CHEK OF SHELL OF CYLINDRICAL ABOVEGROUND STEEL TANKS FOR LOSS OF STABILITY

Lyubomir Angelov Zdravkov[1]

University of Architecture, Civil Engineering and Geodesy – Sofia

Abstract: *Aboveground steel tanks are spatial thin shell structures. Their main parts are bottom, shell and roof. The most responsible, the most long and heavy loaded structural element is the shell. It has to be ensured against:*

- *tearing from loads of stored liquid and internal pressure*
- *lose of stability in radial and longitudinal direction*

World known standards [2], [3], [4], [5] have differences in methodology about ensure the shell against lose of stability. In result we have divergences in necessary thickness of courses and / or necessity of intermediate wind girders on the shell.

Key words: *cylindrical steel tank, shell, wind, vacuum, standard, loss of stability, intermediate wind girders*

Steel vertical cylindrical tanks are spatial facilities with thin walls. Their main constructive elements are bottom, shell and roof. The shell is the most responsible, the most heavily loaded and loaded for the longest time. The shell must be secured against:

- tearing from the hydrostatical load of the stored product and over pressure. In this calculation steel strength is very important;
- stability loss in radial and meridian directions. The shell securing can be done through increase of thickness and courses and / or putting of intermediate stiffening rings.

1. GENERAL CONDITIONS

The cylindrical shells of vertical steel tanks are measured strength according to the membrane theory and there are not considerable differences in the established international standards. Regarding the shells' securing against loss of stability, approaches in above mentioned standards are different and it cause considerable differences in the results. By the same courses' thickness, depending on the particular standard, it will be necessary to increase thickness of some courses and/ or putting intermediate stiffening rings.

Having in mind high metal prices and unceasing requirements for shortage of periods of mounting one or another constructive solution may help to win or lose the tender.

2. STANDARDS

According to the normative documents in vigor in Bulgaria [1], the unique possibility to secure the course against the loss of stability is to increase the thickness of shell' courses. In the methodology shown in some foreign normative documents [2], [3], [4], [5], the shell securing in radial direction can be done also by putting of intermediate stiffening rings. In these standards separately equations for check of shell for radial and longitudinal loss of stability are not shown. Accepting [4] and [5] as our national standards, make interesting the question about initial conditions in the relevant normative documents and obtained results.

2.1 Instruction of Design of Steel Vertical Cylindrical Tanks from 100 to 10 000 m^3 volume, Energoproekt [1].

This instruction is based on the Russian Theoretical School. Almost all tanks in Bulgaria were designed and constructed according to the formulations of this school.

I shall mention here only its main formulations.

[1] Lyubomir Angelov Zdravkov, PhD, Civil Engineer, UACG, Sofia 1046, №1 "Hristo Smirnensky" str., floor. 7 office 733, e-mail: zdravkov_fce@uacg.bg

a) stability check in meridian (shell' longitudinal) direction.

During the uniform pressure parallel to the longitudinal direction, the stability check shall be done according to the following formula:

$$\sigma_1 \le \gamma_c . \sigma_{cr1}, \qquad (1)$$

where:

σ_1 is design summary normal pressure in the shell in longitudinal direction;

σ_{1cr} – critical stress during the pressure by axis (meridian) in the shell;

$\gamma_c = 1$ – coefficient for condition of shell's work during the check for loss of stability.

Critical stress shall be calculated according to the formula:

$$\sigma_{cr1} = C.E.\left(\frac{t_{s,i}}{r}\right), \qquad (2)$$

where:

C is a coefficient reporting geometrical imperfection in the shell;

E – Young modulus of the steel;

r – internal radius of the tank' shell.

For modern conditions of prefabrication and mounting of steel tanks, values of coefficient C shall be calculated according to the formulas:

$$C = 0{,}04 + 40.\frac{t_{s,i}}{r}, \quad 400 \le \frac{r}{t_{s,i}} < 1220 \qquad (3)$$

$$C = 0{,}085 - \frac{r}{100000.t_{s,i}}, \quad 1220 \le \frac{r}{t_{s,i}} \le 2500 \qquad (4)$$

б) check for loss of stability in radial direction

During the uniform pressure perpendicular to the shell, the stability check shall be done according to the following formula:

$$\sigma_2 \le \gamma_c . \sigma_{cr2}, \qquad (5)$$

where:

σ_2 - is calculated summary pressure in the shell in radial direction;

σ_{cr2} – – critical stress during the uniform side pressure in the shell;

$\gamma_c = 1$ – coefficient for condition of shell's work during the check for stability loss.

The ring pressure stress $\boldsymbol{\sigma_2}$ in the shell are caused by following loads in radial direction:

- vacuum in the tank - p_v;
- wind

The wind pressure on the tank surface is uneven and it could be conditionally accepted as evenly distributed on the shell' circumference $\boldsymbol{w_{eq}}$ by multiplying maximum values of wind influence **max** $\boldsymbol{w}$ and coefficient for correction $\boldsymbol{k_w}$:

$$w_{eq} = k_w.\max\ w, \qquad (6)$$

in which according to our instruction [1] ,

$$k_w = 0{,}5 \ . \qquad (7)$$

Caused by these loads summed up ring normal pressure is calculated according to the formula:

$$\sigma_2 = \psi_c\left(w_{eq} + p_v\right).\frac{r}{t_{s,i}}, \qquad (8)$$

During the stability check in the Steel Vertical Tanks we have to consider its various thickness of shell courses. When there is an external radial wind pressure and vacuum by the shell height, a semi wave is formed and on this reason in this case the various thickness shall be replaced by its average value $\boldsymbol{t_{s,m}}$.

$$\sigma_{cr2} = 0{,}55.E.r.\frac{\sqrt{\left(\frac{t_{s,m}}{r}\right)^3}}{H_{ef}}, \quad (9)$$

where:
$t_{s,m}$ is arithmetic mean of shell thickness for the shell with permanent thickness $t_{s,m} = t_s$);
H_{ef} - effective shell height included in stability check.

In the calculations for check of stability in the radial direction it is recommended to work with effective length $\boldsymbol{H_{ef}}$, equal to the distance from upper supporting ring to the center of gravity of the section of the shell part with changeable thicknesses instead of using the all shell height.

In the shell with various thicknesses of shell courses the $\boldsymbol{H_{ef}}$ is calculated with the formula:

$$H_{ef} = H - \Delta h, \quad (10)$$

in which:

$$\Delta h = \frac{h_c}{3}, \quad (11)$$

where:
H is height of tank shell;
h_c – distance from the lower shell edge to the end of changeable thickness.

c) check for shell stability during the simultaneous action of longitudinal and radial stress.

During the simultaneous action from the uniform pressure parallel to the longitudinal (by the loads on the roof) and external uniform pressure perpendicular to the side shell surface (for instance vacuum in empty tank) the stability is checked according to the formula as follow:

$$\frac{\sigma_1}{\sigma_{cr1}} + \frac{\sigma_2}{\sigma_{cr2}} \leq 1, \quad (12)$$

Formula (12) is on way of security comparing with punctual problem solution for stability of cylindrical shell by 2D stress condition.

2.2 API Std 650, Welded Steel Tanks for Oil Storage [2]

The maximum admissible height $\boldsymbol{H_p}$ for the not stiffened tank shell is calculated as follows:

$$H_{e,i} = h_{s,i}.\sqrt{\left(\frac{t_{s,\min}}{t_{s,i}}\right)^5} \quad (13)$$

$$H_E = \sum_{i=1}^{n} H_{e,i} \quad (14)$$

$$H_p = 9{,}47.t_{s,\min}.\sqrt{\left(\frac{t_{s,\min}}{D}\right)^3}.\left(\frac{190}{v_w}\right)^2, \quad (15)$$

where:
D is tank diameter, m;
$t_{s,min}$ – thickness of the upper tank course, mm;
$t_{s,i}$ – thickness of the ***i*** –th course in the shell tank mm;
$h_{s,i}$ – height of the ***i*** –th course in the shell tank, m;
$H_{e,i}$ – equivalent height of the ***i*** –th course in the shell tank with thickness $t_{s,min}$, m;
H_E – equivalent height of the whole shell tank with thickness $t_{s,min}$, m;
H_p – maximum admissible height of the not reinforced tank shell, m;
v_w – speed of blast of wind when they are reported at every 3 seconds, km/h .

The mounting of additional intermediate stiffening rings is not necessary if it is observed:

$$H_p \geq H_E \quad (16)$$

The methodology described herewith is valid when:
- shell tank temperature $t \leq 93\ ^0$C;
- internal vacuum in the tank $p_v \leq 2{,}4$ mbar;

2.3 BS 2654:1989 [3] и **EN 14015:2004** [4]

The maximum admissible height $\boldsymbol{H_p}$ for the not stiffened tank shell is calculated as follows:

$$H_{e,i} = h_{s,i}.\sqrt{\left(\frac{t_{s,\min}}{t_{s,i}}\right)^5} \qquad (17)$$

$$H_E = \sum_{i=1}^{n} H_{e,i} \qquad (18)$$

$$K = \frac{95000}{3{,}563.v_w^2 + 580.p_v} \qquad (19)$$

$$H_p = K.\sqrt{\frac{t_{s,\min}^5}{D^3}}\ , \qquad (20)$$

where:

v_w – speed of blast of wind when they are reported at every 3 seconds, m/s .

The other parameters in the formula are the same as mentioned in (13), (14) and (15).

The mounting of additional stiffening rings is not necessary if it is observed condition (16).

The methodic is valid when:
- shell tank temperature $t \leq 100\ ^0$C;
- internal vacuum in the tank $p_v \leq 5$ mbar;
- when there is a combination of vertical loads snow + internal vacuum or movable load+ internal vacuum which do not exceed 1,2 kN/m^2 .

2.4 EN 1993-4-2: Design of Steel Structures, Part 4-2: Tanks [5]

Maximum of the height $\boldsymbol{H_p}$ of the not stiffened with supplementary intermediate stiffening rings shell shall be calculated according to the formula:

$$H_p = 0{,}46.\left(\frac{E}{p_{n,Ed}}\right).\sqrt{\left(\frac{t_{s,\min}}{r}\right)^5}.K.r\ , \qquad (21)$$

where:

$t_{s,min}$ – thickness of the most thin course in the shell. Usually it is the upper course;

$p_{n,Ed}$ –maximum of the design value of the sum from internal vacuum and directed inside wind pressure calculated according to the formula:

$$p_{n,Ed} = \psi_c.(w_{eq} + p_v)\ , \qquad (22)$$

in which:

w_{eq} is equivalent wind pressure calculated according to (5);

p_v – maximum of the design value of the vacuum in the tank;

ψ_c –coefficient of combination between two or more loads active for short time;

K – coefficient, according to the formula:

$K = 1$ – when the meridian effort in the shell is tension; (23)

$$K = \left\{1 - \left[2{,}67.\left(\frac{\sigma_{x,Ed}}{E}\right).\left(\frac{r}{t_{s,i}}\right).\left(1 + \frac{1}{54}.\left(\frac{r}{t_{s,i}}\right)^{0{,}72}\right)\right]^{1{,}25}\right\}^{0{,}8} \qquad (24)$$

when the meridian effort in the shell is caused by pressure,

where:

$\sigma_{x,Ed}$ is meridian stress caused by pressure in the shell in $\boldsymbol{i}$ – the course, with thickness $\boldsymbol{t_{si}}$;

$t_{s,i}$ – sheets thickness in the ***i*** – th shell course.

Equation (21) is not valid when normal longitudinal stress in the shell is caused by pressure except when the following two conditions are performed:

$$\frac{r}{t_{s,i}} \geq 200 \quad (25)$$

$$f_y \geq 1{,}15.E.\left(\frac{r}{l}\right).\sqrt{\left(\frac{t_{s,i}}{r}\right)^3}, \quad (26)$$

where:

l – distance between shell top angle and intermediate stiffening rings or intermediate stiffening rings and the bottom.

The height of the transformed by height shell H_E shall be calculated according to (14).

Putting of supplementary intermediate stiffening rings on the tank shell is not necessary when the condition (16) is performed.

The methodology described herewith is valid when the internal vacuum inside in the tank is equal to $p_v \leq 8{,}5$ mbar.

3. CALCULATED MODEL OF VERTICAL STEEL TANK AND LOADING

During the check for loss of stability according to different standards are treated tanks with volumes V=5000 m^3, V=10000 m^3, V=20000 m^3, V=30000 m^3. They have dome (self supported) roof. The impacts on them are chosen in the manner that they match the limiting conditions for application of used here standards.

- density of the stored product– ρ = 0,85 t/m^3
- sum of the weight of roof's cover plates and the construction – g_r = 0,75 kN/m^2
- snow loading on the shell roof– S = 0,9 kN/m^2
- tank internal (negative) pressure – p_v = 0,22 kN/m^2
- speed of the wind blasts when they are reported at every three seconds– v_w = 160 km/h
- corrosion allowance of shell sheets is not envisaged.

Necessary thickness of shell sheets is calculated in the following sequence:

- strength – to be able to bear loading by stored product and overpressure;
- calculated thickness shall not be less than constructive minimum .
- loss of stability – shell courses are secured against loss of stability according to the methodology described in [1]

The checks for stability loss according to different standards are performed when:

- normative values of loads on the tank;
- coefficient of loads combination ψ_c = 1,0

4. RESULTS

4.1 Thank with volume V = 5 000 m^3

- main geometrical dimensions - D = 22,80 m and H = 11,95 m;
- shell has 6 courses with height $h_{s,i}$ and thickness $t_{s,i}$ according to the tables;
- steel for shell – S235;

Necessary course thickness according to [1]

course	$t_{s,i}$ mm	σ_1 kN/cm^2	$\sigma_{1,cr}$ kN/cm^2	$\sigma_1 / \sigma_{1,cr}$	k_z	σ_2 kN/cm^2	$\sigma_{2,cr}$ kN/cm^2	$\sigma_2 / \sigma_{2,cr}$	$\sigma_1/\sigma_{1,cr}+\sigma_2/\sigma_{2,cr}$
6	7	0,168	0,886	0,190	1,049	0,143	0,184	0,778	0,967
5	7	0,184	0,886	0,207	1	0,136	0,184	0,742	0,949

4	7	0,199	0,886	0,225	1	0,136	0,184	0,742	0,966
3	7	0,215	0,886	0,242	1	0,136	0,184	0,742	0,984
2	7	0,230	0,886	0,260	1	0,136	0,184	0,742	1,002
1	8	0,217	1,043	0,208	1	0,119	0,184	0,649	0,857

Reduced shell height

course	$h_{s,i}$ m	$t_{s,min}$ mm	$t_{s,i}$ mm	$H_{e,i}$ m
6	1,992	7	7	1,992
5	1,992	7	7	1,992
4	1,992	7	7	1,992
3	1,992	7	7	1,992
2	1,992	7	7	1,992
1	1,990	7	8	1,425
			$H_E = \Sigma H_{e,i} =$	**11,385**

Necessity of intermediate rings mounting

	API 650	**BS 2654**	**EN 14015**	**EC–3, 4.2**
H_E, m	11,385	11,385	11,385	11,385
H_p, m	15,902	13,607	13,607	10,805

4.2 Tank with volume V = 10 000 m^3

- general geometrical dimensions - D = 28,55 m and H = 16,75 m;
- the shell has 7 courses with height $h_{s,i}$ and thickness $t_{s,i}$ according to the tables below;
- steel for shell – S235;

Necessary course thickness according to [1]

course	$t_{s,i}$ mm	σ_1 kN/cm^2	$\sigma_{1,cr}$ kN/cm^2	$\sigma_1 / \sigma_{1,cr}$	k_z	σ_2 kN/cm^2	$\sigma_{2,cr}$ kN/cm^2	$\sigma_2 / \sigma_{2,cr}$	$\sigma_1/\sigma_{1,cr}+\sigma_2/\sigma_{2,cr}$
7	8	0,186	0,790	0,235	1,169	0,175	0,229	0,761	0,996
6	8	0,204	0,790	0,259	1,109	0,166	0,229	0,722	0,981
5	9	0,200	0,915	0,219	1,049	0,139	0,229	0,607	0,826
4	9	0,219	0,915	0,240	1	0,133	0,229	0,579	0,818
3	10	0,216	1,040	0,208	1	0,120	0,229	0,521	0,729
2	11	0,215	1,165	0,185	1	0,109	0,229	0,474	0,658
1	13	0,201	1,461	0,137	1	0,092	0,229	0,401	0,538

Reduced shell height

course	$h_{s,i}$ m	$t_{s,min}$ mm	$t_{s,i}$ mm	$H_{e,i}$ m
7	2,392	8	8	2,392
6	2,392	8	8	2,392
5	2,392	8	9	1,782
4	2,392	8	9	1,782
3	2,392	8	10	1,369
2	2,392	8	11	1,079
1	2,390	8	13	0,710
			$H_E = \Sigma H_{e,i} =$	**11,506**

Necessity of intermediate rings mounting

	API 650	**BS 2654**	**EN 14015**	**EC–3, 4.2**
H_E, m	11,506	11,506	11,506	11,506
H_p, m	15,844	13,557	13,557	10,385

4.3 Tank with volume V = 20 000 m^3
- general geometrical dimensions - D = 37,15 m and H = 19,14 m;
- the shell has 8 courses with height $h_{s,i}$ and thickness $t_{s,i}$ according to the tables below;;
- steel for shell – S275;

Necessary course thickness according to [1]

course	$t_{s,i}$ mm	σ_1 kN/cm^2	$\sigma_{1,cr}$ kN/cm^2	$\sigma_1 / \sigma_{1,cr}$	k_z	σ_2 kN/cm^2	$\sigma_{2,cr}$ kN/cm^2	$\sigma_2 / \sigma_{2,cr}$	$\sigma_1/\sigma_{1,cr}+\sigma_2/\sigma_{2,cr}$
8	11	0,177	0,847	0,209	1,228	0,174	0,228	0,762	0,971
7	11	0,195	0,847	0,231	1,169	0,165	0,228	0,725	0,956
6	11	0,214	0,847	0,253	1,109	0,157	0,228	0,688	0,941
5	11	0,233	0,847	0,275	1,049	0,148	0,228	0,651	0,926
4	12	0,232	0,943	0,246	1	0,130	0,228	0,569	0,815
3	12	0,251	0,943	0,266	1	0,130	0,228	0,569	0,835
2	14	0,234	1,135	0,206	1	0,111	0,228	0,487	0,694
1	16	0,224	1,347	0,166	1	0,097	0,228	0,427	0,593

Reduced shell height

course	$h_{s,i}$ m	$t_{s,min}$ mm	$t_{s,i}$ mm	$H_{e,i}$ m
8	2,392	11	11	2,392
7	2,392	11	11	2,392
6	2,392	11	11	2,392
5	2,392	11	11	2,392
4	2,392	11	12	1,924
3	2,392	11	12	1,924
2	2,392	11	14	1,309
1	2,390	11	16	0,937
			$H_E = \Sigma H_{e,i}$ =	**15,662**

Necessity of intermediate rings mounting

	API 650	**BS 2654**	**EN 14015**	**EC–3, 4.2**
H_E, m	15,662	15,662	15,662	15,662
H_p, m	23,670	20,253	20,253	15,964

4.4 Tank with volume V = 30 000 m^3
- general geometrical dimensions - D = 37,15 m and H = 19,14 m;
- the shell has 8 courses with height $h_{s,i}$ and thickness $t_{s,i}$ according to the tables below;;
- steel for shell – S275;

Necessary course thickness according to [1]

course	$t_{s,i}$ mm	σ_1 kN/cm^2	$\sigma_{1,cr}$ kN/cm^2	$\sigma_1 / \sigma_{1,cr}$	k_z	σ_2 kN/cm^2	$\sigma_{2,cr}$ kN/cm^2	$\sigma_2 / \sigma_{2,cr}$	$\sigma_1/\sigma_{1,cr}+\sigma_2/\sigma_{2,cr}$
8	12	0,197	0,727	0,271	1,228	0,196	0,271	0,722	0,992
7	12	0,216	0,727	0,296	1,169	0,186	0,271	0,687	0,983
6	12	0,234	0,727	0,322	1,109	0,177	0,271	0,651	0,974
5	13	0,235	0,806	0,292	1,049	0,154	0,271	0,569	0,861
4	13	0,254	0,806	0,315	1	0,147	0,271	0,542	0,858
3	15	0,239	0,962	0,248	1	0,128	0,271	0,470	0,718
2	17	0,230	1,118	0,205	1	0,113	0,271	0,415	0,620
1	20	0,214	1,379	0,155	1	0,096	0,271	0,353	0,508

Reduced shell height

course	$h_{s,i}$ m	$t_{s,min}$ mm	$t_{s,i}$ mm	$H_{e,i}$ m
8	2,392	12	12	2,392
7	2,392	12	12	2,392
6	2,392	12	12	2,392
5	2,392	12	13	1,958
4	2,392	12	13	1,958
3	2,392	12	15	1,369
2	2,392	12	17	1,001
1	2,390	12	20	0,666
			$H_E = \Sigma H_{e,i}$ =	**14,129**

Necessity of intermediate rings mounting

	API 650	BS 2654	EN 14015	EC–3, 4.2
H_E, m	14,129	14,129	14,129	14,129
H_p, m	21,562	18,449	18,449	13,745

5. CONCLUSIONS

a) for western standards [2], [3], [4], [5] reduced shell height $\boldsymbol{H_E}$ is calculated by one and the same way. Difference between them is determination of maximum assumed distance $\boldsymbol{H_p}$ between shell stiffening elements;

b) the biggest assumed distance $\boldsymbol{H_p}$ between shell stiffening rings is calculated according to the methodology of API Std 650, the smallest - according to the EN 1993-4-2.

It is underlined in the Standard [5] that mentioned there methodology sometime is very conservative (especially concerning very short courses);

c) it is a paradox that when using the actual European standards EN 14015:2004 and EN 1993-4-2, calculated maximum distance $\boldsymbol{H_p}$ values are different and differences are serious. In the example for tank with volume V = 30000 m^3 calculated difference is Δ_E = 34,2 % ;

d) necessary thickness of shell courses, calculated with the shown in [1] methodology for securing against loss of stability, are calculated with intermediate values between the results from [4] and [5].

Literature:

1. Инструкция за проектиране на СВЦР с обем от 100 до 10 000 m^3 за системата на енергетиката, Енергопроект, 1995.
2. API Std 650, Welded Steel Tanks for Oil Storage, June 2007.
3. BS 2654:1989, Manufacture of vertical steel welded non-refrigerated storage tanks with but – welded shells for the petroleum industry.
4. EN 14015:2004, Specification for the design and manufacture of site built, vertical, cylindrical, flat-bottomed, above ground, welded, steel tanks for the storage of liquids at ambient temperature and above, November 2004.
5. EN 1993-4-2: Design of Steel Structures, Part 4-2: Tanks, February 2007.