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High strength steel application for welded stiffened plate structure of a fixed storage tank roof

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Abstract

High strength steel application for a welded fixed roof of a vertical storage tank is studied. The load from snow and from a 150 mm soil layer is considered. The roof is constructed from stiffened sectorial trapezoidal plate elements and radial beams. The stiffeners are of halved rolled I-section and the radial beams are constructed from rolled I-sections. To find the minimum cost solution the thickness of the base plate, the position, number and size of circumferential stiffeners, the size of radial beams as well as the number of sectors is varied. The distances of stiffeners are equidistant. In the cost function the cost of material, welding and painting is taken into account.

Keywords: *High strength steel, Stiffened plates, Fixed tank roof, Structural optimization*

1. Introduction

The economic design of a tank roof made of normal steel (yield strength f_y = 235 MPa) has been treated in our previous study [1].

The roofs constructed from welded stiffened plate sectorial elements are suitable for carrying the load of a 150 mm soil layer used to decrease the evaporation loss of stored liquid (kerosene).

The adaptation and development of effective mathematical optimization methods makes it possible to use an optimum design system for the economic (minimum cost) design of welded structures [2]-[6].

In the present study this economic design method is applied for a fixed storage tank roof constructed from stiffened plate sectorial elements and radial beams made of high strength steel of yield strength f_y = 690 MPa.. In the optimization procedure the optimum values of the following structural characteristics are sought: number and size of radial rolled I-section-beams, the thickness and the equidistant circumferential stiffening of the deck plate elements.

The roof is designed to carry the snow load as well as the load of 150 mm thick soil layer mentioned earlier. In a previous study it has been shown that the most economic stiffening can be designed with the equidistant stiffener distances with variable base plate thickness. The necessary base plate thicknesses are calculated from the condition that the deck plate part should fulfil the bending stress constraint.

2. Loads

Snow load is calculated according to Eurocode 1 [7]

$$s = \mu_1 C_e C_t s_k \tag{1}$$

$\mu_1 = 0.8, C_e = C_t = 1, s_k = 1.25$ kN/m^2, thus s = 0.8x1.25 = 1.0 kN/m^2.

Soil load: 150 mm thick layer of a humid light sand of bulk density 17 kN/m^3

p_s = 0.15x17 = 2.55 kN/m^2.

Snow and soil together $s + p_s$ = 3.55 kN/m^2, multiplied by a safety factor of 1.5

p = 5.325x10^{-3} N/mm^2.

Safety factor for the self mass of sectorial elements is 1.35, and for self mass of radial beams is 1.1.

3. Numerical data (Figures 1,2,3)

Storage tank diameter D = 20 m, inner ring beam diameter d = 1.0 m, roof angle $\alpha_0 = 15^0$.

Length of a radial beam L = 9500/cos 15^0 = 9835 mm. The characteristic sizes of a trapezoidal deck plate x_A = 618, x_B = 10353 mm. α = 180/ω, where ω = 10, 12, 14, 16 is the number of sectors. The length of stiffeners is calculated for given ω: $y_i = x_i f_\omega$, where $f_\omega = 2\tan\alpha$.

It should be mentioned that the sectorial plate is treated as a trapezoidal one, the curved part is neglected but the height of the trapezoid is taken equal to the length of radial beam (9835 mm).

4. Design of sectorial stiffened deck plate elements

4.1 Calculation of base plate thicknesses

These thicknesses are determined using the condition that the maximum normal stress due to bending in each plate element between stiffeners should not be larger than the yield stress. The maximum bending moment in a deck plate element is calculated approximately for a simply supported rectangular plate according to Timoshenko [8]

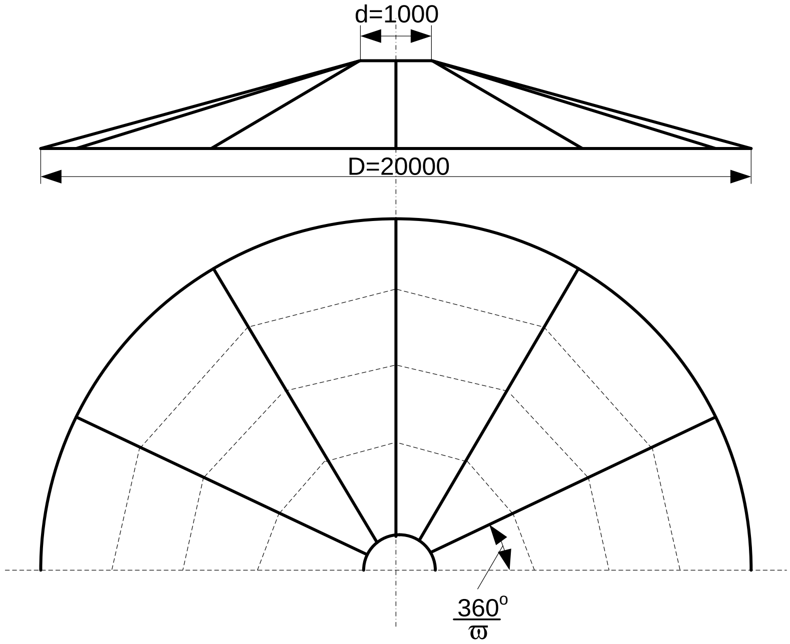

Figure 1. A fixed tank roof

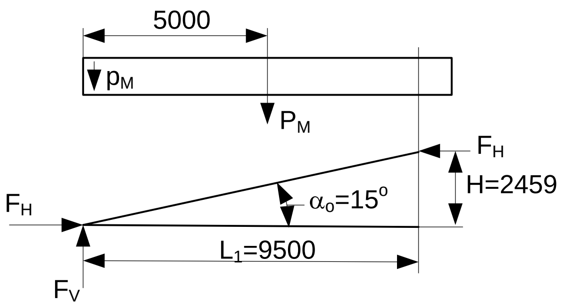

Figure 2. Forces from the roof load

$$M_{i\max} = \beta_i p a_i^2 \qquad (2)$$

where a_i is the smaller side length and β_i is given in function of $b_i / a_i \geq 1$ in Table 1.

Table 1. Bending moment factors

b/a	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0	3.0	4.0	5.0	>5
$10^4\beta$	479	554	627	694	755	812	862	908	948	985	1017	1189	1235	1246	1250

The values of Table 1 are approximated by the following expressions

$$\beta_i = \beta_{\xi i} \quad \text{if} \quad b_0 \leq x_i f_\omega \quad \text{i.e.} \quad b_0 = \frac{9835}{n} = x_i - x_{i-1} \qquad (3)$$

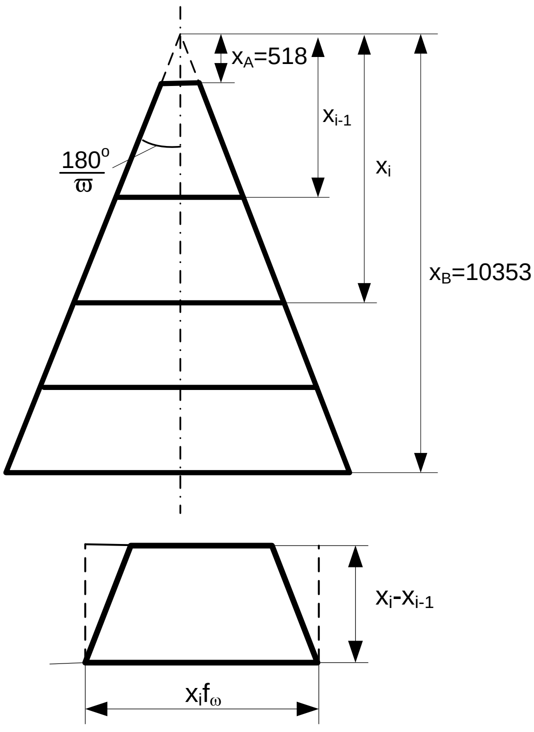

Figure 3. Stiffener distances and a part of the base plate

$$\beta_i = \beta_{\eta i} \quad \text{if} \quad x_i - x_{i-1} > x_i f_\omega \qquad (4)$$

$$\beta_{\xi i} = a_0 + b\xi_i + c\xi_i^2 + d\xi_i^3 + e\xi_i^4 \qquad \xi_i = \frac{x_i f_\omega}{x_i - x_{i-1}} \qquad (5)$$

$$\beta_{\eta i} = a_0 + b\eta_i + c\eta_i^2 + d\eta_i^3 + e\eta_i^4 \qquad \eta_i = \frac{x_i - x_{i-1}}{x_i f_\omega} \qquad (6)$$

a_0 = -0.08022658, b = 0.180443, c = -0.061636, d = 0.009575, e = -0.00056537

From equation

$$M_{i\max} = f_y t_i^2 / 6 \tag{7}$$

t is the deck plate thickness, f_y = 690 MPa is the yield stress,

$$t_i = b_0 \sqrt{\frac{6\beta_i p}{f_y}} \quad \text{if} \quad b_0 \le x_i f_\omega \tag{8}$$

$$t_i = \sqrt{\frac{6\beta_i p x_i^2 f_\omega^2}{f_y}} \quad \text{if} \quad b_0 \ge x_i f_\omega \tag{9}$$

It should be noted that in this calculation the transverse bending moments are neglected but the plate elements are calculated as simply supported and it is also neglected that their edges are partially clamped.

4.2 Design of stiffeners

A stiffener is subject to a bending moment

$$M_{s.i-1} = \frac{p b_0 x_{i-1}^2 f_\omega^2}{8} \tag{10}$$

The cross-sectional area of a stiffener of halved rolled I-section and the effective plate part

$$A_{s.i-1} = A_{i-1} + s_{e.i-1} t_{e.i-1}, \; s_{e.i-1} = \frac{s_i + s_{i-1}}{2}, \; t_{e.i-1} = \frac{t_i + t_{i-1}}{2},$$
$$A_{i-1} = \frac{h_{1.i-1} t_{w.i-1}}{2} + b_{i-1} t_{f.i-1}, \quad h_{1.i-1} = h_{i-1} - 2t_{f.i-1} \tag{11}$$

The effective plate width is calculated as the sum of the half effective widths of the neighbouring plate parts. The effective width is calculated according to the Eurocode 3 [9]

$$s_i = \rho_i b_0, \; \rho_i = \frac{\lambda_i - 0.22}{\lambda_i^2} \text{ if } \lambda_i \ge 0.673 \tag{12a}$$

$$\lambda_i = \frac{b_0}{56.8 \varepsilon t_i}, \quad \varepsilon = \sqrt{\frac{235}{f_y}} \tag{12b}$$

$$\rho_i = 1 \text{ if } \lambda_i \le 0.673 \tag{12c}$$

$$s_{e.i-1} = \frac{s_{i-1} + s_i}{2}, t_{e.i-1} = \frac{t_{i-1} + t_i}{2} \tag{12d}$$

$E = 2.1 \times 10^5$ MPa is the elastic modulus.
The required section modulus is given by

$$W_{0.i-1} = \frac{M_{s.i-1}}{f_y} \tag{13}$$

The distances of the gravity centres G_i

$$z_{G.i-1} = \frac{1}{A_{s.i-1}} \left[\frac{h_{1.i-1} t_{w.i-1}}{2} \left(\frac{h_{1.i-1}}{4} + \frac{t_{e.i-1}}{2} \right) + b_{i-1} t_{f.i-1} \left(\frac{h_{i-1} + t_{e.i-1} - t_{f.i-1i}}{2} \right) \right] \tag{14}$$

and
$$z_{G1.i-1} = \frac{h_{i-1} + t_{e.i-1} - t_{f.i-1}}{2} - z_{G.i-1} \tag{15}$$

the moments of inertia

$$I_{y.i-1} = s_{e.i-1} t_{e.i-1} z_{G.i-1}^2 + \frac{h_{1.i-1}^3 t_{w.i-1}}{96} + \frac{h_{1.i-1} t_{w.i-1}}{2} \left(\frac{h_{1.i-1}}{4} + \frac{t_{e.i-1}}{2} - z_{G.i-1} \right)^2 +$$

$$I_{y.i-1} = \ldots + b_{i-1} t_{f.i-1} \left(\frac{h_{i-1} + t_{e.i-1} - t_{f.i-1}}{2} - z_{G.i-1} \right)^2 \tag{16}$$

The section moduli are defined as

$$W_{y.i-1} = \frac{I_{y.i-1}}{z_{G.i-1}} \tag{17}$$

where $z_{G.i-1}$ is the greater of $z_{G.i-1}$ and $z_{G1.i-1}$.
The required stiffener profile is selected from Table 2 to fulfil the stress constraint

$$W_{y.i-1} \ge W_{0.i-1} \tag{18}$$

Table 2. UB profiles used for halved rolled i-section stiffeners

UB profile	h	b	t_w	t_f
127x76x13	127.0	76.0	4.0	7.6
152x89x16	152.4	88.7	4.5	7.7

4.3 Cost calculation for a sectorial stiffened plate element

A whole sectorial plate element is assembled from the base plate parts, n-1 stiffeners and 2 radial edge plates.
In the case when all the base plate parts are of the same thickness (t_{min} = 4 mm), the welding of the base plate is made from 7 elements (considering the maximum fabricated plate width of 1500 mm) using SAW (Submerged Arc Welding) butt welding. The length of the plate (9835 mm) is divided into 7 parts, the total length of welds is

$$L_{w1} = 32613 f_\omega \tag{19}$$

and the welding time is

$$T_p = 1.3 C_{w1} t^2 L_{w1} \tag{20}$$

where

$k_w = 1.0\$/\min, \Theta_1 = 2, \rho = 7.85x10^{-6}$ kg/mm^3, C_{w1} = 0.1559x10^{-3},

$$V_1 = \frac{10353 + 518}{2} 9835 f_\omega t = 53.4581x10^6 f_\omega t \quad (21)$$

It should be mentioned that these formulae are different when the base plate thicknesses are different (the case of $n = 4$)

Time of welding of the base plate to the edge radial plates as well as to the inner and outer ring beam

$$T_{p1} = 1.3 C_{w2} a_w^2 L_p, L_p = f_\omega (518 + 10323) + 2x9835 \quad (22)$$

Welding of stiffeners to the base plate and to two edge radial plates to complete a sectorial plate element using fillet welds:

$$K_{ws} = k_w \left(\Theta_2 \sqrt{(n+9)\rho V_2} + T_p + T_{p1} + \sum_i T_i + T_s \right) \quad (23)$$

where n-1 is the number of stiffeners, $\Theta_2 = 3$,

$$V_2 = V_1 + V_s + \sum_i V_{sti} \quad (24)$$

the volume of the edge radial plates is

$$V_s = 2x9835 h_s t_s \quad (25)$$

t_s = 6 mm, h_s equals to the maximum stiffener height + 30 mm, volume of a stiffener is

$$V_{stif.i-1} = A_{stif.i-1} x_{i-1} f_\omega, A_{stif.i-1} = \frac{h_{1.i-1} t_{w.i-1}}{2} + b_{i-1} t_{f.i-1} \quad (26)$$

welding time for a stiffener is

$$T_i = 1.3 C_{w2} a_w^2 2 x_{i-1} f_\omega + 1.3 C_{w3} a_w^2 2 (2h_{1.i-1} + 4b_{i-1}) \quad (27)$$

where $C_{w2} = 0.2349x10^{-3}, C_{w3} = 0.7889x10^{-3}$

are the constants for SAW and SMAW (Shielded Metal Arc Welding) fillet welds, respectively,
a_w = 3 mm, the second part is multiplied by 2, since the welding position is mainly vertical.
The time of welding of the two edge radial plates to the base deck plate is

$$T_s = 1.3 C_{w3} a_w^2 L_s, L_s = 2x9835 \quad (28)$$

Material cost of a complete sectorial element is

$$K_{m1} = k_m \rho V_2, k_m = 1.0 \text{ \$/kg.} \quad (29)$$

The painting cost of a complete sectorial element is

$$K_{P1} = k_P S, k_P = 28.8x10^{-6} \text{ \$/mm}^2, \quad (30)$$

$$S = S_s + \sum_i S_{stif} + 2x53.4581x10^6 f_\omega \quad (31)$$

$$S_s = 2x9835 h_s \quad (32)$$

$$S_{stif.i-1} = (h_{1.i-1} + 2b_{i-1}) x_{i-1} f_\omega \quad (33)$$

The total cost of a sectorial element is

$$K_s = K_{m1} + K_{ws} + K_{P1} \quad (34)$$

5. Design of radial beams

Radial beams of rolled I-section are subject to bending and compression. The load is calculated from snow and soil load (p_M), the mass of a sectorial element (q) and the self mass ($\rho_1 A_r$):

$p = p_M + q + \rho_1 A_r$, $q = \rho_1 V_2 / L_1$, ρ_1 = 7.85x10^{-5} N/mm^3,

L_1 = 9500 mm. (35)

The maximum bending moment is

$$M_{r\max} = p L_1^2 / 8 \quad (36)$$

The compression force is

$$N_H = F_M \cos 15^0 + F_V \sin 15^0 \quad (37)$$

where

$F_V = P_M = pL/2, L = 20000$ mm, H = 9500sin15^0 = 2459 mm (38)

$$F_H = \frac{1}{H}\left[F_V L_1 - P_M \left(\frac{L}{2} - \frac{d}{2} \right) \right] = 2.0333 P_M \quad (39)$$

Stress constraint for bending and compression according to Eurocode 3 [9]

$$\frac{N_H}{\chi A_r f_{y1}} + k_{yy} \frac{M_{r\max}}{W_y f_{y1}} \le 1 \quad (40)$$

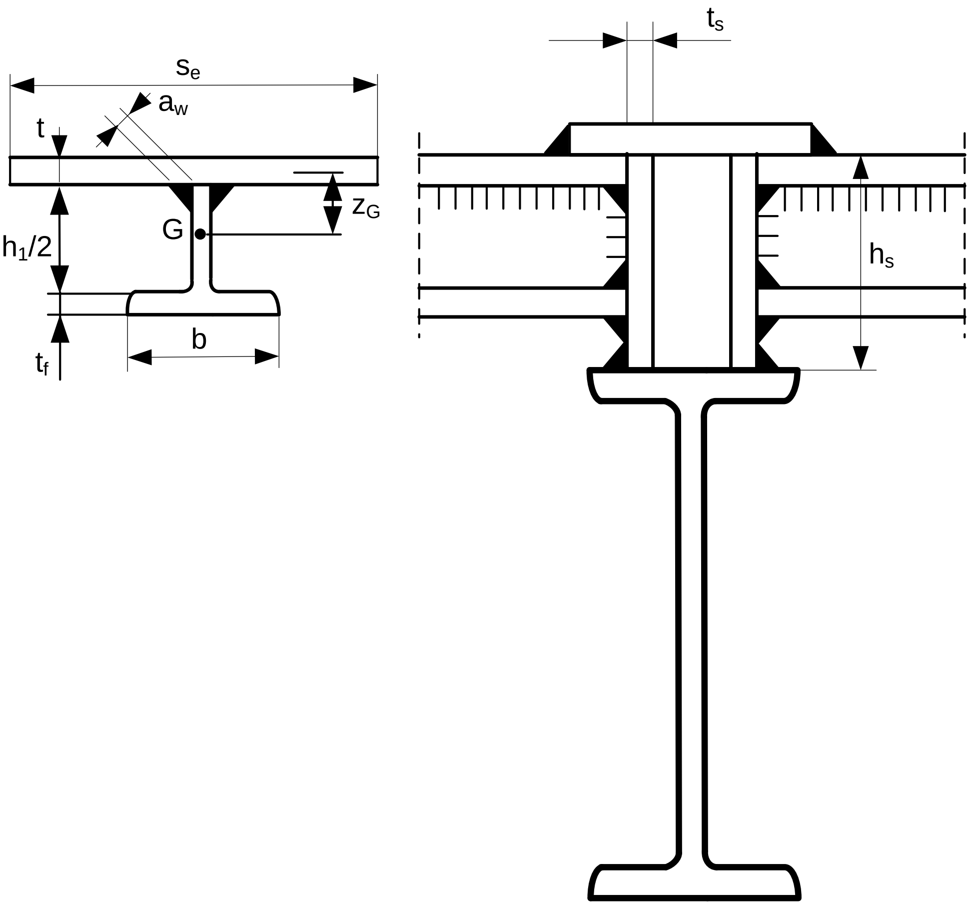

Figure 4. Cross-section of a stiffener and connection to the radial beam

Table 3. Data of UB profiles used for radial beams, dimensions in mm

UB profile	h	b	t_w	t_f	A [mm^2]	Wx10^{-3}[mm^3]	r
305x102x28	308.7	101.8	6	8.8	3588	3476	122.3
305x102x33	312.7	102.4	6.6	10.8	4183	4158	124.7
305x127x37	304.4	123.4	7.1	10.7	4738	4711	123.3

where

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}}, \phi = 0.5\left[1 + 0.21\left(\bar{\lambda} - 0.2\right) + \bar{\lambda}^2\right] \quad (41)$$

$$\bar{\lambda} = \frac{9835}{r\lambda_E}, \lambda_E = \pi\sqrt{\frac{E}{f_y}} = 54.807 \quad (42)$$

r is the radius of gyration, A_r is the cross-sectional area, for $\bar{\lambda} \le 1$

$$k_{yy} = 0.95\left(1 + 0.6\bar{\lambda}\frac{N_H}{\chi A_r f_{y1}}\right) \quad (43)$$

The suitable rolled I-profile is selected from an ArcelorMittal product catalogue using the British UB profiles.

6. Cost of a radial beam

Material cost

$$K_M = k_m \rho V_R, V_R = A_r L_R, L_R = 9825 \text{ mm}, \quad (44)$$

cost of welding to the inner ringbeam and to the tank shell

$$K_W = k_w\left[\Theta_2\sqrt{\rho V_R} + 1.3C_{w3}a_w^2 2x2\left(2h_{1R} + 4b_R\right)\right] \quad (45)$$

the factor of 2 is used since the welding is mainly vertical.

Cost of painting

$$K_P = k_P\left(2h_{1R} + 4b_R\right)L_R \quad (46)$$

Total cost of a radial beam

$$K_R = K_M + K_W + K_P \quad (47)$$

7. Additional cost

Material, welding and painting of a deck plate of size 200x6x9825 connecting the sectorial elements as well as welding of the sectorial elements to the radial beam

$$K_{MA} = k_m \rho V_A \quad (48)$$

$$K_{WA} = k_w \left(\Theta_1 \sqrt{2\rho V_A} + 1.3 C_{w2} a_w^2 4 L_R \right) \quad (49)$$

$$V_A = 200\text{x}6 L_R \quad (50)$$

$$K_{PA} = k_P 200 L_R \quad (51)$$

$$K_A = K_{MA} + K_{WA} + K_{PA} \quad (52)$$

Total cost of the whole roof structure

$$K = \omega \left(K_s + K_R + K_A \right) \quad (53)$$

8 Optimization results

Table 4 and 5 summarize the results (masses and costs) for different values of ω for a sector and for the whole roof

Table 4. Total costs in $ for different numbers of stiffener distances

ω	n	K_{total}
12	4	61000
12	**6**	**51060**
12	8	52230

It can be seen that the optimum number stiffener distances is 6. Therefore, in the further search the number of sectors is varied. The results are shown in Table 5.

Table 5. Masses in kg and costs in $ for the whole roof

ω	n	ρV_{total}	K_{total}
10	**6**	**17670**	**49270**
12	6	18378	51060
14	6	18251	52450

It can be seen that ω = 14 and ω = 10 gives the minimum mass and minimum cost for the whole roof, respectively. It should be noted that the case of ω = 8 is unrealistic, since in that case the sectorial element has not a trapezoidal but a circular sector form, which needs also partial radial stiffeners beside of the circumferential ones and the cost increases.

Table 6 gives the details of the investigated roofs.

Table 6. Details of the investigated roofs. Dimensions in mm. The optima are marked by bolt numbers

ω	n	Base plate thicknesses	Stiffeners 1/2 UB	Radial edge plates	Radial beams UB	ρV_{total} [kg]	K_{total} [$]
12	4	4,5,6,6	1: 152 2,3: 127	106x6	305x102x33	26819	61280
12	6	7 parts all 4	1: 152 2-5: 127	106x6	305x102x33	18615	51060
12	8	7 parts,all 4	all: 127	93.5x6	305x102x33	18417	52230
10	**6**	**7 parts all 4**	**1: 152 2-5: 127**	**106x6**	**305x127x37**	**17670**	**49270**
14	6	7 parts,all 4	all: 127	93.5x6	305x102x28	18251	52450

In order to consider a 10% increase in material and welding cost factors, we multiply the material and welding costs by using k_M = 1.1 $/kg and k_W = 1.1 $/min. Calculate the increased cost for ω = 10 and n = 6.
Eq.(22): K_{ws} = 664.985x1.1 = 731.5, Eq(28): K_{m1} = 1310x1.1 = 1441, Eq.(33): K_s = 731.5+1441+1920= 4092.5 $.
Eq(43): K_M = 364.25x1.1 = 400.67, Eq(44): K_W = 152.52x1.1 = 167.8, Eq.(46): K_R= 300.67+167.77+ 230.2 = 798.64 $, Eq(47): K_{MA} = 92.65x1.1 = 101.9, Eq(48): K_{WA} = 135.3x1.1 = 148.83, Eq(51): K_A = 101.9+148.83+56.6 = 307.33 $, Eq(52): K = 10(4092.5+798.64+307.33) = 51985 $ instead of K_{total} = 49270 $.
It can be concluded that the cost savings in this case is (66550-51985)/66550x100 = 22%.

9. Conclusions

Minimum cost design of a fixed roof of a vertical steel storage tank is worked out for a numerical model structure and for a high strength steel with yield strength of f_y = 690 MPa. Load of snow and a soil layer is considered. The roof is constructed from sectorial stiffened plate elements and radial beams. The number of sectors is varied between 10 and 16.
The sectorial elements are circumferential stiffened with halved rolled I-section stiffeners welded to the base plate. The equidistant distances of stiffeners are used and the necessary base plate thicknesses are calculated so that the plate parts are equally stressed. The radial beams are constructed from rolled I-sections. The cost function contents the cost of material, welding and painting. The cost calculation shows that the minimum roof mass and

cost corresponds to the number of sections of 14 and 10 respectively.

In a previous study [1, 6] we have optimized a tank roof with the same loads and main dimensions using a mild steel of yield stress f_y = 235/1.1 = 213.6 MPa and obtained the optima of ρV_{total} = 23240 kg and K_{total} = 66550 \$. This means that, calculating with cost factors of k_w = 1 \$/min and k_M = 1 \$/kg, the use of high strength steel results in savings in mass (23240-17670)/23240x100 = 24% and in cost (66550-49270)/66550x100 = 26%.

Calculating with cost factors of k_w = 1.1 \$/min and k_M = 1.1 \$/kg the cost savings is 22%.

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