

Using of General Method of Standard EN 1993-1-1 to Design of Self-Supporting Cone roofs

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A part of steel tanks have roofs with an external (above cover plates) structure. It is required by conditions of exploitation and / or should have a smooth internal surface. In that situation roof structure is formed by many radial girders and a few circular elements (rings), see Fig. 1. These elements form a 3D - structure and work together, supporting each other. When radial girders and / or circular elements are compressed and / or bended, they could lose stability on different ways:

- locally - one compressed and / or bended element loses stability;
- general - the whole structure of the roof loses stability.

Classical equations in structural mechanics require a clear effective length of elements to determine their slenderness. When structure is 3D, as a self-supporting cone roofs, is very difficult to determine effective lengths. What we should do then? How to check structure for loss of stability? As a first step we could use General method, described in standard EN 1993-1-1. The following method is very common and may be used to check loss of stability of compressed and / or bended elements, where:

- a) the cross sections of members are not uniform along the length of members;
- b) the members are loaded by combined monoaxial bending, axial forces and shear;
- c) the support conditions of the member is irregular.

1. General method for lateral and lateral torsional buckling. Main principles.

Overall resistance to out-of-plane buckling for any structural component conforming to the scope of General method can be verified by ensuring that:

$$\frac{\chi_{op} \cdot \alpha_{ult,k}}{\gamma_{M1}} \geq 1,0 \quad (1)$$

where:

$\alpha_{ult,k}$ is minimum load amplifier of the design loads to reach the characteristic resistance of the most critical cross section of the structural component considering its in plane behaviour without taking into account lateral or lateral torsional buckling;

χ_{op} - the reduction factor for the non-dimensional slenderness

$\bar{\lambda}_{op}$, to take account of lateral and lateral torsional buckling;

γ_{M1} - partial factor for resistance to buckling.

The global non-dimensional slenderness $\bar{\lambda}_{op}$ for the structural component should be determined from formula:

$$\bar{\lambda}_{op} = \sqrt{\frac{\alpha_{ult,k}}{\alpha_{cr,op}}} \quad (2)$$

where:

$\alpha_{cr,op}$ is the minimum amplifier for the in plane design loads to reach the elastic critical resistance of the structural component with regards to lateral or lateral torsional buckling without accounting for the in plane flexural buckling.

The reduction factor χ_{op} may be determined from either of following methods:

- a) the minimum value of
 - χ - for lateral buckling, according to 6.3.1 of standard EN 1993-1-1;
 - χ_{LT} - for lateral torsional buckling, according to 6.3.2 of standard EN 1993-1-1,each calculated for the global non-dimensional slenderness $\bar{\lambda}_{op}$.
- b) a value interpolated between the values χ and χ_{LT} as determined in a) by using the formula for $\alpha_{ult,k}$ corresponding to the critical cross section.

Main principles of General method, described above, should be applied to real design of self-supporting cone roof.

2. Geometrical data of self-supporting cone roof

Designed here self-supporting cone roof, used as a example how to use General method, has a geometry as it is shown on Fig. 1 bellow, where:

diameter of cylindrical tank – $D = 11950$ mm;

slope of roof – $\alpha = 10^\circ$

height of cone roof – $f = 1054$ mm;

position of structure - external (above roof's plates);

number of radial girders – $n = 34$ pcs., section IPE 140;

number of intermediate rings on roof – 1 ring in the middle of radial girders, with section UPN 80;

diameter of central ring – $d = 2350$ mm;

thickness of cover plates (sheets) – $t_{rp} = 4$ mm.

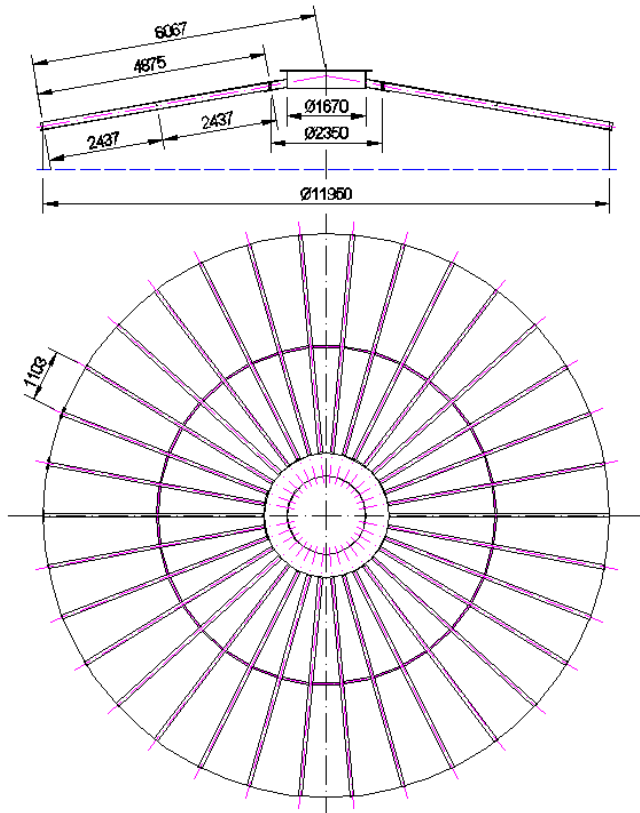


Fig. 1. Scheme of cone roof

Used steel for the roof elements:

- roof plates – 1.4571;
- roof structure – 1.4301

3. Loads on cone roof

Dead loads - weight g_{rp}^n of roof cover plates with thickness $t_{rp} = 4,0$ mm.

$$g_{rp}^n = t_{rp} \cdot \rho_s = 0,004 \cdot 78,5 = 0,314 \text{ kN/m}^2 \quad (3)$$

where:

$\rho_s = 78,5 \text{ kN/m}^3$ is density of the steel.

Temporary loads:

- design snow loads - $S = 3 \text{ kN/m}^2$;
- design overpressure – $p_o = 20 \text{ mbar}$;
- design internal (negative) pressure – $p_v = 20 \text{ mbar}$;
- live loads on platforms on the roof – $Q = 3 \text{ kN/m}^2$;

- design wind speed – $v = 45 \text{ m/s}$.

Wind pressure w could be calculated using formula:

$$w = \frac{v^2}{16.100} \cdot c_e \cdot k_z = \frac{45^2}{16.100} \cdot 0,7 \cdot 1,11 = 0,983 \text{ kN/m}^2 \quad (4)$$

where:

w is design wind pressure on the cone roof;

$c_e = 0,7$ - aerodynamic coefficient for cone roofs;

$k_z = 1,11$ - coefficient, accounting increased height of top of roof above ground level. Total height $h = 14,42 \text{ m}$.

Design temperature of the tank:

- maximum – $t_{\max} = +100^\circ\text{C}$;
- minimum – $t_{\min} = -20^\circ\text{C}$.

4. Combination of loads on the roof

Combination q_1 of loads on cover plates with direction from roof to bottom:

$$q_1 = g_{rp}^n \cdot \gamma_{fg,\text{sup}} + S + \psi_0 \cdot p_v = 0,314 \cdot 1,35 + 3,0 + 0,6 \cdot 2 = 4,62 \text{ kN/m}^2 \downarrow \quad (5)$$

where:

$\gamma_{fg,\text{sup}} = 1,35$ is self-weight overloading coefficient, according to EN 1990;

ψ_0 - coefficient for simultaneously working two or more temporary loads, according to EN 1990.

Combination q_2 of loads on cover plates with direction from bottom to roof :

$$q_2 = g_{rp}^n \cdot \gamma_{fg,\text{inf}} + p_o + \psi_0 \cdot w = -0,314 \cdot 1,0 + 2 + 0,6 \cdot 0,983 = 2,28 \text{ kN/m}^2 \uparrow \quad (6)$$

where coefficients of overloading are:

$\gamma_{fg,\text{inf}} = 1,0$ – self-weight overloading, when acts favourably, see standard EN 1990

5. Static calculations and design of roof structure

Spatial computational model of cone roof is created using appropriate software. In this research is used program product SAP 2000 v.14.2. In the model straight radial girders are defined as frame elements, with their real geometrical characteristics and materials. Preliminary, on first step, using results from mounting condition, hot-rolled sections **IPE 140** are used for radial girders. To stabilize radial girders, hot-rolled profiles **UPN 80** are put on their middle.

Material for all hot-rolled sections is steel grade **1.4301**, with characteristics, from standard EN 10088-3:

Yield strength – $f_y = 190 \text{ MPa}$ at $t = +20^\circ\text{C}$;

– $f_y = 157 \text{ MPa}$ at $t = +100^\circ\text{C}$;

Ultimate tensile strength – $f_u = 500 \text{ MPa}$;

Module of elasticity – $E = 195\,000 \text{ MPa}$;

Density – $\rho = 78,5 \text{ kN/m}^3$

For more accurate results it is advisable to provide the model without the roof plates.

The transmission of the load on the construction is simulated by loading areas. The loads from overpressure, vacuum and wind suction act perpendicular to the major principal axes of the frame elements. The loads from dead weight and snow act in the direction of gravity.

To consider horizontal displacement of supports of roof structure, in the 3D - model are further included upper stiffening ring (top angle) and part of last shell course, with their real dimensions, see Fig. 2.

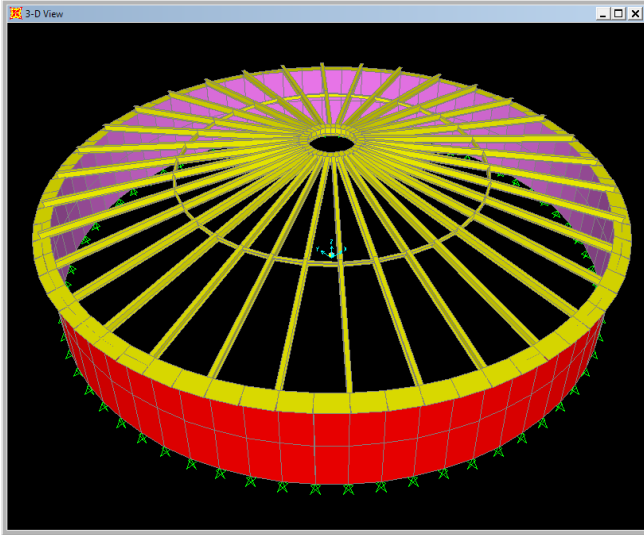


Fig. 2. Spatial frame model of the roof

Used steel section **IPE 140** is class 3, according to EN 1993-1-4. Hot-rolled section is welded to roof cover plates with continuous angle welds on both side of lower flange. Combined section could be seen on Fig. 3:

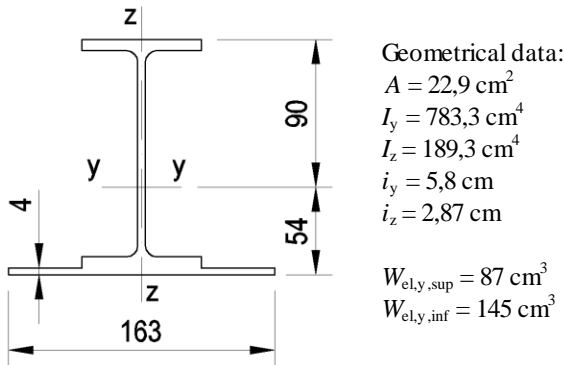


Fig. 3. Combined steel section

a) check of radial girders for maximum stresses:

The design forces in elements of cone roof are obtained with assumption for geometrically linear conditions. The steel works in elastic range.

- normal stress in steel section from compression forces and bending moments

Accounted from 3D - model, values of forces and moments are:

$N_{Ed} = - 44,48$ kN - design value of compression force in radial girder;

$M_{y,Ed} = 5,24$ kN.m - design value of bending moment about main axis "y-y";

$$\frac{N_{Ed}}{N_{el,Rd}} + \frac{M_{y,Ed}}{M_{el,y,Rd}} = \frac{44,48}{326,8} + \frac{5,24 \cdot 100}{1241,7} = 0,558 < 1 \quad (7)$$

where:

$$N_{el,Rd} = A \cdot \frac{f_y}{\gamma_{M0}} = 22,9 \cdot \frac{15,7}{1,1} = 326,8 \text{ kN} \quad (8)$$

$$M_{el,y,Rd} = W_{el,y,sup} \cdot \frac{f_y}{\gamma_{M0}} = 87 \cdot \frac{15,7}{1,1} = 1241,7 \text{ kN.cm} \quad (9)$$

in which:

$f_y = 157$ MPa - yield strength at design temperature $t=100^\circ\text{C}$;
 $\gamma_{M0} = 1,1$ is coefficient of safety by material, according to standard EN 1993-1-4;

A is total area of combined steel section;

$W_{el,y,sup}$ - min elastic section modulus about axis "y-y"

- tangential stress in steel section from shear forces:

Design value of shear force somewhere along the length of radial girder is $V_{z,Ed} = 9,46$ kN

$$\frac{V_{z,Ed}}{V_{z,Rd}} = \frac{9,46}{62,79} = 0,151 < 0,5 \quad (10)$$

where:

$$V_{z,Rd} = A_v \cdot \frac{f_y}{\sqrt{3} \cdot \gamma_{M0}} = 7,62 \cdot \frac{15,7}{\sqrt{3} \cdot 1,1} = 62,79 \text{ kN} \quad (11)$$

in which:

$$A_v = A - 2 \cdot b \cdot t_f + (t_w + 2 \cdot r) \cdot t_f = 16,4 - 2 \cdot 7,3 \cdot 0,69 + (0,47 + 2 \cdot 0,7) \cdot 0,69 = 7,62 \text{ cm}^2 \quad (12)$$

where:

b is width of flange of steel section **IPE 140**;

r - radius of joint web - flange;

t_f - thickness of flange;

t_w - thickness of web .

b) check of radial girders for loss of stability as compressed and bended members:

Buckling Analysis option in software SAP 2000 is used to perform this analysis. It is possible to observe the reserve of resistance, before loss of stability of one particular element or the whole structure. The solution is linear, but taking into account the deformations in the cone roof's structure.

First, dead load due to the self-weight of the steel structure is defined in geometrically non-linear conditions. After that, on a structure, deformed by the loading g_n , is applied loading due to the negative pressure (vacuum) p_v^n and snow S, for whom the reserve should be determined. The loading of self-weight g_n is defined with its characteristic value. Snow S and vacuum p_v^n are defined with their design values.

Minimum load amplifier $\alpha_{ult,k}$ of the design loads to reach the characteristic resistance should be calculated using formula:

$$\alpha_{ult,k} \cdot \left(\frac{M_{y,Ed}}{W_{el,y}} + \frac{N_{Ed}}{A} \right) = f_y \quad (13)$$

After simple transformation, $\alpha_{ult,k}$ will be calculated as follow:

$$\alpha_{ult,k} = \frac{f_y}{\left(\frac{N_{Ed}}{A} + \frac{M_{y,Ed}}{W_{el,y}} \right)} = \frac{15,7}{\left(\frac{44,48}{22,9} + \frac{5,24 \cdot 100}{87} \right)} = 1,971 \quad (14)$$

Minimum amplifier $\alpha_{cr,op}$ for the design loads to reach elastic critical resistance of the frame, with regards to lateral or lateral - torsional buckling, could be calculated as:

$$\alpha_{cr,op} = \frac{g_n + K \cdot (S + \psi_0 \cdot P_v)}{g_n \cdot \gamma_{G,sup} + S + \psi_0 \cdot P_v} = \frac{0,314 + 3,0434 \cdot (3 + 0,6 \cdot 2)}{0,314 \cdot 1,35 + 3 + 0,6 \cdot 2} = 2,832 \quad (15)$$

where:

$K = 3,0434$ is Buckling factor, accounted using software SAP 2000 and spatial model, see Fig. 4.

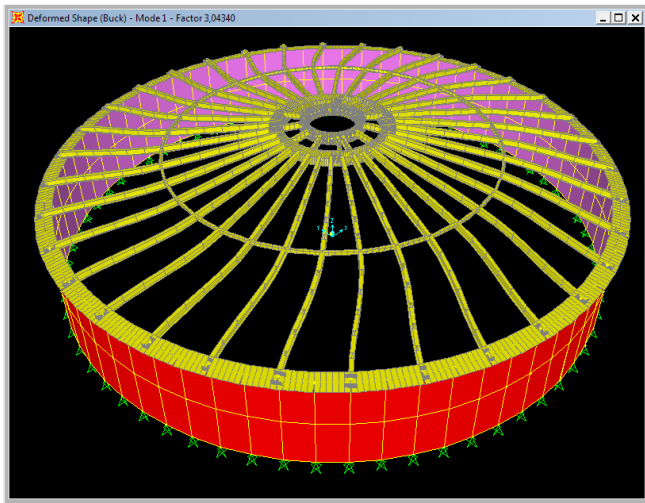


Fig. 4. Deformed shape of cone roof, that loses stability, due to loading of self-weight g_n , snow S and vacuum p_v

The global non-dimensional slenderness $\bar{\lambda}_{op}$ for the structural component should be determined from:

$$\bar{\lambda}_{op} = \sqrt{\frac{\alpha_{ult,k}}{\alpha_{cr,op}}} = \sqrt{\frac{1,971}{2,832}} = 0,834 \quad (16)$$

The reduction factor χ_z for buckling to axis "z-z" should be calculated as follow:

$$\chi_z = \frac{1}{\Phi_z + \sqrt{\Phi_z^2 - \bar{\lambda}_{op}^2}} = \frac{1}{1,088 + \sqrt{1,088^2 - 0,834^2}} = 0,559 \quad (17)$$

where:

$$\Phi_z = 0,5 \cdot [1 + \alpha \cdot (\bar{\lambda}_{op} - \bar{\lambda}_0) + \bar{\lambda}_{op}^2] = 0,5 \cdot [1 + 0,76 \cdot (0,834 - 0,2) + 0,834^2] = 1,088 \quad (18)$$

in which:

α is an imperfection factor, according to EN 1993-1-4;
 $\bar{\lambda}_0$ - limiting slenderness.

The reduction factor χ_{LT} for lateral - torsional buckling should be calculated by formula:

$$\chi_{LT} = \frac{1}{\Phi_{LT} + \sqrt{\Phi_{LT}^2 - \bar{\lambda}_{op}^2}} = \frac{1}{1,013 + \sqrt{1,013^2 - 0,834^2}} = 0,63 \quad (19)$$

where:

$$\Phi_{LT} = 0,5 \cdot [1 + \alpha_{LT} \cdot (\bar{\lambda}_{op} - 0,4) + \bar{\lambda}_{op}^2] = 0,5 \cdot [1 + 0,76 \cdot (0,834 - 0,4) + 0,834^2] = 1,013 \quad (20)$$

in which:

α_{LT} is an imperfection factor, according to EN 1993-1-4.

The minimum reduction factor χ_{op} for buckling to axis "z-z" and lateral - torsional buckling is minimum value reduction factors χ_z and χ_{LT} :

$$\chi_{op} = \min \begin{cases} \chi_z = 0,559 \\ \chi_{LT} = 0,63 \end{cases} \quad (21)$$

Overall resistance to out-of-plane buckling for any structural component can be verified by ensuring that:

$$\frac{1}{\chi_{op}} \cdot \left(\frac{N_{Ed}}{A} + \frac{M_{y,Ed}}{W_{el,y}} \right) = \frac{1}{0,559} \cdot \left(\frac{44,48}{22,9} + \frac{5,24 \cdot 100}{87} \right) = 14,25 \text{ kN/cm}^2 < \frac{f_y}{\gamma_{M1}} = 14,27 \text{ kN/cm}^2 \quad (22)$$

According to performed spatial FEA analysis, and using General Method of EN 1993-1-1, sections of radial girders should be **IPE 140**.

6. Conclusions

When a building structure is spatial (3D), all elements work together. They influence and support each other. On that situation is very difficult to determine who is supporting and who is supported member. It is impossible to calculate

directly their effective lengths. These lengths are used in classic equations of standards to check elements for loss of stability. On that reason is reasonably to use General method, described in European standard EN 1993-1-1. This method is convenient to use, but unfortunately it could not be used without good computer skills and specialised structural software possessing Buckling Analysis module.

General method is very powerful tool to check spatial structures like self-supporting cone, dome or umbrella roofs for local and / or general loss of stability.

References

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