Singapore Standard SS EN 1993-4-1 : 2011

Eurocode 3: Design of steel structures
– Part 4-1 : Silos

AMENDMENT NO. 1

April 2020

1. Page 7, Modification to the Foreword

In the section “National Annex for EN 1993-4-1”, *replace* “6.3.2.7 (3)” with “6.3.2.7 (4)”.

2. Page 8, Modifications to 1.2 Normative references

In the entry dedicated to EN 1990, *replace* "EN 1990" with " EN 1990:2002" and *replace* the title of this reference with "Eurocode – Basis of structural design".

In the entry dedicated to EN 1993, in the list, *replace* "Part 1.6:" with "Part 1.6:2007:".

3. Page 12, Modification to 1.6.1 Roman upper case letters

Replace “R_ϕ local radius at the crest or trough of a corrugation.” with "r_ϕ local radius at the crest or trough of a corrugation.".

4. Page 12, Modification to 1.6.2 Roman lower case letters

Replace "ℓ wavelength of a corrugation in corrugated sheeting;" with "l wavelength of a corrugation in corrugated sheeting;".

5. Page 22, Modification to 2.7, Modelling of the silo for determining action effects

Replace Paragraph (1)P with:

"(1)P The general requirements set out in EN 1990 shall be followed.".

6. Page 23, Modification to 2.9.1, General

Replace Paragraph (1)P with:

"(1)P The general requirements set out in EN 1990 shall be satisfied.".

7. Page 23, Modification to 2.9.2.2 Partial factors for resistances

Add two new Paragraphs (4) and (5) after Paragraph (3)P*:*

(4) Where hot rolled steel sections are used as part of a silo structure, the relevant partial factors for resistance should be taken from EN 1993-1-1.

(5) Where cold-formed steel sections are used as part of a silo structure, the relevant partial factors for resistance should be taken from EN 1993-1-3.

8. Page 24, Modification to 2.10 Durability

Replace Paragraph (1) with:

(1) The general requirements set out in 2.4 of EN 1990 : 2008 should be followed.

9. Page 28, Modification to 4.2.2.1 General

Add the following new Paragraphs (3) to (6) after Paragraph (2):

(3) Where the silo is subject to any form of unsymmetrical bulk solids loading (patch loads, eccentric discharge, unsymmetrical filling etc.), the structural model should be designed to capture the membrane shear transmission within the silo wall and between the wall and rings.

NOTE The shear transmission between parts of the wall and rings has special importance in construction using bolts or other discrete connectors (e.g. between the wall and hopper, between the cylinder wall and vertical stiffeners or support, and between different strakes of the cylinder).

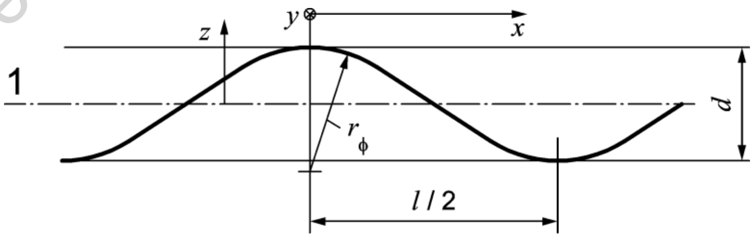
(4) Where a ring girder is used to redistribute silo wall forces into discrete supports, and where bolts or discrete connectors are used to join the structural elements, the shear transmission between the parts of the ring due to shell bending and ring girder bending phenomena should be determined.

(5) The stiffness of the stored bulk solid in resisting wall deformations or in increasing the buckling resistance of the shell structure should only be considered where a rational analysis is used and there is clear evidence that the solid against the wall is not in motion at the specified location during discharge. In such situations, the relevant information on the flow pattern, the pressure in the solid and the properties of the specific stored bulk solid should be determined from SS EN 1991-4.

(6) Where a corrugated silo exhibits mass flow, the solid held stationary within the corrugations should not be considered as stationary in (5).

10. Page 32, Modification to 4.4 Equivalent orthotropic properties if corrugated sheeting paragraph

(a) *Replace* Figure 4.2 with:



Key

1 effective middle surface

Figure 4.2 – Corrugation profile and geometric parameters

(b) *Replace the notation lines in Paragraph (3) with:*

where:

d is the crest to crest dimension;

l is the wavelength of the corrugation;

r_ϕ is the local radius at the crest or trough.

(c) *Delete* Paragraphs (4) to (7) and *add* the following new Paragraphs (4) to (7) after Paragraph (3):

(4) The equivalent properties of the sheeting in each of the two principal directions may be treated as independent, so that strains in one direction do not produce stresses in the orthogonal direction (i.e. no Poisson effects).

(5) The equivalent membrane properties (stretching stiffnesses) may be taken as:

$$C_x = Et_x \qquad \text{... (4.2)}$$

$$C_y = Et_y \qquad \text{... (4.3)}$$

$$C_{xy} = Gt_{xy} \qquad \text{... (4.4)}$$

where:

t_x is the equivalent thickness for the smeared membrane stiffness normal to the corrugations, given by:

$$t_x = \frac{2t^3}{3d^2} \qquad \text{...(4.5)}$$

t_y is the equivalent thickness for the smeared membrane stiffness parallel to the corrugations, given by:

$$t_y = (1 + \frac{\pi^2\, d^2}{4l^2}) \qquad \text{... (4.6)}$$

t_{xy} is the equivalent thickness for the smeared membrane shear stiffness, given by:

$$t_{xy} = \frac{t}{(1+\frac{\pi^2\, d^2}{4l^2})} \qquad \text{... (4.7)}$$

(6) The equivalent bending properties (flexural stiffnesses) are defined in terms of the flexural rigidity for moments causing bending stresses in that direction, and may be taken as:

$$D_x = EI_x \qquad \text{... (4.8)}$$

$$D_y = EI_y \qquad \text{... (4.9)}$$

$$D_{xy} = GI_{xy} \qquad \text{... (4.10)}$$

where:

I_x is the equivalent second moment of area per unit width for the smeared bending stiffness perpendicular to the corrugations, given by:

$$I_x = \frac{t^3}{12(1-\nu^2)} \frac{1}{\left(1+\frac{\pi^2 d^2}{4l^2}\right)} \qquad \text{...(4.11)}$$

I_y is the equivalent second moment of area per unit width for the smeared bending stiffness parallel to the corrugations. For the corrugated profiles described in 4.4(2), it may be taken as:

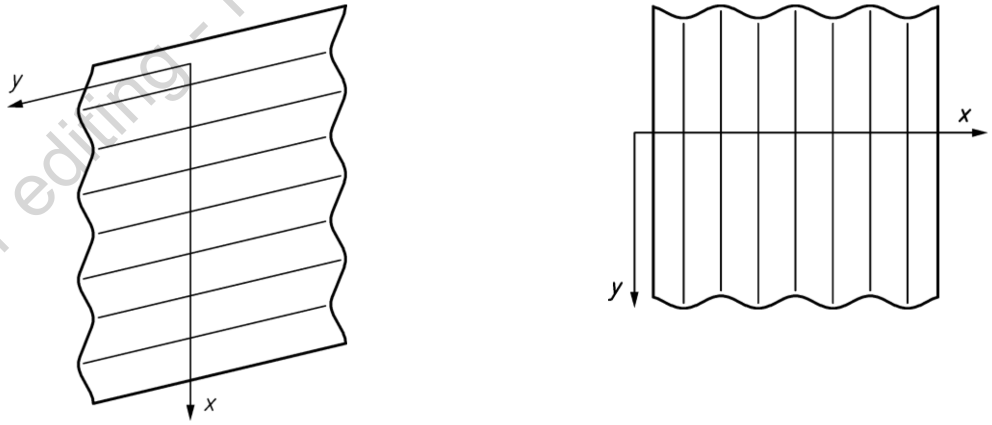
$$I_y = \frac{td^2}{8}\left(1+\frac{\pi^2 d^2}{8l^2}\right) \qquad \text{...(4.12)}$$

I_{xy} is the equivalent second moment of area per unit width for the smeared twisting stiffness:

$$I_{xy} = \frac{t^3}{12}\left(1+\frac{\pi^2 d^2}{4l^2}\right) \qquad \text{…(4.13)}$$

NOTE The convention for bending moments in plates relates to the direction in which the plate becomes curved, so is contrary to the convention used for beams. Bending parallel to the corrugation engages the bending stiffness of the corrugated profile, induces stresses parallel to the corrugation, and is the chief reason for using corrugated construction.

(7) In circular silos, the corrugations are commonly arranged to run circumferentially. In this arrangement, the directions x and y in the above expressions should be taken as the vertical x and circumferential θ directions respectively, see Figure 4.3 a). In the less common arrangement in which the corrugations run vertically, the directions x and y in the above expressions should be taken as the circumferential θ and vertical x directions respectively, see Figure 4.3 b).



a) Corrugations running horizontally b) Corrugations running vertically

Figure 4.3 – Corrugated sheeting and silo wall orientations

Replace Paragraph (9) with the following:

(9) In rectangular silos, the corrugations are commonly arranged to run horizontally. In this arrangement, the directions x and y in the above expressions should be taken as the vertical x and horizontal y directions respectively, see Figure 4.3 a). In the less common arrangement where the corrugations run vertically, the directions x and y in the above expressions should be interchanged on the real structure and taken as the vertical y and horizontal x directions respectively, see Figure 4.3 b).

11. Page 39, Modifications to 5.3.2.4 Buckling under axial compression

In Paragraph (4), *replace* Formula (5.15) with:

$$\text{“}\alpha_0 = \frac{0{,}83}{1+2{,}2\Psi(W_{ok}/t)^{0.88}}\text{”.} \qquad \ldots(5.15)$$

Replace Paragraph (7) with:

(7) The plastic pressurised imperfection reduction factor α_{pp} should be based on the largest local internal pressure p_g at the location of the point being assessed where the local thickness is t, and coexistent with the local value of axial compression that may cause buckling:

$$\alpha_{pp} = \left\{1 - \left(\frac{\bar{p}_g}{\lambda_x^2}\right)\right\}\left[1 - \frac{1}{1{,}12+s^{3/2}}\right]\left[\frac{s^2+1{,}21\bar{\lambda}_x^2}{s(s+1)}\right] \qquad \ldots(5.18)$$

with:

$$\bar{p}_g = \frac{p_g}{\sigma_{x,Rcr}} \cdot \frac{r}{t} \qquad \ldots(5.19)$$

$$s = \left(\frac{1}{400}\right)\left(\frac{r}{t}\right) \qquad \ldots(5.20)$$

$$\bar{\lambda}_x^2 = \frac{f_y}{\sigma_{x,Rcr}} \qquad \ldots(5.21)$$

where:

p_g is the largest design value of the local internal pressure (see EN 1991-4).

Different extremes of the material properties for a solid, defined in EN 1991-4, lead to different coupled values of axial force and internal pressure. A consistent pair of values should be used each time when applying Formulae (5.16) and (5.18).

(7a) The increase in buckling resistance of the shell structure due to the elastic stiffness of stationary bulk solid may only be considered using a rational analysis, where there is clear evidence that the solid against the wall is not in motion at the specified location during discharge and the relevant information on the flow pattern, the pressure in the solid and the properties of the specific stored bulk solid are determined from EN 1991-4.

In Paragraph (9), in the 1st sentence, *replace* “lies in the range 0,3 < s < 1,0, the above” *with* “lies in the range 0,3 < s < 0,8, the above”.

In Paragraph (15), in the NOTE *replace* "The values β = 0,60 and η = 1,0 are recommended." *with* "The values of

$$\beta = 1 - \frac{0{,}95}{1 + 1{,}2\,(W_{ok}/t)} \qquad \eta = \frac{5{,}4}{1 + 4{,}6\,(W_{ok}/t)}$$

and χ_h = 1,0 are recommended.”.

12. Page 44, Modification to 5.3.2.5 Buckling under external pressure, internal partial vacuum and wind

Replace Paragraph (9) with the following and the new Formula (5.40a):

(9) Where the silo is isolated and subject to a combination of both wind loading and internal vacuum, the value of C_w to be used in expression (5.38) should be modified to C_{wc}, as given by:

$$C_{wc} = \frac{P_{nu} + C_w P_{nw}}{P_{nu} + P_{nw}} \qquad \text{…(5.40a)}$$

where:

P_{nu} is the design value of the uniform external pressure;
P_{nw} is the design value of the stagnation pressure of the wind;
C_w is the wind pressure distribution coefficient given in Paragraph (8).

13. Page 47, Modification to 5.3.2.6 Membrane shear paragraph (5)

In Paragraph (5), *replace* equation (5.55) with the following:

$$\ell_0 = \frac{\tau_{x\theta,Ed,max}}{\left(\frac{d\tau_{x\theta,Ed}}{dy}\right)} \qquad \text{…(5.55)}$$

14. Page 48, Modification to 5.3.3.3 Buckling under axial compression

Replace Paragraphs (1) to (4) with:

(1) The spacing of the stiffeners should not exceed the lesser of 24° and 1000 mm.

(2) The axial compressive stress in the silo shell differs from that in the stiffeners due to the effect of internal pressure acting on the silo shell alone. The axial stress resultant per unit circumference in the silo shell $n_{x,Ed}$ should be determined from the total axial force in the wall and stiffeners $N_{x,Ed}$ at every level, as:

$$n_{x,Ed} = \left(\frac{f}{1+f}\right)\left[\frac{N_{x,Ed}}{2\pi r} - \frac{vpr}{f}\right] \qquad \text{... (5.58a)}$$

The axial force in each stiffener $N_{sx,Ed}$ should be determined from the total axial force in the wall and stiffeners $N_{x,Ed}$ at each level, as:

$$N_{sx,Ed} = d_s \left(\frac{1}{1+f}\right)\left[\frac{N_{x,Ed}}{2\pi r} + vpr\right] \qquad \text{... (5.58b)}$$

in which

$$f = \frac{d_s t}{A_s}$$

where:

t is the local value of the shell wall thickness;

d_s is the circumferential distance between adjacent stiffeners;

A_s is the cross-sectional area of each stiffener;

v is Poisson's ratio (taken as 0,30);

p is the local value of the internal pressure (see EN 1991-4).

(3) Where the silo wall is not in contact with the stored solid, the buckling resistance of the stiffener to axial compression should be calculated assuming a uniform compressive stress on the entire cross-sectional area at any level.

(4) The buckling effective length of the stiffener used in determining the reduction factor x should be taken as equal to:

$$L_e = \pi \left(\frac{EI_{sy}}{K}\right)^{1/4} \qquad \text{…(5.58c)}$$

but not greater than the distance between adjacent ring stiffeners

where:

EI_{sy} is the flexural rigidity of the stiffener for bending normal to the plane of the wall (Nmm2);

K is the stiffness offered by the shell wall (N/mm per mm of wall height) to restrain buckling normal to the wall.

(5) The stiffness of the shell wall K in restraining the effective length of the stiffener should be determined assuming that the wall spans between adjacent vertical stiffeners on either side. Two alternative methods may be used, as defined in Paragraphs (6) and (7).

(6) A simple assessment of the value of K may be made treating the shell wall as straight with simply supported boundary conditions (see Figure 5.5). The value of K may then be estimated as:

$$K = k_s E \left(\frac{t}{d_s}\right)^3 \qquad \text{…(5.58d)}$$

where:

k_s is a stiffness coefficient.

NOTE The National Annex may choose the value of k_s. The value $k_s = 0{,}5$ is recommended.

t is the local thickness of the shell wall at the location being assessed;

d_s is the circumferential separation of the vertical stiffeners.

(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 (Figure 5.6). The value of K may then be estimated using:

$$K = \frac{1}{r}\left\{\frac{2Et^3}{ft^2 + 12r^2\{f + \phi\, cos^2\, \phi\, (\tan\phi + 2g)^2 - 2[2g^2 \sin 2\phi - 2g(\cos 2\phi - \cos\phi) - \sin\phi\,(cos\phi - 1)]\}}\right\}$$

…(5.58e)

$$\phi = \frac{d_s}{r}$$ …(5.58f)

$$f = \frac{1}{4}\{(4g^2 + 1)(2\phi + \sin 2\phi) + 4g(1 - \cos 2\phi) - 2\sin 2\phi\}$$ …(5.58g)

$$g = \frac{t^2\, sin^2\phi - 12r^2[(1-\cos\phi)(1+3\cos\phi) - \phi \sin 2\phi]}{t^2(2\phi + \sin 2\phi) - 12r^2[2\phi(2+\cos 2\phi) - 3\sin 2\phi]}$$ …(5.58h)

(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 SS 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 characteristic buckling resistance of the shell wall $n_{x,Rk}$ should be calculated as defined in 5.3.2.4.

(10) Where a rolled section is used for the stiffener, the axial compression buckling resistance of the stiffener $N_{s,b,Rk}$ should be assessed as under concentric compression according to SS EN 1993-1-1, considering only buckling normal to the shell wall.

(11) Where a cold-formed member is used for the stiffener, the axial compression buckling resistance should assessed as under concentric compression according to SS EN 1993-1-3, considering only buckling normal to the shell wall.

(12) The connectors between the stiffener and the silo shell should be at a vertical spacing not greater than $L_e/4$, where L_e is determined using Paragraph (4).

(13) 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.

(14) There should be no cause introducing unintentional bending moments into the 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.).

(15) The eccentricity of the stiffener centroid to the silo shell middle surface may be ignored.

15. Page 49, Modifications to 5.3.4.1 General

Replace Paragraphs (1) and (4) with the following:

(1) All calculations should be carried out with thicknesses exclusive of coatings. Tolerances on thickness should be adopted according to the requirements of EN 1993-1-3.

(4) Where the continuity of stiffeners is obtained by semi-rigid connections such as overlaps or sleeves, etc., the rotational rigidity of the connections should be taken into account in the verification of their resistance and stability under actions due to stored solids as well as under wind or external pressure.

16. Page 50, Modifications to 5.3.4.2 Plastic limit state

Replace Paragraph (3) with the following:

The spacing between fasteners around the circumference should not exceed the lesser of 500 mm and 15° of the circumference, as shown in Figure 5.4.

17. Page 51, Modification to 5.3.4.3.1 General

Replace Paragraph 2(b) with the following:

b) buckling of the individual stiffeners (corrugated wall assumed to carry no axial force, but providing restraint to the stiffeners) and following 5.3.4.3.4.

18. Page 52, Modifications to 5.3.4.3.3 Stiffened wall treated as an orthotropic shell

In Paragraph (2), *replace* "NOTE The National Annex may choose the value of k_{dx}. The value k_{dx} = 7,4 is recommended." with the following:

NOTE The National Annex may choose the value of k_{dx}. The value k_{dx} = 9,1 is recommended.

Replace Paragraph (3) with the following:

(3) The critical buckling stress resultant $n_{x,Rcr}$ per unit circumference of the orthotropic shell (Method a) in 5.3.4.3.1) should be evaluated at each appropriate level in the silo. The critical buckling stress resultant $n_{x,Rcr}$ may be evaluated for any chosen circumferential mode (wave number) j and any prospective height of the buckle ℓ_i by minimising the following expression with respect to both j and ℓ_i. The values of ℓ_i may take any value up to the total height of the wall, but may take any smaller values. The minimisation to find the critical value of $n_{x,Rcr}$ may be made by any appropriate minimisation (optimisation) procedure.

$$n_{\mathrm{x,Rcr}} = \frac{1}{j^2 w^2}\left(A_1 + \frac{A_2}{A_3}\right) \qquad \text{…(5.65)}$$

Where no ring stiffeners are present, the values of A_r, I_r and I_{tr} should be taken as zero, but d_r should be taken as non-zero to avoid division by zero. Where no stringer stiffeners are present, the values of A_s, I_s and I_{ts} should be taken as zero, but d_s should be taken as non-zero to avoid division by zero.

It may be helpful to draw a contour plot of $n_{x,Rcr}$ against j and ℓ_i as this may provide a faster means of optimising Formula (5.65) than simple trial and error.

Replace Paragraph (5) with the following:

(5) The design buckling resistance $n_{x,Rd}$ per unit circumference for the orthotropic shell (Method a) in 5.3.4.3.1) should be determined as the lesser of:

$$n_{x,Rd} = \alpha_x n_{x,Rcr} / \gamma_{M1} \qquad \text{…(5.69)}$$

and

$$n_{x,Rd} = A_{eff}\, f_y / (d_s \gamma_{M0}) \qquad \text{... (5.70)}$$

where:

α_x	is the elastic buckling imperfection reduction factor;
γ_{M1}	is the partial factor given in 2.9.2;
d_s	is the distance between the stringer stiffeners;
A_{eff}	is the effective cross-sectional area of the stringer stiffener.

NOTE The National Annex may choose the value of α_x. The value α_x = 0,80 is recommended.

19. Page 54, Modification to 5.3.4.3.4 Stiffened wall treated as carrying axial compression only in the stiffeners

Replace Paragraphs (2) to (6) with the following:

(2) The effective length of the stiffener for buckling calculations should be determined according to Assumption a) or b) in Paragraph (1).

(3) If Method a) in Paragraph (1) is used, the effective length L_e used in determining the reduction factor χ should be taken as the distance between adjacent ring stiffeners.

(4) If Method b) in Paragraph (1) is used, the buckling effective length of column used in determining the reduction factor χ should be taken as equal to:

$$L_e = \pi \left(\frac{EI_{sy}}{K} \right)^{1/4} \qquad \text{... (5.72)}$$

but not greater than the distance between adjacent ring stiffeners;

where:

EI_{sy}	is the flexural rigidity of the stiffener for bending normal to the plane of the wall (Nmm2);
K	is the flexural stiffness of the corrugated wall sheet (N/mm per mm of wall height) spanning between vertical stiffeners.

(5) The flexural stiffness of the corrugated wall *K* should be determined assuming that the sheeting spans between adjacent vertical stiffeners on either side. Two alternative methods may be used, as defined in Paragraphs (6) and (7).

(6) A simple assessment of the value of *K* may be made treating the wall as straight with simply supported boundary conditions (see Figure 5.5). The value of *K* may then be estimated as:

$$K = k_s \frac{D_y}{d_s^3} \qquad \text{…(5.73)}$$

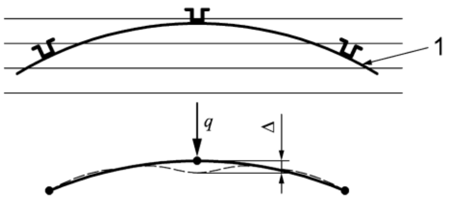
where:

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 value of D_y may be taken from 4.4(6). If other corrugation forms are adopted, the shell bending flexural rigidity for circumferential bending should be determined from first principles.

NOTE The National Annex may choose the value of k_s. The value $k_s = 6$ is recommended.



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:

$$K = \frac{1}{r}\left\{\frac{2C_y D_y}{f D_y + r^2\, C_y\, \{f + \phi\, cos^2\phi\,(\tan\phi + 2g)^2 - 2[2g^2\ \sin 2\phi - 2g(\cos 2\phi - \cos\phi) - \sin\phi\,(\cos\emptyset - 1)]\}}\right\} \quad \text{...(5.74)}$$

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

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

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

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 SS 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:

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

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 SS EN 1993-1-1 for rolled sections and SS 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 SS 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:

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

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;

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

(15) The overall relative slenderness $\overline{\lambda_x}$ for the segment should be determined from :

$\overline{\lambda_x} = \sqrt{R_{pl} \ / \ R_{cr}}$	... (5.76d)

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

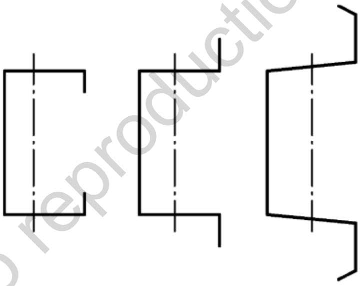


Figure 5.5 a) – Cold-formed stiffeners with edge stiffened flan es EN 1993-1-3 identifies: buckling curve b

$\alpha = 0.80; \quad \beta = 0.70; \quad \eta = 1.05; \quad \lambda_o = 0.2; \quad \chi_h = 1.0$ …(5.76e)

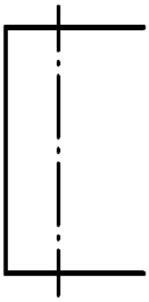


Figure 5.5 b) – Stiffeners with unstiffened flan es SS EN 1993-1-1 identifies: buckling curve c

$\alpha = 0,72; \quad \beta = 0,75; \quad \eta = 0,90; \quad \lambda_o = 0, 2; \quad \chi h = 1,0$ ... (5.76f)

(17) The general buckling relationship of 5.3.2.4(15) or SS 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:

$$\frac{R_k}{\gamma_{M1}} \geq 1.0 \qquad \text{... (5.76h)}$$

20. Page 67, Modification to 6.3.1 General

Replace Paragraph (1) with the following:

(1) The conical hopper should satisfy the provisions of EN 1993-1-6. Alternatively, these may be deemed to be satisfied using the assessments of the design resistance given in 6.3.2.

21. Page 70, Modifications to 6.3.2.5 Local flexure at the transition

Replace equations (6.8), (6.10) and (6.11) with the following:

$$F_h = 2\left(\frac{\chi_h}{\cos\beta}\right)(0{,}85 - 0{,}15\mu\cot\beta)p_{nh} \qquad \text{... (6.8)}$$

$$x_\mathrm{h} = 0{,}39\sqrt{rt_h}\,\cos\beta \qquad \text{…(6.10)}$$

$$\sigma_{b\phi h,Ed} = \left(\frac{6}{\Delta}\right)\left\{(a_2 - 2a_1\eta)M_{e,Ed} - \rho(a_3 - a_2\eta)F_{e,Ed}\right\} - \left(\frac{6}{t_h^2}\right)F_h x_h \qquad \text{…(6.11)}$$

22. Pg. 72, Modifications to 6.3.2.7 Buckling in hoppers

Replace Paragraphs (1) to (4) with the following new Paragraphs (1) to (5):

(1) Whilst hopper structures are normally under biaxial tension, so no problems of buckling arise, some loading conditions can lead to compressive meridional membrane stresses. These include horizontal actions from feeders or attached structures, unsymmetrical vertical actions, and eccentric discharge channels in a hopper. For these conditions, it should be verified that a compressive meridional membrane stress resultant does not cause buckling.

(2) This section is only relevant if the value of $n_{\phi,\mathrm{Ed}}$ at some point in the hopper is compressive. The sign of both $n_{\phi,\mathrm{Ed}}$ and $n_{\phi,\mathrm{Rd}}$ is taken as positive in compression in this section.

NOTE The meridional membrane stress resultant in a hopper is normally tensile.

(3) Checks against buckling in the hopper should be performed at locations where the peak compressive membrane stress resultant is high.

(4) The design buckling resistance $n_{\phi,\mathrm{Rd}}$ at any point in the hopper should be determined from:

$$\mathrm{n}_{\phi,\mathrm{Rd}} = 0{,}6\alpha_{xh}E\left(\frac{t_h^2}{r}\right)\cos\beta\,/\,\gamma_{M1} \qquad \text{…(6.18)}$$

where:

α_{xh} is the elastic buckling imperfection sensitivity factor;

r is the simple radius at the point in the hopper of peak meridional compressive stress resultant;

t_h is the hopper local wall thickness;

and γ_{M1} is given in 2.9.2, but $n_{\phi,Rd}$ should not be taken as greater than $n_{\phi,Rd} = t_h f_y / \gamma_{M0}$.

NOTE 1: The National Annex may choose the value of α_{xh}. The value α_{xh}= 0,30 is recommended.

NOTE 2 Formula (6.18) provides a simplified method of assessing the buckling resistance. For a more complete evaluation, refer to EN 1993-1-6.

(5) The meridional stress resultant at the critical point in the hopper should satisfy the condition:

$$n_{\phi,Ed} \le n_{\phi,Rd} \qquad \text{…(6.19)}$$

23. Page 72, Modification to 6.4.1, Supporting structures

Replace Paragraph (1) with the following:

(1) The effect of discrete supports beneath the silo should be treated as set out in 5.4. The supporting structures themselves should be designed to SS EN 1993-1-1, with the boundary between the silo and supporting structure as defined in 1.1(5).

24. Page 79, Modifications to 8.2.2 Uniformly supported transition junctions

Replace Paragraphs (5) to (7) with the following:

(5) The effective cross-sectional area Aep of the annular plate joining into the junction at the joint centre (see Figure 8.4a) should be determined from the actual area Ap (=btp) as:

$$A_{ep} = \frac{bt_p}{1+0{,}8\frac{b}{r}} \qquad \text{…(8.10)}$$

where:
r is the radius of the silo cylinder wall;
b is the radial width of the annular plate ring;
*t*p is the thickness of the annular plate ring.

(6) The total effective area A_{et} of the ring and contributing parts of the adjacent shell segments in developing circumferential compression should be determined from:

$$A_{et} = A_{ep} + \sum_{i=1}^{all\ segment} A_{ei} \qquad \text{... (8.11)}$$

which may be written for the junction shown in Figure 8.4a as:

$$A_{et} = A_{ep} + 0{,}778\sqrt{r}\left\{t_c^{3/2} + \psi\left(\frac{t_h^{3/2}}{\sqrt{\cos\beta}} + t_s^{3/2}\right)\right\} \qquad \text{…(8.12)}$$

with :

$$\psi = 0{,}5(1 + 3a^2 - 2a^3) \qquad \text{…(8.13)}$$

$$a = \frac{t_c}{\sqrt{t_s^2 + t_h^2}} \qquad \text{…(8.14)}$$

where:

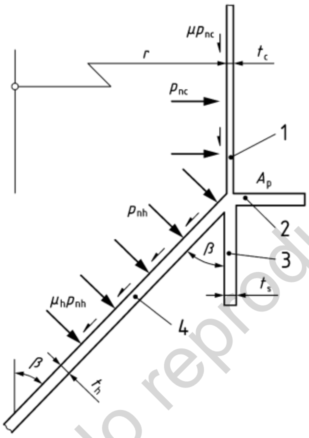
r is the radius of the silo cylinder wall;

t_c is the thickness of the cylinder;

t_s is the thickness of the skirt;

t_h is the thickness of the hopper;

A_{ep} is the effective area of the annular plate ring.

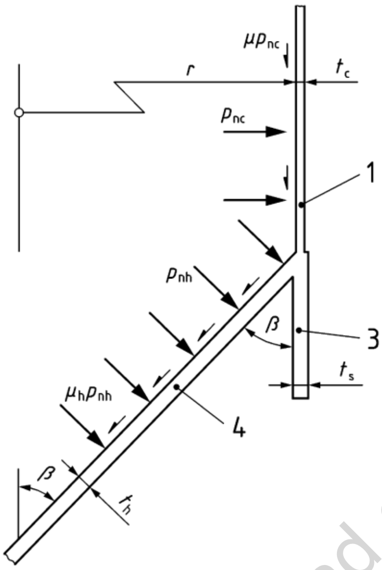


Key
1 cylinder
2 ring
3 skirt
4 hopper

Figure 8.4a: Notation for simple annular plate transition junction

(7) Where the junction consists only of a cylinder, skirt and hopper (see figure 8.4b), the total effective area of the ring A_{et} may be found from:

$$A_e = 0{,}778\sqrt{r}\left\{t_c^{3/2} + \Psi\left(\frac{t_h^{3/2}}{\sqrt{\cos\beta}} + t_s^{3/2}\right)\right\} \qquad \text{…(8.14a)}$$



Key

1 cylinder
3 skirt
4 hopper

Figure 8.4b: Transition junction without added ring

25. Page 88, Modification to 8.3.4.3, Annular plate transition junction

Replace Paragraph (1) with the following:

(1) For junctions in which the ring at the transition is in the form of an annular plate, the design value of the resistance against out-of-plane buckling $\sigma_{op,Rd}$ should be determined using:

26. Page 93, Modification to 8.5.3, Base ring

Replace Paragraph (2) with the following:

(2) The circumferential spacing of anchorage bolts or other attachment points should not exceed $\frac{1}{2}(L^2rt)^{0,25}$ where *t* is the local thickness of the shell plate adjacent to the base and *L* is the lesser of the height of the first ring stiffener above the base, or the total height of the silo wall to the eaves.

27. Page 95, Modification to 9.4.1, General

Replace Paragraph (1) with the following:

(1) The resistance of unstiffened parts of vertical walls should be evaluated in accordance with the provisions set out in 9.3. The resistance evaluation should consider both membrane and plate bending actions.

28. Page 96, Modification to 9.4.2, General bending from direct action of the stored material

Replace Paragraphs (1) to (3) and Figure 9 with the following:

(1) Bending stresses developing in a corrugated or trapezoidal sheet wall should be considered, taking account of the horizontal bending about a vertical axis caused by horizontal

pressure acting on the wall, and local vertical bending about a horizontal axis where an axial force is transmitted through the corrugated or trapezoidal sheeting.

(2) The horizontal bending should consider the axis of bending as vertical, ignoring any effect of frictional drag on the wall from the stored solid (Fig. 9.5).

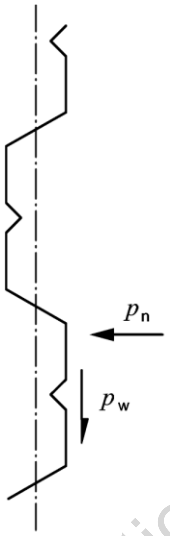


Figure 9.5 – Bending resulting from combined horizontal pressure and friction (vertical section)

29. Page 98, Modification to 9.5.1, Forces in internal ties due to solids pressure on them

Replace Paragraph (2) with the following:

(2) Unless more precise calculations are made, the force exerted by the solid q_t per unit length of tie may be approximated by:

$$q_t = C_t \, p_v b \qquad \dots(9.1)$$

with:

$$C_t = \frac{C_S \beta}{k_L \sqrt{b/b_0}} \qquad \dots(9.2)$$

where:

P_v is the vertical pressure within the stored material at the tie level;

b is the maximum horizontal width of the tie;

b_0 is the reference length of 1 m, expressed in the units that are used for b;

C_t is the load magnification factor;

C_s is the shape factor for the tie cross-section;

k_L is the loading state factor;

β is the tie location factor, that depends on the position of the tie within the silo cell (see Figures 9.8 and 9.9).

NOTE The empirical expression (9.2) would not be dimensionally consistent without the dimension b_o. For example, if b is expressed in inches, b_o = 39,37.