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Unfired pressure vessels - Part 3: Design

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Voorbeeld
Preview

Table 6-1 — Maximum allowed values of the nominal design stress for pressure parts other than bolts

	Normal operating load cases [a] [b]	**Testing and exceptional load cases** b)
Steels other than austenitic as per 6.2 $A < 30\ \%$ [c]	$f_\mathrm{d} = \min\left(\frac{R_{\mathrm{p0,2}/t}}{1{,}5}; \frac{R_{\mathrm{m}/20}}{2{,}4}\right)$	$f_\mathrm{test} = \left(\frac{R_{\mathrm{p0,2}/t_\mathrm{test}}}{1{,}05}\right)$
Austenitic steels as per 6.3 $30\ \% < A \leq 35\ \%$ [c]	$f_\mathrm{d} = \left(\frac{R_{\mathrm{p1,0}/t}}{1{,}5}\right)$	$f_\mathrm{test} = \left(\frac{R_{\mathrm{p1,0}/t_\mathrm{test}}}{1{,}05}\right)$
Austenitic steels as per 6.4 $A > 35\ \%$ [c]	$f_\mathrm{d} = \max\left[\left(\frac{R_{\mathrm{p1,0}/t}}{1{,}5}\right); \min\left(\frac{R_{\mathrm{p1,0}/t}}{1{,}2}; \frac{R_{\mathrm{m}/t}}{3}\right)\right]$	$f_\mathrm{test} = \max\left(\frac{R_{\mathrm{p1,0}/t_\mathrm{test}}}{1{,}05}; \frac{R_\mathrm{m}/t_\mathrm{test}}{2}\right)$
Cast steels	$f_\mathrm{d} = \min\left(\frac{R_{\mathrm{p0,2}/t}}{1{,}9}; \frac{R_{\mathrm{m}/20}}{3}\right)$	$f_\mathrm{test} = \min\left(\frac{R_{\mathrm{p0,2}/t_\mathrm{test}}}{1{,}33}\right)$

[a] For testing category 4 the nominal stress shall be multiplied by 0,9.

[b] Yield strength R_eH may be used in lieu of $R_\mathrm{p0,2}$ if the latter is not available from the material standard.

[c] For definition of rupture elongation see EN 13445-2:2002, Clause 4.

7 Shells under internal pressure

7.1 Purpose

This clause provides requirements for design against internal pressure of axisymmetric shells - cylinders, spheres, parts of spheres, dished ends, cones and cone to cylinder intersections. Methods are also provided for the design of offset cones connecting two cylinders and for nozzles encroaching into the knuckle region of dished ends.

7.2 Specific definitions

The following definitions apply in addition to those in clause 3.

7.2.1
cylinder
right circular cylinder

7.2.2
torispherical end
dished end, made up of a spherical cap, a toroidal knuckle and a cylindrical shell, the three components having common tangents where they meet

7.2.3
Kloepper type
torispherical end for which $R/D_e = 1,0$ and $r/D_e = 0,1$

7.2.4
Korbbogen type
torispherical end for which $R/D_e = 0,8$ and $r/D_e = 0,154$

7.2.5
ellipsoidal end
dished end made on a truly ellipsoidal former

7.3 Specific symbols and abbreviations

The following symbols and abbreviations apply in addition to those in clause 4.

D_e is the outside diameter of shell;

D_i is the inside diameter of shell;

D_m is the mean diameter of shell;

r is the inside radius of curvature of a knuckle.

7.5.3 Torispherical ends

7.5.3.1 Conditions of applicability

The following requirements are limited in application to ends for which all the following conditions are met:

$r \leq 0{,}2\,D_\mathrm{i}$

$r \geq 0{,}06 D_\mathrm{i}$

$\mathrm{r} \geq 2\mathrm{e}$

$e \leq 0{,}08\ D_\mathrm{e}$

$e_\mathrm{a} \geq 0{,}001\ D_\mathrm{e}$

$R \leq D_\mathrm{e}$

7.5.3.2 Design

The required thickness e shall be the greatest of e_s, e_y and e_b, where:

$$e_\mathrm{s} = \frac{P \cdot R}{2f \cdot z - 0{,}5P} \tag{7.5-1}$$

$$e_\mathrm{y} = \frac{\beta \cdot P\left(0{,}75R + 0{,}2D_\mathrm{i}\right)}{f} \tag{7.5-2}$$

where

ß is found from Figure 7.5-1 or the procedure in 7.5.3.5, replacing e by e_y.

and

$$e_\mathrm{b} = \left(0{,}75R + 0{,}2D_\mathrm{i}\right)\left[\frac{P}{111 f_\mathrm{b}}\left(\frac{D_\mathrm{i}}{r}\right)^{0{,}825}\right]^{\left(\frac{1}{1{,}5}\right)} \tag{7.5-3}$$

where

$$f_\mathrm{b} = \frac{R_{\mathrm{p}0{,}2/\mathrm{t}}}{1{,}5} \tag{7.5-4}$$

except for cold spun seamless austenitic stainless steel, where:

$$f_\mathrm{b} = \frac{1{,}6R_{\mathrm{p}0{,}2/\mathrm{t}}}{1{,}5} \tag{7.5-5}$$

At test conditions the value 1,5 in the equations for f_b shall be replaced by 1,05.

NOTE 1 For stainless steel ends that are not cold spun, f_b will be less than f.

NOTE 2 The 1,6 factor for cold spun ends takes account of strain hardening.

NOTE 3 It is not necessary to calculate e_b if $e_y > 0{,}005D_i$.

NOTE 4 The inside height of a torispherical end is given by

$$h_i = R - \sqrt{\left(R - D_i/2\right) \cdot \left(R + D_i/2 - 2r\right)}$$

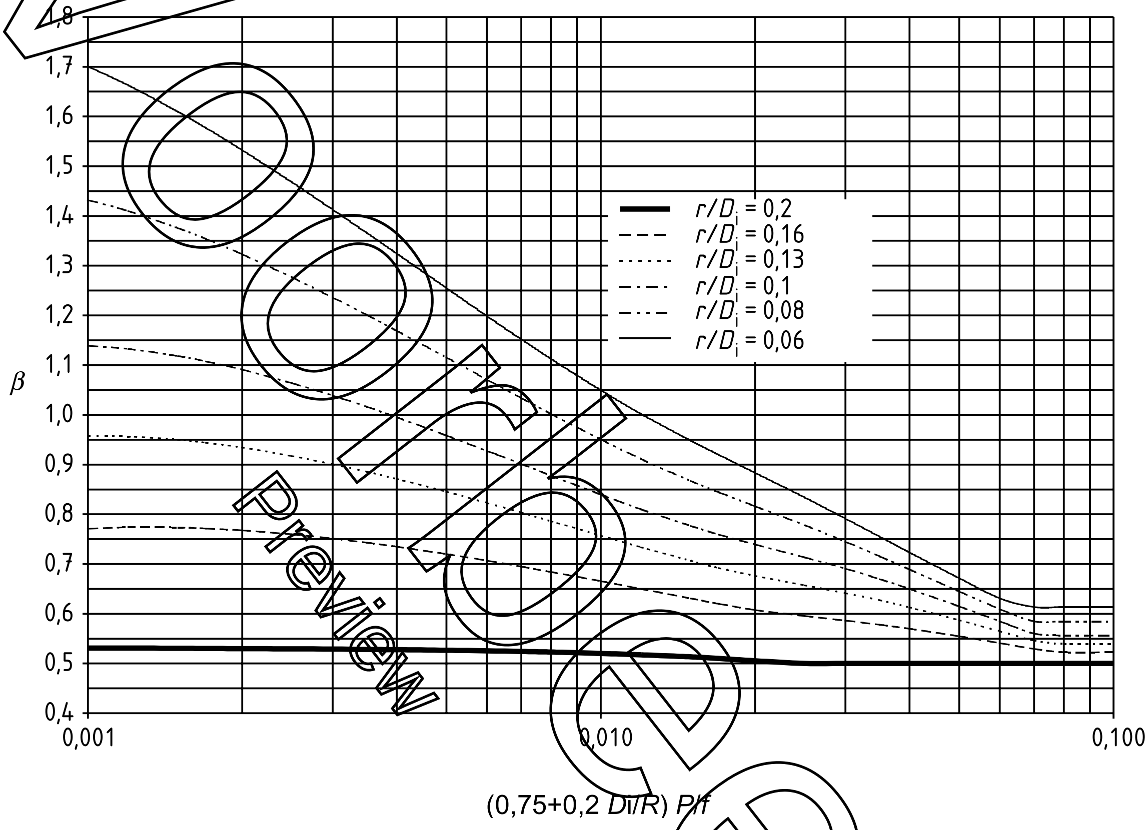


Figure 7.5-1 — Parameter β for torispherical end – Design

7.5.3.3 Rating

For a given geometry P_{max} shall be the least of P_s, P_y and P_b, where:

$$P_s = \frac{2f \cdot z \cdot e_a}{R + 0{,}5e_a} \tag{7.5-6}$$

$$P_y = \frac{f \cdot e_a}{\beta(0{,}75R + 0{,}2D_i)} \qquad (7.5\text{-}7)$$

where

ß is found from Figure 7.5-2 or the procedure in 7.5.3.5, replacing e by e_a.

$$P_b = 111 f_b \left(\frac{e_a}{0{,}75R + 0{,}2D_i}\right)^{1{,}5} \left(\frac{r}{D_i}\right)^{0{,}825} \qquad (7.5\text{-}8)$$

NOTE It is not necessary to calculate P_b if $e_a > 0{,}005D_i$.

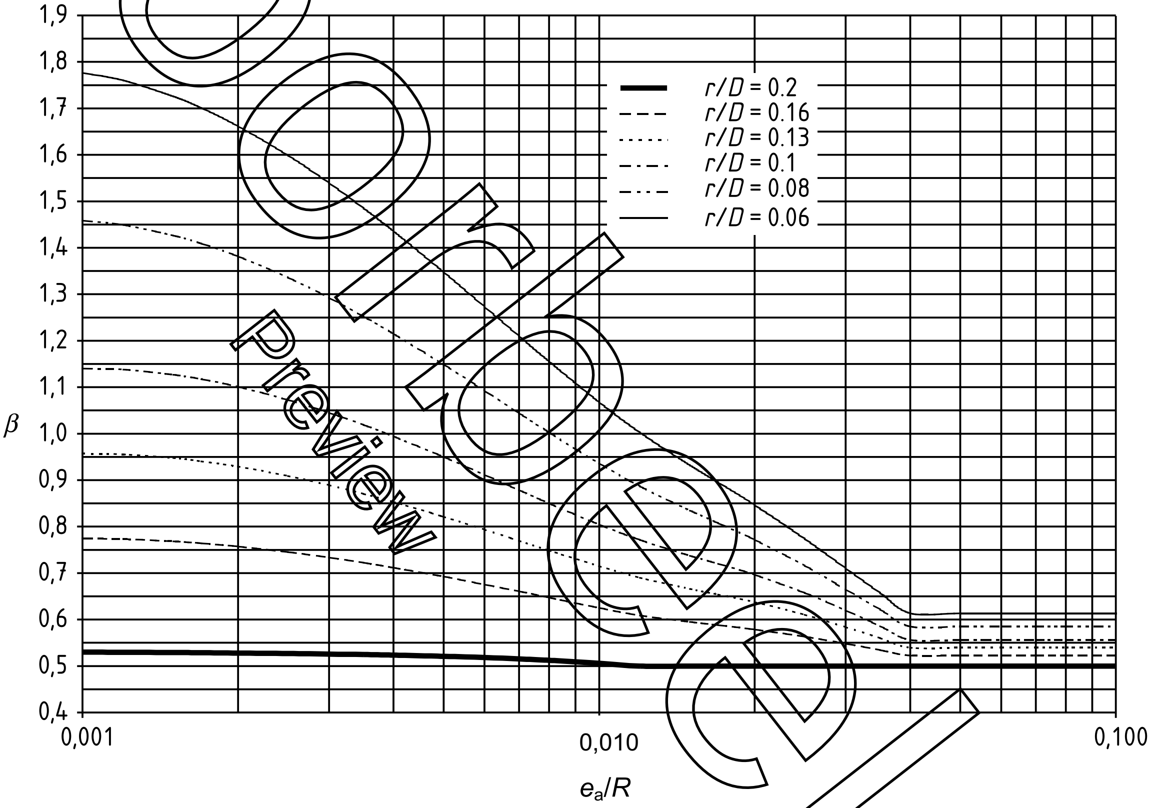


Figure 7.5-2 — Parameter *ß* for torispherical end - rating

7.5.3.4 Exceptions

It is permissible to reduce the thickness of the spherical part of the end to the value e_s over a circular area that shall not come closer to the knuckle than the distance $\sqrt{R \cdot e}$, as shown in Figure 7.5-3.

Any straight cylindrical flange shall meet the requirements of 7.4.2 for a cylinder, if its length is greater than $0{,}2\sqrt{D_i \cdot e}$. When the length is equal or smaller than $0{,}2\sqrt{D_i \cdot e}$, it may be the same thickness as required for the knuckle.

7.5.3.5 Formulae for calculation of factor β

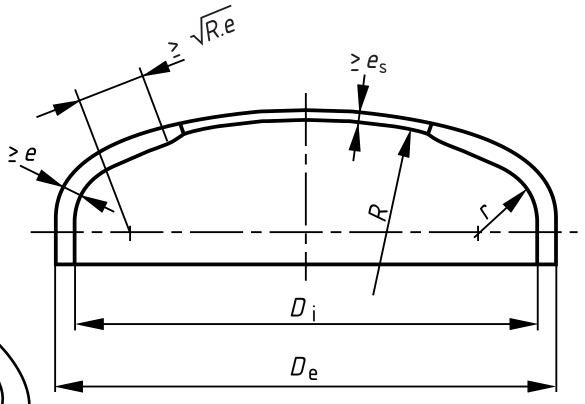


Figure 7.5-3 — Geometry of torispherical end

$$Y = \min(e/R\,;\,0{,}04) \qquad (7.5\text{-}9)$$

$$Z = \log 10\left(1/Y\right) \qquad (7.5\text{-}10)$$

$$X = r/D_i \qquad (7.5\text{-}11)$$

$$N = 1{,}006 - \frac{1}{\{6{,}2 + (90\,Y)^4\}} \qquad (7.5\text{-}12)$$

For $X = 0{,}06$

$$\beta_{0{,}06} = N\left(-0{,}3635Z^3 + 2{,}2124Z^2 - 3{,}2937Z + 1{,}8873\right) \qquad (7.5\text{-}13)$$

For $0{,}06 < X < 0{,}1$

$$\beta = 25\left\{(0{,}1 - X)\,\beta_{0{,}06} + (X - 0{,}06)\,\beta_{0{,}1}\right\} \qquad (7.5\text{-}14)$$

For $X = 0{,}1$

$$\beta_{0{,}1} = N\,(-0{,}1833Z^3 + 1{,}0383Z^2 - 1{,}2943Z + 0{,}837\,) \qquad (7.5\text{-}15)$$

7.6.6.2 Design

The required thickness e_1 of the cylinder adjacent to the junction is the greater of e_{cyl} and e_j where e_j shall be determined by the following procedure:

Assume a value of e_j and calculate :

$$\beta = \frac{1}{3}\sqrt{\frac{D_c}{e_j}} \cdot \frac{\tan(\alpha)}{1 + 1/\sqrt{\cos(\alpha)}} - 0{,}15 \qquad (7.6\text{-}11)$$

$$e_j = \frac{P \cdot D_c \cdot \beta}{2f} \qquad (7.6\text{-}12)$$

The thickness given by equation (7.6-12) is an acceptable thickness if not less than the value assumed.

NOTE The minimum required value for e_j can be obtained by iterative application of this procedure, until equation (7.6-12) gives the same value as that assumed.

β can also be read from the graph in Figure 7.6-3.

This thickness shall be maintained for a distance of at least 1,4l_1 from the junction along the cylinder.

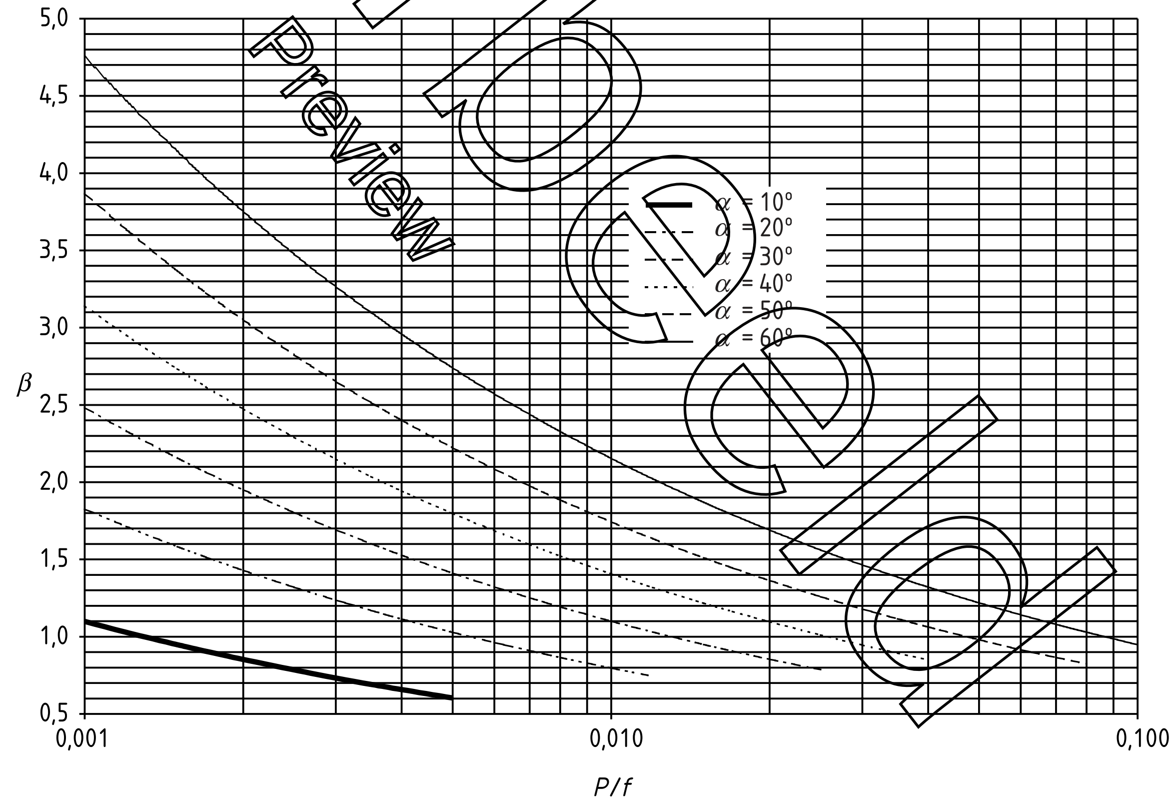


Figure 7.6-3 — Values of coefficient β for cone/cylinder intersection without knuckle

The required thickness e_2 of the cone adjacent to the junction is the greater of e_{con} and e_j. This thickness shall be maintained for a distance of at least $1{,}4l_2$ from the junction along the cone, see Figure 7.6-1.

It is permissible to redistribute the reinforcement in the following way, provided that the minimum thicknesses given by 7.4.2 and 7.6.4 continue to be met.

The thickness for the cylinder may be increased near the junction and reduced further away provided that the cross-sectional area of metal provided by the cylinder within a distance $1{,}4l_1$ from the junction is not less than $1{,}4e_1l_1$. In addition, the thickness of the cone may be increased near the junction and reduced further away provided that the cross-sectional area of metal provided by the cone within a distance $1{,}4l_2$ from the junction is not less than $1{,}4e_2l_2$.

7.6.6.3 Rating

The maximum permissible pressure for a given geometry shall be determined as follows:

a) apply equation (7.4-3) to cylinder;

b) apply equation (7.6-4) to the cone;

c) determine the analysis reinforcing thickness e_{1a} of the cylinder at the junction;

d) determine the analysis reinforcing thickness e_{2a} of the cone at the junction;

e) apply equation (7.6-4) with thickness e_{2a} and diameter D_m;

f) find e_j, the lesser of e_{1a} and e_{2a};

g) calculate β from equation (7.6-11), then,

$$P_{max} = \frac{2f \cdot e_j}{\beta \cdot D_c} \qquad (7.6\text{-}13)$$

h) the maximum permissible pressure is the lowest of the pressures determined in a), b), e) and g).

NOTE The following procedure may be used to find the analysis reinforcing thickness at c) or d) above:

1) Assume e_{1a} (the initial choice should be the thickness at the junction).

2) Calculate

$$l_1 = 1{,}4\sqrt{D_c \cdot e_{1a}} \qquad (7.6\text{-}14)$$

3) If the thickness is constant within the distance l_1 then e_{1a} is confirmed.

4) If not, calculate the metal area A_1 within the distance l_1 from the junction.

5) Obtain a better estimate by.

$$e_{1a} = A_1/l_1 \qquad (7.6\text{-}15)$$

The answer is acceptable if it is not greater than assumed in 1).

6) If the answer is unacceptable, return to 1).

7) Use a similar procedure to find e_{2a} making.

$$l_2 = 1{,}4\sqrt{\frac{D_c \cdot e_{2a}}{\cos(\alpha)}} \qquad (7.6\text{-}16)$$

7.6.7 Junction between the large end of a cone and a cylinder with a knuckle

7.6.7.1 Conditions of applicability

This sub-clause applies provided that all the following conditions are satisfied:

a) the knuckle is of toroidal form and merges smoothly with the adjacent cone and cylinder, and;

b) the inside radius of curvature of the knuckle, $r < 0{,}3\ D_c$.

NOTE This clause does not prescribe a lower limit to the radius of curvature of the knuckle.

7.6.7.2 Design

The value of e_j shall be determined by the following procedure:

Assume a value of e_j and calculate:

$$\beta = \frac{1}{3}\sqrt{\frac{D_c}{e_j}} \cdot \frac{\tan(\alpha)}{1 + 1/\sqrt{\cos(\alpha)}} - 0{,}15 \qquad (7.6\text{-}17)$$

$$\rho = \frac{0{,}028r}{\sqrt{D_c \cdot e_j}} \frac{\alpha}{1 + 1/\sqrt{\cos(\alpha)}} \qquad (7.6\text{-}18)$$

$$\gamma = 1 + \frac{\rho}{1{,}2\left(1 + \dfrac{0{,}2}{\rho}\right)} \qquad (7.6\text{-}19)$$

$$e_j = \frac{P \cdot D_c \cdot \beta}{2f\gamma} \qquad (7.6\text{-}20)$$

The thickness given by equation (7.6-20) is an acceptable thickness for the knuckle if not less than the value assumed.

NOTE The minimum required value for e_j can be obtained by iterative application of this procedure, until equation (7.6-20) gives the same value as that assumed.

The required thickness e_1 of the cylinder adjacent to the junction is the greater of e_{cyl} and e_j.

This thickness shall be maintained for a distance of at least $1{,}4l_1$ from the junction and $0{,}5l_1$ from the knuckle/cylinder tangent line along the cylinder.

The required thickness e_2 of the knuckle and the cone adjacent to the junction is the greater of e_{con} and e_j. This thickness shall be maintained for a distance of at least $1{,}4l_2$ from the junction and $0{,}7l_2$ from the cone/knuckle tangent line along the cone.

7.6.7.3 Rating

The maximum permissible pressure for a given geometry shall be determined as follows:

a) Determine e_{1a}, the analysis thicknesses for the cylinder next to the knuckle, and e_{2a}, the analysis thickness for the knuckle and the adjacent part of the cone;

b) Check that the limitations of 7.6.7.1 are met;

c) Apply equation (7.4-3) to the cylinder with $e_a = e_{1a}$;

d) Apply equation (7.6-4) to the cone with $e_{con} = e_{2a}$;

e) Find e_j, the lesser of e_{1a} and e_{2a} ;

f) Find β and γ from equations (7.6-17) and (7.6-19), then

$$P_{max} = \frac{2f \cdot \gamma \cdot e_j}{\beta \cdot D_c} \qquad (7.6\text{-}21)$$

g) The maximum permissible pressure is the lowest of the pressures determined in c), d) and f).

7.6.8 Junction between the small end of a cone and a cylinder

7.6.8.1 Conditions of applicability

The requirements of 7.6.8.2 and 7.6.8.3 apply provided that all the following conditions are satisfied:

a) the required thickness of the cylinder e_1 is maintained for a distance l_1 and that of the cone e_2 is maintained for a distance l_2 from the junction (see Figure 7.6-4); and

b) the thicknesses meet the requirements of 7.4.2 and 7.6.4;

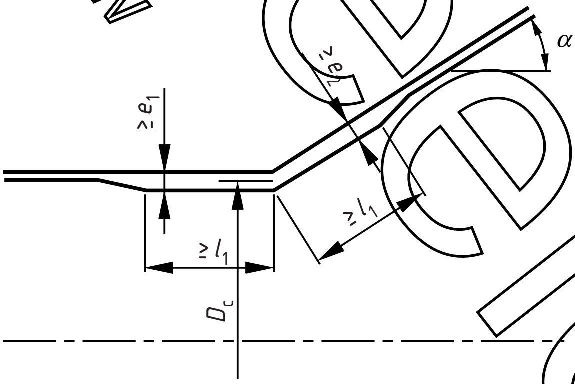


Figure 7.6-4 — Geometry of cone/cylinder intersection: small end

8.6.4 Overall collapse of conical shell and spacing

8.6.4.1 Constant shell thickness, stiffener size and spacing

The requirements for stiffening ring proportions to resist stiffener tripping, given for cylinders in subclause 8.5.3.8, apply without modification.

For the design of light stiffeners on cones of constant thickness, as shown in Figure 8.6-3:

$$P_{\mathrm{g}} = \frac{E \cdot e_{\mathrm{a}} \cdot \beta \cos^3\alpha}{\overline{R}_{\mathrm{n}}} + \frac{(n^2-1) E \cdot l'_e \cos\alpha}{\overline{\mathrm{R}}_{\max}^3 \cdot L_s} \qquad (8.6.4\text{-}1)$$

where β shall be determined from figure 8.5-13 with $\frac{L_H}{2\overline{R}_{\mathrm{n}}\cos\alpha}$ instead of $\frac{L_H}{2R}$ or from equation (8.5.3-25) with $\overline{R}_{\mathrm{n}}\cos\alpha$ instead of R.

$\overline{R}_{\mathrm{n}}$ and $\overline{R}_{\max}$ shall be as defined in figures 8.6-4 and 8.6-5.

$$l'_e = A_f \cdot X_f^2 + A_w \cdot X_w^2 + \left(\frac{e_a \cdot L'_e}{2}\right) X'^2_s + \left(\frac{e_a \cdot L''_e}{2}\right) X''^2_s + l_f + l_w + \left(\frac{e_a}{12}\right)\sin^2\alpha \left[\left(\frac{L'_e}{2}\right)^3 + \left(\frac{L''_e}{2}\right)^3\right]$$

$$+ \left(\frac{e_a^3}{12}\right)\cos^2\alpha \left(\frac{L'_e}{2} + \frac{L''_e}{2}\right) \qquad (8.6.4\text{-}2)$$

L'_{e} shall be derived from 8.5.3.6.3 with:

$$x = n^2\left(\frac{e_a}{R_i \cdot \cos\alpha}\right) \qquad (8.6.4\text{-}3)$$

$$u = \frac{\frac{L_s}{R_i}}{\sqrt{\frac{e_a}{R_i}\cos\alpha}} \qquad (8.6.4\text{-}4)$$

where R_i is the mean shell radius measured at stiffener *i*.

To calculate the maximum stress in the stiffeners use:

$$\sigma_s = S \times S_f \left(\frac{P \times \sigma_{es}}{P_{ys}}\right) + \left(\frac{E \times \overline{d}'}{R_{\max}}\right) \frac{0.005(n^2-1) P \times S \times S_f}{(P_g - P \times S \times S_f)} \qquad (8.6.4\text{-}5)$$

where

$$P_{ys} = \frac{\sigma_{es} \cdot e_a \cdot \cos\alpha \cdot R_f}{R_{\max}^2 \left(1 - \frac{\nu}{2}\right)} \left[1 + \frac{A_m}{e_a \cdot \cos\alpha \left(\frac{w_i}{\cos\alpha} + 2\frac{N}{\delta}\right)}\right] \qquad (8.6.4\text{-}6)$$

where

$$\delta = 1{,}28\sqrt{\frac{\cos\alpha}{R\cdot e_{\mathrm{a}}}} \qquad (8.6.4\text{-}7)$$

$$\overline{d}' = X_{\mathrm{f}} + \frac{e_{\mathrm{f}}}{2} \qquad (8.6.4\text{-}8)$$

8.6.4.2 Varying shell thickness, stiffener size or spacing

The minimum shell thickness for any length between planes of substantial support shall be determined using the procedure given in 8.6.3.

The requirements for stiffening ring proportions shall apply without modification.

For the design of light stiffeners, either of varying size or spacing or on cones of varying thickness, as shown in Figure 8.6-6, it is permissible to use the method of assessment for stiffened cylinders with equations of 8.6.3 with any of the following.

a) Where the stiffener pitch and size is constant use the minimum thickness anywhere along the length of the section under consideration in calculating P_{g} and P_{y} ;

b) Consider each stiffener separately using the appropriate minimum shell thickness and R_{max} for the two half bays on either side of the stiffener and $\beta = 0$;

c) Consider each stiffener separately using the appropriate minimum thickness and R_{max} for the two half bays on either side of the stiffener.

Where $n > 2$ calculate P_{e}, as in b) and where $n = 2$ use the following equation:

$$P_{\mathrm{g}} = \frac{E\cdot\overline{e}\cdot\beta\cos^{3}\alpha}{R_{\mathrm{n}}} + \frac{2E\cos\alpha\left(n^{2}-1\right)}{L_{\mathrm{H}}}\cdot\sum_{i=0}^{i=N_{X}}\frac{I'_{\mathrm{e},i}\cdot\sin^{2}\alpha\left[\frac{\pi X_{\mathrm{i}}}{L_{\mathrm{C}}}\right]}{R_{i}^{3}} \qquad (8.6.4\text{-}9)$$

where β shall be determined from figure 8.5-13 with $\frac{L_H}{2\,\overline{R}_{\mathrm{n}}\cos\alpha}$ instead of $\frac{L_H}{2\,R}$ or from equation (8.5.3-25) with $\overline{R}_{\mathrm{n}}\cos\alpha$ instead of R.

8.6.5 Cone-cylinder intersections

8.6.5.1 Planes of substantial support

Where there is no knuckle, the intersection between a cone and a cylinder (at both large and small ends) is a plane of substantial support if $\alpha \geq 30°$ and if n_{cyl} (the mode number for the minimum buckling pressure obtained from Figure 8.5-4, or found when applying equation 8.5.3-24 when light stiffeners are present) does not equal 2 for either cone or cylinder.

When the above conditions are not met (either $\alpha < 30°$ or $n_{\mathrm{cyl}} = 2$), the distance L between planes of substantial support is the sum of the effective unsupported length(s) of the cylinder or cylinders plus the axial length of the cone. The thickness of the cone and the small cylinder shall not be less than the cylinder thickness required by 8.5.3.4 and if there are light stiffeners they shall be applied at the pitch and size determined in 8.6.3.1 to the cone and small cylinder as well as to the large cylinder.

8.6.5.2 Reinforcement of small end intersection

Reinforcement in the form of additional thickening and/or local stiffening shall be provided if necessary to keep the maximum local hoop stress at the small end of the cone within acceptable limits, using the following procedure.

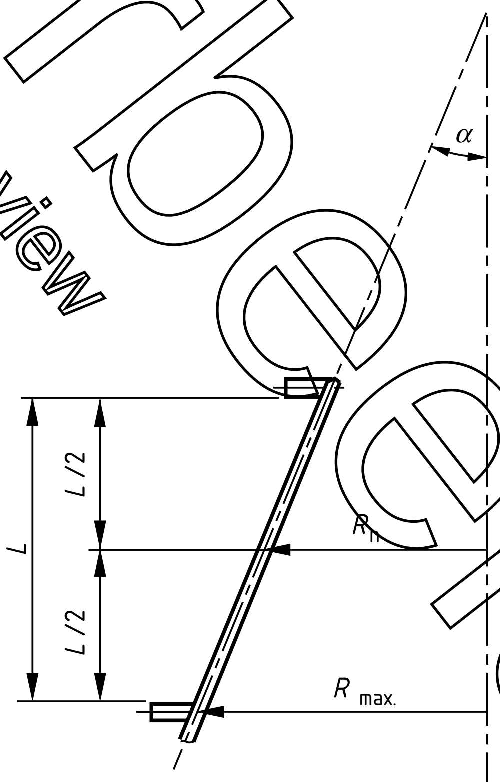
Calculate the maximum hoop stress in the cylinder:

$$\sigma_2 = \frac{P \cdot R\left(1-\gamma \cdot G\right)}{e} \qquad (8.6.5\text{-}1)$$

Calculate the maximum hoop stress σ_1 at the junction without reinforcement, that is with thickness e_a.

NOTE No simple formula is available for the calculation of σ_1 and a stress analysis technique is required.

If $\sigma_1 \leq \sigma_2$ then no reinforcement is required. If reinforcement is required then increase the thickness of either cone or cylinder or both or introduce additional material such as a ring stiffener or a transition piece such that σ_1 when re-calculated is less than or equal to σ_2.



Figures 8.6-2 — Unstiffened cone between stiffening rings


WERK SLIMMER MET NEN CONNECT