

Structural design calculation

Object:	MC-Blending Silo Emmen D=4200mm Vn=290m ³ PET 8,2	Silo type:	Weld Tec MC
		Silo diameter:	4.200 m
Design-Capacity:	290.00 m ³	Bulk material:	PET
Customer:	Morssinkhof Plastics Heerenveen BV Frankrijkdreef 5 NL-8447 SH Heerenveen		
Installation location:	Emmen Netherlands		
Manufacturer:	Zepelin Systems GmbH Graf-Zepelin-Platz 1 D-88045 Friedrichshafen	Telephone:	07541-202-02
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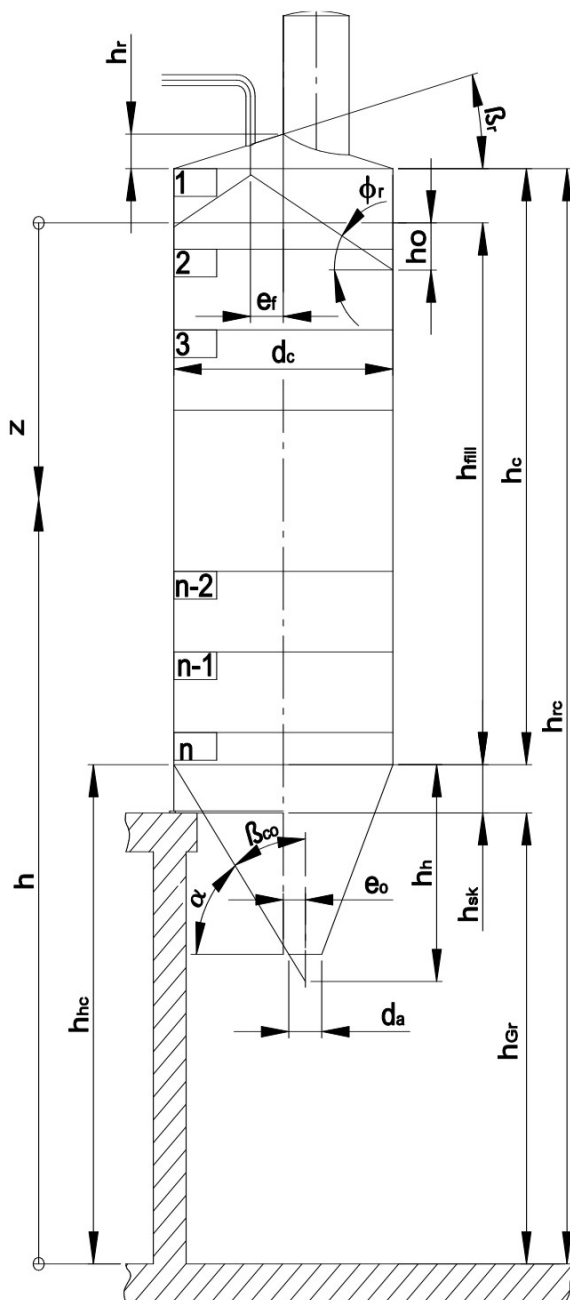
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1 Geometry / Materials

In the following Chapters, there will be an overview of the geometry of the silo.

All pictures are example drafts. The general drawing of the silo is representative.

1.1 Overview of silo



Silo diameter d_c	4.200 m
Roof type	Toriconical roof
Roof slope β_r	15.00°
Number of cylindrical sections	9
Height of cone h_{co}	4.24 m
Number of conical sections	3
Apex angle of cone	50.00 °
Skirt height $h_{sk} = h_{sktot} + t_b$	0.530 m
Number of skirt sections	1
Anchoring type	Continuous - Direct - Steel
Height of support structure – anchoring level h_{Gr}	10.000 m
Cylindrical filling height h_{fill}	19.43 m
Filling volume of silo V_{fill}^1	290.00 m ³
Bulk material	PET
Cylindrical total height h_c	20.750 m
Cylindrical total silo height $h_{ctot} = h_c + h_{sktot} + t_b$	21.280 m
Minium distance between silos - Minium distance from building A	0.6 m
Total dead weight	85.59 kN
Filling eccentricity e_f	392 mm
Discharge eccentricity e_o	0 mm

¹ Cylindrical volume including cone volume up to planed bulk material filling height

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1.1.1 Classification of silo

Action assessment class according to EN 1991-4, table 2.1:

Capacity: 242.49 to

- ⇒ Requirement class 2
- ⇒ Slenderness grade of silo according to EN 1991-1-4: Slender
- ⇒ Steep grade of cone: Steep
- ⇒ Tolerance Class 3
- ⇒ Consequences class 2

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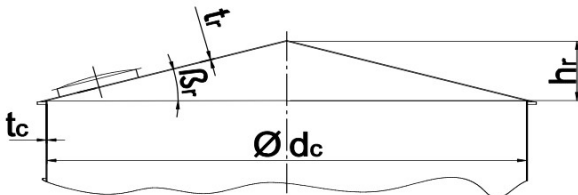


1.2 Code overview

Roof	EN 1999-1-5
Cylinder	EN 1999-1-5
Skirt	EN 1999-1-5
Cone	EN 1999-1-5
Anchoring	EN 1993-4-1
Bulk material	EN 1991-4
Windload	EN 1991-1-4

1.3 Roof

Toriconical roof:



Roof slope β_r	15.00°
Wall thickness t_r	6 mm
Shell material	EN-AW 5454 (SH/ST/PL)
Cross section of roof edge A_{re}	0.00 mm ²
Edge material	EN-AW 5454 (SH/ST/PL)
Knuckle radius of roof edge r_T	30 mm
Live load p_L	1.00 kN/m ²
Snow load p_s	0.70 kN/m ²

1.3.1 Filter

Dead weight of Filter G_F	2.00 kN
Diameter of Filters d_F	0.7 m
Filter height h_F	2 m
Height of filter flange over roof edge h_{Fre}	0.5 m
Shape coefficient of filter c_{wF}	1.20

1.3.2 Ladder and Railing

Dead weight of ladder G_L	2.50 kN
Dead weight of railing G_R	0.80 kN
Horizontal projection length of railing l_{hR}	4.7 m
Height of lower edge of railing over roof edge h_R	0 m
Shape coefficient of railing c_{wR}	1.40
Dead weight of additional attachments G_{add}	2.00 kN

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1.4 Cylinder

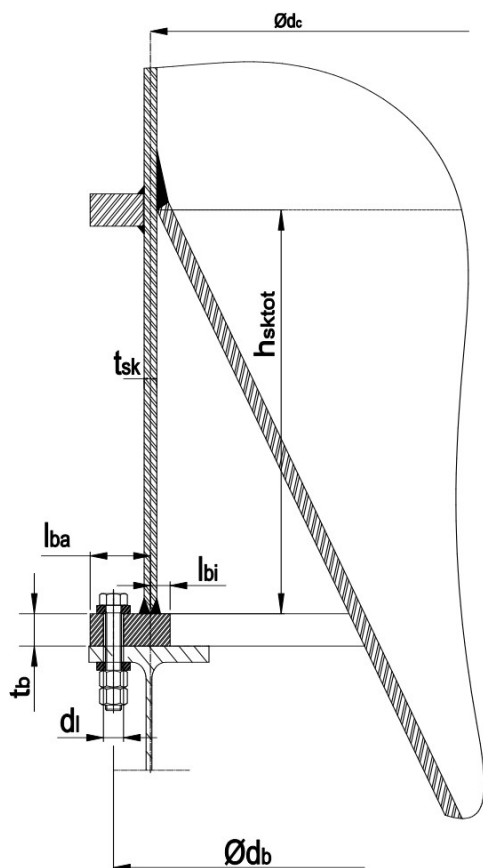
Silo diameter d_c	4.200 m
Number of cylindrical sections	9
Total cylindrical volume V_c	287.48 m ³
Cylindrical height h_c	20.75 m
Cylindrical filling height h_{fill}	19.43 m
Filling volume of cylinder (according to the filling height) V_{cfill}	269.21 m ³

Sections (Cylinder):

Nr.	Section height h_{c_sec} [mm]	Wall thickness t_c [mm]	Material
1	2500	5	EN-AW 5454 (SH/ST/PL)
2	2500	5	EN-AW 5454 (SH/ST/PL)
3	2500	5	EN-AW 5454 (SH/ST/PL)
4	2500	5.5	EN-AW 5454 (SH/ST/PL)
5	2500	6	EN-AW 5083 (SH/ST/PL)
6	2500	7	EN-AW 5083 (SH/ST/PL)
7	2500	8	EN-AW 5083 (SH/ST/PL)
8	2500	9	EN-AW 5083 (SH/ST/PL)
9	750	10	EN-AW 5083 (SH/ST/PL)

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1.5 Skirt

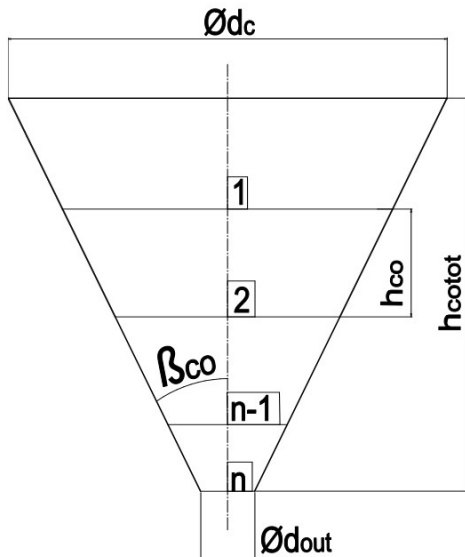


Number of skirt sections	1
Skirt height h_{sktot}	0.5 m
Base ring thickness t_b	30 mm
Total skirt height $h_{sktot} + t_b$	0.530 m

Sections (Skirt):

Nr.	Section height h_{sk_sec} [mm]	Wall thickness t_{sk} [mm]	Material
1	500	10	EN-AW 5083 (SH/ST/PL)

1.6 Cone



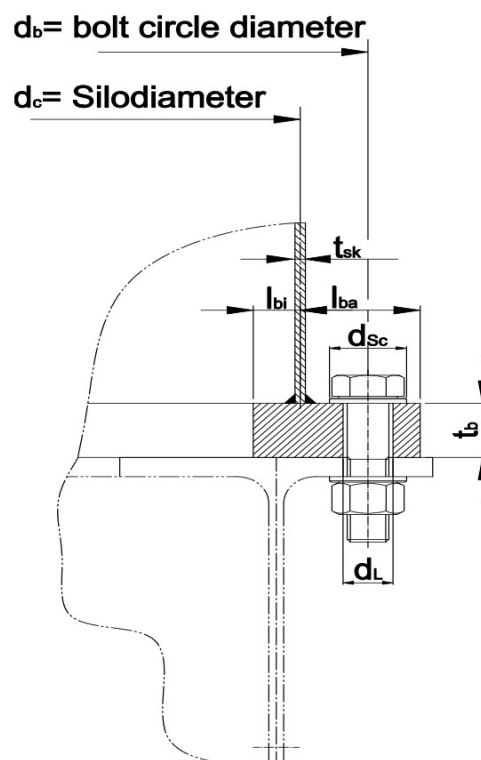
Half apex angle of cone β_{co}	25.00 °
Apex angle of cone	50.00 °
Outlet diameter d_{out}	0.25 m
Total cone height h_{cotot}	4.24 m
Total cone volume V_{cotot}	20.79 m ³
Width of stiffening ring b_j	0 mm
Height of stiffening ring h_j	0 mm
Material of reinforcing ring	EN-AW 5083 (SH/ST/PL)

Sections:

Nr	Section height h_{co} [mm]	Wall thickness t_{co} [mm]	Lower diameter d_{lco} [mm]	Material
1	1930.06	10	2400	EN-AW 5083 (SH/ST/PL)
2	1286.7	6	1200	EN-AW 5454 (SH/ST/PL)
3	1018.64	4	250	EN-AW 5454 (SH/ST/PL)

1.7 Anchoring

Support of silo continual on steel support with direct anchoring



Number of anchor bolts n_{An}	24
Height of anchoring level h_{Gr}	10.000 m
Calculation method	Zeppelin standard
Anchor circle diameter d_b	4120 mm
Post tension of anchor ($\geq 10\%$ of anchor tensile force) f_v	30.00 N/mm ²
Bolting torque M_A^2	43.22 Nm
Diameter of anchor bolt holes d_L	26 mm

Anchor properties

Anchor size	M20
Strength class of anchor	Resistance class 8.8
Yield strength of anchor bolts f_{yb}	640.00 N/mm ²
Number of anchor bolts n_{An}	24

² Min. required tightening torque to obtain the given pre stress: Torque has to be done by a calibrated torque wrench and a slightly greased bolt; Calculation according to the simplified procedure in Rolof/ Matek Gl. 8.22

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Base ring

Base ring thickness t_b	30 mm
Base ring width	100 mm
Width inside of anchor circle diameter l_{bi}	70 mm
Width outside of anchor circle diameter l_{ba}	30 mm
Base ring material	EN-AW 6082 (ET/EP/ER)

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2 Materials

EN-AW 5454 (SH/ST/PL):

Alloy information:

Description	AlMg3Mn
Alloy condition	O/H111
Alloy product form	SH/ST/PL
Youngs modulus E	70000.00 N/mm ²
Thrust modulus	27000.00 N/mm ²
Lateral strain	0.30
Yield strength f_{oc}	85.00 N/mm ²
Ultimate tensile strength f_{uc}	215.00 N/mm ²
Characteristic strength of weld material f_{wc}	220.00 N/mm ²

Partial safety coefficients:

Partial safety coefficient for material (resistance to yielding) γ_{M1}	1.10
Partial safety coefficient for material (resistance to fracture) γ_{M2}	1.25
Partial safety coefficient for weld seams γ_{Mw}	1.25

Allowable stresses:

Yield strength f_o	Allowable stress base material f_{od}	Allowable stress HAZ f_{hazd}	Allowable stress weld seam f_{wd}	Allowable stress f_{Rd} Min (f_{od}, f_{hazd}, f_{wd})
[N/mm ²]	[N/mm ²]	[N/mm ²]	[N/mm ²]	[N/mm ²]
85.00	77.27	77.27	176.00	77.27

Calculation information:

Bending class	C
HAZ-factor of yield strength p_{ohaz}	1.00
HAZ-factor of ultimate tensile strength p_{uhaz}	1.00
Max thickness	80 mm
Tolerance class	3
Calculation temperature T_B	50.00 °
Density of material	2700.00 kg/m ³

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EN-AW 5083 (SH/ST/PL):

Alloy information:

Description	AlMg4,5Mn
Alloy condition	O/H111
Alloy product form	SH/ST/PL
Youngs modulus E	70000.00 N/mm ²
Thrust modulus	27000.00 N/mm ²
Lateral strain	0.30
Yield strength f_{oc}	125.00 N/mm ²
Ultimate tensile strength f_{uc}	275.00 N/mm ²
Characteristic strength of weld material f_{wc}	240.00 N/mm ²

Partial safety coefficients:

Partial safety coefficient for material (resistance to yielding) γ_{M1}	1.10
Partial safety coefficient for material (resistance to fracture) γ_{M2}	1.25
Partial safety coefficient for weld seams γ_{Mw}	1.25

Allowable stresses:

Yield strength f_o	Allowable stress base material f_{od}	Allowable stress HAZ f_{hazd}	Allowable stress weld seam f_{wd}	Allowable stress f_{Rd} Min (f_{od}, f_{hazd}, f_{wd})
[N/mm ²]	[N/mm ²]	[N/mm ²]	[N/mm ²]	[N/mm ²]
125.00	113.64	113.64	192.00	113.64

Calculation information:

Bending class	C
HAZ-factor of yield strength p_{ohaz}	1.00
HAZ-factor of ultimate tensile strength p_{uhaz}	1.00
Max thickness	50 mm
Tolerance class	3
Calculation temperature T_B	50.00 °
Density of material	2700.00 kg/m ³

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EN-AW 6082 (ET/EP/ER):

Alloy information:

Description	AlSi1MgMn
Alloy condition	T6
Alloy product form	ET/EP/ER
Youngs modulus E	70000.00 N/mm ²
Thrust modulus	27000.00 N/mm ²
Lateral strain	0.30
Yield strength f_{oc}	260.00 N/mm ²
Ultimate tensile strength f_{uc}	310.00 N/mm ²
Characteristic strength of weld material f_{wc}	210.00 N/mm ²

Partial safety coefficients:

Partial safety coefficient for material (resistance to yielding) γ_{M1}	1.10
Partial safety coefficient for material (resistance to fracture) γ_{M2}	1.25
Partial safety coefficient for weld seams γ_{Mw}	1.25

Allowable stresses:

Yield strength f_o	Allowable stress base material f_{od}	Allowable stress HAZ f_{hazd}	Allowable stress weld seam f_{wd}	Allowable stress f_{Rd} Min (f_{od}, f_{hazd}, f_{wd})
[N/mm ²]	[N/mm ²]	[N/mm ²]	[N/mm ²]	[N/mm ²]
260.00	236.36	113.45	168.00	113.45

Calculation information:

Bending class	A
HAZ-factor of yield strength p_{ohaz}	0.48
HAZ-factor of ultimate tensile strength p_{uhaz}	0.60
Max thickness	150 mm
Tolerance class	3
Calculation temperature T_B	50.00 °
Density of material	2700.00 kg/m ³

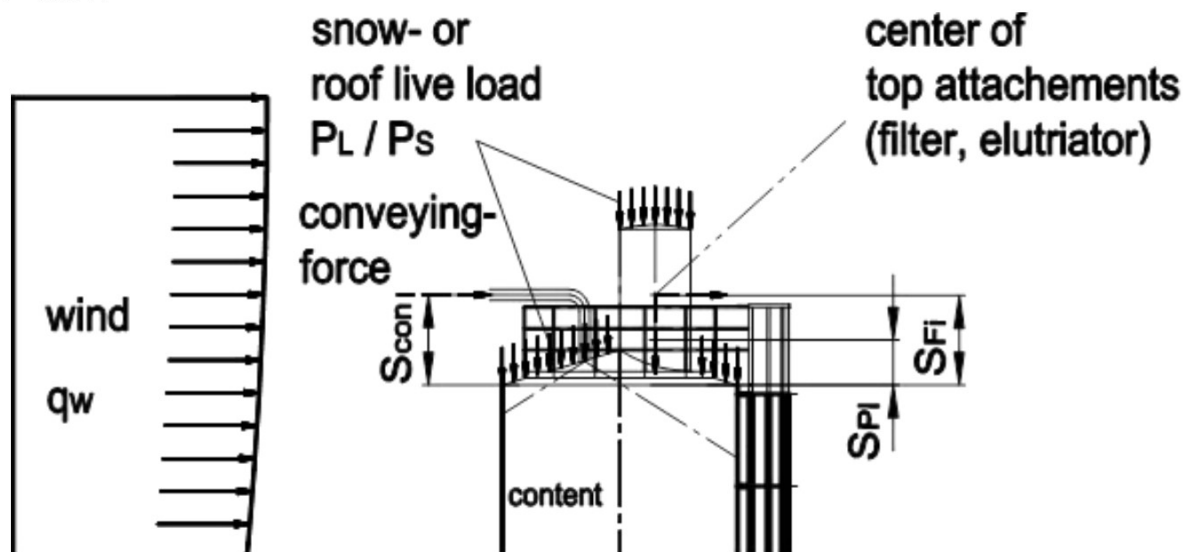
3 Assumed loads

3.1 Preliminary note

In the following paragraphs, the assumed loads for the structural design calculation of the silo will be listed.

3.2 Dead load

3.2.1 Roof



Dead weight of roof G_k	2.28 kN
Dead weight of filter G_F	2.00 kN
Dead weight of ladder G_L	2.50 kN
Dead weight of railing G_R	0.80 kN
Dead weight of additional attachments G_{add}	2.00 kN
Dead weight of reinforcing ring at roof junction	0.00 kN
Σ Total	9.58 kN

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3.2.2 Cylinder

Section	Material	Wall thickness t_c	Section height h_c	Dead load G_1	Dead load flange G_{bfl}	Additional dead load ³ G_2	ΣG
		[mm]	[mm]	[kN]	[kN]	[kN]	[kN]
1	EN-AW 5454 (SH/ST/PL)	5	2500	4.37	0.00	1.50	5.87
2	EN-AW 5454 (SH/ST/PL)	5	2500	4.37	0.00	1.50	11.73
3	EN-AW 5454 (SH/ST/PL)	5	2500	4.37	0.00	1.50	17.60
4	EN-AW 5454 (SH/ST/PL)	5.5	2500	4.80	0.00	1.50	23.91
5	EN-AW 5083 (SH/ST/PL)	6	2500	5.24	0.00	1.50	30.65
6	EN-AW 5083 (SH/ST/PL)	7	2500	6.11	0.00	1.50	38.26
7	EN-AW 5083 (SH/ST/PL)	8	2500	6.99	0.00	1.50	46.75
8	EN-AW 5083 (SH/ST/PL)	9	2500	7.86	0.00	1.50	56.11
9	EN-AW 5083 (SH/ST/PL)	10	750	2.62	0.00	0.60	59.33
Σ Total dead load of cylinder				46.73	0.00	12.60	59.33

3.2.3 Skirt

Section	Material	Wall thickness t_s	Section height h_s	Dead load G_1	Dead load flange G_{bfl}	Additional dead load G_2	ΣG
		[mm]	[mm]	[kN]	[kN]	[kN]	[kN]
1	EN-AW 5083 (SH/ST/PL)	10	500	1.75	0.00	0.00	1.75
Σ Total dead load of skirt				1.75	0.00	0.00	1.75

³ Can contain additional dead load (flanges) or additional attachments (isolation, sun protection).

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3.2.4 Cone

Section	Material	Wall thickness t_{co}	Section height h_{co}	Dead load G_1	Dead load flange G_{bfl}	Additional dead load G_2	ΣG
		[mm]	[mm]	[kN]	[kN]	[kN]	[kN]
1	EN-AW 5083 (SH/ST/PL)	10	1930.06	5.85	0.00	1.50	7.35
2	EN-AW 5454 (SH/ST/PL)	6	1286.7	1.28	0.00	3.00	11.62
3	EN-AW 5454 (SH/ST/PL)	4	1018.64	0.27	0.00	2.00	13.89
Σ Total dead load of cone				7.39	0.00	6.50	13.89

3.2.5 Total dead load of silo

	Dead load [kN]	Attachment dead load [kN]	Total dead load [kN]
Roof $G_D =$	2.28	7.30	9.58
Roof junction G_{RJ}	0.00	0,00	0.00
Cylinder $G_Z =$	46.73	12.60	59.33
Skirt $G_{SK} =$	1.75	0.00	1.75
Vertical ribs G_{rtot}	0.00	0,00	0.00
Cone $G_{TR} =$	7.39	6.50	13.89
Cylinder cone junction $G_{Tr,Eck} =$	0.00	0,00	0.00
Base ring $G_{br} =$	1.05	0,00	1.05
Total =	59.19	26.40	85.59

3.3 Live load

3.3.1 Roof

Live load $P_L = 1.00 \text{ kN/m}^2$

Snow load $P_S = 0.70 \text{ kN/m}^2$

A concurrent impact of both loads is excluded.

⇒ The calculation uses $P_L = 1.00 \text{ kN/m}^2$.

	Lever arm [m]	Horizontal live load ⁴ [kN]	Vertical live load [kN]
Roof MAX(P_L, P_S)	-	-	13.85
Total	-	0.00	13.85

3.3.2 Cylinder

Section	Wall thickness t_c [mm]	Section height h_c [mm]	Live loads Q_{Ac} ⁵ [kN]	ΣQ [kN]
1	5	2500	0.00	0.00
2	5	2500	0.00	0.00
3	5	2500	0.00	0.00
4	5.5	2500	0.00	0.00
5	6	2500	0.00	0.00
6	7	2500	0.00	0.00
7	8	2500	0.00	0.00
8	9	2500	0.00	0.00
9	10	750	0.00	0.00
Σ Total live load of cylinder			0.00	0.00

3.3.3 Skirt

Section	Wall thickness t_s [mm]	Section height h_s [mm]	Live loads Q_{As} ⁴ [kN]	ΣQ [kN]
1	10	500	0.00	0.00
Σ Total live load of skirt			0.00	0.00

⁴ Can contain additional variable load (conveying).

⁵ Can contain additional variable loads (site inspection, circular platform, sprinkler system)

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3.3.4 Cone

Section	Wall thickness t_{co}	Section height h_{co}	Live loads Q_{Aco} ⁶	ΣQ
	[mm]	[mm]	[kN]	[kN]
1	10	1930.06	0.00	0.00
2	6	1286.7	0.00	0.00
3	4	1018.64	0.00	0.00
Σ Total live load of cone			0.00	0.00

⁶ Can contain additional variable loads.

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3.4 Design pressure and design temperature

Characteristic external pressure P_U	5.00 mbar	0.0005 MPa
Characteristic internal pressure P_O	45.00 mbar	0.0045 MPa
Design temperature of silo T_B	50.00 °C	

3.5 Bulk material according to EN 1991-4

3.5.1 Characteristic values of bulk material PET

Characteristic values	Min	Max
Bulk density γ_{\max}	-	8.20 kN/m ³
Angle of response φ_r	-	35.00 °
Angle of internal friction ϕ_i	35.00 °	48.00 °
pressure ratio K	0.28	0.47
Coefficient of wall friction particulate solid - cylinder μ	0.14	0.36
Coefficient of wall friction particulate solid - cone μ_h	0.14	0.36
Bottom load magnifying factor C_B	1.20	
Patch load solid reference factor C_{op}	0.80	
Discharge factor for horizontal pressure C_h	1.15	

The following combinations of the characteristic values of bulk material will be considered.

Cylinder: (with coefficient of wall friction particulate solid - cylinder)

Combination of characteristic values of bulk material 1 – MK 1	$\mu_{\min}, K_{\max}, \phi_{i,\min}$
Combination of characteristic values of bulk material 2 – MK 2	$\mu_{\max}, K_{\max}, \phi_{i,\min}$
Combination of characteristic values of bulk material 3 – MK 3	$\mu_{\min}, K_{\min}, \phi_{i,\max}$

Cone: (with coefficient of wall friction particulate solid - cone)

Combination of characteristic values of bulk material 3 – MK 3	$\mu_{h,\min}, K_{\min}, \phi_{i,\max}$
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3.5.2 Normal pressure to silo wall

Section	Wall thickness t_c	Section height h_c	Pressure to silo wall - Filling $p_{hBulkFill}(h)$	Min. pressure to sillo wall - Filling $p_{hBulkFillmin}(h)$	Pressure to silo wall – Discharging $p_{hBulkDis}(h)$
	[mm]	[mm]	[kN/m ²]	[kN/m ²]	[kN/m ²]
1	5	2500	4.78	4.15	5.95
2	5	2500	13.80	10.70	17.18
3	5	2500	21.52	15.08	26.78
4	5.5	2500	28.12	18.01	34.99
5	6	2500	33.76	19.97	42.01
6	7	2500	38.58	21.28	48.01
7	8	2500	42.70	22.15	53.15
8	9	2500	46.23	22.74	57.53
9	10	750	47.18	22.87	58.72

Project: MC-Blending Silo Emmen D=4200mm Vn=290m³ PET 8,2
 Customer: Morssinkhof Plastics Heerenveen BV
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3.5.3 Summed up wall friction

Section	Wall thickness t_c	Section height h_c	Summed up wall friction - Filling $n_{wBulkFillmax}(h)$	Min. summed up wall friction - Filling $n_{wBulkFillmin}(h)$	Summed up wall friction- Discharging $n_{wBulkDis}(h)$
	[mm]	[mm]	[kN/m]	[kN/m]	[kN/m]
1	5	2500	0.99	0.39	1.36
2	5	2500	8.49	3.30	11.64
3	5	2500	21.27	8.27	29.17
4	5.5	2500	37.60	14.62	51.56
5	6	2500	56.28	21.89	77.19
6	7	2500	76.55	29.77	104.98
7	8	2500	97.88	38.06	134.23
8	9	2500	119.91	46.63	164.44
9	10	750	126.62	49.24	173.64

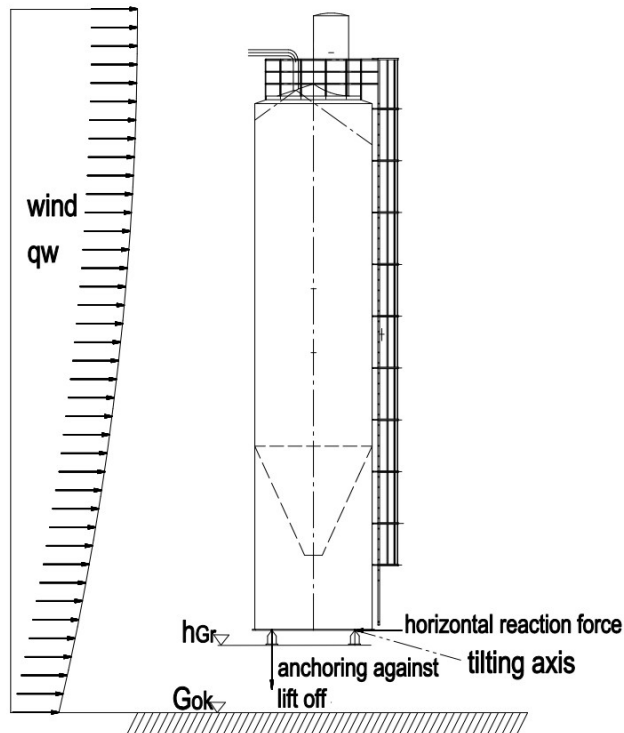
3.5.4 Smallest reliable design value of local inner pressure

Section	Wall thickness t_c	Section height h_c	Smallest reliable design value $p_s(h)$
	[mm]	[mm]	[kN/m ²]
1	5	2500	2.09
2	5	2500	5.94
3	5	2500	9.11
4	5.5	2500	11.72
5	6	2500	13.87
6	7	2500	15.64
7	8	2500	17.10
8	9	2500	18.30
9	10	750	18.62

3.5.5 Pressure flow on the sloped wall of cone

Section	Wall thickness t_{co}	Section height h_{co}	Pressure to silo wall - Filling $p_{hBulkFill}(h)$	Min. Pressure to silo wall - Filling $p_{hBulkFillmin}(h)$	Pressure to silo wall – Discharging $p_{hBulkDis}(h)$
	[mm]	[mm]	[kN/m ²]	[kN/m ²]	[kN/m ²]
1	10	1930.06	129.69	124.12	317.22
2	6	1286.7	112.19	72.28	45.75
3	4	1018.64	88.82	36.86	9.80

3.6 Wind according to EN 1991-1-4



EN 1991-1-4:

Terrain category	Area with regular vegetation (III)
Distance between silos or between silo and building w_s	0.6 m
Thickness of insulation t_{iso}	0 mm
Basic air drag coefficient of cylinder c_{fs}	0.70
Basic wind speed v_b	24.50 m/s
Turbulence factor k_l	1.00
Coefficient depending on topography c_o	1.00
Increase air drag coefficient c_w	0.90

Air drag coefficient of additional attachments:

Air drag coefficient of filter c_{WF}	1.20
Air drag coefficient of railing c_{WR}	1.40

Wind load of roof:

	Wind load Q [kN]	⁷ Moment M [kNm]
Filter Q_{WF} / M_{WF}	1.58	2.37
Railing Q_{WR} / M_{WR}	3.10	1.55
Attachments Q_{WA} / M_{WA}	0.00	0.00

Wind load of cylinder:

Section	Section height h_c	Height over ground ⁸	Impact pressure ⁹ $p_{w,i}$	Line load n_{hWindc}	Wind load Q_{wc} ¹⁰	Moment at section bottom line M_{wc}
	[m]	[m]	[kN/m ²]	[kN/m]	[kN]	[kNm]
1	2.5	30	0.93	1.27	13.50	26.65
2	2.5	27.5	0.91	1.24	22.10	71.15
3	2.5	25	0.88	1.20	30.44	136.82
4	2.5	22.5	0.85	1.16	38.50	223.00
5	2.5	20	0.82	1.12	46.27	328.96
6	2.5	17.5	0.78	1.07	53.70	453.92
7	2.5	15	0.74	1.01	60.75	596.98
8	2.5	12.5	0.70	0.95	67.35	757.11
9	0.75	10.88	0.66	0.90	69.24	808.33
Σ					69.24	808.33

Wind load of skirt:

Section	Section height h_s	Height over ground	Impact pressure ¹¹ $p_{w,i}$	Line load n_{hWinds}	Wind load Q_{ws}	Moment at section bottom line M_{ws}
	[mm]	[m]	[kN/m ²]	[kN/m]	[kN]	[kNm]
1	500	10.25	0.65	1.11	70.47	843.25
Base ring	30	10	-	-	70.47	845.37
Σ					70.47	845.37

⁷ The calculated moment refers to the roof edge of the silo.

⁸ The value describes the distance between the middle of the cylindrical section and the ground level.

⁹ The impact value refers to the middle of the cylindrical section.

¹⁰ Moments and shearing forces referring to the bottom line of the section

¹¹ The impact value refers to the middle of the cylindrical section.

4 Stress verifications

4.1 Preliminary note

The stress analysis and the structural safety verifications for the silo will be realized in the following chapters.

The stress analysis takes place in table form according to the partition theory.

Only the load combination that leads to the highest utilisation will be declared.

4.2 Roof according to EN 1999-1-5

4.2.1 Buckling safety verifications

4.2.1.1 Buckling safety verification for external pressure

Maximum external pressure of load combinations 1 and 2

LC 1: Dead weight + underpressure (main load) + Max(live load, snow load)

LC 2: Dead weight + underpressure + Max(live load, snow load) (main load)

Wall thickness t_T	Max. external pressure of load combinations p_{exd}^{12}	Max. allowed external pressure p_{nRd}	Buckling safety verification
[mm]	[kN/m ²]	[kN/m ²]	
6	2.24	3.23	0.69

4.2.1.2 Stress verification of internal pressure

internal pressure of load combination 1 :

LC 1: Dead weight + Overpressure

Roof wall thickness t_r	internal pressure of load combination p_{ind}	Required wall thickness e_{pex}	Stress verification
[mm]	[kN/m ²]	[kN/m ²]	
6	6.59	0.69	0.12

4.2.2 Verification of roof edge

Section	Wall thickness t_c	Available cross section of roof edge A_{reex}	Required cross section of roof edge A_{rereq}	Roof edge
	[mm]	cm ²	cm ²	
Outer	6	11.02	6.30	0.57

¹² Without partial safety factor

4.3 Cylinder according to EN 1999-1-5

4.3.1 Stress verification

Circumferential tensile stress

LC DE: Bulk material load - Discharging (main load) + overpressure

Section	Wall thickness t_c	Section height h_c	Max. section force n_{dtensc}	Associated stress σ_{dtensc}	Allowed stress f_{Rd}	Stress verification
	[mm]	[m]	kN/m	N/mm ²	N/mm ²	
1	5	2.5	28.67	5.73	77.27	0.07
2	5	2.5	64.04	12.81	77.27	0.17
3	5	2.5	94.29	18.86	77.27	0.24
4	5.5	2.5	120.15	21.85	77.27	0.28
5	6	2.5	142.26	23.71	113.64	0.21
6	7	2.5	161.17	23.02	113.64	0.20
7	8	2.5	177.33	22.17	113.64	0.20
8	9	2.5	191.15	21.24	113.64	0.19
9	10	0.75	194.89	19.49	113.64	0.17
						max.:0,28

Axial tensile stress¹³: Max (LC DE resp. DF, LC 2, LC WE resp. WF)

LC DE resp. DF: Dead weight + overpressure (main load) + horizontal live loads + wind load

LC 2: Dead weight + horizontal live load (main load) + overpressure + wind load

LC WE resp. WF: Dead weight + wind load (main load) + horizontal live loads + overpressure

Section	Wall thickness t_c	Section height h_c	Max. section force $n_{daxtensc}$	Associated stress $\sigma_{daxtensc}$	Allowed stress f_{Rd}	Stress verification
	[mm]	[m]	kN/m	N/mm ²	N/mm ²	
1	5	2.5	8.32	1.66	77.27	0.02
2	5	2.5	11.83	2.37	77.27	0.03
3	5	2.5	18.61	3.72	77.27	0.05
4	5.5	2.5	27.57	5.01	77.27	0.06
5	6	2.5	38.65	6.44	113.64	0.06
6	7	2.5	51.72	7.39	113.64	0.07
7	8	2.5	66.68	8.33	113.64	0.07
8	9	2.5	83.42	9.27	113.64	0.08
9	10	0.75	88.76	8.88	113.64	0.08
						max.:0,08

¹³ If the values are < 0, there is no axial tensile stress existing.

Project: MC-Blending Silo Emmen D=4200mm Vn=290m³ PET 8,2
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 Created: 26.05.2023
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Axial tensile stress:

LC SF: Dead weight + Min. bulk material load - Filling

Section	Wall thickness t_c	Section height h_c	Max. section force $n_{daxtensc}$	Associated stress $\sigma_{daxtens}$	Allowed stress f_{Rd}	Stress verification
	[mm]	[m]	kN/m	N/mm ²	N/mm ²	
1	5	2.5	-0.50	-0.10	77.27	0.00
2	5	2.5	-0.83	-0.17	77.27	0.00
3	5	2.5	-1.17	-0.23	77.27	0.00
4	5.5	2.5	-1.53	-0.28	77.27	0.00
5	6	2.5	-1.93	-0.32	113.64	0.00
6	7	2.5	-2.39	-0.34	113.64	0.00
7	8	2.5	-2.92	-0.36	113.64	0.00
8	9	2.5	-3.52	-0.39	113.64	0.00
9	10	0.75	-3.71	-0.37	113.64	0.00
						max.:0,00

4.3.2 Equivalent cylinder calculation according to EN 1999-1-5

Cylindrical shell with stepwise wall thickness:

Effective length l_n		Effective wall thickness	
	[m]	[m]	[mm]
$l_{a\text{eff}}$	10.38	$t_{a\text{eff}}$	5.16
$l_{b\text{eff}}$	5.19	$t_{b\text{eff}}$	6.7
$l_{c\text{eff}}$	5.19	$t_{c\text{eff}}$	8.77

K = 0.76

4.3.3 Buckling safety verification

Circumferential compressing stress:

LC WE resp. WF: Wind load + underpressure

Section n	Wall thickness t_c	Section height h_c	Max. section force n n_{dcomc_b}	Associated stress σ_{dcom_b}	Ideal buckling stress $\sigma_{\theta cri}$	Allowed stress $\sigma_{\theta Rd}$	Buckling safety verification
	[mm]	[m]	kN/m	N/mm ²	N/mm ²	N/mm ²	
1	5	2.5	2.32	0.46	1.25	0.81	0.57
2	5	2.5	2.29	0.46	1.25	0.81	0.56
3	5	2.5	2.25	0.45	1.25	0.81	0.55
4	5.5	2.5	2.21	0.40	1.13	0.74	0.54
5	6	2.5	2.17	0.36	1.04	0.68	0.53
6	7	2.5	2.12	0.30	0.89	0.59	0.52
7	8	2.5	2.06	0.26	0.78	0.51	0.50
8	9	2.5	2.00	0.22	0.69	0.46	0.48
9	10	0.75	1.95	0.20	0.62	0.42	0.47
							max.:0,57

Axial compressing stress on full silo Max(LC DE, LC DF, LC WF+S):

LC DE: Dead weight + bulk material load - discharging + wind load + live loads + underpressure

LC DF: Dead weight + bulk material load – filling + wind load + live loads + underpressure

LC WF+S: Dead weight + wind load + bulk material load - filling+ live loads + underpressure

Section	Wall thickness t_c	Section height h_c	Max section force n_{daxc}	Associated stress σ_{daxc}	Ideal buckling stress $\sigma_{x cri}$	Allowed stress $\sigma_{x Rd}$	Buckling safety verification
	[mm]	[m]	kN/m	N/mm ²	N/mm ²	N/mm ²	
1	5	2.5	7.45	1.49	100.83	29.90	0.05
2	5	2.5	25.91	5.18	100.83	29.90	0.17
3	5	2.5	57.08	11.42	100.83	29.90	0.38
4	5.5	2.5	96.90	17.62	110.66	32.07	0.55
5	6	2.5	142.92	23.82	119.64	41.60	0.57
6	7	2.5	193.51	27.64	137.19	46.61	0.59
7	8	2.5	247.54	30.94	154.24	50.84	0.61
8	9	2.5	304.22	33.80	170.84	54.44	0.62
9	10	0.75	321.68	32.17	187.00	57.52	0.56
							max.:0,62

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Axial compressing stress on empty silo:

LC 1: Wind load (main load) + underpressure

Section	Wall thickness t_c	Section height h_c	Max section force n_{daxc}	Associated stress σ_{daxc}	Ideal buckling stress σ_{xcrl}	Allowed stress σ_{xRd}	Buckling safety verification
	[mm]	[m]	kN/m	N/mm ²	N/mm ²	N/mm ²	
1	5	2.5	3.44	0.69	100.83	29.90	0.02
2	5	2.5	8.25	1.65	100.83	29.90	0.06
3	5	2.5	15.36	3.07	100.83	29.90	0.10
4	5.5	2.5	24.69	4.49	110.66	32.07	0.14
5	6	2.5	36.17	6.03	119.64	41.60	0.14
6	7	2.5	49.70	7.10	137.19	46.61	0.15
7	8	2.5	65.19	8.15	154.24	50.84	0.16
8	9	2.5	82.52	9.17	170.84	54.44	0.17
9	10	0.75	88.07	8.81	187.00	57.52	0.15
							max.:0,17

Axial compressing stress on empty silo:

LC 1: Underpressure (main load) + wind load

Section	Wall thickness t_c	Section height h_c	Max section force n_{daxc}	Associated stress σ_{daxc}	Ideal buckling stress σ_{xcrl}	Allowed stress σ_{xRd}	Buckling safety verification
	[mm]	[m]	kN/m	N/mm ²	N/mm ²	N/mm ²	
1	5	2.5	2.52	0.50	100.83	29.90	0.02
2	5	2.5	5.41	1.08	100.83	29.90	0.04
3	5	2.5	9.68	1.94	100.83	29.90	0.06
4	5.5	2.5	15.27	2.78	110.66	32.07	0.09
5	6	2.5	22.16	3.69	119.64	41.60	0.09
6	7	2.5	30.27	4.32	137.19	46.61	0.09
7	8	2.5	39.57	4.95	154.24	50.84	0.10
8	9	2.5	49.97	5.55	170.84	54.44	0.10
9	10	0.75	53.30	5.33	187.00	57.52	0.09
							max.:0,10

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 Customer: Morssinkhof Plastics Heerenveen BV
 Created: 26.05.2023
 Project-Nr.: 1000069251 (2000098710)



Interaction verification: Wind load (main load) + underpressure

Interaction of utilisation of

Circumferential compressing stress

LC WE resp. WF: Wind load (main load) + underpressure

Axial compressing stress of empty silo

LC WE resp. WF: Wind load (main load) + overpressure

Section	Wall thickness t_c	Section height h_c	Buckling verification WE resp. WF	Buckling verification WE resp. WF	Interaction Parameters			Verifica- tion
					k_x	k_θ	k_i	
	[mm]	h[m]						
1	5	2.5	0.57	0.02	1.50	1.00	9.217e-5	0.58
2	5	2.5	0.56	0.06	1.50	1.00	9.217e-5	0.58
3	5	2.5	0.55	0.10	1.50	1.00	9.217e-5	0.59
4	5.5	2.5	0.54	0.14	1.54	1.00	8.251e-5	0.59
5	6	2.5	0.53	0.14	1.41	1.00	2.508e-5	0.59
6	7	2.5	0.52	0.15	1.47	1.00	2.130e-5	0.58
7	8	2.5	0.50	0.16	1.52	1.00	1.815e-5	0.56
8	9	2.5	0.48	0.17	1.56	1.00	1.555e-5	0.55
9	10	0.75	0.47	0.15	1.60	1.00	1.342e-5	0.52
								max.:0,59

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Interaction verification: Underpressure (main load) + wind load

Interaction of utilisation of

Circumferential compressing stress

LC DE resp. DF: Underpressure (main load) + wind load

Axial compressing stress of empty silo

LC DE resp. DF: Underpressure (main load) + wind load

Section	Wall thickness t_c	Section height h_c	Buckling verification DE resp. DF	Buckling verification DE resp. DF	Interaction Parameters			Verifica- tion
					k_x	k_θ	k_i	
	[mm]	h[m]						
1	5	2.5	0.58	0.02	1.50	1.00	9.217e-5	0.58
2	5	2.5	0.57	0.04	1.50	1.00	9.217e-5	0.58
3	5	2.5	0.57	0.06	1.50	1.00	9.217e-5	0.58
4	5.5	2.5	0.56	0.09	1.54	1.00	8.251e-5	0.58
5	6	2.5	0.55	0.09	1.41	1.00	2.508e-5	0.58
6	7	2.5	0.54	0.09	1.47	1.00	2.130e-5	0.57
7	8	2.5	0.53	0.10	1.52	1.00	1.815e-5	0.56
8	9	2.5	0.52	0.10	1.56	1.00	1.555e-5	0.55
9	10	0.75	0.51	0.09	1.60	1.00	1.342e-5	0.53
								max.:0,58

4.4 Skirt according to EN 1999-1-5

4.4.1 Stress verification

Axial tensile stress¹⁴: Max (LC DE resp. DF, LC WE resp. WF)

LC DE resp. DF: Dead weight + horizontal live loads (main load) + wind load

LC WE resp. WF: Dead weight + wind load (main load) + horizontal live loads

Section	Wall thickness t_s	Section height h_s	Max section force $n_{daxstns}$	Associated stress $\sigma_{daxstns}$	Allowed stress f_{Rd}	Stress verification
	[mm]	[m]	kN/m	N/mm ²	N/mm ²	
1	10	0.5	86.89	8.69	113.64	0.08
						max.:0,08

Axial tensile stress:

LC SF: Dead weight + min. bulk material load - filling

Section	Wall thickness t_s	Section height h_s	Max section force $n_{daxstns}$	Associated stress $\sigma_{daxstns}$	Allowed stress f_{Rd}	Stress verification
	[mm]	[m]	kN/m	N/mm ²	N/mm ²	
1	10	0.5	-148.59	-14.86	113.64	-0.13
						max.: -0,13

4.4.2 Buckling safety verification

Circumferential compressing stress:

LC WE resp. WF: Wind load (main load)

Section	Wall thickness t_s	Section height h_s	Max section force n_{dcoms}	Associated stress σ_{dcoms}	Ideal buckling stress σ_{Bcri}	Allowed stress σ_{BRd}	Buckling safety verification
	[mm]	[m]	kN/m	N/mm ²	N/mm ²	N/mm ²	
1	10	0.5	1.11	0.11	88.88	45.02	0.00
							max.:0,00

¹⁴ If the values are < 0, there is no axial tensile stress existing.

Axial compressing stress: Max(LC DE, LC DF)

LC DE: Dead weight + bulk material load – discharging (main load) + wind load + live loads

LC DF: Dead weight + live loads + bulk material load - filling (main load) + wind load

Section	Wall thickness t_s	Section height h_s	Max section force n_{daxs}	Associated stress σ_{daxs}	Ideal buckling stress σ_{xcrit}	Allowed stress σ_{xRd}	Buckling verification n
	[mm]	[m]	kN/m	N/mm ²	N/mm ²	N/mm ²	
1	10	0.5	401.39	40.14	201.67	60.01	0.67
							max.:0,67

Axial compressing stress:

LC WF + S: Dead weight + wind load + bulk material load - filling

Section	Wall thickness t_s	Section height h_s	Max section force n_{daxs}	Associated stress σ_{daxs}	Ideal buckling stress σ_{xcrit}	Allowed stress σ_{xRd}	Buckling verification n
	[mm]	[m]	kN/m	N/mm ²	N/mm ²	N/mm ²	
1	10	0.5	385.85	38.59	201.67	60.01	0.64
							max.:0,64

Axial compressing stress:

LC SF: Dead weight + bulk material load - filling + live loads

Section	Wall thickness t_s	Section height h_s	Max section force n_{daxs}	Associated stress σ_{daxs}	Ideal buckling stress σ_{xcrit}	Allowed stress σ_{xRd}	Buckling verification n
	[mm]	[m]	kN/m	N/mm ²	N/mm ²	N/mm ²	
1	10	0.5	150.90	15.09	201.67	60.01	0.25
							max.:0,25

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Interaction verification: Wind load + bulk material load - filling + live loads

Interaction of utilisation of

Circumferential compressing stress

LC WE resp. WF: wind load

Axial compressing stress

LC WF + S: Dead weight + wind load + bulk material load - filling

Section	Wall thickness t_s	Section height h_s	Buckling verification WE resp. WF	Buckling verification WF + S	Interaction Parameters			Verification
					k_x	k_θ	k_i	
	[mm]	h[m]						
1	10	0.5	0.00	0.64	1.62	1.15	9.602e-2	0.49
								max.:0,49

4.5 Cone according to EN 1999-1-5

4.5.1 Stress verification

**Tensile stress in circumferential direction at plate and HAZ at upper edge of cone section:
Max(LC 1, LC 2)**

LC 1: Bulk material load - discharging (main load) + overpressure

LC 2: Bulk material load - filling (main load) + overpressure

Section	Wall thickness t_{co}	Section height h_{co}	Max section force $n_{dtensco}$	Associated stress $\sigma_{dtensco}$	Allowed stress f_{Rd}	Stress verification
	[mm]	[m]	kN/m	N/mm ²	N/mm ²	
1	10	1.93	1113.49	111.35	113.64	0.98
2	6	1.29	229.08	38.18	77.27	0.49
3	4	1.02	91.33	22.83	77.27	0.30
						max.:0,98

**Tensile stress in circumferential direction at weld seams at upper edge of cone section:
Max(LC 1, LC 2)**

LC 1: Bulk material load - discharging (main load) + overpressure

LC 2: Bulk material load - filling (main load) + overpressure

Section	Wall thickness t_{co}	Section height h_{co}	Max section force $n_{dtensco}$	Associated stress $\sigma_{dtensco}$	Allowed stress f_{Rd}	Stress verification
	[mm]	[m]	kN/m	N/mm ²	N/mm ²	
1	10	1.93	1113.49	111.35	192.00	0.58
2	6	1.29	229.08	38.18	176.00	0.22
3	4	1.02	91.33	22.83	176.00	0.13
						max.:0,58

Tensile stress in circumferential direction at plate and HAZ at upper edge of cone section:

LC 1: Bulk material load - filling + overpressure

Section	Wall thickness t_{co}	Section height h_{co}	Max section force $n_{dtensco}$	Associated stress $\sigma_{dtensco}$	Allowed stress f_{Rd}	Stress verification
	[mm]	[m]	kN/m	N/mm ²	N/mm ²	
1	10	1.93	243.54	24.35	113.64	0.21
2	6	1.29	120.63	20.10	77.27	0.26
3	4	1.02	47.93	11.98	77.27	0.16
						max.:0,26

Tensile stress in circumferential direction at weld seams at upper edge of cone section:

LC 1: Bulk material load - filling + overpressure

Section	Wall thickness t_{co}	Section height h_{co}	Max section force $n_{dstensco}$	Associated stress $\sigma_{dstensco}$	Allowed stress f_{Rd}	Stress verification
	[mm]	[m]	kN/m	N/mm ²	N/mm ²	
1	10	1.93	243.54	24.35	192.00	0.13
2	6	1.29	120.63	20.10	176.00	0.11
3	4	1.02	47.93	11.98	176.00	0.07
						max.:0,13

Tensile stress in meridional direction at plate and HAZ: Max(LK 1, LK 2)

LC 1: Dead weight + attachments + bulk material load- discharging (main load) + overpressure + live load of attachments

LC 2: Dead weight + attachments + bulk material load - filling (main load) + overpressure + live load of attachments

Section	Wall thickness t_{co}	Section height h_{co}	Max section force $n_{dstensco}$	Associated stress $\sigma_{dstensco}$	Allowed stress f_{Rd}	Stress verification
	[mm]	[m]	kN/m	N/mm ²	N/mm ²	
1	10	1.93	264.73	26.47	113.64	0.23
2	6	1.29	128.21	21.37	77.27	0.28
3	4	1.02	50.44	12.61	77.27	0.16
						max.:0,28

Tensile stress in meridional direction at the round weld seams: Max(LK 1, LK 2)

LC 1: Dead weight + attachments + bulk material load- discharging (main load) + overpressure + live load of attachments

LC 2: Dead weight + attachments + bulk material load - filling (main load) + overpressure + live load of attachments

Section	Wall thickness t_{co}	Section height h_{co}	Max section force $n_{dstensco}$	Associated stress $\sigma_{dstensco}$	Allowed stress f_{Rd}	Stress verification
	[mm]	[m]	kN/m	N/mm ²	N/mm ²	
1	10	1.93	264.73	26.47	192.00	0.28
2	6	1.29	128.21	21.37	176.00	0.12
3	4	1.02	50.44	12.61	176.00	0.07
						max.:0,28

Tensile stress in meridional direction at plate and HAZ:

LC 1: Dead weight + attachments + bulk material load - filling + overpressure + live load of attachments

Section	Wall thickness t_{co}	Section height h_{co}	Max section force $n_{dtensco}$	Associated stress $\sigma_{dtensco}$	Allowed stress f_{Rd}	Stress verification
	[mm]	[m]	kN/m	N/mm ²	N/mm ²	
1	10	1.93	140.16	14.02	113.64	0.12
2	6	1.29	67.87	11.31	77.27	0.15
3	4	1.02	26.70	6.68	77.27	0.09
						max.:0,15

Tensile stress in meridional direction at the round weld seams:

LC 1: Dead weight + attachments + bulk material load - filling + overpressure + live load of attachments

Section	Wall thickness t_{co}	Section height h_{co}	Max section force $n_{dtensco}$	Associated stress $\sigma_{dtensco}$	Allowed stress f_{Rd}	Stress verification
	[mm]	[m]	kN/m	N/mm ²	N/mm ²	
1	10	1.93	140.16	14.02	192.00	0.15
2	6	1.29	67.87	11.31	176.00	0.06
3	4	1.02	26.70	6.68	176.00	0.04
						max.:0,15

Stress verification of cone edge: Max (LC1)

LC 1: Dead weight + attachments + bulk material load - filling (main load) + overpressure + live load of attachments

Effective total cross section A_{et}	Max pressure $n_{\theta Edj}$	Associated stress $\sigma_{u\theta Edj}$	Resistance against plastic collapse f_{pRdj}	Stress verification
[cm ²]	[kN]	[N/mm ²]	[N/mm ²]	[-]
33.16	208.66	62.92	125.00	0.50

Buckle verification out of the ring level:

Associated stress $\sigma_{u\theta Edj}$	Buckle resistance out of the ring level σ_{opRdj}	Buckle verification out of the ring level
[N/mm ²]	[N/mm ²]	[-]
62.92	448.44	0.14

Project: MC-Blending Silo Emmen D=4200mm Vn=290m³ PET 8,2
 Customer: Morssinkhof Plastics Heerenveen BV
 Created: 26.05.2023
 Project-Nr.: 1000069251 (2000098710)

4.6 Anchoring according to EN 1993-4-1

4.6.1 Anchor utilisation¹⁵

4.6.1.1 Load case WE - empty silo with maximum of wind load

Max tensile force per anchor	Allowed stress anchor bolts	Max stress per anchor	Anchor utilisation
[kN]	[N/mm ²]	[N/mm ²]	
48.09	576.00	196.27	0.34

4.6.2 Base ring utilisation

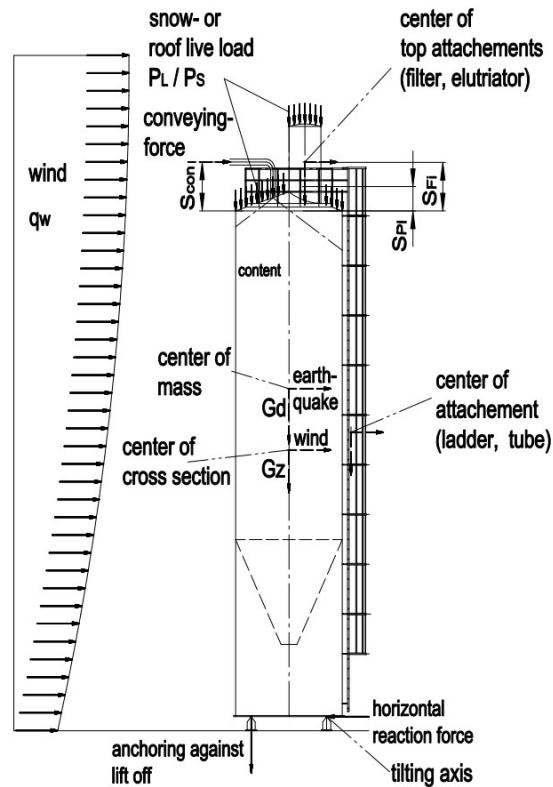
4.6.2.1 Load case WE - empty silo with maximum of wind load

Section modules of base ring	Reverse-drawing moment of base ring	0,2%- yield strength of base ring profile	Bending stress of base ring	Base ring utilisation
[cm ³]	[kN m]	[N/mm ²]	[N/mm ²]	
333.35	22.64	124.80	67.92	0.60

¹⁵ Just for anchoring relevant load cases are considered.

5 Loads to silo-foundation and anchoring

Support of silo continual on steel support with direct anchoring



5.1 Characteristic loads

Vertical loads

Weight of empty silo G_{silo}	59.19 kN
Weight of attached equipment G_{eq}	26.40 kN
Maximum snow/live load on roof or platform etc. G_{ll}	13.85 kN
Live load (silo content) except roof live load G_{cont}	2378.00 kN
Σ Maximum vertical load to support or G_d	2477.45 kN

Conveying loads

Horizontal load from conveying F_{HQAlbr}	0.00 kN
Moment resulting from conveying M_{QAbr}	0.00 kNm

Wind loads

Horizontal load to support or foundation F_{HQWbr}	70.47 kN
Moment resulting from wind loads M_{Wbr}	845.37 kNm
Height of center of area exposed to wind h_{sw}	12 m

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5.2 Design loads

The here given loads containing a partial safety factor according to DIN EN 1991-4

Load case D/WF – full silo with attachments, roof live load and maximum of wind load

Line load at base ring – lee side n_{leeWF}	362.89 kN/m
Compression below base ring σ_{compWF}	5.02 N/mm ²

Load case WE – empty silo with maximum of wind load

Tensile (uplifting) force per anchoring bolt N_{Fza}	48.09 kN
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