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Silos Design by Global Numerical Analysis

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Abstract

The design and verification of silos resistance was comply with the Eurocodes. Stress and deformations is calculated using a global numerical analysis that used the finite element method (FEM). According to EN 1993-1-6:2008, the type of analysis performed was GMNA - geometric nonlinear analysis with material nonlinearity, where the behavior of material was nonlinear and the geometry of the structure (plate) was perfect. In accordance with EN 1991-4:2006, stresses and strains was determined for several loading hypotheses. The level of the calculated stress was assessed for the plastic limit state LS1.

Key words: *numerical analysis, silo, FEM*

Introduction

The design and checking calculation of steel structures is carried out in accordance with the standards of Eurocode 3. Eurocodes establish a single set of technical rules used in the construction resistance and civil engineering design, in order to standardize design rules in the EU Member States. There are 25 standards governing the design of steel structures.

The silo review is cylindrical metallic constructions with conical bottoms, mounted vertically, used to store powders or granulated materials. Their structure is modular, made up of components assembled together by screws.

The calculations used the following data:

- deposited material: cement with specific weight $\gamma = 16$ kN/m^3 and the rest angle $\delta = 25^o$;
- 1500 Pa pressure produced by wind action;
- 3000 Pa pressure produced by snow loads;
- seismic zone with an acceleration of the earth $a_g = 0.25g$ (g - gravitational acceleration).

Stress and deformations were calculated using a global numerical analysis that used the finite element method (FEM). According to EN 1993-1-6:2008, the type of analysis performed was GMNA - geometric nonlinear analysis with material nonlinearity, where the behavior of material was nonlinear and the geometry of the structure (plate) was perfect.

In accordance with EN 1991-4:2006, stresses and strains was determined for several loading hypotheses. The level of the calculated stress was assessed for the plastic limit state LS1.

Developing the Model

Based on the design of silo and on the production drawings of its parts, we chose to model the silo using two types of finite elements, namely:

- a shell-type element was used for the shaping of the silo body and base, SHELL93;
- a beam finite element, like element BEAM188, to shape the diagonals, made of angle bar.

The shell-type finite element was chosen because the silo is part of the curved thin plate structures group. For a most accurate modeling of how the silo legs should be mounted on its conical mantle area, we chose the same type of plate finite element, for both connection pieces and feet. This way, we could better monitor the transmission of the stress between the mantle and feet.

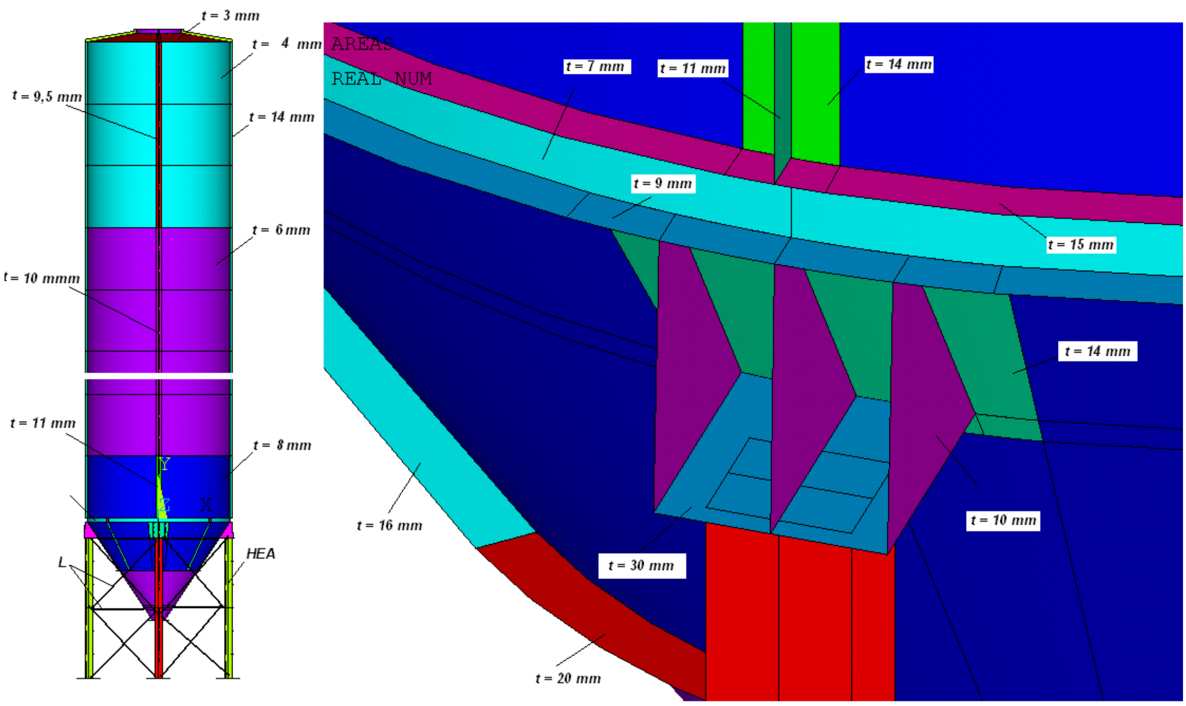

Fig. 1. Geometrical model of silo

The constituent elements of silo are made of S235JR and S275JR steels.

The modeling of the conventional characteristic curve of the material was made on the assumption that it is plastically deformed with non-linear hardening and the characteristic stress-strain curve has the following analytical expression:

$$\sigma = \begin{cases} E \cdot \varepsilon & \text{for } \varepsilon \le \varepsilon^e = R_{p0,2} / E \\ K \cdot \varepsilon^m & \text{for } \varepsilon > \varepsilon^e \end{cases} \tag{1}$$

with the following mechanical characteristics of the material being involved: ε^e – specific elastic strain (corresponding to the elastic limit R_e), $R_{p0,2}$ – Conventional yield, m – hardening exponent, K – coefficient (modulus) of resistance.

For the calculation of m and K the following relations were used:

$$m = \frac{\ln(R_m / R_{p0,2})}{\ln[A/(0.002 + R_{p0,2}/E)]}, \tag{2}$$

$$K = R_m / A^m \, . \tag{3}$$

Based on the formulas (1)...(3) and on the data provided in Table 1, we introduced the stress-strain relationship, σ - ε, for the two steels in the program.

We also considered that the volume density of steel is ρ_{steel} = 7.85 kg/dm^3.

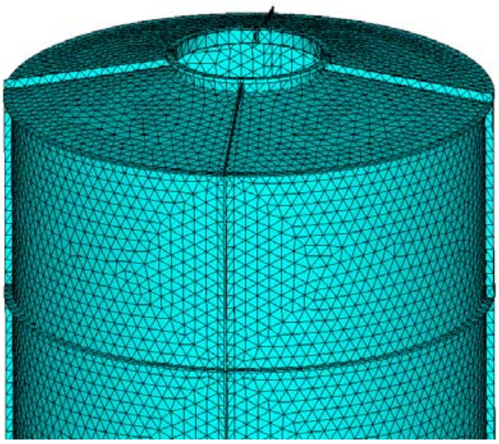

Fig. 2. Network of finite elements for silo. The cylinder area.

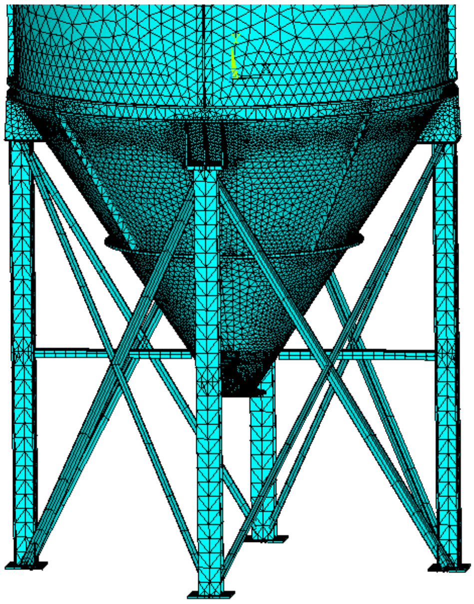

Fig. 3. Network of finite elements for silo. Conic area and base (legs).

These values of the mechanical characteristics were used to calculate the silo loads resulted from its own weight and from inertia forces in case of seismic action.

Figures 2 and 3 present the finite element networks in which the geometric model of silo was rendered discreet.

Modeling Loads and Links

The loadings have been determined in accordance with [1, 2, 3, 4, 5]. In compliance with Appendix A of EN 1991-4, the following force categories have been considered, as presented in Table 1. In Table 1, SW is the load of the specific weight; SWGM – load of the pressure generated by the granular or powder material; SN – snow load; WI – wind load; SA – load generated by the seismic activity. The first too load groups G1 and G2 correspond to the S, WE and WF combinations in designing the silo [1]. Moreover, these three groups correspond to the I, WE and WF combinations for the calculation in the ultimate limit state, without taking into account the imposed loads and the imposed displacement, the two being considered null.

Figure 4 depicts how the normal pressure applied to granular or powdery material produced on the silo model.

In G3 load case, the loads generated by the seismic activity are calculated with a method with may be applied to buildings having a response which is not significantly affected by the modes` of vibration contributions higher than the fundamental mode in each principal direction. Because the fundamental period of vibration of the silo is T_1 = 0.1796 s < 2.0 s, we can apply this type of analysis.

Table 1. Force categories in silo.

Category index	Action type										Obs.
	SW	$\Psi_{0.1}$	SWGM	$\Psi_{0.2}$	SN	$\Psi_{0.3}$	WI	$\Psi_{0.4}$	SA	$\Psi_{0.5}$	
G1	**X**	1.35	**X**	1.35	**X**	0.6	**X**	0.6			LS1 – Plastic limit EN 1993-4-1:2006
G2	**X**	1.35			**X**	0.9	**X**	1.5			LS1 EN 1993-4-1:2006
G3	**X**	0.9	**X**	0.8	**X**	0.3	**X**	0.3	**X**	1.0	LS1 EN 1993-4-1:2006

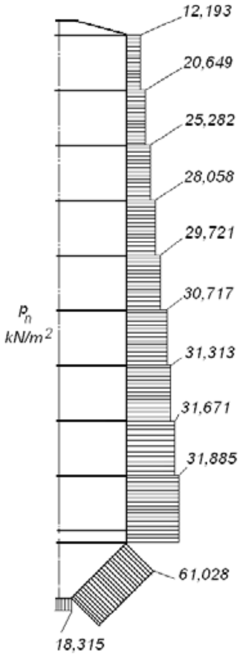

Fig. 4. Normal pressure on the silo wall produced by powdery material

Table 2. Seismic forces values

i	d_i, mm	F_i, kN
1	10.98	134.22
2	9.62	121.75
3	8.91	108.92
4	7.82	95.59
5	6.70	81.90
6	5.57	68.09
7	4.45	54.40
8	3.38	41.32
9	2.46	30.07
10	1.95	23.84
11	1.45	17.72

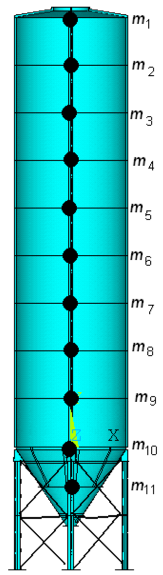

Fig. 5. Seismic model of silo.

The seismic base shear force F_b will be determined using the following:

$$F_b = S_d(T_1) \cdot m \cdot \lambda \tag{4}$$

where: T_1 is the fundamental period of vibration of the building for lateral motion in the considered direction; m is the total mass of the building (self-weight and 80% cement weight), above the foundation or above the top of a rigid basement; λ is a correction factor, which value is equal to: $\lambda = 0.85$ if $T_1 < 2\ T_C$ and the building has more than two stores, or $\lambda = 1.0$ otherwise. $S_d\ (T_1)$ is the ordinate of the design spectrum at period T_1. If $T_B = 0.15$ s $\leq T_1 \leq T_c = 0.4$ s [4] then:

$$S_d(T_1) = a_g S \frac{2.5}{q} = 1.667 a_g \tag{5}$$

where: $a_g = 0.25g$ ($g = 9.81$ m/s^2) is the design ground acceleration; $S = 1$ is the soil factor; $q = 1.5$ is the behavior factor; $T_B = 0.15$ s is the lower limit of the period of the constant spectral acceleration branch. The result is: $S_d\ (T_1) = 1.667a_g$ and $F_b = 777.81$ kN.

This force was distributed in 11 points of the silo's axis, as it can be seen in Figure 5. In order to determine the forces` values, F_i (i = 1, ..., 11), we determined, using FEM, the displacements along the horizontal component of the seismic action (Z axis), produced by a load given by the inertia forces having the Z axis as direction.

Using the displacements values, we determined the F_i forces:

$$F_i = F_b \frac{m_i d_i}{\sum_1^8 m_j d_j} \quad (6)$$

The values of these forces are given in Table 2 (included in fig. 5). These forces F_i were distributed in nodes which correspond to the stiffening rings` circles of the shells.

Silo is fixed to the foundation by screws through the HEA welded plates that its legs are made of. For this reason, on the finite element model (see figs. 1 and 3), both the translations and the rotation of the nodes corresponding to the leg plates have been blocked.

Results

A model has been made and run for each force category. After data processing through the computer program, the stress and displacements have been highlighted for the most important parts of silo.

Thus, for the skirts of the silos' cylindrical area, we have highlighted the von Mises stress $\sigma_{ech,\max}^{VM}$, as well as the compression stress following the direction of the silo axis σ_y (axis Y coincides with the symmetry axis of the silo). Moreover, we have highlighted the overall maximum displacements $\Delta_{tot,\max}$.

For the upper and lower cone of the silo we have retained the maximum equivalent von Mises stresses, as well as the overall maximum displacements pertaining to the direction of the Z axis.

Since running has highlighted the fact that the most pressured part of the silo is the contact zone between the shell of the upper cone and the silo legs, we have studied the maximum equivalent von Mises stresses.

These stresses and displacements have been retained in the case of the silo legs, as well.

In the case of modeling diagonals and horizontals where BEAM elements have been used, we have retained the maximum axial tension and compression stress.

All the values of the stresses and displacements retained in the case of each group are presented in Table 3. In Table 4 are written stresses calculated by FEM and analytic AC.

In order to check the limit state of the plastic limit, the calculation stresses must comply with the following [6]:

$$\sigma_{e,Ed} \leq f_{e,Rd} = f_y / \gamma_{M0} \quad (7)$$

where $\sigma_{e,Ed}$ is the maximum calculation stress; $f_{e,Rd}$ – specific equivalent calculation resistance; f_y – specific yield strength; γ_{M0} – partial strength coefficient.

From [7], Table 2.2, for the ultimate limit state of the plastic limit γ_{M1} = 1 , and for the ultimate state of the stability limit γ_{M3} = 1.1. The following equivalent calculation resistance values was used: for steel S235JR: $f_{e,Rd}$ = 235 MPa and for steel S275JR: $f_{e,Rd}$ = 275 MPa.

In Figures 6 and 7 are the maps of equivalent von Mises stress variations, in MPa, corresponding to the **G3** category in the 9th skirt and the leg plates of silo.

Table 3. The values of maximum stresses and displacements corresponding to the category, in the main parts of silo.

Part	Category index					
	G1		G2		G3	
	$\sigma_{ech,\max}$ MPa	$\sigma_{y,\max}$ MPa	$\sigma_{ech,\max}$ MPa	$\sigma_{y,\max}$ MPa	$\sigma_{ech,\max}$ MPa	$\sigma_{y,\max}$ MPa
Skirt 1	14.11	–5.71	15.38	–7.84	10.14	–5.22
Skirt 2	10.49	–5.07	12.23	–6.55	14.36	–8.85
Skirt 3	9.91	–5.55	16.12	–9.46	23.35	–17.14
Skirt 4	11.12	–5.19	15.09	–8.316	27.70	–19.55
Skirt 5	13.27	–5.30	17.11	–10.79	39.20	–28.84
Skirt 6	17.57	–7.20	19.87	–13.87	53.58	–40.81
Skirt 7	23.97	–11.36	24.19	–17.93	72.15	–56.61
Skirt 8	31.11	–17.6	30.92	–25.39	101.49	–84.91
Skirt 9	61.84	–48.22	55.01	–42.17	213.30	–138.94
„U” ring	112.41		92.62		277.56	
Upper cone	53.04		43.30		205.00	
Lower cone	68.47		41.81		68.83	
Leg plate	259.85		232.02		280.32	
Legs	227.50		222.18		292.05	
	σ_{ax}, MPa		σ_{ax}, MPa		σ_{ax}, MPa	
Diagonals	–36.03	27.0	–38.73	36.83	–127.74	129.76
Horizontals	–9.00	12.4	–10.23	10.36	–17.77	20.77
$\Delta_{\max}$, mm	7.936		16.581		72.661	

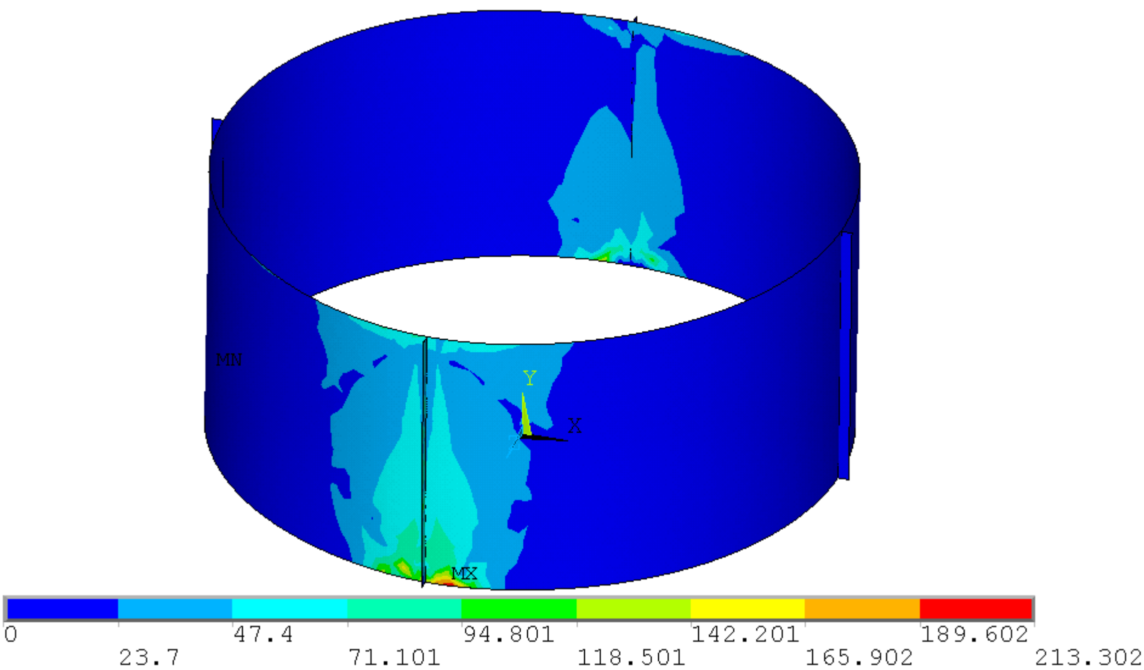

Fig. 6. Equivalent von Mises stress variations, in MPa, corresponding to the **G3** category, in the 9th skirt of silo.

Table 4. The values of maximum stresses corresponding to the category, in the 9th skirt.

Category index	9th skirt			
	$\sigma_{ech,\max}$, MPa		$\sigma_{y,\max}$, MPa	
	FEM	AC	FEM	AC
G1	61.84	42.6	–48.22	–47.39
G2	55.01	35.54	–42.17	–39.37
G3	213.3	107.97	–138.94	–105.75

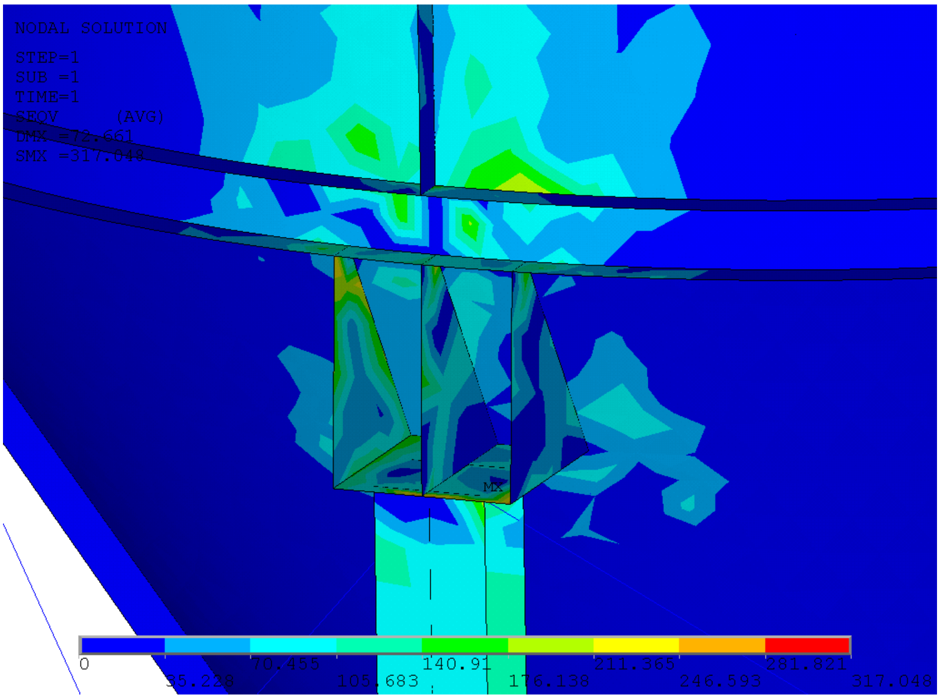

Fig. 7. Equivalent von Mises stress variations, in MPa, corresponding to the **G3** category, in the leg plates.

Conclusions

In the paper is make a comparison between standards-based design (analytical) and numerical analysis of the stress of a silo for bulk materials storage.

Analysis of equivalent maximum von Mises stresses and compression stresses, presented in Tables 3 and 4, the following was found:

For groups **G1** and **G2**, the equivalent maximum stresses developed in the silo walls based on standard values are something smaller than the stresses values calculated by global analysis using the finite element method (FEM); A significant difference is, $\sigma_{ech,\max} = 213.3$ MPa (FEM), respective, $\sigma_{ech,\max} = 107.97$ MPa (AC), in the case of the **G3**;

For groups **G1** and **G2**, the compression maximum stresses developed in the silo walls based on standard values are almost equal with the stresses values calculated by global analysis using the finite element method (FEM); A significant difference is $\sigma_{y,\max} = -138.94$ MPa (FEM), respectively $\sigma_{y,\max} = -105.75$ MPa (AC), in the case of the **G3**.

Differences that may arise in the case of the G3 group can be explained by the very similar geometry of the model with finite elements used by the geometry of the silo: stresses concentrations, the interaction between the dimensions of the components of the silo, the work between silo walls and leg plates.

Because the equivalent maximum stresses values calculated both analytical and finite element method satisfy the criteria of strength it can be concluded that both analytical method and numerical method are qualified for the design of the silo.

In addition, the method of design by numerical analysis highlights the stresses concentration.

One can say that ideally, the design should be made on the basis of norms and then a global numerical analysis to highlight the dangerous areas, and finally a review of the detail of these zones using numerical finite element method, to verify the conditions of the resistance.

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Proiectarea silozurilor prin analiză numerică globală

Rezumat

Proiectarea şi verificarea rezistenţei silozurilor destinate depozitării materialelor pulverulente a fost făcută in conformitate cu Eurocodurile. Tensiunile şi deformaţiile acestor structuri s-a efectuat pe baza de standarde şi prin analiză numerică globala folosind metoda elementului finit (MEF). În conformitate cu EN 1993-1-6: 2008 tipul de analiză efectuat a fost GMNA – analiză neliniar geometrică şi cu neliniaritate de material, în care materialul are o comportare neliniară iar geometria structurii (plăcii) este perfectă. În conformitate cu EN 1991-4:2006 tensiunile şi deformaţiile au fost determinate pentru cele mai severe cazuri de încărcare. Valoarea tensiunilor a fost verificată pentru starea limită plastică LS1.