ГОДИШНИК НА УНИВЕРСИТЕТА ПО АРХИТЕКТУРА, СТРОИТЕЛСТВО И ГЕОДЕЗИЯ
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INFLUENCE OF THE ROOF STRUCTURE ON THE FORCES IN TOP ANGLE UNDER WIND LOADING

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ABSTRACT

When determining the required cross-section of the top angle of a fixed roof tank, standards BS 2654:1989, EN 14015:2004, EN 1993-4-2:2007 and API650, 12th Edition, specify the same type of formulas. They do not take into account the wind load on the cylindrical shell and the influence of the roof structure. Can they really be ignored? Using the spatial models of five designed and in service steel tanks, the author has found answers to these questions.

1. Introduction

When determining the required cross-section of the top angle of a tank with a fixed roof, according to standards BS 2654:1989 [1] and EN 14015:2004 [2] the formula below should be used:

$$A \geq \frac{50 p_c r^2}{S_c . \operatorname{tg}(\theta)}, \tag{1}$$

where A is the necessary section of the top angle, mm^2;

p_c – the internal pressure, which is equal to the design value of the overpressure less the weight of the roof cover plates, mbar;

$r = D/2$ – the radius of the tank's shell, m;

S_c = 120 MPa – the allowable value of the compressive stress for all steel grades;

θ – the slope of roof meridian at the roof to shell connection.

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In addition, the cross-section of the top angle should be checked for tensile forces in it due to external loads and/or negative pressure in the tank.

The formula for determining the required cross-section of the top angle, written in standard EN 1993-4-2:2007 [3], has the view:

$$A \geq \frac{p_{v,Ed}.r^2}{2.f_{y,d}.\mathrm{tg}(\theta)}, \tag{2}$$

where $p_{v,Ed}$ is the maximum vertical component of the distributed design load, including the dead weight of the supporting structure;

$f_{y,d}$ – design value of the yield strength of the steel. It is determined by the formula:

$$f_{y,d} = \frac{f_y}{\gamma_{M0}}, \tag{3}$$

where f_y is the characteristic value of the yield strength of the steel;

γ_{M0} – coefficient of safety by material.

In standard API650, 12th Edition [4], the necessary cross-section of the top angle should be accounted by the expression:

$$A \geq \frac{p.D^2}{8F_a.\mathrm{tg}(\theta)}, \tag{4}$$

where p is the biggest combination of the loads, acting from the top of the tank to the bottom;

D – the nominal diameter of the tank's shell;

F_a – the least allowable tensile stress for the materials in the roof to shell connection. It should be calculated by the formula;

$$F_a = 0.6f_y \tag{5}$$

After comparing the formulas written above, the following conclusions can be drawn:

a) they have the same structure, which doesn't surprise given the global leading role of American standards for the design of oil facilities and their universal borrowing;

b) they do not take into account the influence of the roof structure;

c) all formulas do not consider the wind load on the shell.

It can be added that in the cited standards [1-4] only the minimum required cross-section of the top angle is sought. Other geometric characteristics, such as the second moment of area and/or resistance, are neglected. So the author wondered how credible this acceptance was? And does the roof structure really not affect the forces in the top angle? He will find answers to his questions in this article.

2. The research

To find answers to the above questions, the author conducted a numerical study of five designed and mounted steel vertical cylindrical tanks, the main dimensions of which are shown in Table 1. Using a program for spatial analysis are modelled their shell, top angles and roof structure. The shell is modelled by multiple shell elements, and the roof structure and top angle are by frame elements, see fig. 1. The radial girders are a pin joined to the top angle. The roof cover plates of the studied tanks are not welded to the structure and therefore it is not modelled.

Table 1. Dimensions of the studied tanks

Tank №	1	2	3	4	5
Location	Czech Republic	Bulgaria	La Reunion	The Netherlands	Belgium
Volume, m^3	500	5,000	15,000	25,000	40,000
Diameter D, mm	7,200	22,800	36,000	41,500	40,000
Height H, mm	12,995	11,940	14,400	20,000	32,000
Thickness t_s, mm	5	5	9	8	10
Type of the roof	cone	dome	dome	dome	dome
Slope in top angle°	11°	24.025°	24.12°	21.82°	22.62°
Section of the top angle	UPN140	UPN180	- 28x500	- 20x700	- 25x460
Number of the radial girders	12	32	48	52	56
Section of the radial girders	IPN100	IPN140	IPN200	IPE240	IPE240

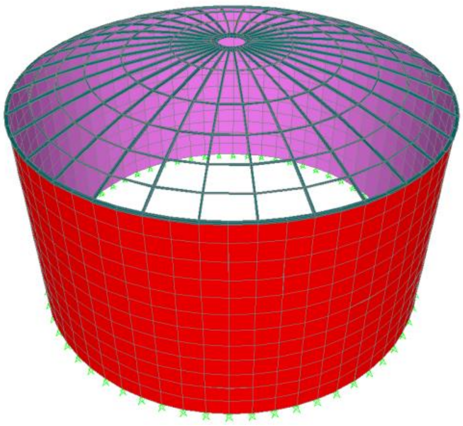

Fig. 1. Numerical model of an aboveground steel tank

All tank’s elements are made of steel S235, having mechanical characteristics according to standard EN 10025-2:2004 [5].

All five tanks are designed for wind speed v = 45 m/s. Unlike the research of *Zeybek* [6-7], here the uneven wind pressure on the tank’s shell is replaced by an equivalent evenly distributed load $q_{w,eq}$, see fig. 2.

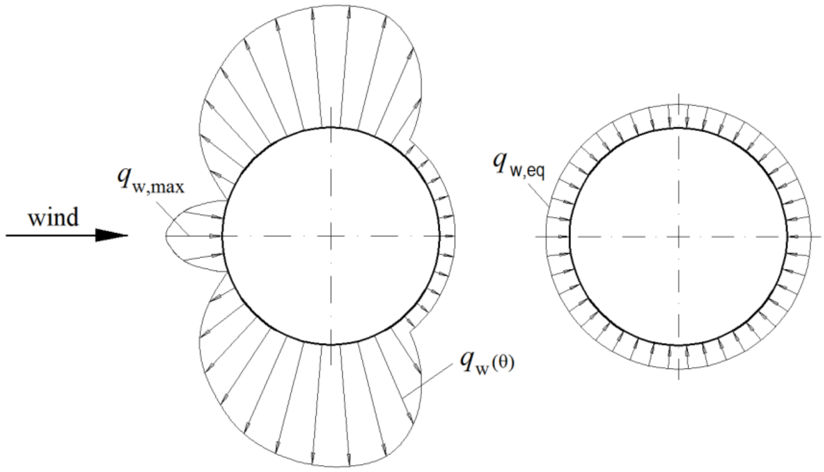

Fig. 2. Wind loads on tank's shell

The value of the equivalent uniform wind load is calculated by the expression:

$$q_{w,eq} = k_w \cdot q_{w,max}, \tag{6}$$

where according to standard EN 1993-4-2:2007 [3]:

$$k_w = \frac{1}{C_w}, \tag{7}$$

in which C_w is accounted by:

$$C_w = \frac{2.2}{1 + 0.1\sqrt{C_b \frac{r}{l}\sqrt{\frac{r}{t_s}}}} \geq 1.0\,, \tag{8}$$

where t_s is the thinnest shell's course in the considered section of the shell, between stiffening rings;

l – the distance between stiffening rings;

C_b = 1,0 – in tanks with fixed roofs or open-top tanks, but with a rigid stiffening ring close to the top.

According to standard EN 1993-1-6:2007 [8], the coefficient k_w should be within the limits $0.65 \leq k_w \leq 1.0$.

The maximum value of wind load on the shell $q_{w,max}$, see fig.2, is calculated by the formula:

$$q_{w,max} = \frac{1}{2}\rho \cdot v^2 = \frac{1}{2} \cdot 1.25 \cdot 45^2 = 1265.6\ N/m^2, \tag{9}$$

where $\rho = 1.25$ kg/m^3 is the written in EN 1991-1-4 [9] air density;

v = 45 m/s – design wind speed.

The reference European standard for wind load EN 1991-1-4 [9] does not have a methodology for determining the equivalent uniform wind load on the roof. For this reason, the author has adopted the one, specified in API650, 12th Edition [4] expression:

$$q_{w,\mathrm{r},eq} = 1.44\left(\frac{3.6 \cdot v}{190}\right)^2 = 1.44\left(\frac{3.6 \cdot 45}{190}\right)^2 = 1.046\ kN/m^2, \quad (10)$$

where $3.6v$ is the design wind speed in km/h.

By $q_{w,r,eq}$ can be calculated tensile forces R in the plane of roof cover plates at its connection to the shell, caused by the wind suction on the roof plates:

$$R = q_{w,\mathrm{r},eq}\frac{\pi D^2}{4}\frac{1}{\pi D}\frac{1}{\sin(\theta)} = q_{w,\mathrm{r},eq}\frac{D}{4\sin(\theta)}\ . \quad (11)$$

From there, the horizontal component of tensile force R in the top angle will be:

$$R_h = R \cdot \cos(\theta) = q_{w,\mathrm{r},eq}\frac{D}{4\,\mathrm{tg}(\theta)} \quad (12)$$

Axial force in the top angle will be:

$$N_{Ed} = \frac{R_h.D}{2} = q_{w,\mathrm{r},eq}\frac{D^2}{8\,\mathrm{tg}(\theta)}, \quad (13)$$

whence the origin of formulae (1), (2) and (4) becomes clear.

In addition to the wind load, the five tanks were researched for the load of the elements' self-weight, snow on the roof and negative pressure. The load combination has the view:

$$q_1 = \begin{cases} (g_{r,pl} + g_{r,str}).\gamma_{G,sup} + s.\gamma_Q + \psi_0.p_v.\gamma_Q \\ (g_{\mathrm{r,pl}} + g_{r,str}).\gamma_{G,sup} + p_v.\gamma_Q + \psi_0.s.\gamma_Q \end{cases}, \quad (14)$$

where $g_{r,pl}$ is the characteristic value of the load from the self-weight of the roof plates;
$g_{r,str}$ - the characteristic value of the load from the self-weight of the roof structure;
s – the characteristic value of the snow load on the roof;
p_v – the characteristic value of negative pressure into steel tank;
$\gamma_{G,sup} = 1.35$ – partial factor for permanent loads, when they act unfavourably;
$\gamma_Q = 1.5$ – partial factor for temporary loads;
$\psi_0 = 0.6$ – coefficient for combination of temporary loads.

The top angle of the tanks has a section as is shown in Table 1. In the process of the research, top angles in the numerical models are positioned once horizontally, with a large bending stiffness in the horizontal plane, and a second time – vertically, with the smallest bending stiffness in the horizontal plane.

3. Results

The results of the study, in kN and kN.m, are as follow:

Tank №1 with a volume V = 500 m^3
$C_w = 1.7287$

k_w = 0.65
$q_{w,eq}$ = 0.822 kPa
R_h = 9.686 kN/m

Forces in the horizontally positioned section UPN140

Element	Force due to:	N_{Ed}	$M_{Ed,o}$	$M_{Ed,m}$
top angle	wind on the shell	-0.3821	-0.0033	0.00166
	wind on the roof	-21.452	-0.3015	-0.0213
radial girder	wind on the shell	-0.021		-0.0034
	wind on the roof	-1.201		-0.1909
	combination q_1 ↓	-25.164		2.261

Forces in the vertically positioned section UPN140

Element	Force due to:	N_{Ed}	$M_{Ed,o}$	$M_{Ed,m}$
top angle	wind on the shell	-0.386	-0.0028	0.001403
	wind on the roof	-21.652	-0.2723	-0.0359
radial girder	wind on the shell	-0.01848		-0.0029
	wind on the roof	-1.0363		-0.1647
	combination q_1 ↓	-21.987		2.77

In calculations according to formula (13), force in the top angle from wind load on the roof has a value N_{Ed} = -34,936 kN

Bending moment $M_{Ed,o}$ is accounted in the top angle, at the joint with the radial girders.
Bending moment $M_{Ed,m}$ is accounted:
a) in the top angle, in the middle between the joints with the radial girders
b) in radial girder, in the closest field to the top angle.

Accounted in the radial girders axial forces N_{Ed} and bending moments $M_{Ed,m}$ refer to the closest to the top angle fields.

Tank №2 with a volume V=5,000 m^3
C_w = 1.313
k_w = 0.762
$q_{w,eq}$ = 0.963 kPa
R_h = 13.376 kN/m

Forces in the horizontally positioned section UPN180

Element	Force due to:	N_{Ed}	$M_{Ed,o}$	$M_{Ed,m}$
top angle	wind on the shell	-2.005	-0.0051	0.0029
	wind on the roof	-92.898	-1.7	0.5445
radial girder	wind on the shell	-0.024		-0.018

	wind on the roof	-2.017		-1.039
	combination q_1 ↓	-89.361		4.4122

Forces in the vertically positioned section UPN180

Element	Force due to:	N_{Ed}	$M_{Ed,o}$	$M_{Ed,m}$
top angle	wind on the shell	-2.029	-0.004	0.0038
	wind on the roof	-92.82	-1.6778	0.551
radial girder	wind on the shell	-0.025		-0.0174
	wind on the roof	-1.887		-0.9722
	combination q_1 ↓	-84.762		6.6878

In calculations according to formula (13), force in the top angle from wind load on the roof has a value N_{Ed} = -152.48 kN

Tank №3 with a volume V = 15,000 m^3
C_w = 1.259
k_w = 0.794
$q_{w,eq}$ = 1.005 kPa
R_h = 21.026 kN/m

Forces in the horizontally positioned plate - 28x500

Element	Force due to:	N_{Ed}	$M_{Ed,o}$	$M_{Ed,m}$
top angle	wind on the shell	-4.03	-0.00644	0.0064
	wind on the roof	-279.2	-2.88	0.96
radial girder	wind on the shell	-0.0406		-0.0211
	wind on the roof	-2.81		-1.46
	combination q_1 ↓	-155.17		4.526

Forces in the vertically positioned plate - 28x500

Element	Force due to:	N_{Ed}	$M_{Ed,o}$	$M_{Ed,m}$
top angle	wind on the shell	-4.321	-0.0046	0.0046
	wind on the roof	-278.573	-2.132	0.848
radial girder	wind on the shell	-0.0346		-0.0179
	wind on the roof	-2.229		-1.156
	combination q_1 ↓	-129.32		18.0381

In calculations according to formula (13), force in the top angle from wind load on the roof has a value N_{Ed} = -378.46 kN

Tank №4 with a volume V = 25,000 m³
C_w = 1.274
k_w = 0.785
$q_{w,eq}$ = 0.993 kPa
R_h = 27.105 kN/m

Forces in the horizontally positioned plate - 20x700

Element	Force due to:	N_{Ed}	$M_{Ed,o}$	$M_{Ed,m}$
top angle	wind on the shell	-7.809	-0.352	0.1793
	wind on the roof	-421.46	-14.164	6.913
radial girder	wind on the shell	-0.12		-0.0608
	wind on the roof	-5.889		-2.993
	combination q_1 ↓	-203.037		11.117

Forces in the vertically positioned plate - 20x700

Element	Force due to:	N_{Ed}	$M_{Ed,o}$	$M_{Ed,m}$
top angle	wind on the shell	-7.393	-0.0532	0.1065
	wind on the roof	-359.21	-3.28	4.196
radial girder	wind on the shell	-0.1151		-0.0585
	wind on the roof	-5.155		-2.6205
	combination q_1 ↓	-203.23		11.01

In calculations according to formula (13), force in the top angle from wind load on the roof has a value N_{Ed} = -562.43 kN

Tank №5 with a volume V = 40,000 m³
C_w = 1.439
k_w = 0.695
$q_{w,eq}$ = 0.879 kPa
R_h = 25.104 kN/m

Forces in the horizontally positioned plate - 25x460

Element	Force due to:	N_{Ed}	$M_{Ed,o}$	$M_{Ed,m}$
top angle	wind on the shell	-5.51	-0.0125	0.0125
	wind on the roof	-355.58	-3.439	1.004
radial girder	wind on the shell	-0.083		-0.0392
	wind on the roof	-5.334		-2.531
	combination q_1 ↓	-158.99		9.856

Forces in the vertically positioned plate - 25x460

Element	Force due to:	N_{Ed}	$M_{Ed,o}$	$M_{Ed,m}$
top angle	wind on the shell	-5.976	-0.0089	0.0089
	wind on the roof	-358.636	-3.166	1.041
radial girder	wind on the shell	-0.0696		-0.0331
	wind on the roof	-4.18		-1.983
	combination q_1 ↓	-131.97		22.84

In calculations according to formula (13), force in the top angle from wind load on the roof has a value N_{Ed} = -500.156 kN

4. Conclusions

The following conclusions can be drawn from the study:

a) the forces in the top angle, caused by the wind load on the cylindrical shell, are smaller and can be neglected;

b) the presence of a roof structure reduces the values of the internal forces in the top angle, as in the case of small tanks the difference may exceed 60%;

c) with one exception, the change of the second moments of area while maintaining the cross-section of the top angle leads to minimal changes in the values of the internal forces in it;

d) reduction of the second moments of area of the top angle while maintaining their cross-section leads to smaller axial forces in the radial girders, but more significant bending moments in them. From the point of view of achieving a lighter roof structure, it is appropriate for the section of the top angle to have a large bending stiffness in the horizontal plane.

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