{M1} = 1{,}10$	$\gamma_{M2} = 1{,}25$
$\gamma_{M4} = 1{,}00$	$\gamma_{M5} = 1{,}25$	$\gamma_{M6} = 1{,}10$