



### Research Article

## Influencing factors on effective width of compressed zone in joint column - cylindrical shell of steel silo

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### ABSTRACT

In order to ensure unloading of whole amount of stored product by gravity, steel silos are often placed on supporting structure. The simplest way to design these complicated facilities is to divide cylindrical shell on two parts in our minds - discretely supported ring beam and continuously supported shell above it. Obviously, to ensure continuously support of shell, bending stiffness of ring beam should be high. In European standard EN 1993-4-1, that concept is recognized but it keeps silence about recommended stiffness of ring beam. Another way to design is to know law of distribution of compressive axial stresses due to discrete column reactions  $R$ , by height of shell. Knowing it, we could calculate the effective width  $l_{eff}$  of distribution of compressive stresses on every level. Where effective width is equal to distance between discrete supports, there critical height of shell ends and above it cylindrical body is continuously supported. Unfortunately the above quoted standard EN 1993-4-1 does not give an information how to calculate  $l_{eff}$ . The questions here are; should we accept linear distribution of compressive forces by height? In addition, could we use directly the results of Whitmore (1952), where angle of distribution  $\alpha = 30^\circ$ ? Or, even to accept a far more brave opinion that  $\alpha = 45^\circ$ , used by many of the elder designers? Moreover, is value of angle  $\alpha$  constant or does it depend on various influencing factors?

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### 1. Introduction

Steel silos are often placed on supporting structure. The purpose is easily and completely unload of all stored product by gravity. For every project the supporting structure is different, depending on real conditions of exploitation. Traditionally in Bulgaria were designed and executed supporting structures composed by 4 columns and horizontal girders between them, see Fig. 1a). Lately, under the influence of foreign designers, we can see other types of supporting structures, composed by columns only and vertical braces between them, see Fig. 1b).

Independently of type of supporting structure - built from girders and columns, or from columns only, it causes concentrated meridional forces in the cylindrical body of the silo. As a result, the thin shell could loses local stability.

The simplest way to design steel silos is to divide in our minds cylindrical shell on two parts - discretely supported ring beam and continuously supported shell above it. Obviously, to ensure continuously support of shell, bending stiffness of ring beam should be high. In European standard EN 1993-4-1 that concept is recognized but it keeps silence about recommended stiffness of ring beam. Rotter (1985) suggested that a value of ratio between stiffness of cylindrical shell and ring beam  $\psi=0.25$  might be suitable for adoption in design.

Another approach to design steel silos is to know law of distribution of compressive axial stresses due to discrete column reactions  $R$ , by height of shell. Knowing the law, we could calculate effective width  $l_{eff}$  of distribution of compressive stresses on every level. Where effective width is equal to distance between discrete supports, there critical height of shell ends and above it cylindrical body is continuously supported. If the low is

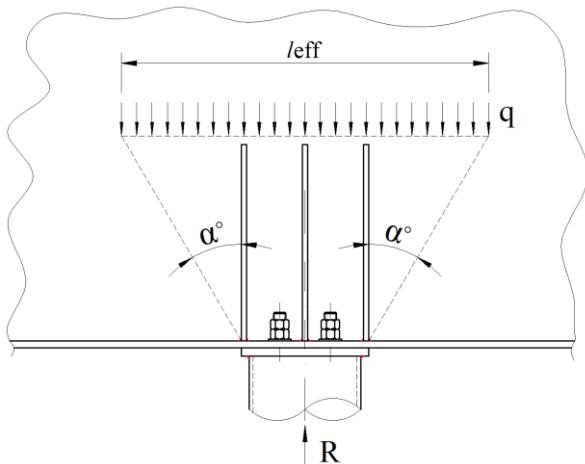
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simple, linear, we should know an angle  $\alpha$  of distribution to the vertical axis only, see Fig. 2. Values of the angle  $\alpha$  are of essential importance. Obviously as bigger would be the angle  $\alpha$  as bigger would be the effective width  $l_{\text{eff}}$ , respectively meridional stress  $\sigma_{x,Ed}$  will be smaller.



a) columns and horizontal girders between them  
b) columns with circular sections only vertical braces between them

**Fig. 1.** Variations of supporting structure under the silo.



**Fig. 2.** Angle  $\alpha$  of the distribution of compressive forces in the cylindrical shell and effective width  $l_{\text{eff}}$  if law is linear.

Unfortunately corresponding standards EN 1993-1-6:2007 and EN 1993-4-1:2007 do not give information about the values of the angle  $\alpha$  and respectively of  $l_{\text{eff}}$ . Maybe because they are focused on idea about ring beam. Only in the standard EN 1993-1-5:2006 we can find a formula for determining  $l_{\text{eff}}$  due to concentrated force in the plain of the steel plate. The equation is as following:

$$l_{\text{eff}} = s_e \sqrt{1 + \left(\frac{z}{n \cdot s_e}\right)^2}, \quad (1)$$

in which:

$$s_e = s_s + 2t_f, \quad (2)$$

$$n = 0.636 \sqrt{1 + \frac{0.878 \cdot a_{st,1}}{t_w}}, \quad (3)$$

where  $s_s$  is the width of a loading patch;  $t_f$  – thickness of flange where the force is applied;  $t_w$  - thickness web of the steel plate;  $z$  – distance from the flange to the studied section;  $a_{st,1}$  – surface of the gross cross section of the stiffeners, put on the length  $s_e$ .

Eq. (1) is valid when the inequality (4) is valid. In another case the contribution of the stiffeners should be ignored.

$$\frac{s_{st}}{s_e} \leq 0.5, \quad (4)$$

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

The question here is whether the formula (1) for plain plates is valid also for cylindrical shells such as the silos? Or to accept simple linear distribution, see Fig. 2 and use directly the results of Whitmore (1952), published in distant 1952, showing angle  $\alpha=30^\circ$ ? Or even to accept far more brave opinion that  $\alpha=45^\circ$  used by many of the elder designers?

## 2. Research of Joint Cylinder - Supporting Structure

In order to find the answer of all these questions above, the author developed several spatial research models of different silos. Software SAP 2000 v.14.2 is used in the research. All elements in numerical models of the facilities were introduced as shells with their real thickness. In order to reduce time for computer calculations, the supporting structure was replaced by unmovable hinge supports. They are 8 pcs. per silo, equally spaced by circumference of shell. Width of each support varies by silo.

Discharging conical hopper of silos is joined to the cylindrical shell at some distance above his lower end, see Fig. 3. This solution is classical. It permits to the girders or columns of the supporting structure to be placed exactly under the cylindrical shell, i.e. there will not be generated additional torsional or bending moments.

In order to study the effect of every one of influencing factors, research is conducted by different constructive solutions for the joints, as follow:

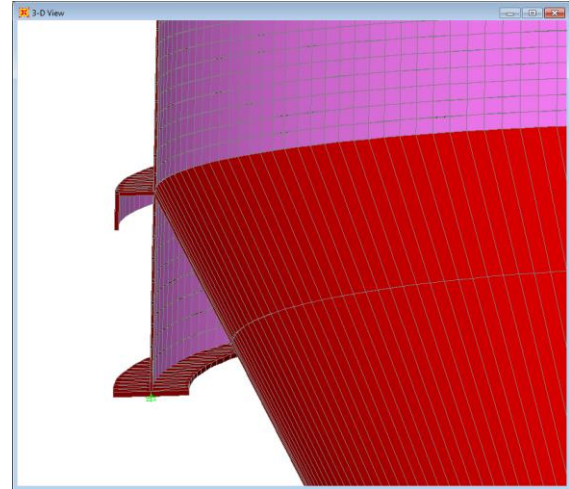
a) The silo is composed by cylindrical shell only, without a discharging conical hopper and without vertical stiffeners above supports, see Fig. 4a). In two separate cases, on vertical shell are applied loads as follow:

- Vertical load  $P_{we}(z)$  only, due to friction of a stored product to the shell;
- Initially the shell is loaded by radial pressure  $P_{he}(z)$ , caused by product. After that, in deformed by  $P_{he}(z)$  condition, is applied load  $P_{we}(z)$  due to the friction.

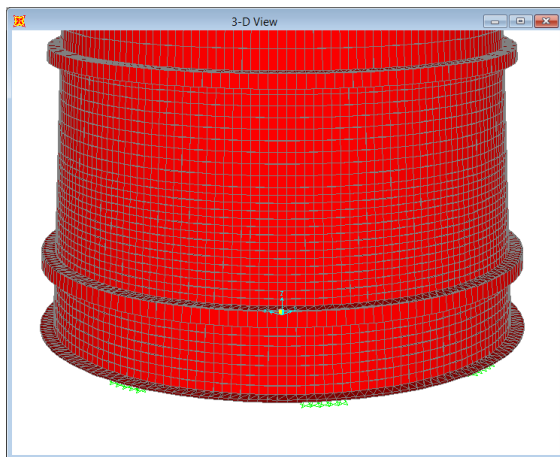
- b) Conical discharging hopper is added to cylindrical shell. There are not vertical stiffening elements, see Fig. 4b). In two separate cases, on vertical shell are applied the same loads, described above, in point a);
- c) The silo is composed by cylindrical shell without discharging hopper. Vertical stiffeners are placed on shell, above supports, see Fig. 4c). In two separate cases, on vertical shell are applied the same loads, described above, in point a);
- d) The silo is composed by cylindrical shell and a discharging hopper. Vertical stiffeners are placed above supports, see Fig. 4d). In two separate cases, on vertical shell are applied the same loads, described above, in point a);
- e) The silo is composed by cylindrical shell and a discharging conical hopper. Vertical stiffeners are placed above supports, see Fig. 4d). In two separate cases, on vertical shell and conical hopper are applied loads as follow:
- Vertical load  $P_{we}(z)$  on the shell and meridional load  $P_{te}(z)$  on the hopper. The loads are caused by friction of the product to the steel structure;
  - Initially the shell is loaded by radial pressure  $P_{he}(z)$  and respectively conical hopper - by normal pressure  $P_{ne}(z)$ .

After that, in the deformed by loads  $P_{he}(z)$  и  $P_{ne}(z)$  condition, the friction loads  $P_{we}(z)$  and  $P_{te}(z)$  are applied.

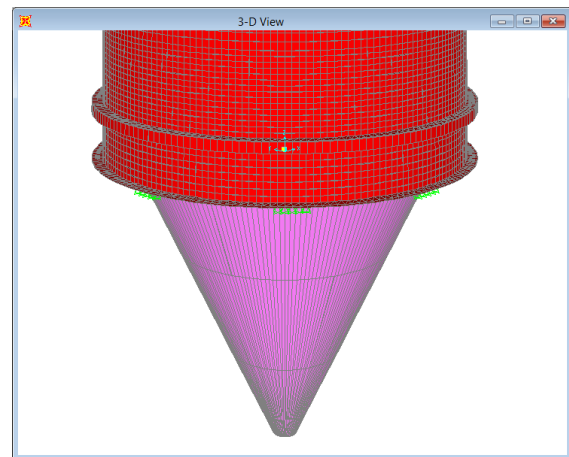
Loads  $P_{we}(z)$ ,  $P_{te}(z)$ , internal pressure  $P_{he}(z)$ ,  $P_{ne}(z)$ , friction loads  $P_{we}(z)$  and  $P_{te}(z)$ , are calculated for real stored products, according to standard EN 1991-4.



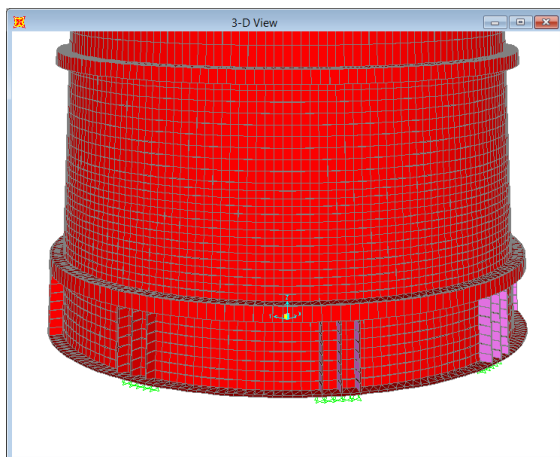
**Fig. 3.** Joint of cylindrical shell with a cone hopper.



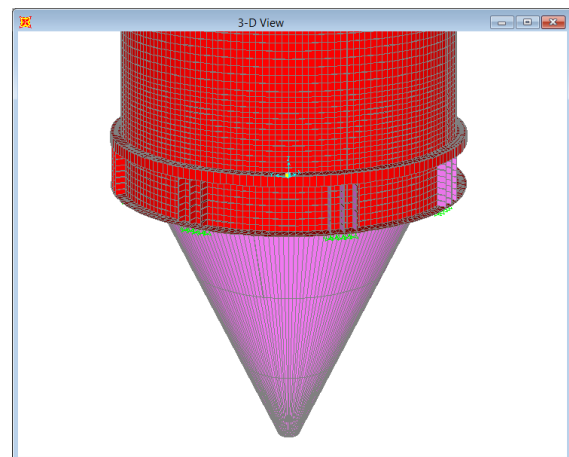
a) cylindrical shell only



b) cylindrical shell and a conical hopper, without vertical stiffening plates



c) cylindrical shell and vertical stiffeners



d) cylindrical shell and a conical hopper vertical stiffening plates were placed on shell

**Fig. 4.** Variants of researched silos and joints.

Normal meridional stresses  $\sigma_{x,Ed}$  caused by vertical load  $P_{we}(z)$ , are measured in points in first course, above stiffening ring. As we know value of the shell's thickness  $t$  and value of the reaction  $R$  in support, effective width  $l_{eff}$  can be calculated according to formula:

$$l_{eff} = \frac{R - \Delta F}{\sigma_{x,Ed} t}, \quad (5)$$

where  $R$  is a vertical reaction in the discrete support, see Fig. 2, caused by the vertical load  $P_{we}(z)$ , due to friction of a stored product to the shell;  $\sigma_{x,Ed}$  – normal meridional stress in the cylindrical shell, above joint between cylinder and conical hopper;  $t$  – thickness of the cylindrical steel shell in the joint cylinder - conical hopper;  $\Delta F$  – force, caused by the friction on the shell with a height  $\Delta h$ . It could be calculated by the formula:

$$\Delta F = \frac{2\pi r_i \Delta h \cdot P_{we}(z)}{n_s}, \quad (6)$$

where  $r_i$  is the radius of the internal surface of the cylindrical shell;  $\Delta h$  – the distance between the point of measurement of normal stresses  $\sigma_{x,Ed}$  and the joint between cylinder and conical hopper;  $n_s$  – number of supports in the cylindrical shell.

The angle  $\alpha$  of distribution of normal stresses in shell, due to reactions  $R$  in supports, could be calculated according to formula:

$$\alpha = \arctg\left(0.5 \frac{l_{eff} - b_s}{h}\right), \quad (7)$$

in which  $b_s$  is the width of the support;  $h$  – vertical distance between point of applying of reactions  $R$  and point of measurement of meridional normal stresses  $\sigma_{x,Ed}$ .

In all models is used steel S235, with a properties according to standard EN 10025-2:2004.

Buckling Analysis option is activated in used software SAP 2000 v.14.2. This option allows to determine reserve of bearing capacity  $k$  of the cylindrical shell before buckling, partly or entirely. Multiplication the result of total vertical reactions and the reserve of the bearing capacity  $k$  gives the value of the total meridional critical force  $\Sigma R_{cr}$  in which perfect shell will loses stability in the elastic condition. In this case meridional elastic critical buckling stress  $\sigma_{x,Rcr}$  could be calculated according to the formula:

$$\sigma_{x,Rcr} = \frac{\Sigma R_{cr}}{2\pi r t}, \quad (8)$$

where  $r$  is the radius of the middle surface of cylindrical shell.

Critical normal stresses  $\sigma_{x,Rcr}$  and calculated through them design meridional critical stresses  $\sigma_{x,Rd}$  give quantitative assessment of the influence of different solutions of base joints on the stability of the shell.

### 3. Results of the Research of Joint of Cylindrical Shell - Supporting Structure

#### 3.1. Silo № 1

volume  $V = 110 \text{ m}^3$   
 stored product - slack lime;  
 diameter  $D = 3\,492 \text{ mm}$ ;  
 height  $h_c = 10\,950 \text{ mm}$ ;  
 thickness of 1<sup>st</sup> course  $t_{s,1} = 6 \text{ mm}$ ;  
 width of supports -  $b_s = 240 \text{ mm}$ .

Case	Buckling factor $k$	Element which loses stability	$l_{eff}$ cm	$\alpha$ deg.
1	a)	1 <sup>st</sup> course, above the column, under the stiffening ring	104,1	33,8
	b)		104,1	33,8
2	a)	1 <sup>st</sup> course, above vertical stiffeners and stiffening ring	105,3	34,2
	b)		105,2	34,2
3	a)	1 <sup>st</sup> course, above vertical stiffeners and stiffening ring	75,1	23,1
	b)		75,1	23,1
4	a)	1 <sup>st</sup> course, above vertical stiffeners and stiffening ring	82,5	26,1
	b)		82,5	26,1
5	a)	1 <sup>st</sup> course, above vertical stiffeners and stiffening ring	82,5	26,1
	b)		82,5	26,1

#### 3.2. Silo № 2

volume  $V = 110 \text{ m}^3$   
 stored product - slack lime;  
 diameter  $D = 3\,492 \text{ mm}$ ;  
 height  $h_c = 10\,950 \text{ mm}$ ;  
 thickness of 1<sup>st</sup> course  $t_{s,1} = 4 \text{ mm}$ ;  
 width of supports -  $b_s = 240 \text{ mm}$ .

Case	Buckling factor $k$	Element which loses stability	$l_{eff}$ cm	$\alpha$ deg.
1	a)	1 <sup>st</sup> course, above the column, under the stiffening ring	107,1	34,8
	b)		107,1	34,8
2	a)	1 <sup>st</sup> course, above vertical stiffeners and stiffening ring	108,4	35,2
	b)		108,4	35,2
3	a)	1 <sup>st</sup> course, above vertical stiffeners and stiffening ring	80,8	25,4
	b)		80,8	25,4
4	a)	1 <sup>st</sup> course, above vertical stiffeners and stiffening ring	81,8	25,8
	b)		81,8	25,8
5	a)	1 <sup>st</sup> course, above vertical stiffeners and stiffening ring	81,9	25,8
	b)		81,8	25,8

#### 3.3. Silo № 3

volume  $V = 40 \text{ m}^3$   
 stored product - grained (fine) fraction of sand;  
 diameter  $D = 2\,500 \text{ mm}$ ;  
 height  $h_c = 8\,470 \text{ mm}$ ;  
 thickness of 1<sup>st</sup> course  $t_{s,1} = 6 \text{ mm}$ ;  
 width of supports -  $b_s = 230 \text{ mm}$ .

Case	Buckling factor $k$	Element which loses stability	$l_{eff}$ cm	$\alpha$ deg.	
1	a)	1 <sup>st</sup> course, above the column, under the stiffening ring	79,8	33,4	
	b)		79,8	33,4	
2	a)		81,9	34,3	
	b)		81,9	34,3	
3	a)		2 <sup>nd</sup> course, above vertical stiffeners and stiffening ring. 1 <sup>st</sup> course does not buckle	67,8	27,8
	b)			67,8	27,8
4	a)	73,0		30,3	
	b)	73,0		30,3	
5	a)	72,98		30,3	
	b)	72,98		30,3	

### 3.4. Silo No 4

volume  $V = 40 \text{ m}^3$   
 stored product - grained (fine) fraction of sand;  
 diameter  $D = 2\,500 \text{ mm}$ ;  
 height  $h_c = 8\,470 \text{ mm}$ ;  
 thickness of 1<sup>st</sup> course  $t_{s,1} = 4 \text{ mm}$ ;  
 width of supports -  $b_s = 230 \text{ mm}$ .

Case	Buckling factor $k$	Element which loses stability	$l_{eff}$ cm	$\alpha$ deg.	
1	a)	1 <sup>st</sup> course, above the column, under the stiffening ring	81,4	34,0	
	b)		81,4	34,0	
2	a)		83,4	34,9	
	b)		83,4	34,9	
3	a)		1 <sup>st</sup> course, above vertical stiffeners and stiffening ring	66,4	27,1
	b)			66,4	27,1
4	a)	71,9		29,8	
	b)	71,9		29,8	
5	a)	71,9		29,8	
	b)	71,9		29,8	

### 3.5. Silo No 5

volume  $V = 150 \text{ m}^3$   
 stored product - sand;  
 diameter  $D = 4\,500 \text{ mm}$ ;  
 height  $h_c = 8\,940 \text{ mm}$ ;  
 thickness of 1<sup>st</sup> course  $t_{s,1} = 8 \text{ mm}$ ;  
 width of supports -  $b_s = 350 \text{ mm}$ .

Case	Buckling factor $k$	Element which loses stability	$l_{eff}$ cm	$\alpha$ deg.	
1	a)	1 <sup>st</sup> course, above the column, under the stiffening ring	162,5	37,2	
	b)		162,5	37,2	
2	a)		163,3	37,4	
	b)		163,3	37,4	
3	a)		2 <sup>nd</sup> course, above vertical stiffeners and stiffening ring. 1 <sup>st</sup> course does not buckle	131,3	29,8
	b)			131,3	29,8
4	a)	140,1		32,1	
	b)	140,1		32,1	
5	a)	140,08		32,0	
	b)	140,07		32,0	

### 3.6. Silo No 6

volume  $V = 150 \text{ m}^3$   
 stored product - sand;  
 diameter  $D = 4\,500 \text{ mm}$ ;  
 height  $h_c = 8\,940 \text{ mm}$ ;  
 thickness of 1<sup>st</sup> course  $t_{s,1} = 5 \text{ mm}$ ;  
 width of supports -  $b_s = 350 \text{ mm}$ .

Case	Buckling factor $k$	Element which loses stability	$l_{eff}$ cm	$\alpha$ deg.	
1	a)	1 <sup>st</sup> course, above the column, under the stiffening ring	166,5	38,1	
	b)		166,5	38,1	
2	a)		166,1	38,0	
	b)		166,1	38,0	
3	a)		1 <sup>st</sup> course, above vertical stiffeners and stiffening ring	125,2	28,2
	b)			125,3	28,3
4	a)	135,9		31,0	
	b)	135,9		31,0	
5	a)	1 <sup>st</sup> course, between vertical stiffeners		135,9	31,0
	b)			135,9	31,0

Graphics in Fig. 5 show how the angle of distribution  $\alpha$  changes on the height of cylindrical shell. Points (joints) where the measurements were done, are situated in the 1<sup>st</sup> course, above the joint between cylinder – conical hopper.

Obviously the value of angle  $\alpha$  is not constant, it decrease by height. In other words, distribution of compressive forces by height is not linear. Zdravkov (2017a; 2017b) made similar conclusion in another research. Fortunately the effective width  $l_{eff}$  increases, see Fig. 6. Practical consequence is that if the values for  $l_{eff}$  are determined for a point close above the joint between cylinder – conical hopper, these values will be conservative, on side of safety for next manual (algebraic) calculations.

The above mentioned results show that, when vertical distance above base increases, the influence of various stiffening elements decrease. Values of  $\alpha$  and  $l_{eff}$  going to be practically the same on higher level.

Influence of the conical discharging hopper is positive in all researched silos, but its contribution is a small. The most probably it is due to:

- all studied models have stiffening ring on point where cylindrical shell and the hopper joint;
- all researched models have relatively close spaced 8 supports.

More significant is effect of using of vertical stiffening elements. They considerably increase the bearing capacity of cylindrical shell subjected to meridional pressure by patch loads. On other hand, angle of distribution  $\alpha$ , respectively the effective width  $l_{eff}$ , are bigger when the shells do not have stiffeners, compared with stiffened shells. For preliminary manual calculations, averaged angle  $\alpha$  could be accepted as follow:

- cylindrical shell, without vertical stiffeners above the discrete supports -  $\alpha = 34^\circ \div 36^\circ$ ;
- cylindrical shell with vertical stiffeners above the discrete supports -  $\alpha = 26^\circ \div 30^\circ$ .

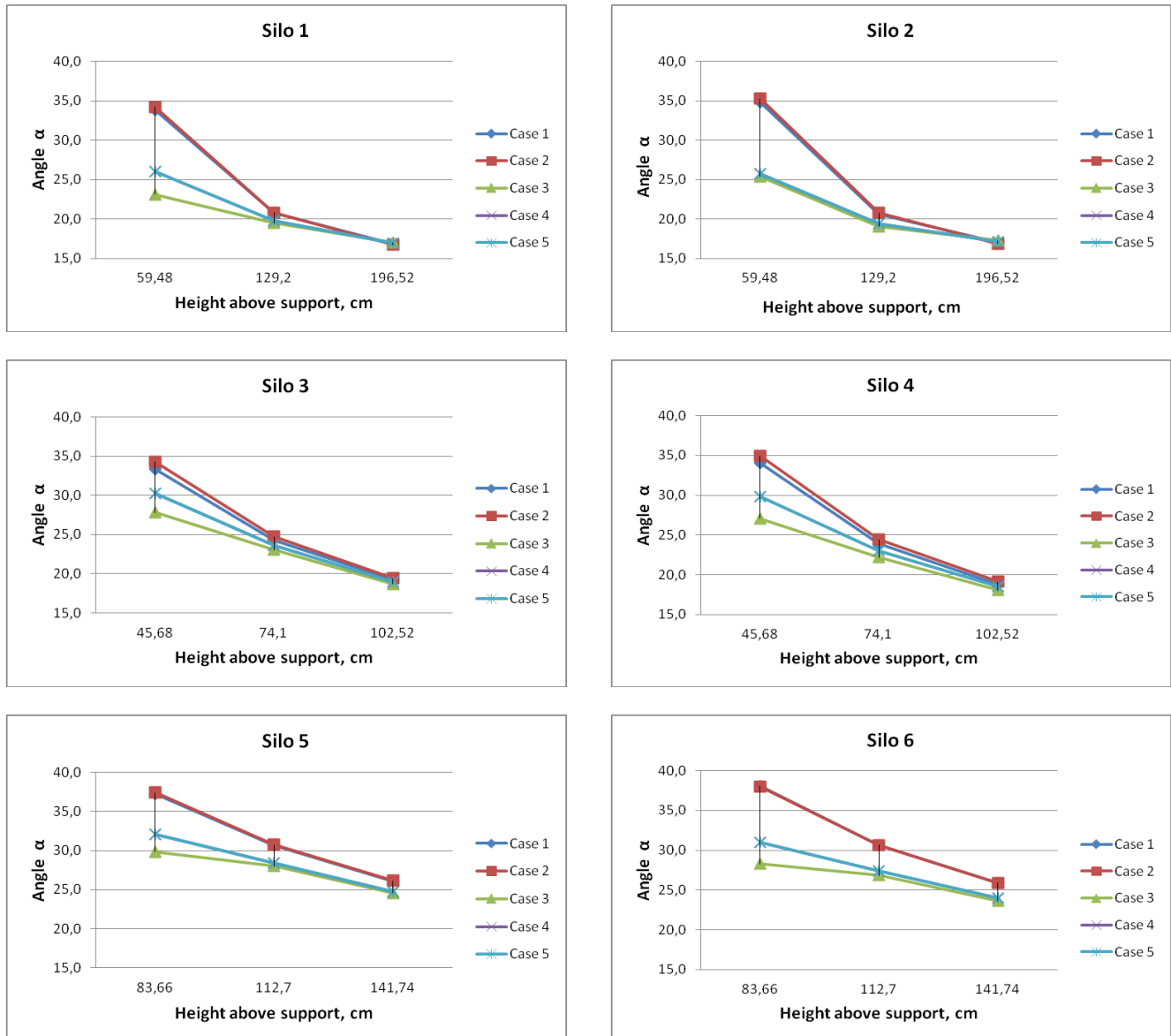


Fig. 5. Change of angle of distribution  $\alpha$  of normal stresses  $\sigma_{x,Ed}$  on the height of the cylindrical shell.

In studied there 6 models of silos, everyone with 5 variants, are not reported an averaged angle  $\alpha \approx 45^\circ$ . Maybe because all skirts of silos, respectively points of measurements, are relative height. Knoedel and Ummenhofer (2009) claim that value  $\alpha \approx 45^\circ$  can be obtained when the stiffening ring is enough rigid.

As we can notice, the distribution angle  $\alpha$  decreases when the ratio of  $D/t_s$  increases. Similar correlation is noticed by Knoedel and Ummenhofer (1998) in another research.

Internal pressures  $P_{ne}(z)$  and  $P_{ne}(z)$  do not have noticeable influence on angle  $\alpha$  and  $l_{eff}$  if the joint cylinder – conical hopper is made as is shown on the Fig. 3.

The courses of the researched here silos have various thickness. They decrease from lower to the higher parts, which is related with the different values of internal pressure on them. In some of the silos, like Silo N<sup>o</sup>3 and Silo N<sup>o</sup>4, buckles not the lowest 1<sup>st</sup> course, under which are the supports, but the upper 2<sup>nd</sup> course, which is thinner, see Fig. 7. It means that in silos with stepped wall

thickness is not sufficient to study only loaded by the concentrated meridional forces the lowest 1<sup>st</sup> course. The thinner upper courses also should be checked. And here again appears the problem for the value of the effective width  $l_{eff}$  in horizontal joint of the 1<sup>st</sup> and 2<sup>nd</sup> course and how to determine it correctly.

#### 4. Conclusions

Design of steel silos is a complicated and responsible task. The difficulties become more serious when the silos are elevated and supports beneath are discrete. One of most discussed question is how to calculate effective width  $l_{eff}$  of compressive meridional stresses above supports. Unfortunately the responsive standards EN 1993-1-6:2007 and EN 1993-4-1:2007 do not give an answer of this question. Obviously influencing factors are a lot of and could not be included in one formula. Therefore it is not correct shown in EN 1993-1-5:2006 formulae to be applied in silos.

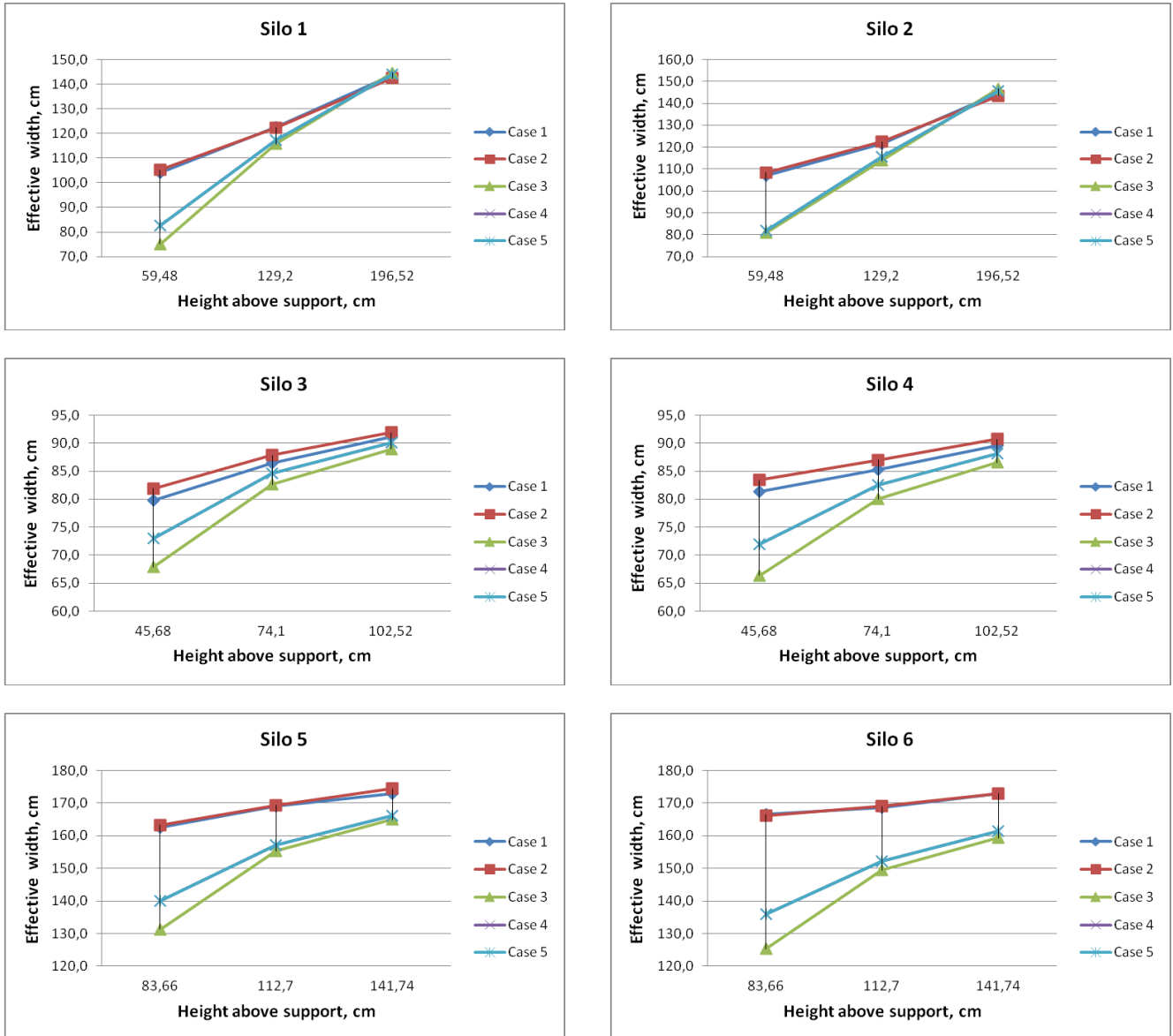


Fig. 6. Change of effective width  $l_{eff}$  of compressive stresses  $\sigma_{x,Ed}$  by height of the cylindrical shell.

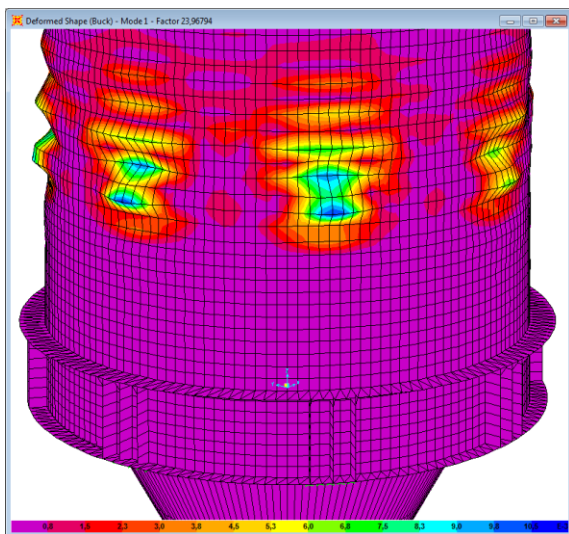


Fig. 7. The loss of stability in the cylindrical shell of the silos in thinner 2<sup>nd</sup> course.

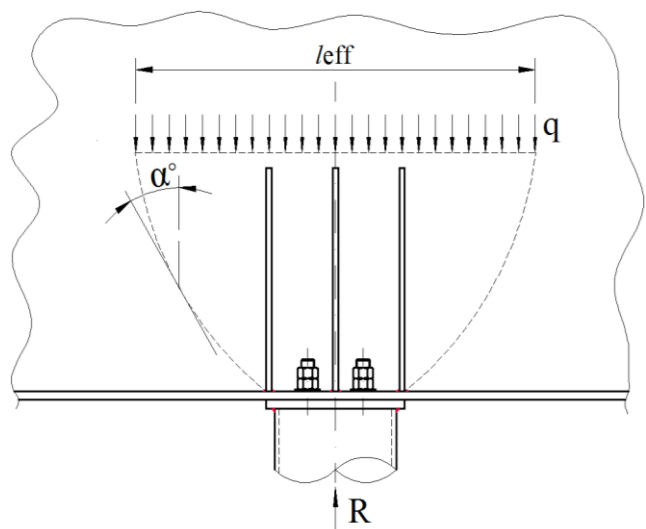


Fig. 8. Real distribution of compressive forces in the cylindrical shell and effective width  $l_{eff}$ .

The main outcomes from the current research of 6 silos on 8 supports are:

- The value of angle  $\alpha$  is not constant, it decreases by height. Real distribution of compressive forces looks like as is shown on Fig. 8.
- The vertical stiffeners above the supports have considerable influence of angle of distribution  $\alpha$  and effective width  $l_{\text{eff}}$ . For preliminary manual calculations, the averaged angle  $\alpha$  could be accepted as follow:
  - cylindrical shell, without vertical stiffeners above the supports -  $\alpha = 34^\circ \div 36^\circ$ ;
  - cylindrical shell with vertical stiffeners above the supports -  $\alpha = 26^\circ \div 30^\circ$ .
- The angle of distribution  $\alpha$  decreases when the ratio  $D/t_s$  increases.
- When there is a stiffening ring in joint cylindrical shell – hopper, the influence of hopper is very small.
- In joint cylinder - conical hopper as is shown on the Fig. 3, internal pressure does not have a noticeable effect on angle  $\alpha$  and  $l_{\text{eff}}$ .

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