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SOME SPECIFIC FEATURES OF DESIGN OF STEEL SILO WITH CAPACITY V = 110 M^3

L. Zdravkov[1]

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ANNOTATION

A steel silo for storage of lime with volume V = 110 m^3 is mounted in a cement plant in Bulgaria. It has the following main elements - flat roof, cylindrical body and a conical discharge hopper. On the roof is mounted a filter and under the hopper - a vibration device which ensures complete emptying of the plant. In order to transport the hydrated lime, beneath the silo has been placed a steel screw with a diameter Ø219. To provide the opportunity for conflict - free insertion and service of the screw, the silo is mounted on the supporting structure, built by frame elements. Structure may have a different kind and composition. Of any kind it generates concentrated meridional forces in the cylindrical body of the silo. As a result, thin-walled shell may loses local stability.

In the article below will be shown specific features which should be taken into account in analysis and design of this interesting facility.

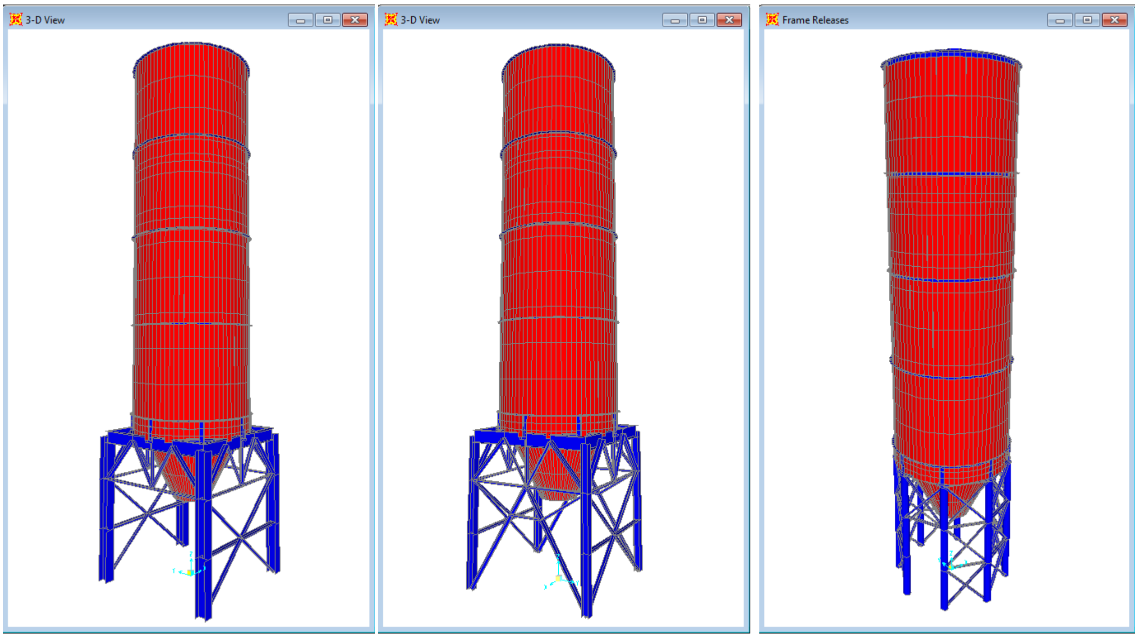
1. Composition of supporting structure under the silo

The steel structure under the silo’s body can have different composition and geometry, each of which is related to use of different bearing elements, joints and material consumption. The researched 3 variants are shown on the fig. 1.

The solutions shown on the fig. 1 - a) and b) have the following characteristics:

- vertical columns are only 4 pieces ;
- between the columns are mounted horizontal girders which assure “the stepping” of the cylindrical body of the silo on 8 points;
- in the plane of the screw are “developed” vertical X-braces, bearing horizontal loads;
- in the other plane, perpendicular to the screw, are formed steel frames see fig. 1 - a), or are put λ-braces, see fig. 1 - b). This ensures a free mounting works and access to the screw.

[1] Lyubomir Zdravkov, PhD, associate professor, civil engineer, UACEG, Sofia 1046, №1 „Hristo Smirnensky” str., floor 7, office 733, e-mail: zdravkov_fce@uacg.bg



a) 4-columns and girders between them X-braces in one plain and frames in the other

b) 4-columns and girders between them X-braces in one plain and λ-braces in the other

c) 8 tube columns X-braces between them

Fig. 1. Variants of supporting structure under the silo

The shown on fig. 1 - c) solution has the following particular features:

- immediately bellow the cylindrical body are placed 8 columns with circular sections;
- as the columns are in direct contact with the silo, it is not necessary to put additional horizontal girders;
- for horizontal loads, between columns are placed vertical X-braces. For passing through the screw and easy access to it, parts of the braces are removed in two of the fields.

Everyone of above mentioned variants of the solutions is related to different sections, respectively - weights of the elements. Each has its advantages and disadvantages. But the lack of girders in the last solution is prerequisite to be the most economical regarding the quantity of used material and the joints between elements to be uniform and relatively simple.

May be it is not a coincidence that when under the silos do not pass large size vehicles, very often the supporting structure under the silo is built only from columns and vertical braces.

2. Earthquake design

Area where the facility is built is a characterized as a seismic. For bearing of horizontal loads, between the columns are placed vertical braces, see fig. 1 - c). If they have X-shape, in class of ductility DCM we can accept the coefficient of behavior $q \leq 4.0$ [4]. Taking into consideration irregularity by height of the silo's structure, the standard БДС EN 1998-4 [5] requires the determined according to БДС EN 1998-1:2005 [4] coefficient q to be multiplied by 0.7. As a result, the upper limit of the coefficient of behavior q of the silo with X-braces and ductility's class DCM will be:

$$q_{[2]} = q_{[1]} \cdot 0.7 = 4.0 \cdot 0.7 = 2.8 \qquad (1)$$

Considering the fact that the silo will be exploited outdoor, in the aggressive industrial environment, it is accepted minimum cross section of the diagonal bars in the vertical X-braces to be composed by two profiles L50x5. Their tensile bearing capacity will be calculated according to formula:

$$N_{t,Rd} = A \cdot \frac{f_y}{\gamma_{M0}} = 2 \cdot 4.8 \cdot \frac{23.5}{1.05} = 214.9\text{kN}\,, \qquad (2)$$

where:
$A = 9.6$ cm^2 is the area of the composed by two angular profiles L50x5 steel section;
$f_y = 23.5$ kN/cm^2 – characteristic value of the yield strength of the steel S235;
$\gamma_{M0} = 1.05$ – coefficient of partial security by the material.

The accounted forces in diagonal of the X-brace during earthquake, when the coefficient of behavior $q = 1.5$, has the value $N_{Ed} = 185.35$ kN, i.e. $N_{t,Rd} > N_{Ed}$. It means that during the earthquake the vertical X-braces will remain elastic, will not yield and will not dissipate energy. The silo will work in elastic stage, and coefficient of behavior $q = 2.8$ cannot be achieved. The mentioned in document Ordinance № РД-02-20-2 [6] value for response factor $R = 0.30$, i.e. $q = 1/R = 3.33$ does not even make sense to be commented.

The direct consequence of the forced design with $q = 1.5$ are the bigger forces in the steel elements of the silo, in anchor bolts and in the foundation below, compared to design when $q = 2.8$. Yes, the efforts are bigger but are closer to the reality.

3. Effective width of compressed zone

The cylindrical body of the silo “stepped” on 8 pipe columns. This leads to appearance of 8 concentrated forces in thin shell in axial direction. In order to avoid loss of stability caused by axial compression in the shell, as is shown on the fig. 2, above the columns are placed additional stiffening plates, see fig. 3. They greatly decrease the propensity of the cylindrical shell to loses stability. The numerical research, done with the software SAP 2000 [8], shows that the coefficient for loss of stability in first case is $k = 12.781$, and in the second - $k = 25.165$, see fig. 5.

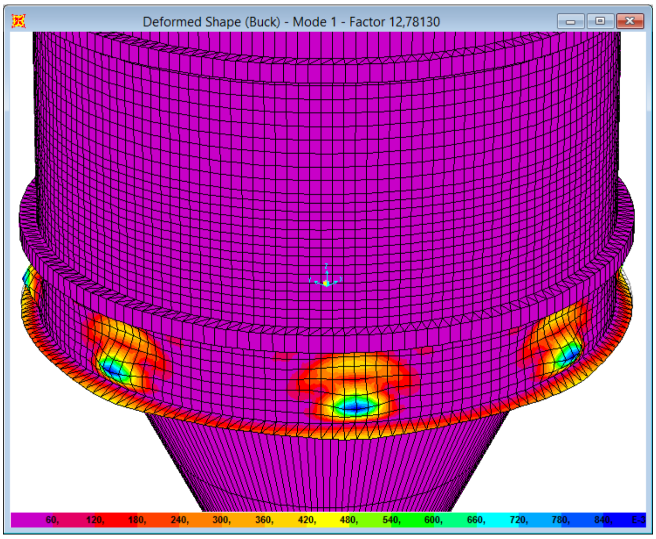


Fig. 2. Loss of stability in the cylindrical body of the silo above the supports caused be axial forces

In silos with discrete supports, without ring girder, standard БДС EN 1993-4-1:2007 [3] determines that minimum height of the stiffeners L_{min} should be:

$$L_{\min} = 0.4 \cdot r \cdot \sqrt{\left(\frac{r}{t}\right) \cdot \frac{1}{n \cdot \left(n^2 - 1\right)}}, \quad (3)$$

where:
r is radius of the cylindrical body of the silo;
t – thickness of the cylindrical shell;
n – number of the support on the circumference of the shell.

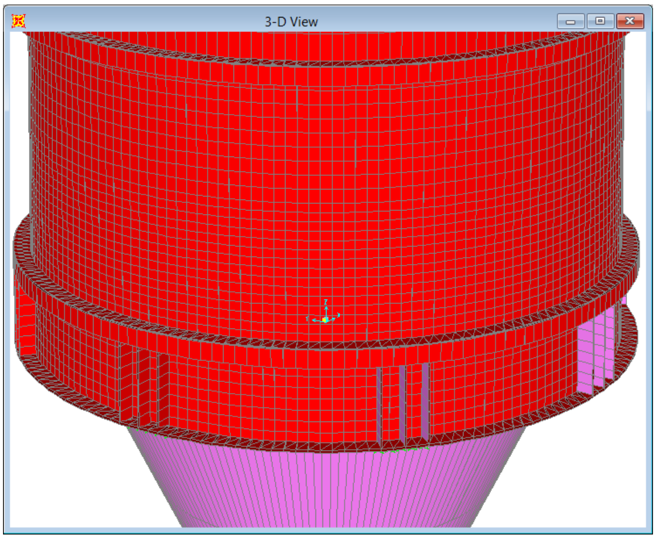


Fig. 3. Stiffening the cylindrical body of the silo by placing stiffening plates

In this case the emptying hopper is jointed to the cylindrical body at some distance from its lower edge, see fig. 4. The height of the joint is consistent with minimum height L_{min} of the stiffeners. This solution gives the possibility columns to be positioned centrically under the cylindrical body, so in them and in the cylinder bending moments do not rise.

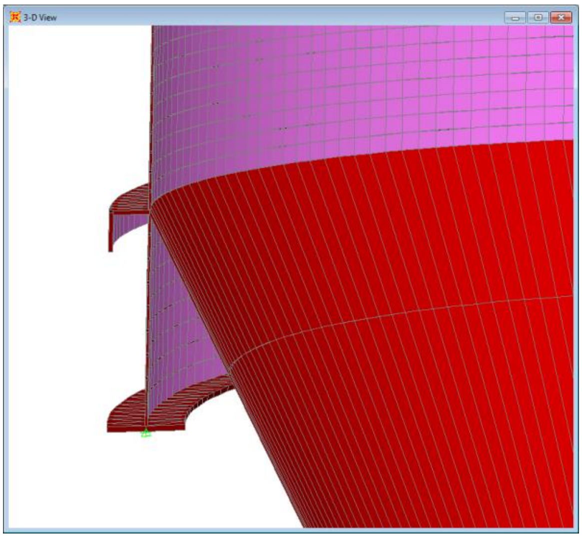


Fig. 4. Joint of cylindrical body with emptying hopper.

The stiffening plates, put above the supports, prevent loss of stability of shell immediately above the application point of concentrated forces. But it does not mean that in zone above stiffeners, even if they have height bigger than minimum L_{min}, the loss of stability of the shell is avoided, see fig. 5.

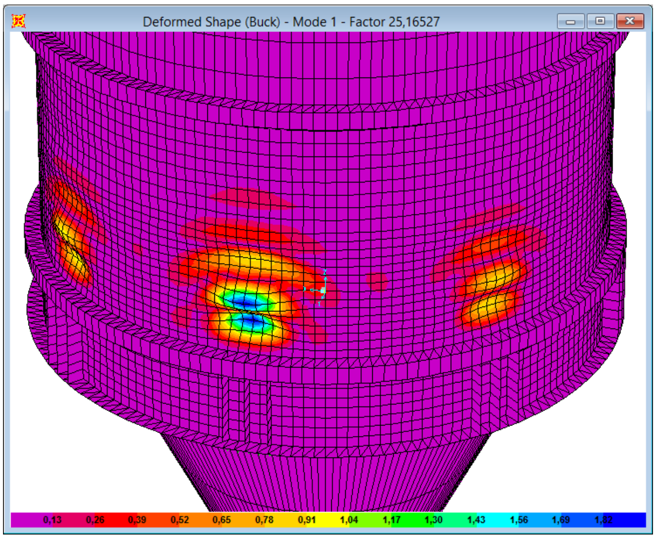


Fig. 5. Loss of stability in cylindrical body of the silo above the stiffening plates by axial pressure

The cylindrical body must be checked for loss of stability of meridional (axial) pressure according to methodology shown in the standard БДС EN 1993-1-6:2007 [2] or БДС EN 1993-4-1:2007 [3]. Having in mind the discrete supports, concentrated axial forces will appear in the cylindrical shell. They will spread under some angle α with vertical axis, see fig. 6, and they will smoothly decrease on height. The value of the angle is in direct dependency with the effective width l_{eff}. Obviously as this angle α is larger, the width l_{eff} will be bigger, respectively the meridian stresses $\sigma_{x,Ed}$, will be smaller.

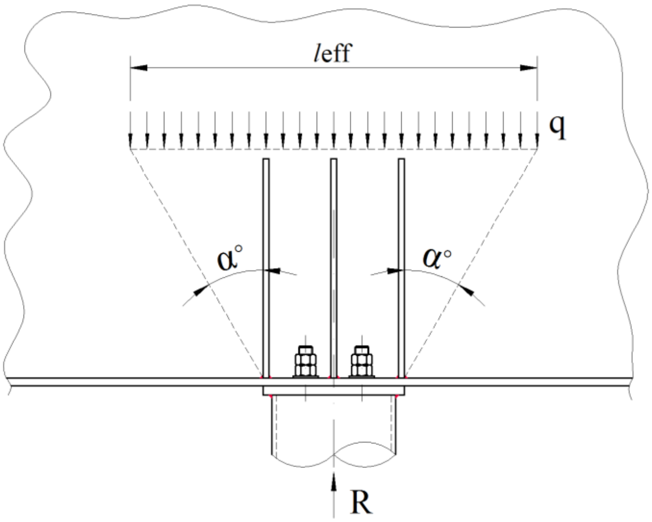


Fig. 6. Angle α of distribution of the compression forces in the cylindrical shell and the effective width l_{eff}

The angle α of distribution of compressive forces in the shell, due to reactions *R* in supports, can be determined according to the formula:

$$\alpha = \text{arctg}\left(0.5 \cdot \frac{l_{eff} - s_s}{z}\right), \qquad (4)$$

where:

s_s is the width of the force' application (loading patch);

l_{eff} – effective width of distribution of the pressure forces;

z – the distance from the point of application of the force *R* to the researched section.

Unfortunately the above quoted standards [2] and [3] do not give information nor for the value of the angle α, neither for the effective width l_{eff}. Only in the standard БДС EN 1993-1-5:2005 [1] exists a formulae for calculating of the l_{eff} due to a local pressure in the plain in the steel plate. It is:

$$l_{eff} = s_e . \sqrt{1+\left(\frac{z}{n.s_e}\right)^2}\ , \qquad (5)$$

where:

$$s_e = s_s + 2.t_f \qquad (6)$$

$$n = 0.636 \cdot \sqrt{1+\frac{0.878 \cdot a_{st,1}}{t_w}}\ , \qquad (7)$$

t_f – thickness of flange, where the force is applied;
t_w – thickness of web of steel plate;
$a_{st,1}$ – the gross cross-sectional area of longitudinal stiffeners, smeared over the length s_e.

The formula (5) is valid when inequality (8) is true. Otherwise the contribution of the stiffeners should be neglected.

$$s_{st} / s_e \leq 0,5\ , \qquad (8)$$

where:
s_{st} is the axial distance between the longitudinal stiffeners.

The question here is whether this formula for plain plate is applicable to cylindrical shells, such as the silos? Or to use the results of *Whitmore* [9], published long ago in the distant 1952, indicating that the angle of distribution $\alpha = 30^0$? For finding an answer of these questions, the author created spatial researching models of the silos using software product ANSYS [7]. For the facility's modeling are accepted values as follow:

- internal diameter of cylindrical body - D = 3485 mm;
- height of the cylindrical body - h_c = 10 950 mm;
- used steel - S235;
- all elements are entered as a shells (shell181) with their thickness;
- the maximum dimension of the shell's elements is 50 mm;
- the frame structure under the silo's body is simulated only with 8 columns, which are fixed to the foundation;
- the vertical loading is equally distributed and is applied to the superior edge of the cylindrical body ;
- the calculations are done with accounting of influence of deflections caused by loading, in other words the secondary effects are accounted.

Option symmetry is used in order to make the calculations lighter. It allows to research only a part of the construction, which has axis of symmetry and symmetrical loading.

Normal meridional stresses $\sigma_{x,Ed}$ above the support are accounted on all heights of the cylindrical body. Knowing the shell's thickness t and the values of the of the supporting reaction R, effective width l_{eff} can be calculated according to the equation:

$$l_{eff} = \frac{R}{\sigma_{x,Ed} \cdot t}\ , \qquad (9)$$

where:
R is the vertical reaction of the discrete support, see fig. 6;
$\sigma_{x,Ed}$ – meridional normal compression on height z in the cylindrical body;
t – thickness of the cylindrical steel shell.

For comparison, the effective width l_{eff} of the compressed zone above the support is calculated according to the formula (5) from standard БДС EN 1993-1-5:2005 [1].

Charts are created using the obtained according to the formulas (5) and (9) results. They show the changes of l_{eff} on the height of the cylindrical body, see fig. 7.

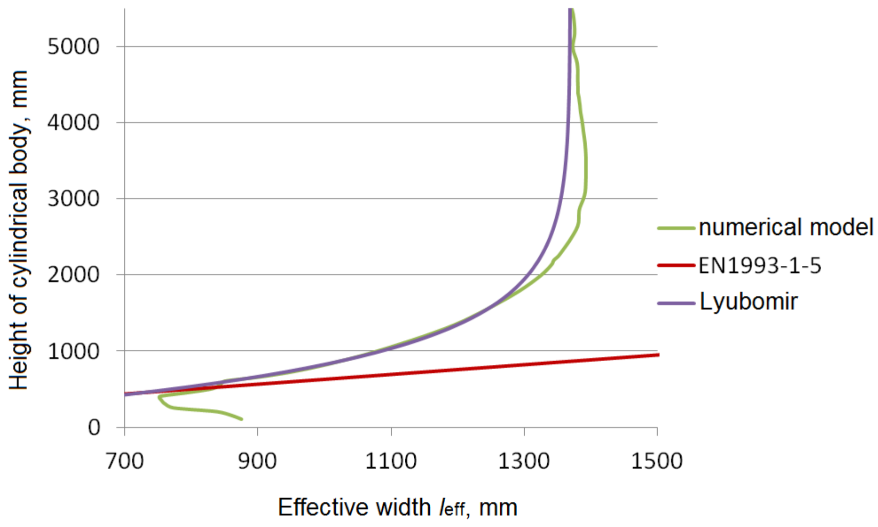


Fig. 7. Change of effective width l_{eff} on the height of the cylindrical body

Obviously there are considerable differences between the effective width l_{eff}, respectively stresses $\sigma_{x,Ed}$, obtained by the numerical model of the silos and by the standard БДС EN 1993-1-5:2005 [1].

For the concrete silo for lime, with a volume V = 110 m^3 and 8 columns under it, the author created analytical expression for calculation of the values l_{eff} on the height. It is:

$$l_{eff} = s_e . e^{-\frac{k.z}{l - s_e}} + l.(1 - e^{-\frac{k.z}{l - s_e}}), \quad (10)$$

where:

s_e is minimum width, according to the formula (5);

e = 2,71828 - Napier's constant;

k = 1,9 - coefficient for correction, valid for the researched silo;

z – vertical distance between the support of the cylindrical body and the researched section of the cylindrical shell;

l – horizontal arc distance between the supports, calculated though the simple expression:

$$l = \frac{2.\pi.r}{n_c}, \quad (11)$$

where:

r is the radius of the middle surface of the cylindrical body of the silo;

n_c – number of the columns /supports/ under of the cylindrical body.

Referring to fig. 7, that the effective width l_{eff} does not increase linearly, it can be concluded that the angle of distribution α is not constant in height. It has highest values at the base and decrease gradually by height.

4. Conclusion

The coefficient of behavior q for seismic impact does not have permanent value. It depends on the type and section of the used elements. When they are more powerful from the necessary, dissipating of seismic energy could not be done. While the standard БДС EN 1998-4:2006 [5] accepts possible decrease of the values of q , depending on dissipating elements, in Ordinance № РД-02-20-2 [6] the value is fixed to q = 3.33. Unfounded big value in the second document leads to the following:

- forces in the silo's elements due to earthquake are falsely low;
- tension and shear forces in anchor bolts, respectively in the foundations, are several times lower than the real ones.

The stiffeners placed above supports prevent local loss of stability of shell immediately above the place of application of concentrated forces. But it does not mean that in the zone above stiffeners, even if they have height bigger than the minimum, the loss of stability of the shell is prevented.

The difference between the value of the effective width l_{eff}, calculated through numerical study and determined according to the formula (5) from БДС EN 1993-1-5:2005 [1], is considerable for this silo. On that reason the author will not recommend to use formula (5) for determining of l_{eff} in cylindrical steel silos.

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