Metal Structures II

Lecture I

Steel shell structures

Contents

Bar and shell members

Bar member

$10 \cdot$ max. dimension of cross-section $\leq$ length of element

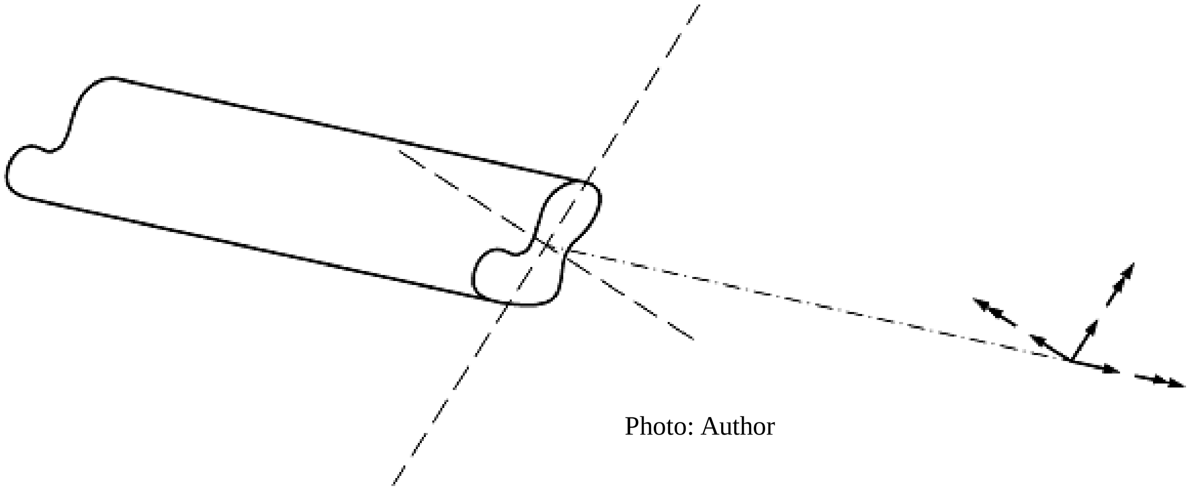


Photo: Author

Geometry of cross-sections $(A, A_V, J_y \ldots)$

$$T_\sigma = \begin{matrix} \sigma_{11} & \tau_{12} & \tau_{13} \\ \tau_{21} & \sigma_{22} & \tau_{23} \\ \tau_{31} & \tau_{32} & \sigma_{33} \end{matrix}$$

$N \;\; V_1 \;\; V_2$ [kN]

$M_1 \;\; M_2 \;\; M_T$ [kNm]

„Stress = Force / Geometry”

Shell member

$10 \cdot \text{thickness} \leq \text{min. length of plane}$

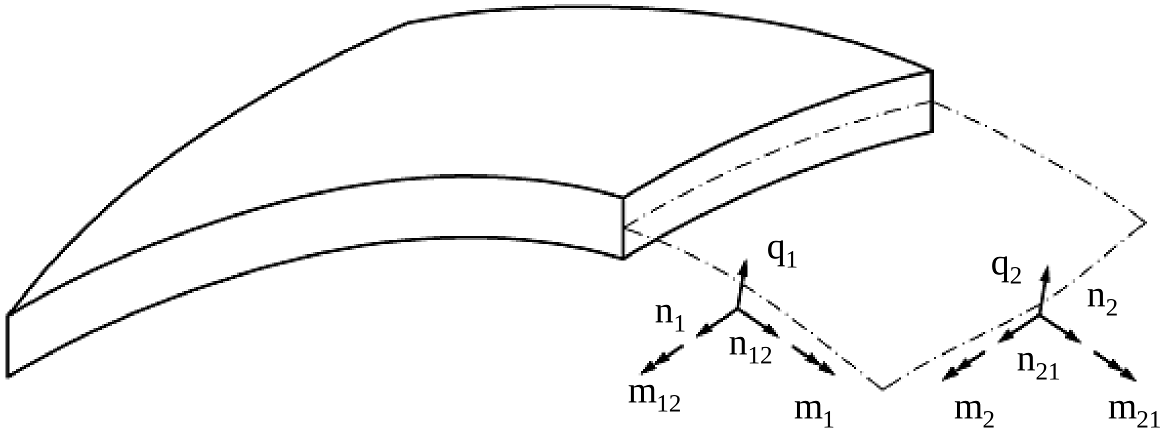


Photo: Author

Geometry: thickness of shell

$$T_\sigma = \begin{matrix} \sigma_{11} & \tau_{12} & \tau_{13} \\ \tau_{21} & \sigma_{22} & \tau_{23} \\ \tau_{31} & \tau_{32} & \sigma_{33} \end{matrix}$$

$n_1 \ n_{12} \ q_1 \ n_2 \ n_{21} \ q_2$ [kN / m]

$m_1 \ m_{12} \ m_2 \ m_{21}$ [kNm / m]

„Stress = Force / Geometry"

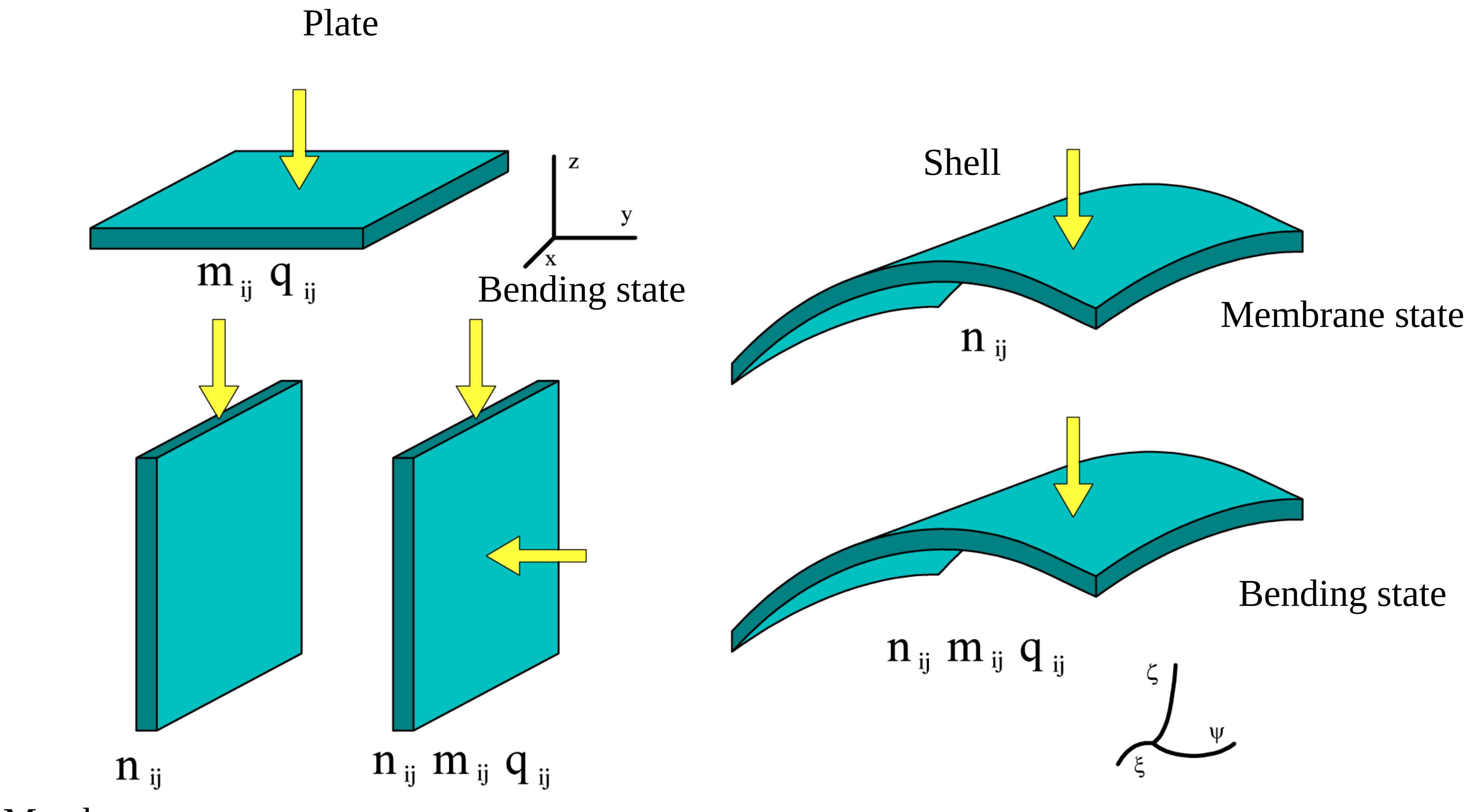
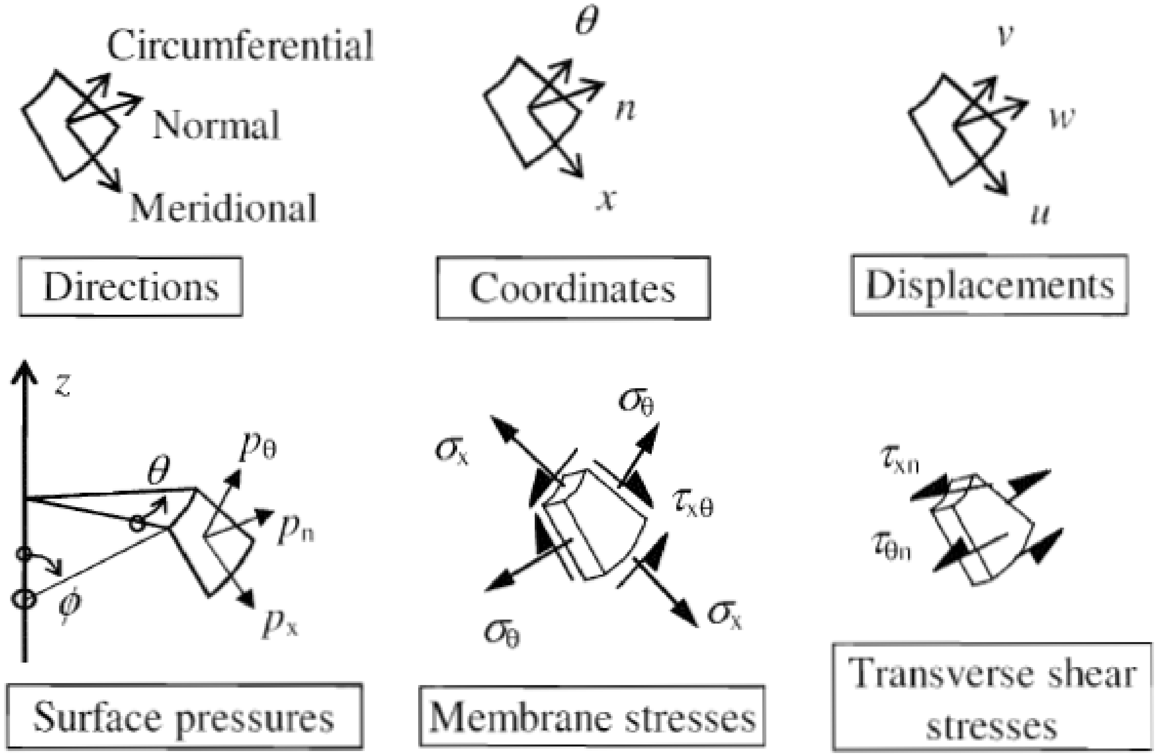


Photo: Author

Photo: EN 1993-1-6 fig. 1.1



EN 1993-1-6 (6.3), (6.4)

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

$$\tau_{x\theta,Ed} = (n_{x\theta,Ed} / t) \pm [m_{x\theta,Ed} / (t^2 / 4)] \quad ; \quad \tau_{xn,Ed} = (q_{xn,Ed} / t) \quad ; \quad \tau_{\theta n,Ed} = (q_{\theta n,Ed} / t)$$

Recalculation from cross-sectional forces to stresses

There is possible, that on subject Plate and Shell Structures these formulas are presented in other form:

$$\sigma_{x,\,Ed} = (n_{x,\,Ed} / t) \pm [m_{x,\,Ed} / (t^2 / 6)] \quad \text{instead} \quad \sigma_{x,\,Ed} = (n_{x,\,Ed} / t) \pm [m_{x,\,Ed} / (t^2 / 4)] \;;$$

$$\sigma_{\theta,\,Ed} = (n_{\theta,\,Ed} / t) \pm [m_{\theta,\,Ed} / (t^2 / 6) \quad \text{instead} \quad \sigma_{\theta,\,Ed} = (n_{\theta,\,Ed} / t) \pm [m_{\theta,\,Ed} / (t^2 / 4)];$$

$$\tau_{x\theta,\,Ed} = (n_{x\theta,\,Ed} / t) \pm [m_{x\theta,\,Ed} / (t^2 / 6)] \quad \text{instead} \quad \tau_{x\theta,\,Ed} = (n_{x\theta,\,Ed} / t) \pm [m_{x\theta,\,Ed} / (t^2 / 4)]$$

It is effect of different assumptions about behaviour of material: elsatic for 1/6 and plastic for 1/4.

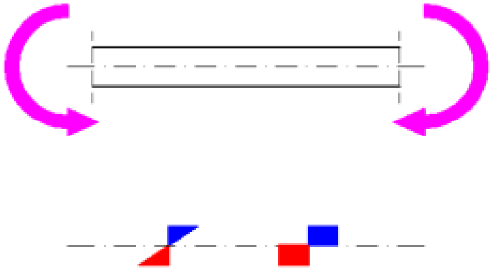


Photo: Author

Examples

Silos
EN 1993-4-1

Photo: wakro.com.pl

Photo: gpd24.pl

Photo: altimex.pl

Pipelines
(gas / fuel / water)
EN 1993-4-3

Photo: wikipedia

Photo: iniekt-system.pl

Chimneys
EN 1993-3-2

Photo: dept-wp.nmsu.edu

Photo: carrasquilloassociates.com

Photo: vertical.sk

Electro – energetic towers
EN 50341-1
EN 1993-3-1

Photo: inzynieria.com

Windmill towers
IEC 61 400
EN 1993-3-1

Photo: wikipedia

Lighting towers
EN 1993-3-1

Photo: ls-group.prom.ua

Telecomunication towers
EN 1993-3-1

Photo: towerproduct.com

Vertical cylindrical tanks
with catch basin
EN 1993-4-2
EN 14 015

Photo: kbpomorze.pl

Vertical cylindrical tanks
„normal”
EN 1993-4-2
EN 14 015

Photo: sinkos.pl

Vertical cylindrical tanks
with floating roof
EN 14 015

Photo: ko.pwr.wroc.pl

Cylindrical tanks
EN 12 285

Vertical cylindrical tanks
PN B 03211

Photo: tanksandvessels.com

Photo: petroconsulting.pl

Photo: jaso.com.pl

Cylindrical tanks
EN 12 285

Spherical gas tanks
PN B 03211

Photo: wikipedia

Watertowers
PN B 03211
EN 1993-3-1

Photo: wikipedia

Conveyor galleries

EN 1993-1-1
EN 1993-1-5
EN 1993-1-6

Photo: tsman.com

Photo: mwconveyor.com

Reliability of structures

EN 1990 Basis of structural design - basic division of structures into consequence classes (Ist step of study):

For six type of strucutre separate rules of division have benn introduced.

Photo: wikipedia

Shell structures

Shell or bar structures

Separate rules for reliability (other than in EN 1990)

Separate rules not important for Poland

1993-3 Towers, masts and chimneys :

- 1993-3-1 Towers and masts
- 1993-3-2 Chimneys

1993-4 Silos, tanks and pipelines:

- 1993-4-1 Silos
- 1993-4-2 Tanks
- 1993-4-3 Pipelines

General rules

Consequences calsses	Description	Examples
CC3	**High consequence** for loss of human life or economic, social or environmental consequences **very heavy**	Grandstands; public buildings where consequences of failure are high
CC2	**Medium** for loss of human life or economic, social or environmental consequences **considerable**	Residential; office buildings; public buildings where consequences of failure are medium
CC1	**Low** for loss of human life and economic, social or environmental consequences **small or neglegible**	Agricultural buildings where people do not normally enter; greenhouses

EN 1990 tab B1

Effects for designing and executing; EN 1990, tab. B1 + B4 + B5

Consequences classes	Design Supervision Levels (during designing)	Characteristics	Minimum recommended requirements	Inspection Level (during execution)	Characteristics	Requirements
CC3	DSL3	Extended supervision	Third part checking (performed by an organsation different from that, which has prepared the design)	IL3	Extended inspection	Third party inspection
CC2	DSL2	Normal supervision	Checking by different person, that those originally responsible and in accordance with the procedure of the organisation	IL2	Normal inspection	Inspection in accordance with the procedures of the organisation
CC1	DSL1	Normal supervision	Self-checking (performed by the person, who has prepared the design)	IL1	Normal inspection	Self inspection

Masts and towers – reliability classes (RC), number RC the same as number CC

Reliability class	Description
RC3	Towers and masts erected in urban locations, or there their failure is likely would cause injury or loss of life; towers and masts used for vital telecommunication facilities; other major structures where the consequences of failure would be likely to be very high
RC2	Al1 towers and masts that cannot be defined as RC1 or RC3
RC1	Towers and masts built on unmanned sites in open countryside; towers and masts, the failure of which wolud not be likely to cause injury of people

EN 1993-3-1 tab. A.1

Partial factors for permanent and variable actions for masts and towers			
Type of effects	Reliability class	Permanent actions	Variable actions
Unfavourable	RC3	1,2	1,6
	RC2	1,1	1,4
	RC1	1,0	1,2
Favourable	RC1, RC2, RC3	1,0	0,0
Accidental situations		1,0	1,0

EN 1993-3-1 tab. A.2

Chimneys – reliability classes (RC), number RC the same as number CC

Reliability class	Description
RC3	Chimneys erected in strategic locations such as nuclear power plants or in densely populated urban locations. Major chimneys in manned industrial sites where the economic and social consequences of their failure would be very high
RC2	Al1 normal chimneys at industrial sites or other locations that cannot be defined as RC1 or RC3
RC1	Chimneys built in open countryside whose failure would not cause injury. Chimneys less than 16m high in unmanned sites

EN 1993-3-2 tab. A.1

Reliability class	Recommendations for maximum amplitudes of cross-wind vibrations - limits to cross-wind vibration amplitude
RC3	0,05 D
RC2	0,10 D
RC1	0,15 D

EN 1993-3-2 tab. 7.1

(D - diameter of chimney)

Partial factors for permanent and variable actions for chimneys			
Type of effects	Reliability class	Permanent actions	Variable actions
Unfavourable	RC3	1,2	1,6
	RC2	1,1	1,4
	RC1	1,0	1,2
Favourable	RC1, RC2, RC3	1,0	0,0
Accidental situations		1,0	1,0

EN 1993-3-2 tab. A.2

Tanks – consequences classes (CC)

Consequences calss	Description
CC3	Tanks storing liquids or liquefied gases with toxic or explosive potential and large size tanks with flammable or water-polluting liquids in urban areas
CC2	Medium size tanks with flammable or water-polluting liquids in urban areas
CC1	Agricultural tanks or tanks containing water

„Medium size” = according to unofficial definition, volume ≤ 10.000 m^3

EN 1993-4-2 2.2

Consequences calss	Circular shell structure of a tank	Box structure of a rectangular tank
CC3	+ numerical analysis (finite element shell analysis)	An analysis based on nonlinear plate bending and stretching theory
CC2	+ membrane theory with bending theory or + numerical analysis (finite element shell analysis)	An analysis based on linear plate bending and stretching theory
CC1	+ membrane theory and + simplified formulas to describe local bending effects	Static equilibrium for membrane forces and beam theory for bending

EN 1993-4-2 4.2.2 4.3.3

Partial factors for permanent and variable actions for tanks			
Type of effects	Reliability class	Permanent actions	Variable actions
Unfavourable	CC3	1.50 (1.35)	1,65
	CC2	1.35	1,50
	CC1	1.20 (1.35)	1,35
Favourable	CC1, CC2, CC3	1,0	0,0
Accidental situations		1,0	1,0

T. Michałowski, M. Piekarczyk, Selected Issues of Special Steel Structures, Cracow University of Technology 2019

Silos – consequences classes (CC) and action assessment classes (AAC)

Consequences calss	Description
CC3	Ground supported silos or silos supported on a complete skirt extending to the ground with capacity in excess of 5 000 tones or discretely supported silos with capacity in excess of 1 000 tones or silos with capacity in excess of 200 tones in which any of the following design situations occur: a) eccentric discharge b) local patch loading b) unsymmetrical filling
CC2	All silos covered by EN 1993-4-1 and not placed in C1 or CC3
CC1	Silos with capacity between 10 and 100 tones

EN 1993-4-1 tab 2.1

Action assessment class	Description
AAC3	Silos with capacity in excess of 10 000 tones or silos with capacity in excess of 1000 tones in which any of the following design situations occur: a) eccentric discharge with $e_0 / d_c > 0,25$ b) squat silos with top surface eccentricity with $e_t / d_c > 0,25$
AAC2	All silos covered by EN 1993-1-4 and not placed in AAC1 or AAC3
AAC1	Silos with capacity below 100 tones.

EN 1991-4 tab 2.1

Consequences calss	Circular shell structure of a silo	Box structure of a rectangular silo
CC3	+ numerical analysis (finite element shell analysis)	An analysis based on nonlinear plate bending and stretching theory
CC2	+ membrane theory with bending theory or + numerical analysis (finite element shell analysis)	An analysis based on linear plate bending and stretching theory
CC1	+ membrane theory and + simplified formulas to describe local bending effects	Static equilibrium for membrane forces and beam theory for bending

EN 1993-4-1 4.2.2 4.3.3

Partial factors for permanent and variable actions for silos			
Type of effects	Reliability class	Permanent actions	Variable actions
Unfavourable	CC3	1.50 (1.35)	1,65
	CC2	1.35	1,50
	CC1	1.20 (1.35)	1,35
Favourable	CC1, CC2, CC3	1,0	0,0
Accidental situations		1,0	1,0

T. Michałowski, M. Piekarczyk, Selected Issues of Special Steel Structures, Cracow University of Technology 2019

Additionally - there are differen values of representative imperfection for different CC (fabrication tolerance quality ↔ CC, EN 1993-4-1 tab. 5.1)

Fabrication tolerance quality of construction	Representative imperfection amplitude	Reliability class restriction
normal	$\sqrt{rt}/16$	compulsory when the silo is designed to CC1 rules
high	$\sqrt{rt}/25$	
excellent	$\sqrt{rt}/40$	only permitted when the silo is designed to CC3 rules

EN 1993-1-6 8.7.2

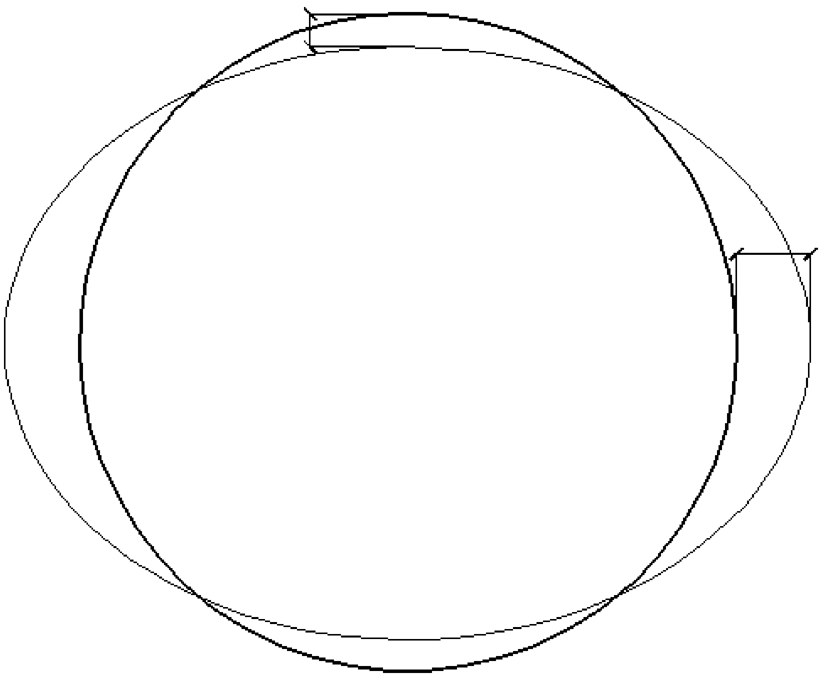


Photo: Author

Imperfections should be analysed as equivalent geometrical imperfections. First of all, geometry of modes of instability should be taken into consideration.

Action assessment class AAC

Generally, the higher number of action assessment class is the more complicated cases of actions combinations must be analysed.

Examples of internal pressure for AAC3:

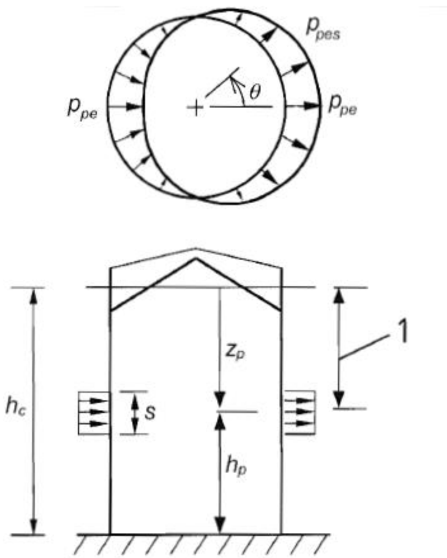


Photo: EN 1991-4 fig. 5.4

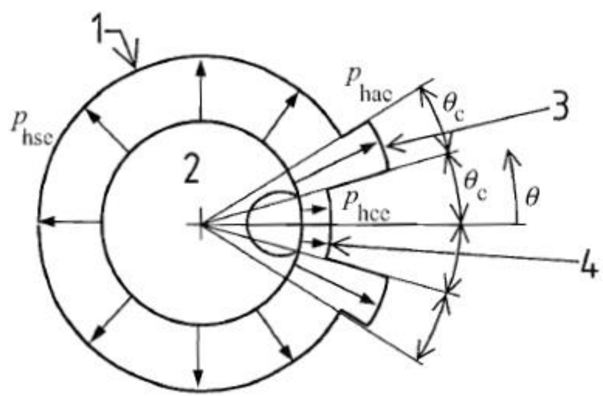


Photo: EN 1991-4 fig. 5.5

Pipelines - importance calsses (IC)

Importance calss	Description
IC4	Exceptional risk to life is low and the economic and social consequences of failure (~ CC3 according to EN 1990)
IC3	High risk to lifeis low and the economic and social consequences of failure (~ CC3 according to EN 1990)
IC2	Medium risk to life and local economic or social consequences of failure (~ CC2 according to EN 1990)
IC1	Risk to life is low and the economic and social consequences of failure are small or neglegible (~ CC1 according to EN 1990)

EN 1998-4 2.1.4

These rules are important for earthquake actions (out of Poland)

Importance calss	Safety factors for seismic actions
IC4	$\gamma_I = 1,6$
IC3	$\gamma_I = 1,2$
IC2	$\gamma_I = 1,0$
IC1	$\gamma_I = 0,8$

EN 1998-4 2.1.4

The same safety factors for tanks and silos in seismic situations;

Tank, silo, chimney – structures, the most often erected as shell structures

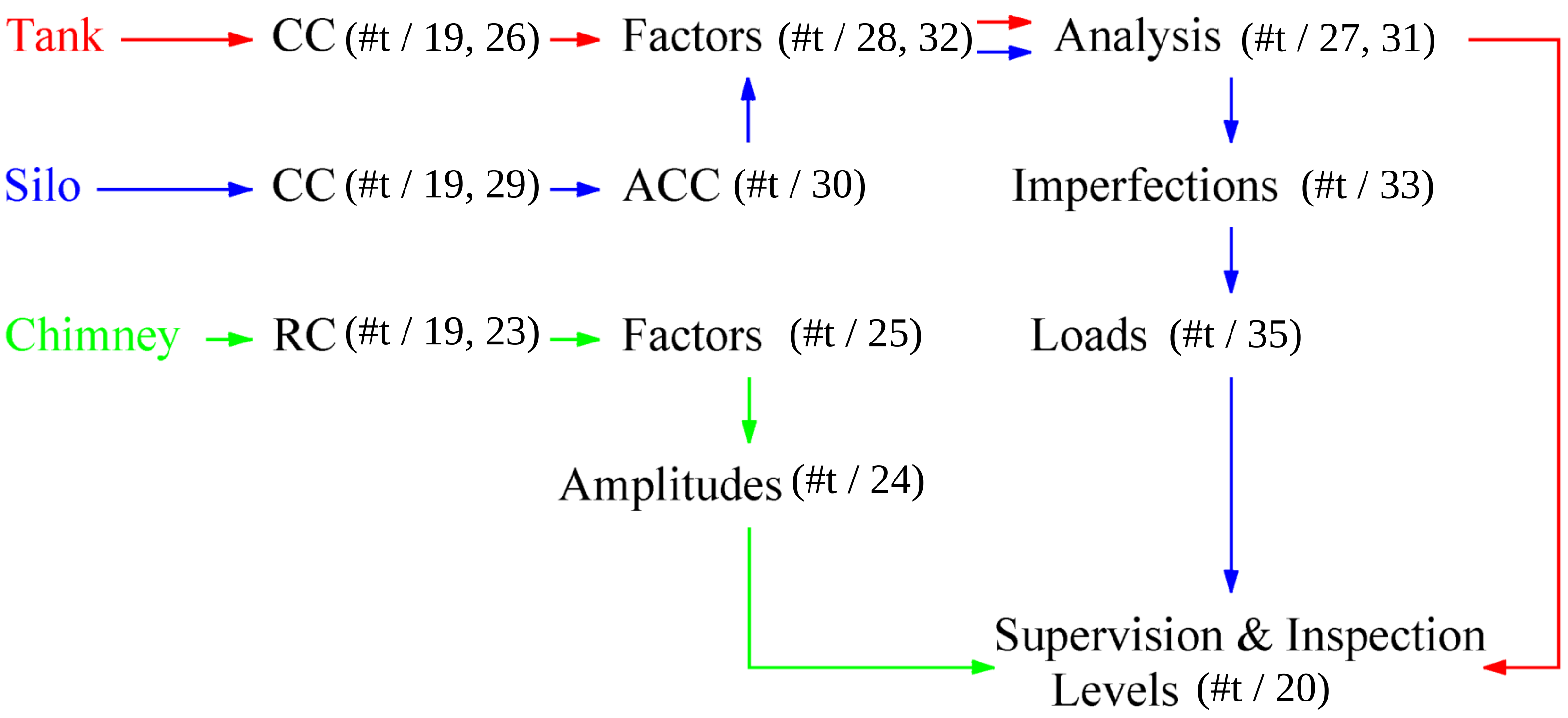


Photo: Author

Vertical cylindrical tanks

(main topic)

EN 1993-4-2

EN 14 015

PN B 03211

Photo: sinkos.pl

Photo: kbpomorze.pl

Photo: ko.pwr.wroc.pl

Basic standard for tanks in EN 1993-4-2. Standard EN 14 015 is recalled in EN 1993-4-2 as complementary standard. Old Polish Standard PN B 03211 can be treated as auxiliary standard for initial assumption of geometry. But these three standards based on different assumptions.

Standard	Method	f_k	Safety factors
EN 1993-4-2	Limit States Method	5%	Two separated: for actions and for material, calculated for special values of quantiles
EN 14 015	Permissible Stress Design	5%	One for proportion between effects and resistance
PN B 03211	Limit States Method	2%	Two separated: for actions and for material, calculated for special values of quantiles

There are special standards for actions and for values of safety factors, dedicated for each method of calculations. Calculation according EN 14 015, based on actions and safety factors from Eurocodes, does not give correct results. It is inconsequence in Eurocode, when EN 14 015 is recalled.

Consequence Class	Way of analysis			
	Approximate formulas		Precise	
	EN 1993-1-6 app A, B, C	EN 1993-4-2, EN 14 015	FEM and EN 1993-1-6	Approximate forumlas as initial data for FEM
CC1	+	+	(+)	(+)
CC2	+	+	+	+
CC3			+	+

Simplified formulas (EN 1993-4-2 11):

The simplified analysis of this section may be applied where al1 the following conditions are satisfied:

- the tank structure is of the form shown in figure;
- the only internal actions are liquid pressure and gas pressure above the liquid surface;
- maximum design liquid level not higher than the top of the cylindrical shell;
- the following loadings can all be neglected: thermally induced loads, seismic loadings, loads resulting from uneven settlement or connections and emergency loadings;
- no course is constructed with a thickness less than that of the course above it, except for the zone adjacent to the eaves ring;
- the design value of the circumferential stress in the tank shell is less than 435 *MPa;*
- for a spherical roof, the radius of curvature is between 0,8 and 1,5 times the diameter of the tank;
- for a conical roof, the slope of the roof is between 1:5 and 1:3 if the roof is only supported from the she (no internal support);
- the design gradient of the tank bottom is not greater than 1:100;
- the bottom is fully supported or supported by closely spaced parallel girders;
- the characteristic internal pressure is not below -8,5 mbar (0,85 kPa) and not greater than 60 mbar (6 kPa);
- the number of load cycles is such that there is no risk of fatigue failure.

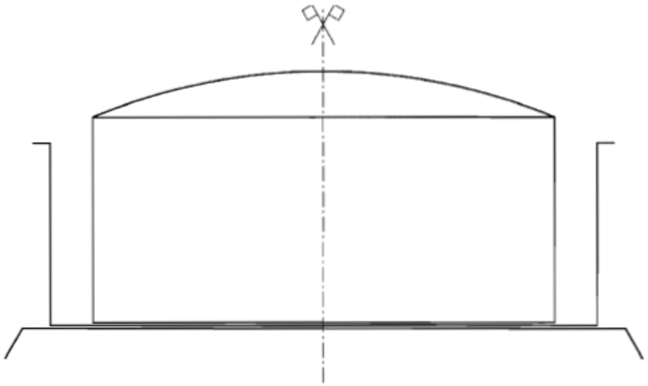


Photo: Author

Loadbearing - loads

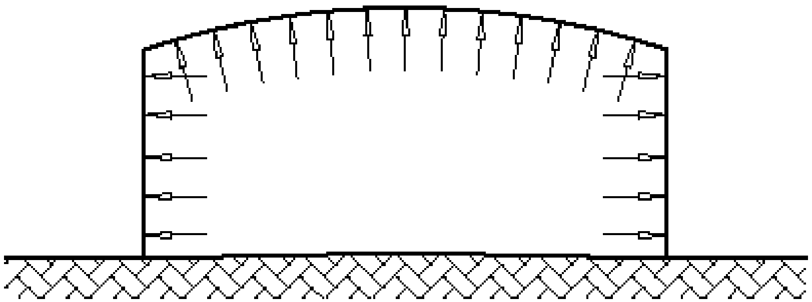


Photo: Author

Photo: przelom.pl

Photo: journalism.columbia.edu

Stability - loads

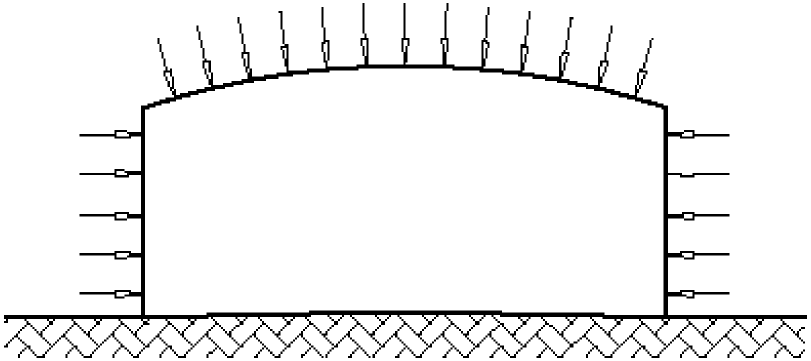


Photo: Author

Two cases: blowing air into the can and sucking

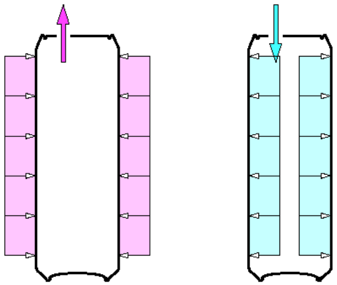


Photo: T. Michałowski, M. Piekarczyk, Selected Issues of Special Steel Structures, Cracow University of Technology 2019

Roof:

Loadbearing of roof:

- Floating covers
- Floating roof
- Unstiffened dome roof shell
- Unstiffened conical roof shell
- Self supporting roof with roof structure

Stability of roof:

- Unstiffened dome roof shell

Floating covers EN 14 015 app. C

Floating roof EN 14 015 app. D

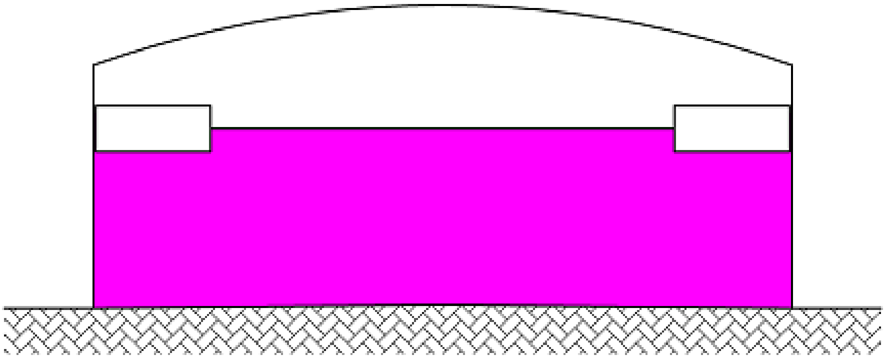


Photo: Author

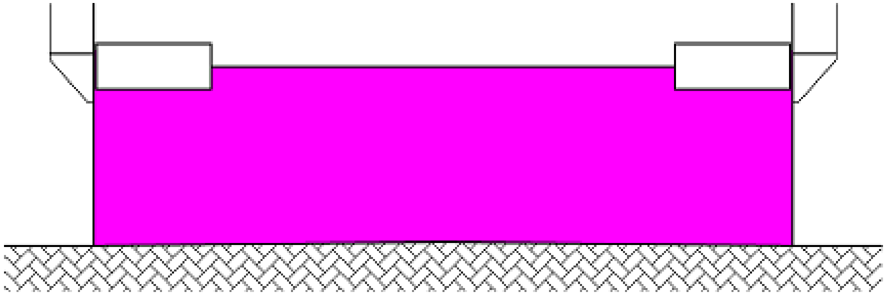


Photo: Author

Unstiffened roof shell

Photo: cstindustries.com

Self supporting roof with roof structure EN 1993-4-2 11.2.2, 11.2.3, 11.2.4

- Roof planting
- Rafters
- Centre ring
- Bracings
- Column supported roof

Photo: artson.net

Edge ring:

- Loadbearing
- Stability
- Interaction with rafters
- Edge ring in tanks with floating roof

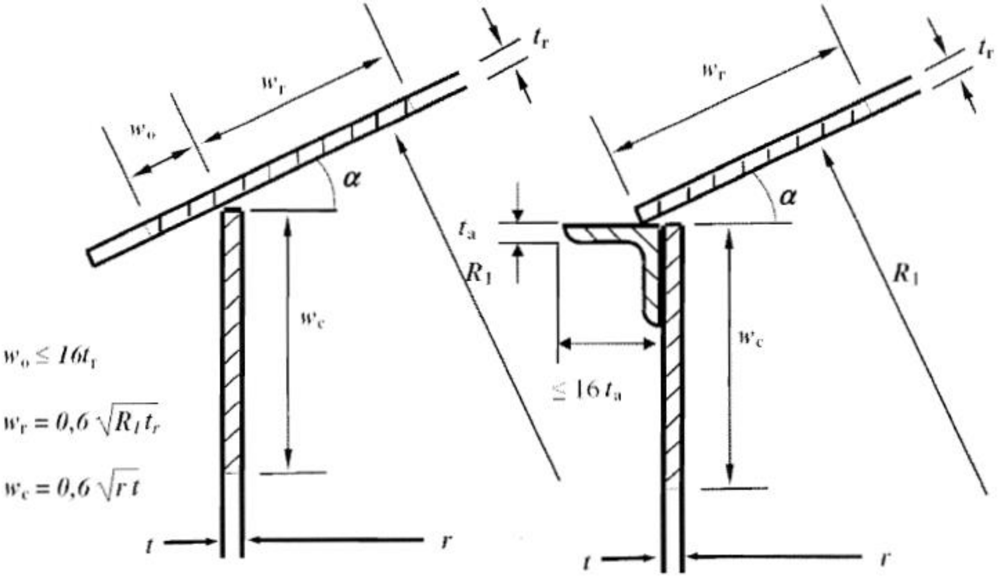
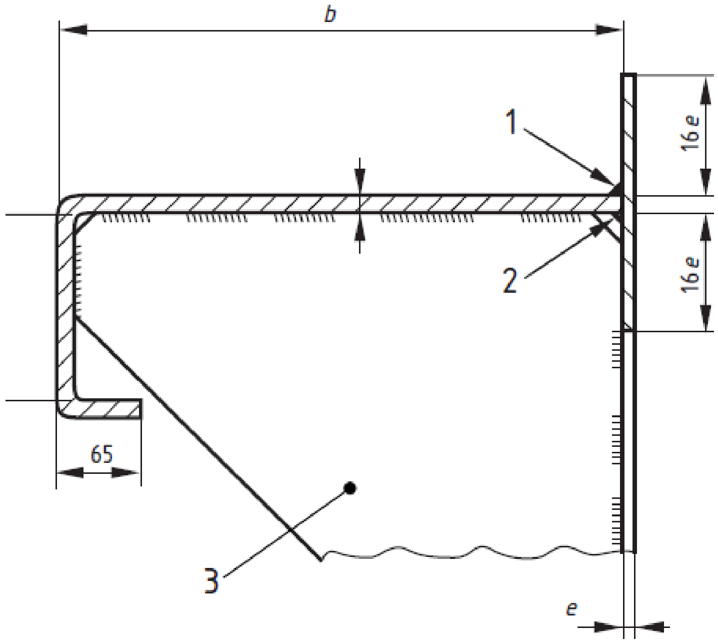


Photo: EN 1993-4-2 fig. 11.4, EN 14 015 fig. 8

Doom / conical roof

For floating roof:

EN 14015 (7)



e) Formed plate

Key

1 Continuous fillet weld 2 Intermittent weld 3 Bracket

Photo: EN 14015 fig J1

Information about way of calculation:

EN 1993-4-2 [A]

EN 14 015 [B]

PN B 03210 [C]

Type of roof	Resistance of shell	Stability of shell	Central ring	Edge ring
conical unstiffened	[A] – yes [B] – yes **[C] – no**	**[A] – no** [B] – yes **[C] – no**	[A] – yes **[B] – no** **[C] – no**	[A] – yes [B] – yes [C] – yes
conical with rafters	[A] – no [B] – no [C] – no	[A] – no [B] – no [C] – no	[A] – yes **[B] – no** **[C] – no**	[A] – yes **[B] – no** **[C] – no**
dome unstiffened	[A] – yes [B] – yes **[C] – no**	[A] – yes [B] – yes **[C] – no**	[A] – yes **[B] – no** **[C] – no**	[A] – yes [B] – yes **[C] – no**
dome with rafters	[A] – yes **[B] – no** **[C] – no**	[A] – no [B] – no [C] – no	[A] – yes **[B] – no** **[C] – no**	[A] – yes **[B] – no** **[C] – no**

Cylindrical shell:

- Loadbearing
- Stability:
  - Checking conditions for formulas
  - Formulas
  - Types of secondary rings
  - Distance between secondary rings
  - Stiffeness of secondary rings

I stage: water test (tested of leaks; sometimes the need to seal)

Loads: water pressure

Duration: 1 week - 1 month

II stage: exploatation

Loads: fuel pressure, overpressure, corrosion

Duration: many many years (in this design project: 50 years)

There is possible, than tank is not completely hermetic after erection. Hermeticity must be tested before start of exploatation. Water is used for test - economic and environmental losses in case of leaks are much much less than in case of, for example, gasoline leak.

Photo: photo.tepco.co.jp

Photo: photo.tepco.co.jp

Density of water is different than density of liquid during operation (other loads). Time of test is too short to start corrosion. There is no need to analyse overpressure during test.

$$t = \max(t_{min}\ ;\ t_I\ ;\ t_{II})$$

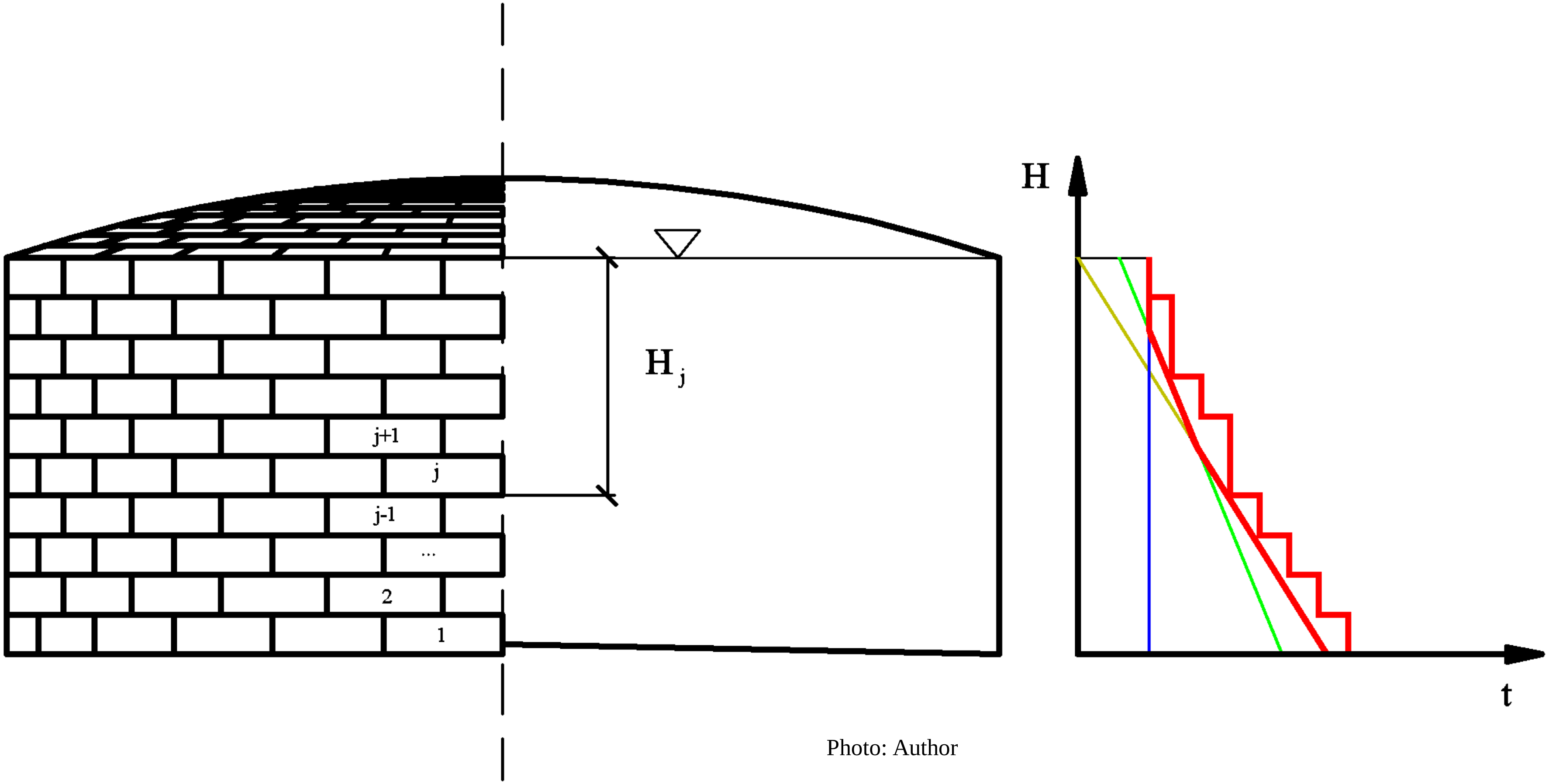


Photo: Author

Shell man holes

Shell nozzles

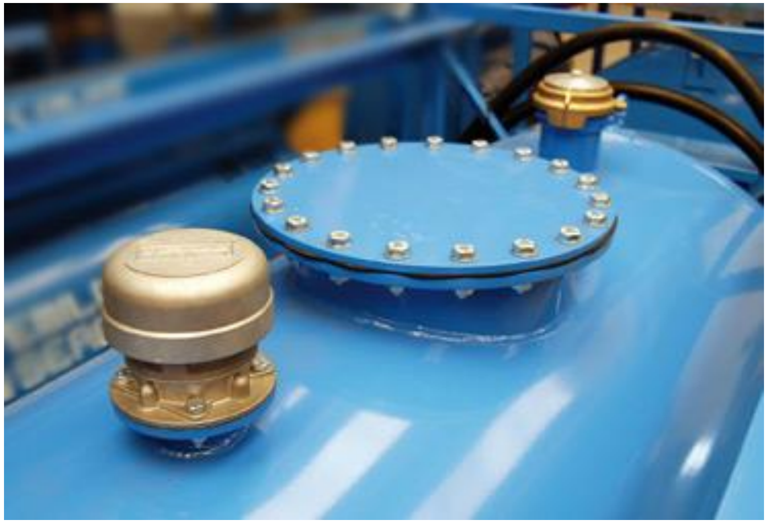
Bottom

Global stability

Foundations

Man holes, nozzles

Photo: dystrybutory-paliw.pl



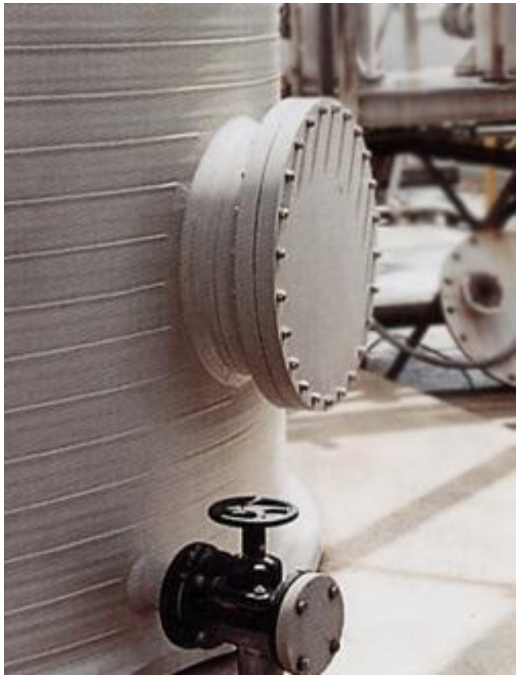


Photo: formoplast.com

EN 1993-4-2 5.4.6
EN 14015 13.1 – 13.9

General idea - cylindrical shell must be thicker around holes

There are three ways of calculation:

- Provision of nozzle or manhole body;
- Reinforced plate ($1{,}5\ d \le d_n \le 2{,}0\ d$);
- Thicker shell plate;

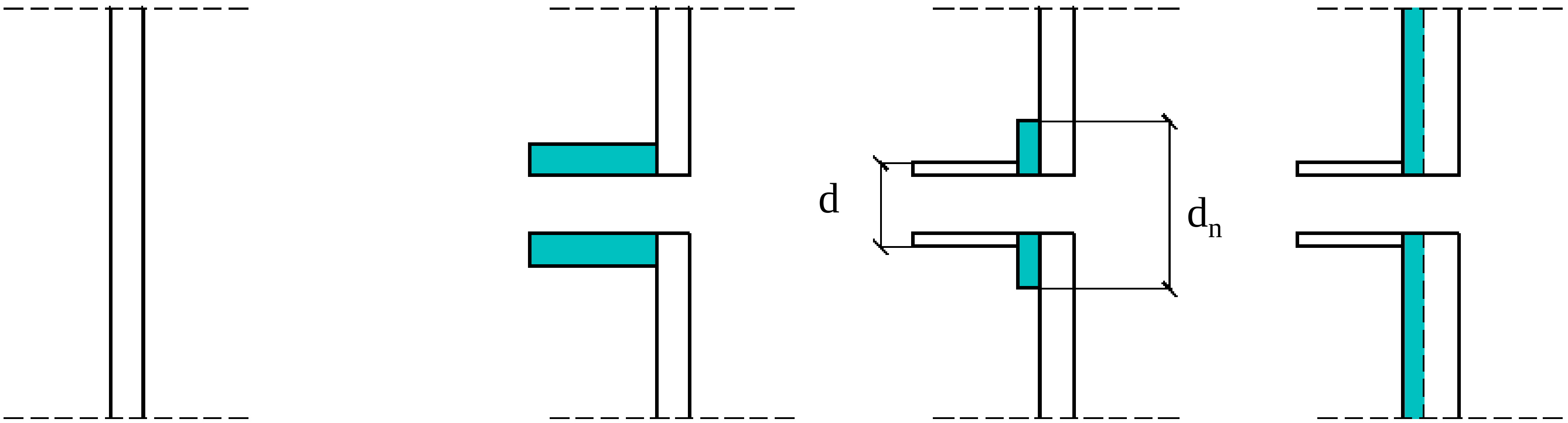


Photo: Author

Limit states

After FEM model:

EN 1993-1-6

EN 1993-1-7

Plastic limit state (LS1)
Cyclic plasticity limit state (LS2)
Buckling limit state (LS3)
Fatigue limit state (LS4)

Global stability

Serviceability limit state

EN 1990	EN 1993-1-6, EN 1993-1-7
EQU LS	Global stability (#t / 82)
STR LS	LS1 (#t / 60-61, 81) LS3 (#t / 67-73, 81)
FAT LS	LS2 (#t / 62-66, 81) LS4 (#t / 74-81)
GEO LS	Foundations (#t / 83-84)
SLS	SLS (#t / 85)

Plastic limit state LS1 (EN 1993-1-6 6):

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

$$\tau_{x\theta,\,Ed} = (n_{x\theta,\,Ed} / t) \pm [m_{x\theta,\,Ed} / (t^2 / 4)] \quad ; \quad \tau_{xn,\,Ed} = (q_{xn,\,Ed} / t) \quad ; \quad \tau_{\theta n,\,Ed} = (q_{\theta n,\,Ed} / t)$$

$$\sigma_{eq,Ed} = \sqrt{[\sigma_1^2 + \sigma_2^2 - \sigma_1 \sigma_2 + 3(\tau_{12}^2 + \tau_{13}^2 + \tau_{23}^2)]} \leq f_{eq,Rd} = f_{yd}$$

Condition for shell member:

$$\sigma_{eq,Ed} / f_{eq,Rd} \leq 1{,}0$$

This is the same type codition, as, for example

$$N_{Ed} / N_{Rd} \leq 1{,}0 \quad \text{or} \quad M_{Ed} / M_{Rd} \leq 1{,}0$$

for bar member.

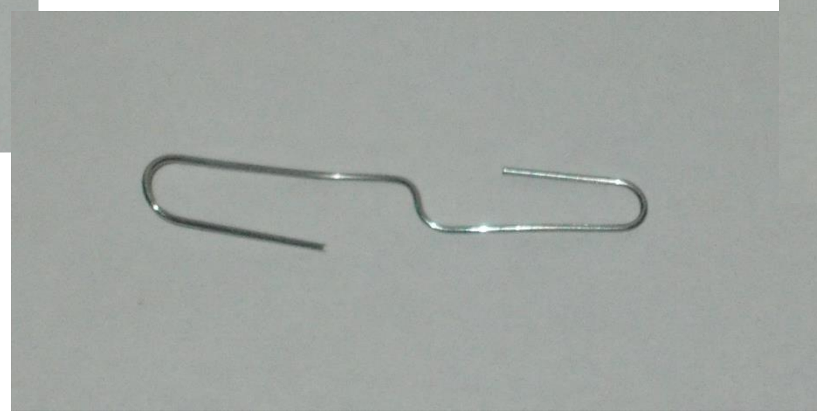
Cyclic plasticity limit state LS2 (EN 1993-1-6   7)

$$\Delta\sigma_{eq,Ed,i} = \sqrt{\left[\Delta\sigma_{1,i}^2 + \Delta\sigma_{2,i}^2 - \Delta\sigma_{1,i}\,\Delta\sigma_{2,i} + 3\Delta\tau_{12,i}^2\right]} \leq \Delta f_{eq,Rd,i} = 2f_{yd}$$

$\Delta\sigma_{1,i}$, $\Delta\tau_{1,i}$ = amplitude between two opposite extreme combinations of loads

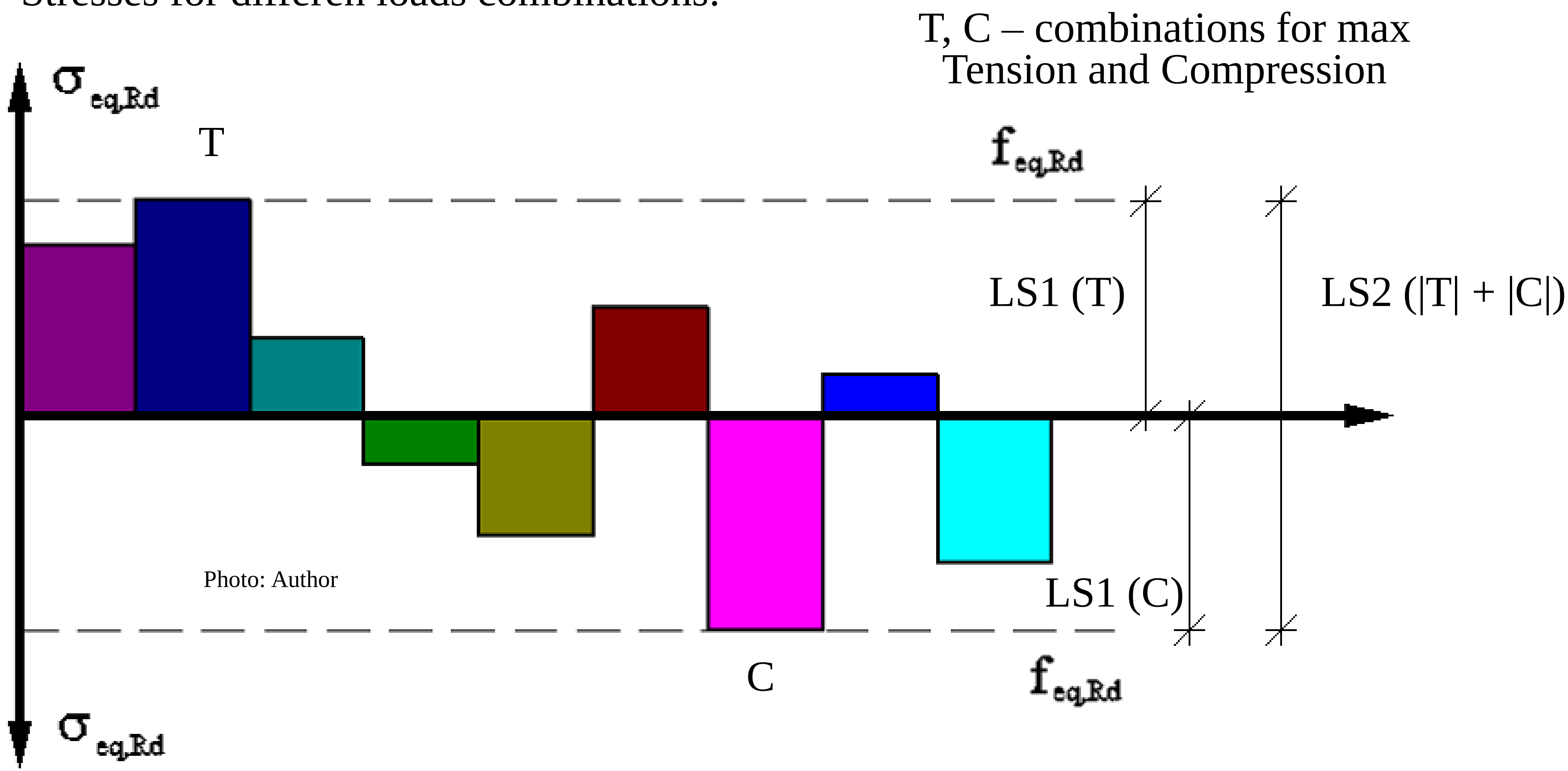
There are no analogical condition for bar member

Photo: Author



Analogy - a popular fun with paper clip

Stresses for differen loads combinations:



LS1 (T) = LS1 for combination T; equivalent stress not greated than f_y

LS1 (C) = LS1 for combination C; equivalent stress not greated than f_y

LS2 (|T| + |C|) = LS2 for range T-C; equivalent stress not greated than $2f_y$

<u>LS2 (|T| + |C|) = LS1 (T) + LS1 (C) or not?</u>

$$LS1(T): \sigma_{eq,Ed,T} = \sqrt{[\sigma_{1T}^2 + \sigma_{2T}^2 - \sigma_{1T}\sigma_{2T} + 3(\tau_{12T}^2 + \tau_{13T}^2 + \tau_{23T}^2)]} \leq f_{yd}$$

$$LS1(C): \sigma_{eq,Ed,C} = \sqrt{[\sigma_{1C}^2 + \sigma_{2C}^2 - \sigma_{1C}\sigma_{2C} + 3(\tau_{12C}^2 + \tau_{13C}^2 + \tau_{23C}^2)]} \leq f_{yd}$$

$$LS2: \Delta\sigma_{eq,Ed,i} = \sqrt{[\Delta\sigma_{1,i}^2 + \Delta\sigma_{2,i}^2 - \Delta\sigma_{1,i}\Delta\sigma_{2,i} + 3\Delta\tau_{12,i}^2]} \leq 2f_{yd}$$

$$\Delta\sigma_{a,i} = |\sigma_{ai,T}| + |\sigma_{ai,C}|$$

$$\Delta\tau_{ai} = |\tau_{ai,T}| + |\tau_{ai,C}|$$

$$[LS2(|C|+|T|)]^2 \leq 4f_{yd}^2$$

$$[LS2(|C|+|T|)]^2 = [LS1\ (T)]^2 + [LS1\ (C)]^2 +$$

$$+ 2(|\sigma_{1T}||\sigma_{1C}|) + 2(|\sigma_{2T}||\sigma_{2C}|) - |\sigma_{1T}||\sigma_{2C}| - |\sigma_{2T}||\sigma_{1C}| + 3\,(|\tau_{1T}||\tau_{1C}| + |\tau_{2T}||\tau_{2C}| + |\tau_{3T}||\tau_{3C}|\,) \leq$$

$$\leq f_{yd}^2 + f_{yd}^2 + 2f_{yd}^2$$

$$[LS2\ (T + C)]^2 = [LS1\ (T)]^2 + [LS1\ (C)]^2 + \Delta \leq f_{yd}^2 + f_{yd}^2 + 2f_{yd}^2$$

$$[LS2\ (T + C)]^2 = [LS1\ (T)]^2 + [LS1\ (C)]^2 + \Delta \leq f_{yd}^2 + f_{yd}^2 + 2f_{yd}^2$$

LS1 (T) could be **not** satisfied (> f_{yd}), but still LS2 could be **satisfied** (LS1 (C) and Δ small)

LS1 (C) could be **not** satisfied (> f_{yd}), but still LS2 could be **satisfied** (LS1 (T) and Δ small)

LS1 (T) and LS1 (C) could be **satisfied** ($\leq f_{yd}$), but LS2 could be **not** satisfied (Δ very big)

Condition for LS2 $\neq$ 2 · (condition for LS1):

$$LS2 = LS1_T + LS1_C \text{ +/- addition}$$

Buckling limit state LS3 (EN 1993-1-6   8)

Reminder: Metal Structures I; interaction lateral buckling and flexural buckling:

EN 1993-1-1 6.3.3

$$N_{Ed} / (\chi_i N_{Rd}) + k_{yi} M_{yEd} / (\chi_{LT} M_{yRd}) + k_{zi} M_{zEd} / M_{zRd} \leq 1{,}0 \quad {\scriptstyle i = y,\, z}$$

N_{Ed}, M_{yEd}, M_{zEd} – effects of loads

N_{Rd}, M_{yRd}, M_{zRd} – resistances

$\chi_{y,}$ $\chi_{z,}$ χ_{LT} - buckling factors; $\chi_{gh} = \chi_{gh}$ (slenderness, imperfections)

k_{yy}, k_{yz}, k_{yy}, k_{zz} - interaction factors; $k_{ij} = k_{ij} (\chi_{gh} R_{rd})_{,}$

EN 1993-1-6 8:

$$(\sigma_{x,Ed} / \sigma_{x,Rd})^{kx} - k_i (\sigma_{x,Ed} / \sigma_{x,Rd}) (\sigma_{\theta,Ed} / \sigma_{\theta,Rd}) + (\sigma_{\theta,Ed} / \sigma_{\theta,Rd})^{k\theta} + (t_{x\theta,Ed} / \tau_{x\theta,Rd})^{k\tau} \leq 1,0$$

$\sigma_{x,Ed}$, $\sigma_{\theta,Ed}$, $\tau_{xE,Rd}$ - effects of loads

$\sigma_{x,Rd}$, $\sigma_{\theta,Rd}$, $\tau_{x\theta,Rd}$ - resistances

χ_f - buckling factors; $\chi_f = \chi_f$ (slenderness, imperfections)

k_x, k_θ, k_τ, k_i - interaction factors; $k_f = k_f (\chi_f)_,$

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

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

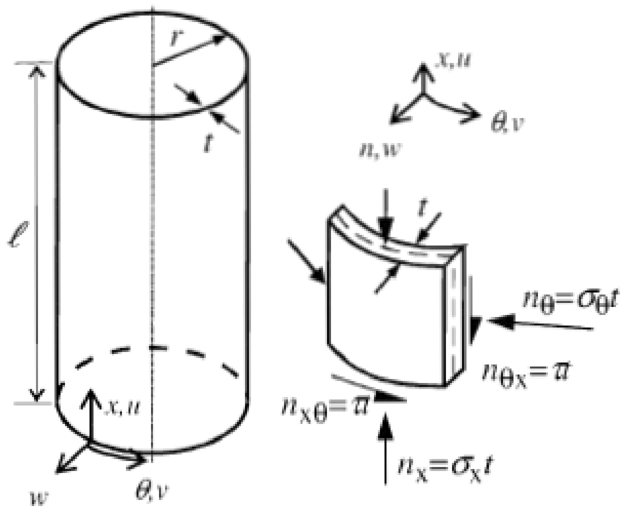
$$\tau_{x\theta,Rd} = \chi_\tau f_{yk} / (\gamma_{M1} \sqrt{3})$$

buckling factors, interaction factors → 1993-1-6, 8.5.2, 8.5.3, appendix D

Buckling factors χ_f are function of non-dimensional length of shell:

$$\omega = L / \sqrt{(r\,t)}$$

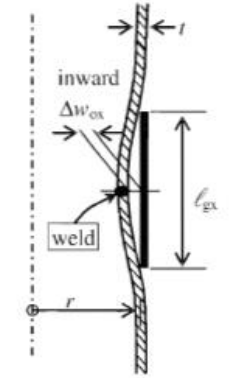
Photo: EN 1993-1-6 fig. D1



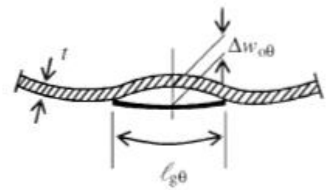
ω increasae → χ_f decrease → resistance decrease

Imperfections can be very important for LS3

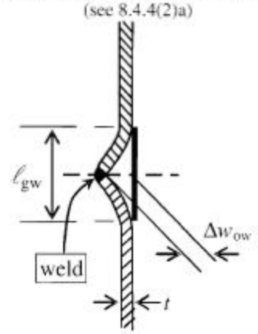
Photo: EN 1993-1-6 fig. 8.4



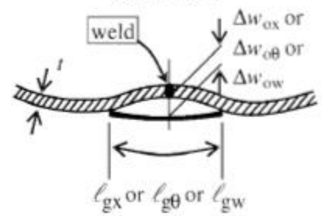
c) First measurement on a meridian across a weld (see 8.4.4(2)a)



d) Second measurement on circumferential circle (see 8.4.4(2)b)



e) Second measurement across a weld with special gauge (see 8.4.4(2)c)



f) Measurements on circumferential circle across weld (see 8.4.4(2)c)

LS3 for meridional and circunferential stresses; effect of imperfections.

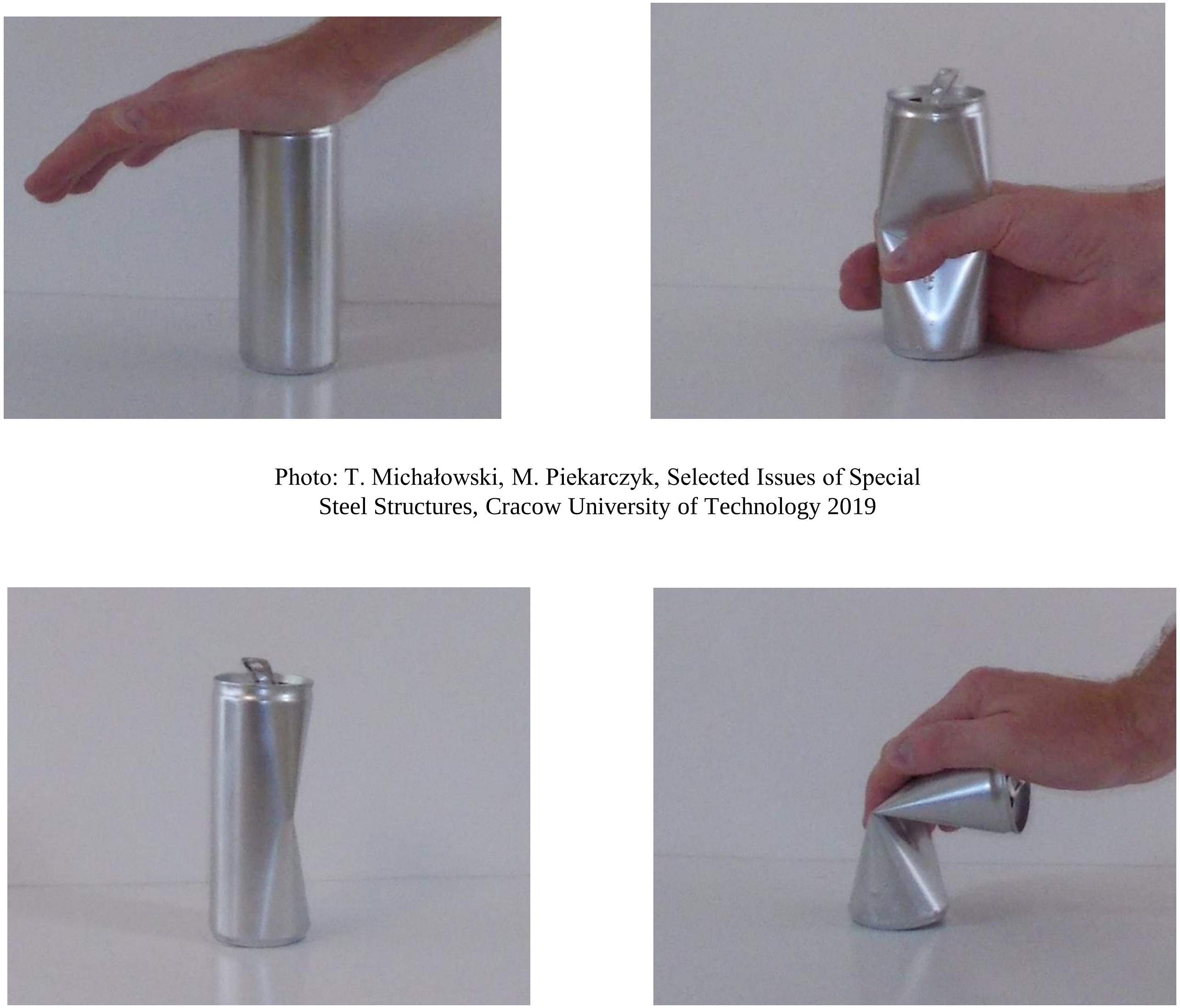


Photo: T. Michałowski, M. Piekarczyk, Selected Issues of Special Steel Structures, Cracow University of Technology 2019

l [m]	ω	Meridional critical resistance $\sigma_{x, Rd}$ [MPa]	Circumferential critical resistance $\sigma_{\theta, Rd}$ [MPa]	Shear critical resistance $\tau_{x\theta, Rd}$ [MPa]
10	48.795	178.726	19.797	68.354
7	31.157	181.067	28.282	76.980
4	19.518	183.213	49.493	89.056

Photo: T. Michałowski, M. Piekarczyk, Selected Issues of Special Steel Structures, Cracow University of Technology 2019

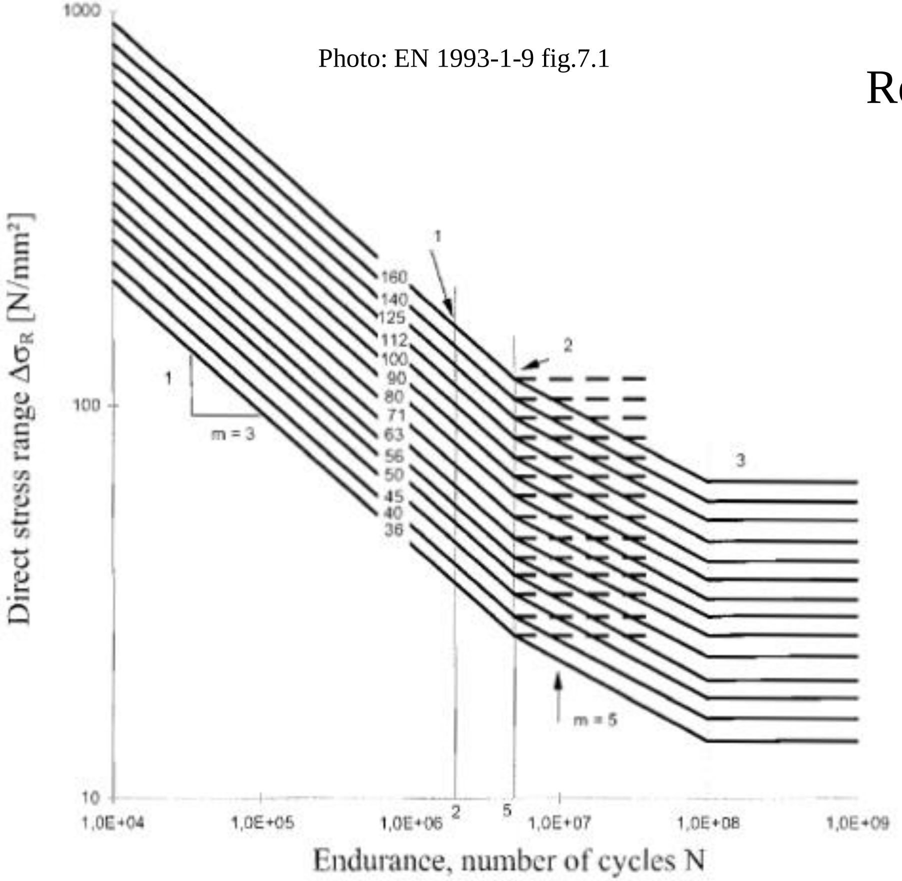
Quality level class	Meridional critical resistance $\sigma_{x, Rd}$ [MPa]	Circumferential critical resistance $\sigma_{\theta, Rd}$ [MPa]	Shear critical resistance $\tau_{x\theta, Rd}$ [MPa]
normal (C) → #t / 33	183.213	49.493	89.056
high (B) → #t / 33	188.803	64.341	95.857
excellent (A) → #t / 33	192.027	74.239	98.896

Fatigue limit state LS4 (EN 1993-1-6   9)

$$\gamma_{Ff}\,\Delta\sigma_E / (\Delta\sigma_R / \gamma_{Mf}) \leq 1,0$$
$$\gamma_{Ff}\,\Delta\tau_E / (\Delta\tau_R / \gamma_{Mf}) \leq 1,0$$

The same formulas are important for bar structures (for example - crane supporting structures)

Photo: EN 1993-1-9 fig.7.1



1 Detail category $\Delta\sigma_C$

2 Constant amplitude fatigue limit $\Delta\sigma_D$

3 Cut-off limit $\Delta\sigma_L$

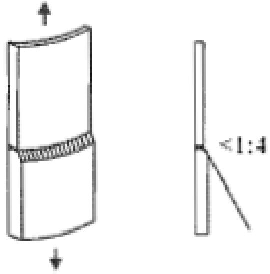
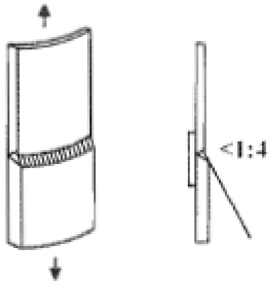
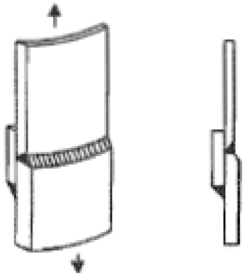
Resistance depends on number of cycles N_R

EN 1993-1-9 7.1 (2)

$$\Delta\sigma_R = \Delta\sigma_C \sqrt[m]{(2 \cdot 10^6 / N_R)}$$
$$\Delta\tau_R = \Delta\tau_C \sqrt[m]{(2 \cdot 10^6 / N_R)}$$

m = 3 for N_R = 10 000 - 5 000 000
m = 5 for N_R = 5 000 000 - 100 000 000
$\Delta\sigma_R$, $\Delta\tau_R$ are constant for N_R > 100 000 000

EN 1993-3-2 tab. C1 for shell members

EN 1993-1-9 Table 8.3 Detail 4 and 7	
EN 1993-1-9 Table 8.3 Detail 14	
EN 1993-1-9 Table 8.3 Detail 16 (<1:4)	

There is concentration of stress around each notches

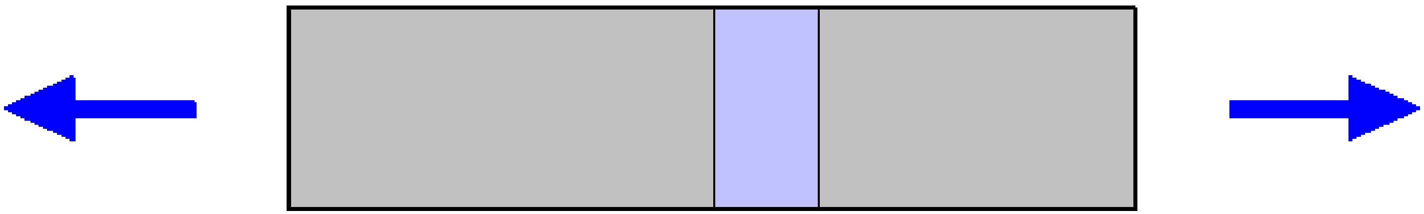
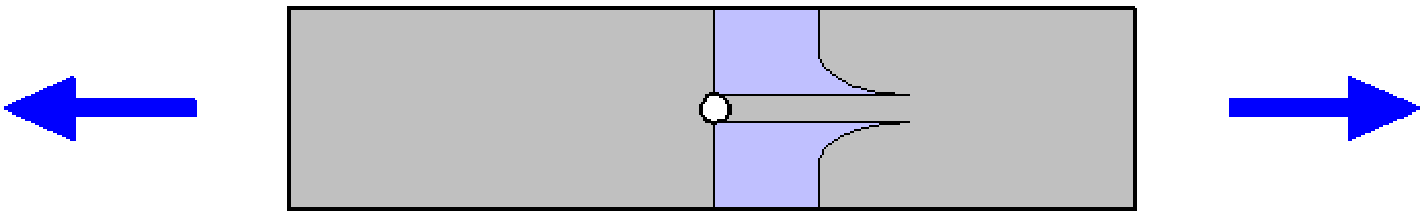


Photo: Author



$$\sigma_{Ed} \leq f_y \quad \text{but} \quad \mu\, \sigma_{Ed} \geq f_y$$

μ stress concentration factor

σ_{Ed} stress as for ideal cross-section

Big values of stresses at edges of notches can locally destruct material and increase diameter of notches.

During many cycles of loads, notches increase increase and ultimately can destroy member. Because of this, resistance for LS4 decreases when number of cycles increases.

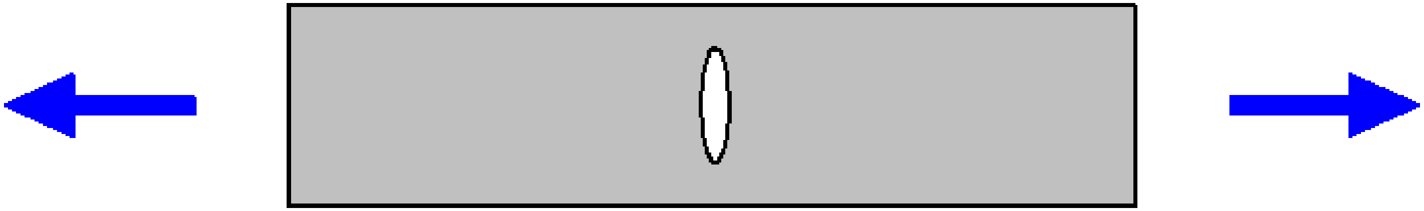


Photo: Author

We make calculations as for ideal cross-sections:

$$\mu \, \sigma_{Ed} \leq f_y$$

$$\sigma_{Ed} \leq f_y / \mu$$

$$\Delta\sigma_E \leq \Delta\sigma_R / (\gamma_{Mf} \, \gamma_{Ff})$$

$$\gamma_{Ff} \, \Delta\sigma_E / (\Delta\sigma_R / \gamma_{Mf}) \leq 1{,}0$$

For LS4 we take into consideration characteristic value of loads

LS2 - calculation for low number of cycles (< 10 000); destruction depends on strength of material;

LS4 - calculation for high number of cycles (> 10 000); destruction depend on fatigue resistance, not strength of material;

50 years = 18 263 days.

Chimneys – thousands impulses from wind excitation per day → many milions cycles per 50 years

Tanks, silos – in case of **enormous intensive** exploitation, few cycles full-empty per day → 18 000 ≤ number of cycles ≤ 100 000 per 50 years
In normal condition, one cycle per few days → number of cycles < 10 000 per 50 years

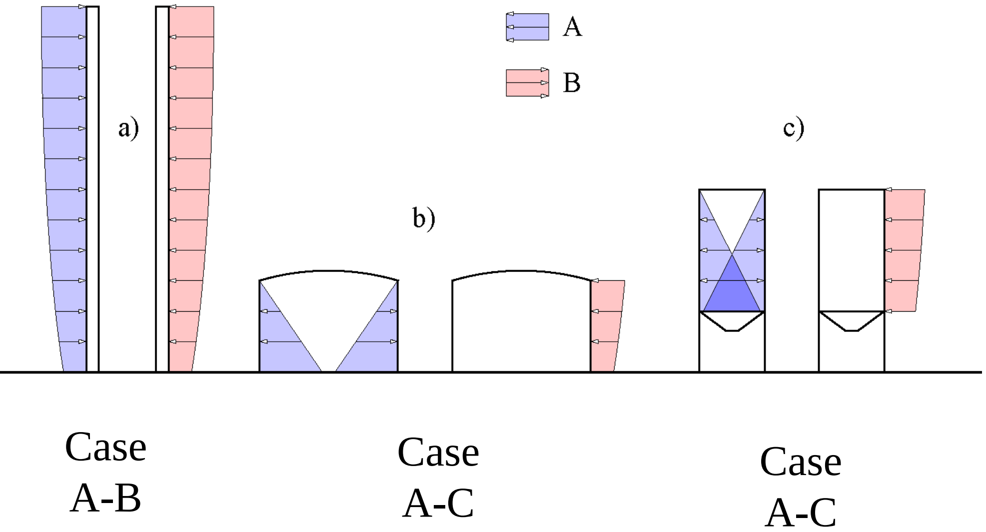
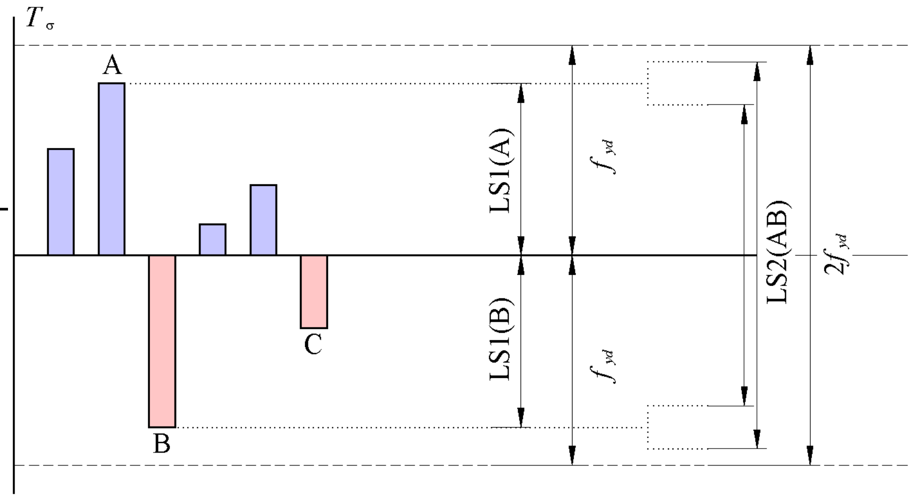


Photo: Author



	LS1	LS2	LS3	LS4
chimney	important	important	important	important
tank	important	can be neglected	important	can be neglected
silo	important	can be neglected	important	can be neglected

Global stability

EN 1993-4-2 11.5

Tank can't be lifted up, pushed, rotated. Wind action and overpressure must be smaller than dead weight of tank. There is important position of wind action on cylinder (y) and dome (x). This is EQU LS.

W - wind pressure on cylindrical shell

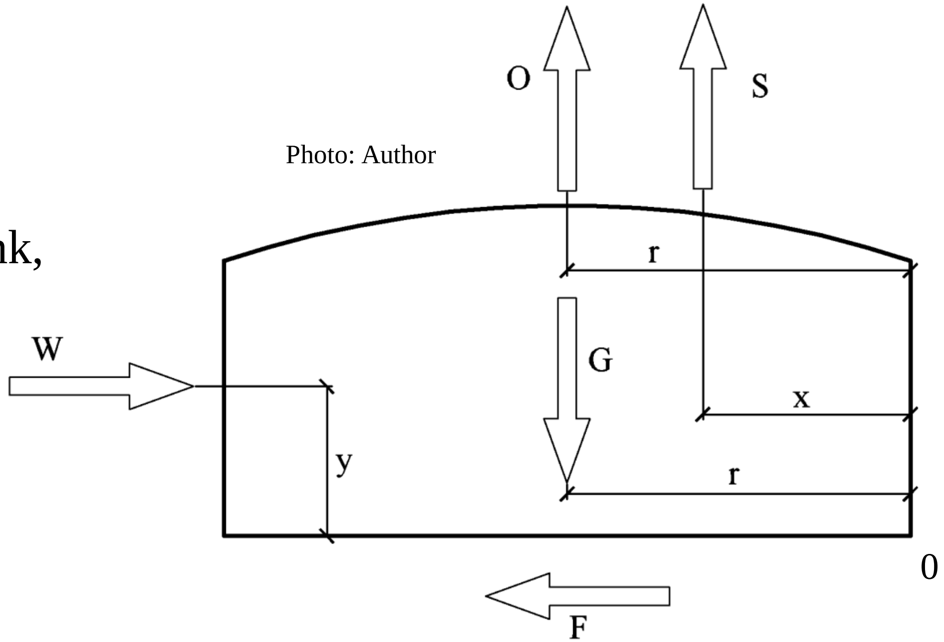
S - wind suction on dome roof

G_k - dead weight of steel structure (empty tank, characteristic value)

O - overpressure

F_k - friction (characteristic value)

Photo: Author



Requirements for global stability:

No lifting up: $O + S < 0{,}9\ G_k$

No pushing: $W < 0{,}9\ F_k$

No rotation around point 0: $W\ y + S\ x + O\ r < 0{,}9\ G_k\ r$

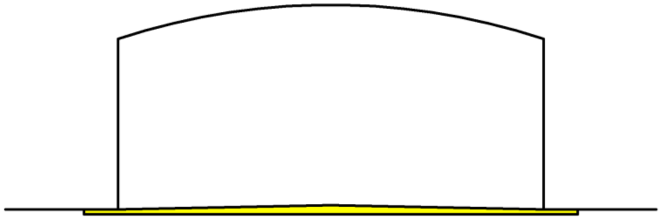
$O = \pi\ r^2\ p_{over}$

$F_k = (G_k - S - O)\ \mu$

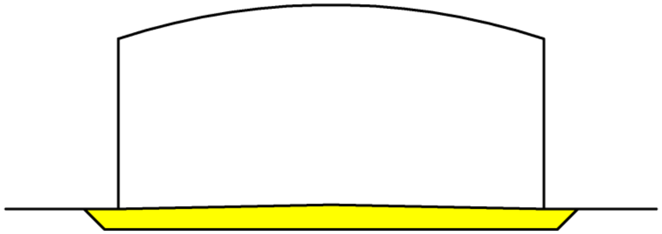
$\mu = 0{,}3$

Foundations - ground conditions

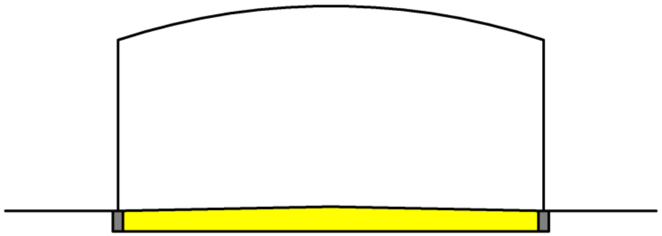
Photo: Author



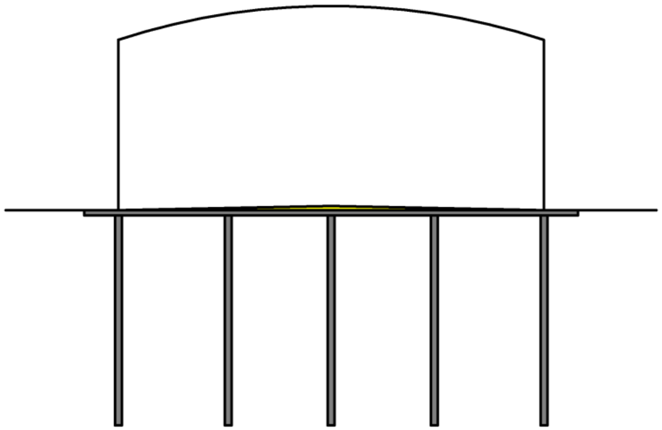
Very good (cohesionless bearing); sand bed to a depth of humus (about 30 cm)



Good (cohesive bearing); sand bed to a depth of frost penetration (about 120 cm)



Bad (cohesive non-bearing or cohesionless non-bearing); reinforced concrete ring under the shell + sand bed to a depth of frost penetration (about 120 cm)



Very bad (peat, made ground) sand bed, reinforced concrete slab, piles

Ground conditions	Foundations	
	Conditions for global stability satisfied	Conditions for global stability not satisfied
Very good	Sand bed ~ 30 cm	Concrete ring
Good	Sand bed ~ 120 cm	
Bad	Concrete ring	
Very bad	Concrete slab and piles	

Serviceability limit state

EN 1993-4-2 2.9.3, 9.4

2.9.3 Serviceability limit states

(1) Where simplified compliance rules are given in the relevant provisions dealing with serviceability limit states, detailed calculations using combinations of actions need not be carried out.

(2) For all serviceability limit states the values of γ_{Mser} should be specified.

NOTE: The National Annex may provide information on the value for the partial factor for serviceability γ_{Mser}. $\gamma_{Mser} = 1$ is recommended.

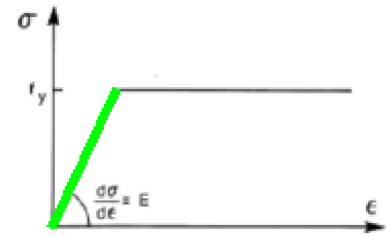
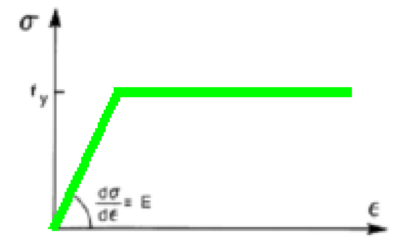
9.4 Serviceability limit states

(1) The serviceability limit states for walls of rectangular steel tanks should be taken as follows:

- deformations or deflections which adversely affect the effective use of the structure
- deformations, deflections and vibrations which cause damage to non-structural elements.

(2) Deformations, deflections and vibrations should be limited to meet the above criteria.

(3) Specific limiting values, appropriate to the intended use, should be agreed between the designer, the client and the relevant authority, taking account of the intended use and the nature of the liquids to be stored.

Analysis	Class of corss-section	Stress-strain relationship
Elastic	I, II, III, IV	
Plastic	I	

There are two types of analysis for bar structures - elastic and plastic.

There are seven types of analysis for shell structures (i.e. seven types of FEM analysis are acceptable).

Types of analysis	deformations	$\sigma \leftrightarrow \varepsilon$	imperfections
Linear elastic shell Analysis (LA)	Small	Linear	No
Linear elastic Bifurcation Analysis (LBA)	Small	Linear	No
Geometrically Nonlinear elastic Analysis (GNA)	Large	Linear	No
Materially Nonlinear Analysis (MNA)	Small	Nonlinear	No
Geometrically and Materially Nonlinear Analysis (GMNA)	Large	Nonlinear	No
Geometrically Nonlinear elastic Analysis with Imperfections included (GNIA)	Large	Linear	Yes
Geometrically and Materially Nonlinear Analysis with Imperfections included (GMNIA)	Large	Nonlinear	Yes

+ acceptable

(+) conditionally acceptable

Types of analysis	LS1	LS2	LS3	LS4
LA	+	+	+	+
LBA			+	
GNA		+	(+)	+
MNA	+	+	+	
GMNA	+	+	(+)	
GNIA			(+)	
GMNIA			+	

Ist order calculations (geometrically linear analysis, range of small deformations): only initial geometry of structure is taken into account (initial stiffness matrix)

IInd order calculations (geometrically nonlinear analysis, P-Δ analysis, range of large deformations): change in geometry of structure under influence of load makes additional cross-sectional forces ("moments on eccentricities" are taken into account; loads are applied gradually and after each step stiffness matrix is recalculated from attention to structure deformations)

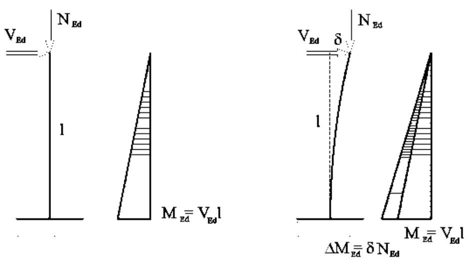
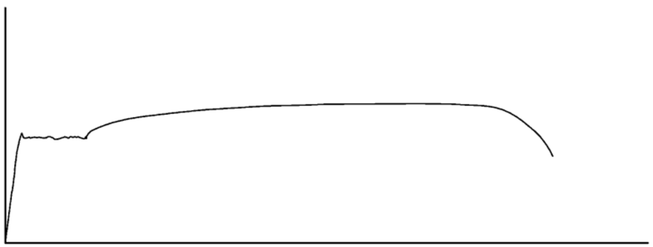


Photo: Autor

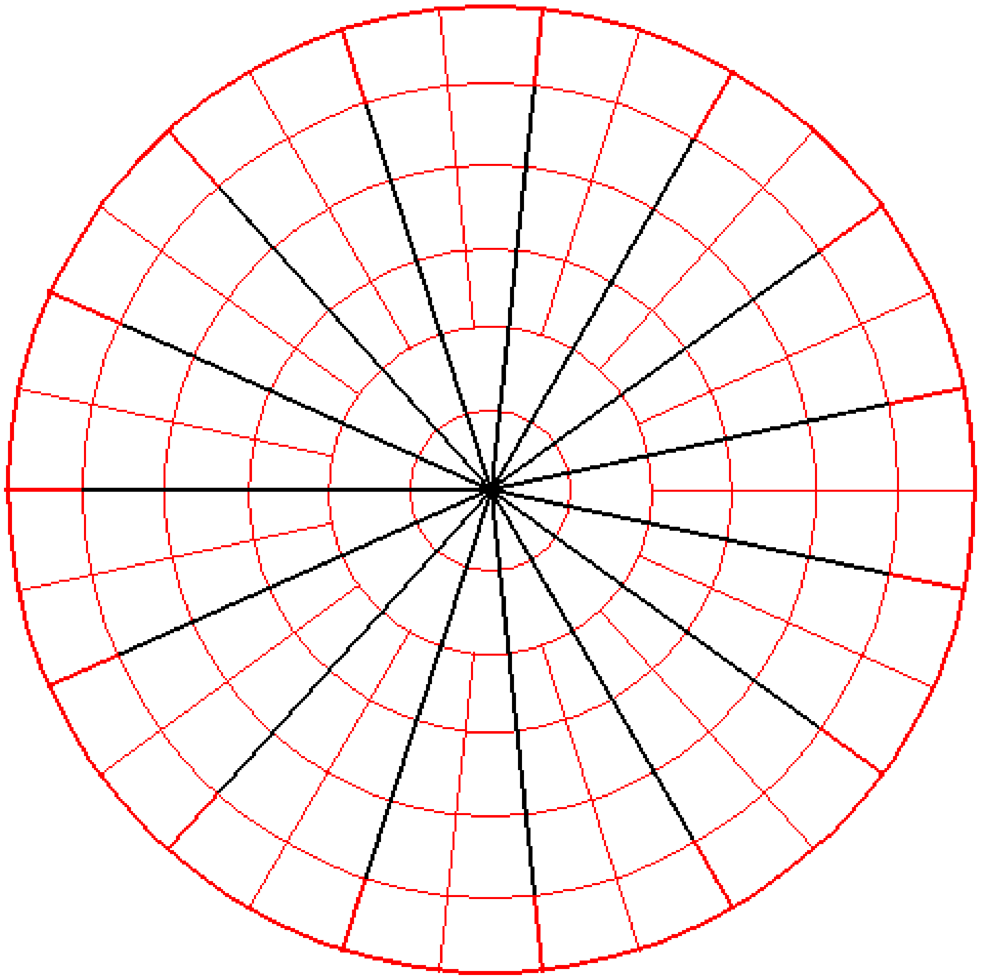


Material-linear analysis (physically linear analysis, elastic analysis): material model taking into account only linear-elastic range $\sigma = E\,\varepsilon$

Material nonlinear analysis (physically nonlinear analysis, plastic analysis): material model that takes into account: linear-elastic range and nonlinear part (**usually only plastic shelf**; in case of advanced calculations also material strengthening, cracking, rheology, change of parameters in weld compared to native material, cooperation in case of combining different materials...).

Technical rules for forming of steel cylindrical tanks

Photo: Author



Plates of roof shell are welded each other, but not to rafters (and purlins, if exist). Olny outer ring of plates is welded to edge ring and rafters.

There is contact and cooperation between plates and rafters for snow load, underpressure and wind presure.

There is nearly no contact between rafters and plates for overpressure and wind suction. Because of this, in case of a sudden increase in the pressure plate they are easily damaged and the rest of the structure is not affected.

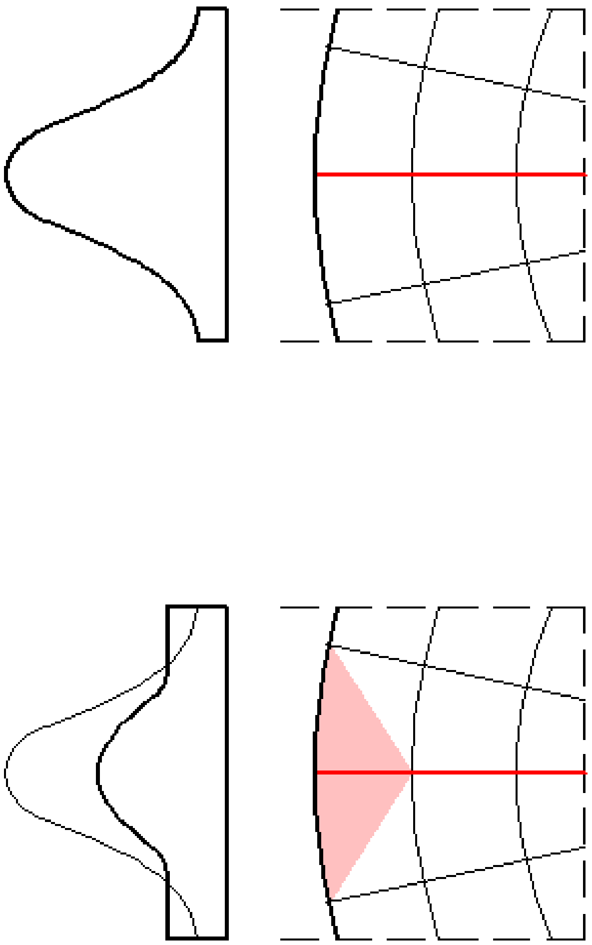


Photo: Author

There are cooperation between roof and raftres for axial forse in rafters because of welds between outer ring of plates and rafters. The effect are smaller and smoother values of stresses in edge ring.

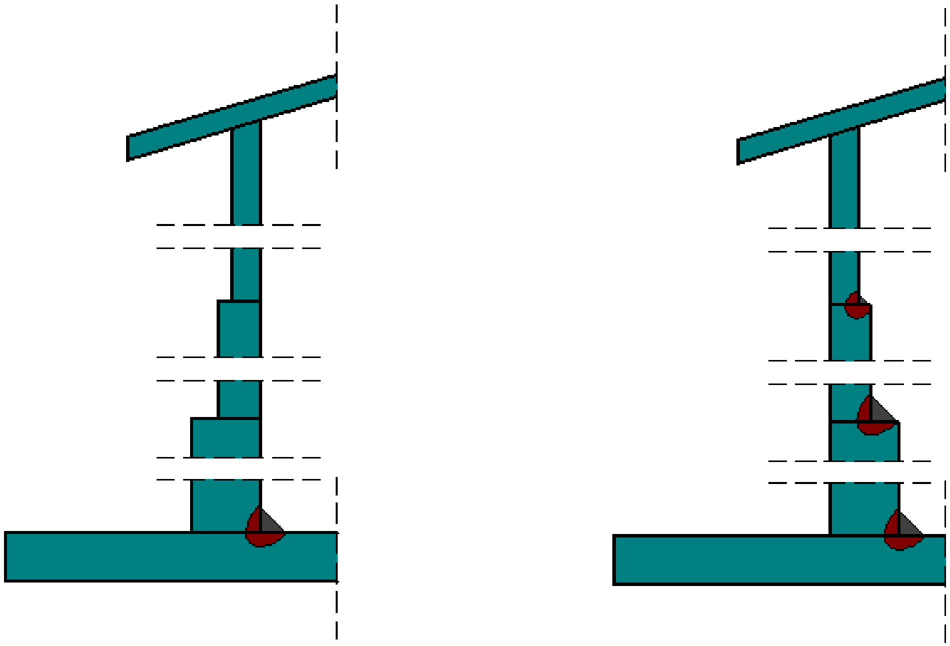
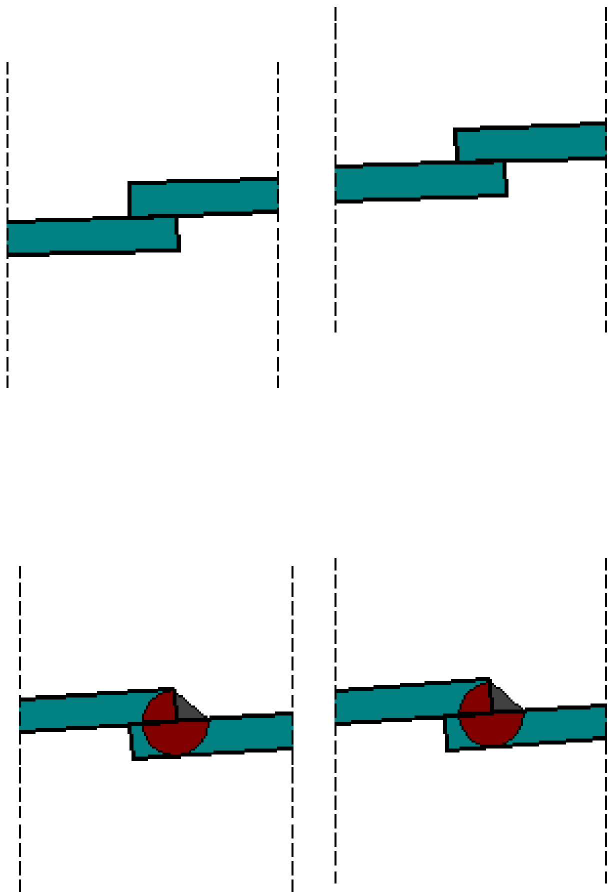


Photo: Author

Internal surface of cylinder should be smooth. It prevents from deposition of pollutants on edges. Sometimes there are sulfides in pollutions, cause corrosion. It is especially dangerous for top part of cylinder, for thin plates.

Photo: Author



Because of the same reason, internal rings of bottom plates should be over external rings.

Additional phenomenons

Grade and subgrade of steel

S 235 RJ

S 235 - steel, f_y = 235 MPa

RJ - type of impact resistance

Impact resistance = the ability of a material to absorb energy and plastically deform without fracturing.

Impact resistance is tested by Charpy hammer.

There is big risk of destruction steel structure in very low temperature under impact, even if force is very small.

Photo: journalism.columbia.edu

Photo: acellent.com

There are special subgrades of steel for structures, operated in low temperatures.

Corrosion - aggresive chemical compounds in liquids or gases in tanks, chimneys and pipelines

Erosion - grinding by solid materials in silos

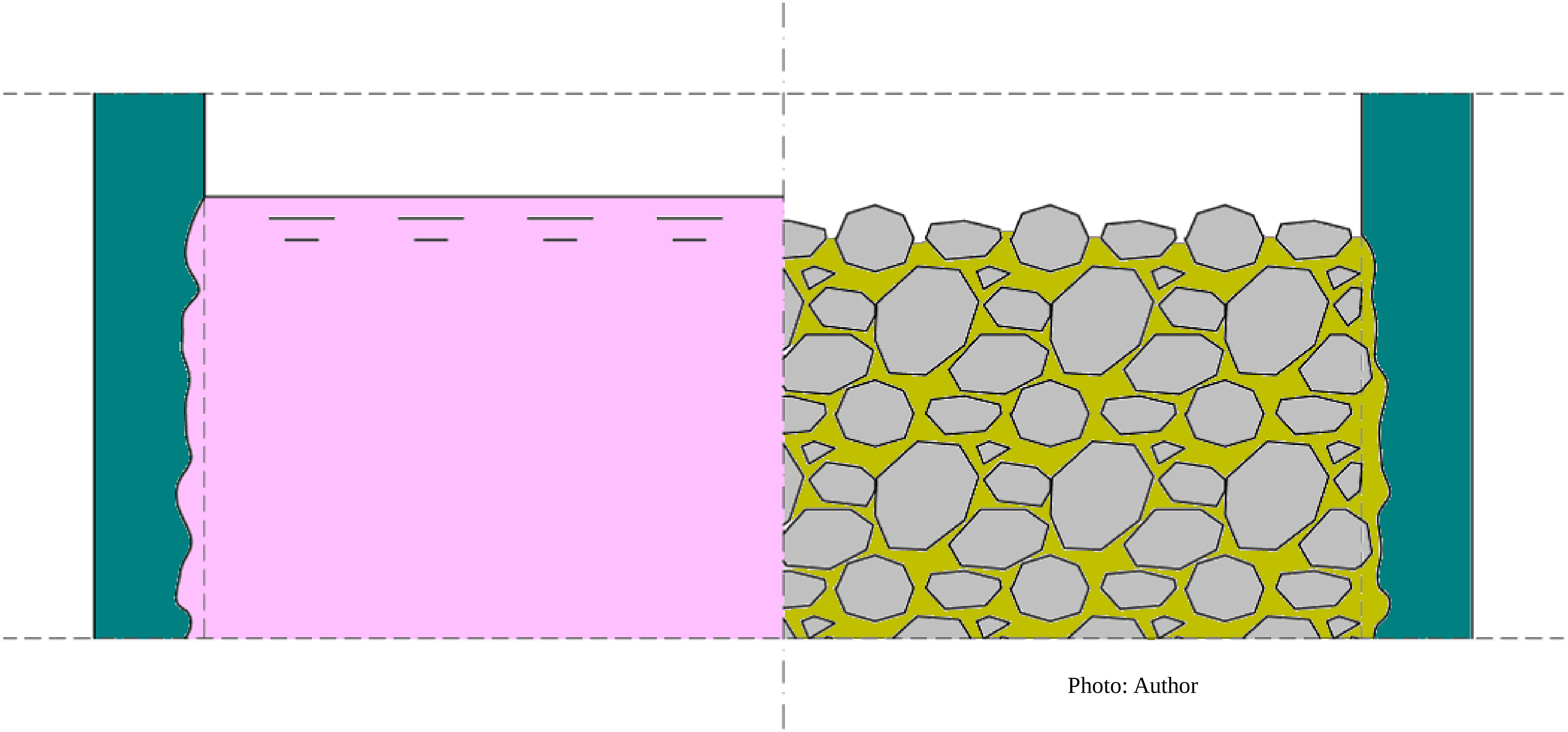


Photo: Author

$$X\ [mm\ /\ year] \cdot Y\ [years] = XY\ [mm]$$

Examination issues

Importance of consequences classes for design of tanks

Relationship height-thickness of shell of tanks

Limit states for takns

Types of analysis for tanks

Materially linear and nonlinear analysis – similiarites and differences

Geometrically linear and nonlinear analysis – similiarites and differences

Plastic limit state - zniszczenie plastyczne

Cyclic plasticity limit state - nieprzystosowanie plastyczne

Buckling limit state - niestateczność

Fatigue limit state – zmęczenie

Catch basin - basen awaryjny

Roof planting - poszycie dachu

Rafter - krokiew

Bracing - stężenie

Central ring - pierścień zwornikowy

Nozzle - króciec

Man hole - właz

Thank you for attention

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