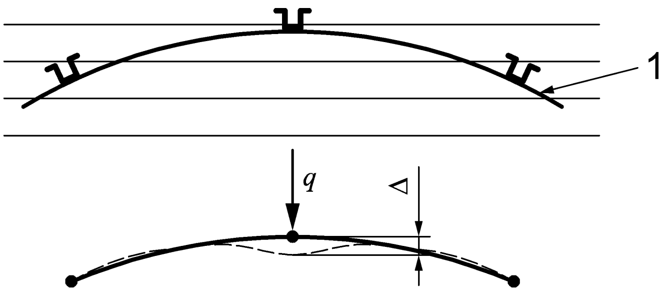


Key

1 wall

$K = q/\Delta$

Figure 5.5: Evaluation of restraint stiffness against stiffener column buckling using a curved wall treatment

(7) A more advanced assessment of the value of K may be made by treating the curved wall as an arch spanning between adjacent stiffeners, see Figure 5.5. The value of K may then be estimated using:

$$K = \frac{1}{r}\left\{\frac{2C_y D_y}{fD_y + r^2 C_y\left\{f + \phi\cos^2\phi(\tan\phi + 2g)^2 - 2\left[2g^2\sin 2\phi - 2g(\cos 2\phi - \cos\phi) - \sin\phi(\cos\phi - 1)\right]\right\}}\right\}$$

... (5.74)

$$\phi = \frac{d_s}{r}$$ ... (5.75)

$$f = \frac{1}{4}\left\{(4g^2 + 1)(2\phi + \sin 2\phi) + 4g(1 - \cos 2\phi) - 2\sin 2\phi\right\}$$ ... (5.76)

$$g = \frac{D_y \sin^2\phi - r^2 C_y\left[(1 - \cos\phi)(1 + 3\cos\phi) - \phi\sin 2\phi\right]}{D_y(2\phi + \sin 2\phi) - r^2 C_y\left[2\phi(2 + \cos 2\phi) - 3\sin 2\phi\right]}$$ ... (5.76a)

where:

C_y is the shell membrane stiffness of the corrugated wall sheet for circumferential stretching (see 4.4);

D_y is the shell bending flexural rigidity of the corrugated wall sheet for circumferential bending (see 4.4);

d_s is the circumferential separation of the vertical stiffeners.

If the corrugation form is an arc-and-tangent or sinusoidal profile, the values of C_y and D_y may be taken from 4.4(5) and (6). If other corrugation forms are adopted, both the shell circumferential membrane stiffness C_y and the shell circumferential bending flexural rigidity D_y should be determined from first principles.

(8) Where the flow pattern in the granular solid, the pressure in the solid, the properties of the solid, and the relationship of the solid's stiffness to the local pressure can all be reliably predicted using EN 1991-4, a rational analysis of the stiffness of stationary solid against the silo wall may be included in the assessment of the stiffness of the shell wall K.

(9) The following conditions should all be met for the simplified method of Paragraph (10) to be used:

i) at each level, the cross-section of the stringer stiffener should be taken as the smallest value within the effective length L_e determined using Paragraph (3) or (4);

ii) the stringer stiffener should be flexurally continuous, with moment resisting connections between segments;

iii) where the centroid of one segment of the stiffener is not co-linear with the centroid of the adjacent segment, consideration should be given to the use of a longer sleeve and the connection should be designed to transmit the bending moment arising from the eccentricity of the axial force transferred; and

iv) there should be no cause introducing unintentional bending moments into the stringer stiffener (e.g. resulting from an eccentricity between the section centroidal axis and the centroid of the bolts used in connections, such as sleeves, overlaps, etc.). The eccentricity of the frictional traction on the silo wall to the stiffener may be ignored.

(10) If the conditions of Paragraph (9) are all met, the following simple calculation may be used at every point on the shell wall. The compression on the stiffener cross-section may be assumed to be uniform and equal to the maximum compression force $N_{b,Ed}$ acting at the bottom of the stiffener segment. The resistance of the stiffener may be assessed using:

$$N_{b,Ed} \leq N_{b,Rk} / \gamma_{M1} \qquad \text{... (5.76b)}$$

where:

$N_{b,Ed}$ is the design value of the maximum normal force acting in the stiffener segment;

$N_{b,Rk}$ is the characteristic value of resistance to axial compression calculated according to EN 1993-1-1 for rolled sections and EN 1993-1-3 for cold-formed sections.

(11) The reduction factor χ used to determine the value of $N_{b,Rk}$ should be taken for buckling normal to the silo wall (i.e. about the circumferential axis).

(12) Where the conditions (i), (ii), (iii) and (iv) in Paragraph (9) are not met, the resistance at any level of the stiffener should be verified taking into account:

— the variation of compression in the stiffener;

— the variation of the second moment of area of the stiffener;

— any eccentricity between the section centroidal axis and the centroid of the bolts used in connections (e.g sleeves, overlaps, etc.);

— the flexural rigidity of the connections (see 5.3.4.1(4)); and

— the variation of flexural stiffness of the wall.

The procedure set out in (13) to (18) may be used.

(13) A linear eigenvalue (LBA) calculation according to EN 1993-1-6 should be performed on any section of the stiffener, using the design value of the force in the stiffener N_{Ed} at that location and including the effect of the restraint of the corrugated sheeting. This yields the elastic critical load amplifier R_{cr} on the design loads.

(14) The design plastic reference load multiplier for each section of the stiffener should be taken as:

$$R_{pl} = \frac{A_{eff} f_y}{N_{Ed,max}} \qquad \text{... (5.76c)}$$

where:

A_{eff} is the lowest effective cross-sectional area within the segment of the stiffener according to the provisions of EN 1993-1-3;

$N_{Ed,max}$ is the maximum compression load in the segment of the stiffener.

(15) The overall relative slenderness $\bar{\lambda}_x$ for the segment should be determined from:

$$\bar{\lambda}_x = \sqrt{R_{pl}/R_{cr}} \qquad \text{... (5.76d)}$$

(16) The values of the buckling parameters α, β, η, and λ_o should be taken as follows:

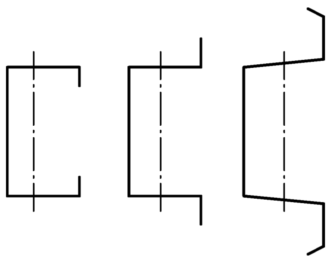


Figure 5.5 a): Cold-formed stiffeners with edge stiffened flanges EN 1993-1-3 identifiers: buckling curve b

$$\alpha = 0{,}80; \quad \beta = 0{,}70; \quad \eta = 1{,}05; \quad \lambda_o = 0{,}2; \quad \chi_h = 1{,}0 \qquad \text{... (5.76e)}$$

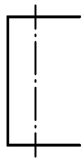


Figure 5.5 b): Stiffeners with unstiffened flanges EN 1993-1-1 identifiers: buckling curve c

$$\alpha = 0{,}72; \quad \beta = 0{,}75; \quad \eta = 0{,}90; \quad \lambda_o = 0{,}2; \quad \chi_h = 1{,}0 \qquad \text{... (5.76f)}$$

(17) The general buckling relationship of 5.3.2.4(15) or EN 1993-1-6:2007, 8.6 should be used to obtain the buckling reduction factor χ, and the characteristic buckling load multiplier R_k found as:

$$R_k = \chi R_{pl} \qquad \text{... (5.76g)}$$

(18) It should be verified that:

$$\frac{R_k}{\gamma_{M1}} \geq 1{,}0 \qquad \text{... (5.76h)}$$ A1

5.3.4.4 Local, distortional and flexural torsional failure of stiffeners

(1) The resistance of the stiffeners to local, distortional and flexural torsional buckling should be determined using EN 1993-1-3 (cold formed construction).

5.3.4.5 Buckling under external pressure, partial vacuum or wind

(1) The equivalent membrane and flexural properties of the sheeting should be found using 4.4.

(2) The bending and stretching properties of the ring and stringer stiffeners, and the outward eccentricity of the centroid of each from the middle surface of the shell wall should be determined, together with the separation between the stiffeners d_s.

(3) The horizontal distance between stiffeners d_s should not be more than $d_{s,max}$ given by:

$$d_{s,\max} = k_{d\theta}\left(\frac{r^2 D_y}{C_y}\right)^{0,25} \qquad \text{... (5.77)}$$

where:

- D_y is the flexural rigidity per unit width of the thinnest sheeting parallel to the corrugations;
- C_y is the stretching stiffness per unit width of the thinnest sheeting parallel to the corrugations;
- r is the cylinder radius.

NOTE: The National Annex may choose the value of $k_{d\theta}$. The value $k_{d\theta} = 7,4$ is recommended.

(4) The critical buckling stress for uniform external pressure $p_{n,Rcru}$ should be evaluated by minimising the following expression with respect to the critical circumferential wave number, j:

$$p_{n,Rcru} = \frac{1}{rj^2}\left(A_1 + \frac{A_2}{A_3}\right) \qquad \text{... (5.78)}$$

with:

$$A_1 = j^4\left[\omega^4 C_{44} + 2\omega^2(C_{45}+C_{66}) + C_{55}\right] + C_{22} + 2j^2 C_{25} \qquad \text{... (5.79)}$$

$$A_2 = 2\omega^2 (C_{12}+C_{33})(C_{22}+j^2C_{25})(C_{12}+j^2\omega^2C_{14})$$

$$- (\omega^2C_{11}+C_{33})(C_{22}+j^2C_{25})^2 - \omega^2(C_{22}+\omega^2C_{33})(C_{12}+j^2\omega^2C_{14})^2 \qquad \text{... (5.80)}$$

$$A_3 = (\omega^2C_{11} + C_{33})(C_{22} + C_{25} + \omega^2C_{33}) - \omega^2(C_{12} + C_{33})^2 \qquad \text{... (5.81)}$$

with:

$C_{11} = C_\phi + EA_s / d_s$ $\qquad C_{22} = C_\theta + EA_r / d_r$

$C_{12} = \nu\sqrt{C_\phi C_\theta}$ $\qquad C_{33} = C_{\phi\theta}$

$C_{14} = e_s EA_s / (rd_s)$ $\qquad C_{25} = e_r EA_r / (rd_r)$

$C_{44} = [D_\phi + EI_s/d_s + EA_s e_s^2/d_s] / r^2$ $C_{55} = [D_\theta + EI_r/d_r + EA_r e_r^2/d_r] / r^2$

$C_{45} = \nu\sqrt{D_\phi D_\theta} / r^2$ $C_{66} = [D_{\phi\theta} + 0{,}5(GI_{ts}/d_s + GI_{tr}/d_r)] / r^2$

$$\omega = \frac{\pi r}{j l_i}$$

where ℓ_i, r, A_s, I_s, I_{ts}, d_s, e_s, A_r, I_r, I_{tr}, d_r and e_r have the meanings defined in 5.3.4.3.3 (3).

(5) Where the stiffeners or sheeting change with height up the wall, several potential buckling lengths ℓ_i should be examined to determine which is the most critical, assuming always that the upper end of a buckle is at the top of the zone of thinnest sheeting.

NOTE: If a zone of thicker sheeting is used above the zone that includes the thinnest sheeting, the upper end of the potential buckle could occur either at the top of the thinnest zone, or at the top of the wall.

(6) Unless more precise calculations are made, the thickness assumed in the above calculation should be taken as the thickness of the thinnest sheeting throughout.

(7) Where the silo has no roof and is potentially subject to wind buckling, the above calculated pressure should be reduced by the factor 0,6.

(8) The design buckling stress for the wall should be determined using the procedure given in 5.3.2.5, with $C_b = C_w = 1{,}0$ and taking $\alpha_n = 0{,}5$, but adopting the critical buckling pressure $p_{n,Rcru}$ from (4) above.

5.3.4.6 Membrane shear

(1) The buckling resistance of the shell under membrane shear should be determined using the provisions of EN 1993-1-6.

5.3.5 Vertically corrugated walls with ring stiffeners

5.3.5.1 General

(1) If the cylindrical wall is fabricated using corrugated sheeting with the corrugations running vertically, both of the following conditions should be met:

a) The corrugated wall should be assumed to carry no horizontal forces.

b) The corrugated sheeting should be assumed to span between attached rings, using the centre to centre separation between rings, and adopting the assumption of sheeting continuity.

(2) The joints between sheeting sections should be designed to ensure that assumed flexural continuity is achieved.

(3) The evaluation of the axial compression force in the wall arising from wall frictional tractions from the bulk solid should take account of the full circumference of the silo, allowing for the profile shape of the corrugation.

(4) If the corrugated sheeting extends to a base boundary condition, the local flexure of the sheeting near the boundary should be considered, assuming a radially restrained boundary.

(5) The design stress resultants, resistances and checks should be carried out as in 5.3.2, but including the additional provisions set out in 5.3.5.2 to 5.3.5.5.

5.3.5.2 Plastic limit state

(1) In checking the plastic limit state, the corrugated wall should be assumed to carry no circumferential forces.

(2) The spacing of ring stiffeners should be determined using a beam bending analysis of the corrugated profile, assuming that the wall is continuous over the rings and including the consequences of different radial displacements of ring stiffeners that have different sizes. The stresses arising from this bending should be added to those arising from axial compression when checking the buckling resistance under axial compression.

> **NOTE:** The vertical bending of the sheeting can be analysed by treating it as a continuous beam passing over flexible supports at the ring locations. The stiffness of each support is then determined from the ring stiffness to radial loading.

(3) The ring stiffeners designed to carry the horizontal load should be proportioned in accordance with EN 1993-1-1 and EN 1993-1-3 as appropriate.

5.3.5.3 Buckling under axial compression

(1) The critical buckling stress for the wall should be determined using the provisions of EN 1993-1-3 (cold formed construction), and treating the corrugated sheeting cross-section as a column acting between stiffening rings. The effective length should be taken as not less than the separation of the centroids of adjacent rings.

5.3.5.4 Buckling under external pressure, partial vacuum or wind

(1) The design resistance under external pressure should be assessed in the same manner as for horizontally corrugated silos (see 5.3.4.5), but taking account of the changed orientation of the corrugations as noted in 4.4 (7).

5.3.5.5 Membrane shear

(1) The design resistance under membrane shear should be assessed as for horizontally corrugated silos, see 5.3.4.6.

5.4 Special support conditions for cylindrical walls

5.4.1 Shell with bottom fully supported or resting on a grillage

(1) Where the base of the cylindrical shell is fully supported, the forces and moments in the shell wall may be deemed to be only those induced under axisymmetric actions and patch loads as set out in EN 1991-4.

(2) Where stiffened wall construction is used, the vertical stiffeners should be fully supported by the base and connected to the base ring.

5.4.2 Shell supported by a skirt

(1) If the shell is supported on a skirt (see figure 5.6), the shell may be assumed to be uniformly supported provided that the skirt satisfies one of the two following conditions:

a) The skirt is itself fully uniformly supported by the foundation;

b) The thickness of the skirt is not less than 20% greater than the shell, and the ring girder design procedures given in section 8 are used to proportion the skirt and its adjoining flanges.

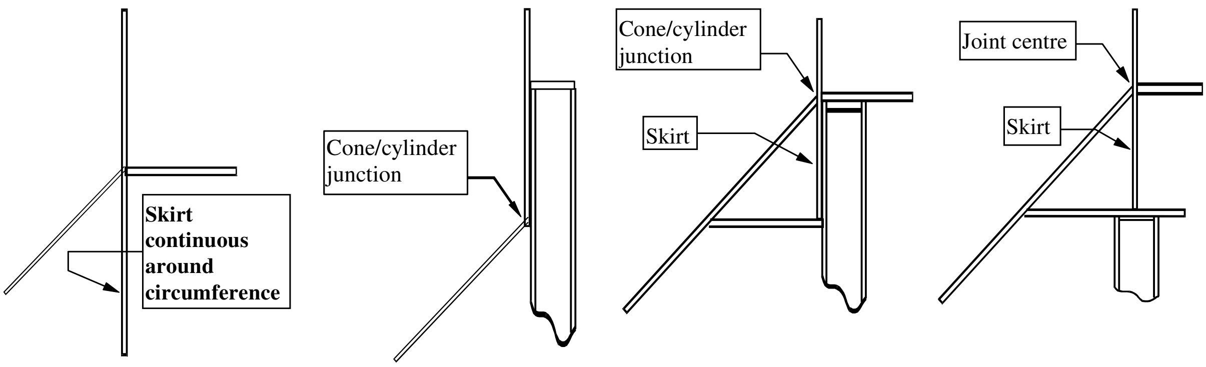
(2) The skirt should be designed to carry the axial compression in the silo wall without the beneficial effect of internal pressure.

5.4.3 Cylindrical shell wall with engaged columns

(1) If the shell is supported on discrete columns that are engaged into the wall of the cylinder (see figure 5.6b), the effects of the discrete forces from these supports should be included in determining the internal forces in the shell for silos of Consequence Classes 2 and 3.

(2) The length of the engagement of the column should be determined according to 5.4.6.

(3) The length of the rib should be chosen taking account of the limit state of buckling in shear adjacent to the rib, see 5.3.2.6.



a) shell supported on skirt | b) cylindrical shell with engaged column | c) column eccentrically engaged to skirt | d) column beneath skirt or cylinder

Figure 5.6: Different arrangements for support of silo with hopper

5.4.4 Discretely supported cylindrical shell

(1) If the shell is supported on discrete columns or supports, the effects of the discrete forces from these supports should be included in determining the internal forces in the shell, except where the provisions of (2) and (3) permit them to be ignored.

(2) If the shell is analysed using only the membrane theory of shells for axisymmetric loading, the following four criteria should all be satisfied:

a) The radius-to-thickness ratio r/t should not be more than $(r/t)_{max}$.

b) The eccentricity of the support beneath the shell wall should not be more than $k_1\, t$.

c) The cylindrical wall should be rigidly connected to a hopper that has a wall thickness not less than $k_2\, t$ at the transition.

d) The width of each support should be not less than $k_3 \sqrt{rt}$.

NOTE: The National Annex may choose the values of $(r/t)_{max}$, k_1, k_2 and k_3. The values $(r/t)_{max} = 400$, $k_1 = 2{,}0$, $k_2 = 1{,}0$, $k_3 = 1{,}0$ are recommended.

(3) If the shell is analysed using only the membrane theory of shells for axisymmetric loading, AC› one of the following criteria ‹AC should be met:

a) The upper edge shell boundary condition should be kept circular by structural connection to a roof.

b) The upper edge shell boundary should be kept circular by using a top edge ring stiffener with a flexural rigidity EI_z for bending in the plane of the circle greater than $EI_{z,min}$ given by:

$$EI_{z,min} = k_s \; Ert^3 \quad \text{... (5.82)}$$

where t should be taken as the thickness of the thinnest part of the wall.

NOTE: The National Annex may choose the value of k_s. The value $k_s = 0{,}10$ is recommended.

c) The shell height L should not be less than $L_{s,min}$, which may be calculated as:

$$L_{s,min} = k_L r \sqrt{\left(\frac{r}{t}\right) \cdot \frac{1}{n(n^2-1)}} \quad \text{... (5.83)}$$

where n is the number of supports around the shell circumference.

NOTE: The National Annex may choose the value of k_L. The value $k_L = 4{,}0$ is recommended.

(4) If linear shell bending theory or a more precise analysis is used, the effects of locally high stresses above the supports should be included in the verification for the axial compression buckling limit state, as detailed in 5.3.2.4.

(5) The support for the shell should be proportioned to satisfy the provisions of 5.4.5 or 5.4.6 as appropriate.

5.4.5 Discretely supported silo with columns beneath the hopper

(1) A silo should be deemed to be supported beneath its hopper if the vertical line above the centroid of the supporting member is more than t inside the middle surface of the cylindrical shell above it.

(2) A silo supported beneath its hopper should satisfy the provisions of section 6 on hopper design.

(3) A silo supported by columns beneath its hopper should be analysed using linear shell bending theory or a more precise analysis. The local bending effects of the supports and the meridional compression that develops in the upper part of the hopper should be included in the verification for both the plastic limit state and the buckling limit state, and these verifications should be carried out using EN 1993-1-6.

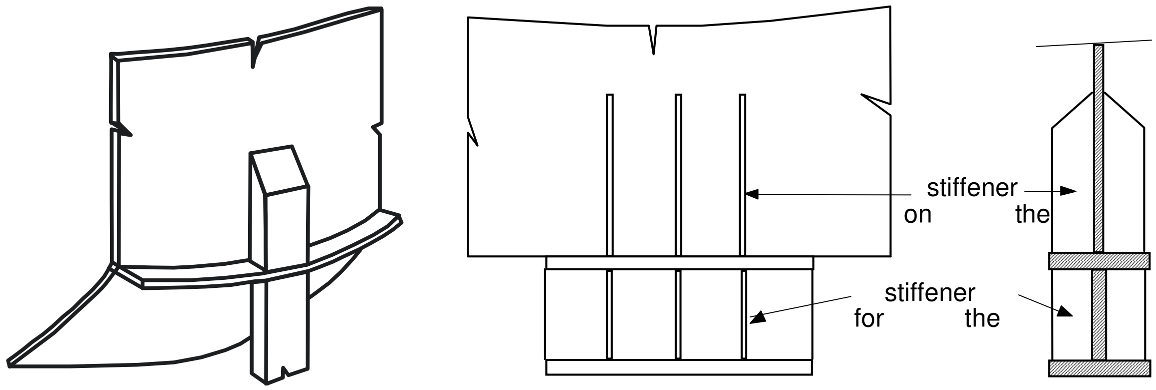
5.4.6 Local support details and ribs for load introduction in cylindrical walls

5.4.6.1 Local supports beneath the wall of a cylinder

(1) A local support bracket beneath the wall of a cylinder should be proportioned to transmit the design force without localised irreversible deformation to the support or the shell wall.

(2) The support should be proportioned to provide appropriate vertical, circumferential and meridional rotational restraint to the edge of the cylinder.

NOTE: Some possible support details are shown in figure 5.7.



Local support at transition ring with engaged column | **Possible stiffening arrangement for cylindrical wall with high local support loads**

Figure 5.7: Typical details of supports

(3) The length of engagement should be chosen taking account of the limit state of buckling of the shell in shear adjacent to the engaged column, see 5.3.2.6.

(4) Where discrete supports are used without a ring girder, the stiffener above each support should be either:

a) engaged into the shell as far as the eaves;

b) engaged by a distance not less than L_{min}, determined from:

$$L_{\text{min}} = 0{,}4r\sqrt{\left(\frac{r}{t}\right)\cdot\frac{1}{n(n^2-1)}} \quad \text{... (5.84)}$$

where n is the number of supports around the shell circumference.

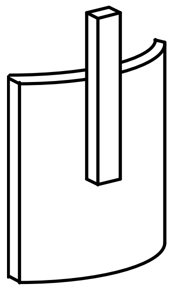
5.4.6.2 Local ribs for load introduction into cylindrical walls

(1) A rib for local load introduction into the wall of a cylinder should be proportioned to transmit the design force without localised irreversible deformation to the support or the shell wall.

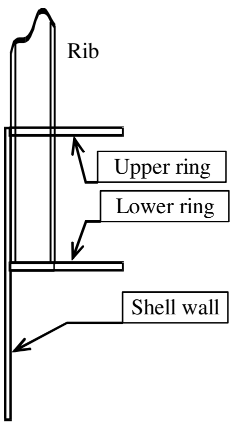
(2) The engagement length of the rib should be chosen taking account of the limit state of buckling of the shell in shear adjacent to the rib, see 5.3.2.6.

(3) The design of the rib should take account of the need for rotational restraint of the rib to prevent local radial deformations of the cylinder wall. Where necessary, stiffening rings should be used to prevent radial deformations.

NOTE: Possible details for load introduction into the shell using local ribs are shown in figure 5.8.



Local rib without rings attached to cylindrical wall



Local rib with stiffening rings to resist radial displacements

Figure 5.8: Typical details of loading rib attachments

5.4.7 Anchorage at the base of a silo

(1) The design of the anchorage should take account of the circumferential non-uniformity of the actual actions on the shell wall. Particular attention should be paid to the local high anchorage requirements needed to resist wind action.

> **NOTE:** Anchorage forces are usually underestimated if the silo is treated as a cantilever beam under global bending.

(2) The separation between anchorages should not exceed the value derived from consideration of the base ring design, given in 8.5.3.

(3) Unless a more thorough assessment is made using numerical analysis, the anchorage design should have a resistance adequate to sustain the local value of the uplifting force $n_{x,Ed}$ per unit circumference:

$$n_{x,Ed} = p_{n,Edw}\left(\frac{L^2}{2r}\right)\left[C_1 + \sum_{m=2}^{M} m^2 C_m \left\{1 - \frac{3}{4}\left(\frac{a_1}{a_2 + a_3}\right)\right\}\right] \quad \text{... (5.85)}$$

$$a_1 = 1 + 10,4\left(\frac{r}{mL}\right)^2 \quad \text{... (5.86)}$$

$$a_2 = 1 + 7,8\left(\frac{r}{mL}\right)^2 \quad \text{... (5.87)}$$

$$a_3 = 3\frac{r^3 t}{I_z}\left(\frac{r}{L}\right)^3\left(\frac{1}{m^4(m^2-1)^2}\right) \quad \text{... (5.88)}$$

where:

$p_{n,Edw}$ is the design value of the stagnation point pressure under wind;
L is the total height of the cylindrical shell wall;
t is the mean thickness of the cylindrical shell wall;