$$\sigma_{\theta,\mathrm{c}}(P)=\frac{1}{2}\frac{D_\mathrm{c}^2\cdot L_\mathrm{t}\cdot E_\mathrm{c}\cdot k}{e\cdot(D_\mathrm{i}+e)\cdot L_\mathrm{t}\cdot E_b+e_\mathrm{c}\cdot D_\mathrm{c}\cdot L_\mathrm{c}\cdot E_\mathrm{c}\cdot k}\cdot P \qquad (14.5.3\text{-}2)$$

shall comply with:

$$\sigma_{\theta,\mathrm{c}}(P)\leq f_\mathrm{c}$$

14.5.3.3 Bellows convolutions

a) The circumferential membrane stress due to pressure:

— For end convolutions

$$\sigma_{\theta,\mathrm{E}}(P)=\frac{1}{2}\cdot\frac{q\cdot D_\mathrm{m}+L_\mathrm{t}\,(D_\mathrm{i}+e)}{A+e^*\cdot L_t}\cdot P \qquad (14.5.3\text{-}3)$$

shall comply with:

$$\sigma_{\theta,\mathrm{E}}(P)\leq f$$

— For intermediate convolutions

$$\sigma_{\theta,\mathrm{I}}(P)=\frac{1}{2}\cdot\frac{q\cdot D_\mathrm{m}}{A}\cdot P \qquad (14.5.3\text{-}4)$$

shall comply with:

$$\sigma_{\theta,\mathrm{I}}(P)\leq f$$

b) The meridional membrane stress due to pressure is given by:

$$\sigma_{\mathrm{m,m}}(P)=\frac{w}{2\,e^*}\cdot P \qquad (14.5.3\text{-}5)$$

c) The meridional bending stress due to pressure is given by:

$$\sigma_{\mathrm{m,b}}(P)=\frac{1}{2\,n_\mathrm{p}}\cdot\left(\frac{w}{e_\mathrm{p}^*}\right)^2\cdot C_\mathrm{p}\cdot P \qquad (14.5.3\text{-}6)$$

d) The meridional membrane and bending stresses shall comply with:

$$\sigma_{\mathrm{m,m}}(P)+\sigma_{\mathrm{m,b}}(P)\leq K_\mathrm{f}\cdot f \qquad (14.5.3\text{-}7)$$

where:

$K_\mathrm{f}=3{,}0$ for as-formed bellows (with cold work) (14.5.3-8)

$K_\mathrm{f}=1{,}5$ for annealed bellows (without cold work) (14.5.3-9)

14.5.4 Instability due to internal pressure

14.5.4.1 Column instability

The allowable internal design pressure to avoid column instability, $P_{s,c}$, is given by:

$$P_{s,c} = 0{,}34 \frac{\pi K_b}{Nq} \tag{14.5.4-1}$$

The internal pressure P shall not exceed $P_{s,c}$:

$$P \leq P_{s,c}$$

14.5.4.2 In-plane instability

The allowable internal design pressure to avoid in-plane instability, $P_{s,i}$, is given by:

$$P_{s,i} = (\pi - 2) \frac{A R_e^*}{D_m q \sqrt{\alpha}} \tag{14.5.4-2}$$

where R_e^* is the effective proof stress at design temperature of bellows material in the as-formed or annealed condition.

In absence of values for R_e^* in material standards, the following values shall be used for austenitic steel:

a) $R_e^* = K_d \; R_{p1,0/T}$ for as-formed bellows (with cold work) (14.5.4-3)

b) $R_e^* = 0{,}75 \; R_{p1,0/T}$ for annealed bellows (without cold work) (14.5.4-4)

where

$R_{p1,0/T}$ is the yield stress at 1 % at design temperature, as defined in clause 4;

K_d is the bellows cold-work factor, given by:

$$K_d = \begin{cases} 1 + 5 \times s_d & if \; s_d \leq 0.2 \\ 2{,}0 & if \; s_d > 0{,}2 \end{cases} \tag{14.5.4-5}$$

For non-austenitic steel: $R_e^* = R_{p\,0,2/t}$

The internal pressure P shall not exceed $P_{s,i}$:

$$P \leq P_{s,i}$$

14.5.5 External pressure design

14.5.5.1 Stresses due to external pressure

The rules of 14.5.3 shall be applied taking P as the absolute value of the external pressure.

NOTE When the expansion bellows is submitted to vacuum, the design shall be performed assuming that only the internal ply resists the pressure. The pressure stress equations of 14.5.3 shall be applied with $n_p = 1$.

14.5.5.2 Instability due to external pressure

The design shall be performed according to the rules of Clause 8 by replacing the bellows with an equivalent cylinder, using:

— an equivalent outside diameter D_{eq} given by:

$$D_{eq} = D_i + w + 2e_{eq} \tag{14.5.5-1}$$

— an equivalent thickness e_{eq} given by:

$$e_{eq} = \sqrt[3]{12\left(1-\upsilon^2\right)\cdot\frac{I_{xx}}{q}} \tag{14.5.5-2}$$

where I_{xx} is the moment of inertia of one convolution cross section relative to the axis passing by the center of gravity and parallel to the axis of the bellows (see Figure 14.5.5-1).

NOTE If $L_t = 0$, then I_{xx} is given by:

$$I_{xx} = e^* \cdot \left[\frac{(2w-q)^3}{48} + 0{,}4\,q\cdot(w-0{,}2\,q)^2\right] \tag{14.5.5-3}$$

The portion of cylindrical shell shall be taken between the two closest stiffening rings adjacent to the bellows.

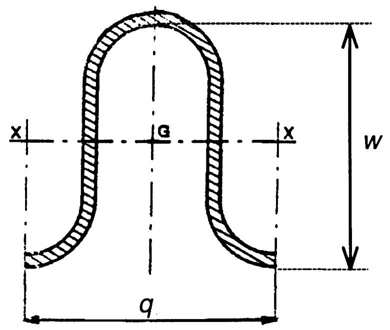


Figure 14.5.5-1 — Dimensions to determine I_{xx}

14.5.6 Fatigue evaluation

14.5.6.1 Calculation of stresses due to the total equivalent axial displacement range Δq of each convolution

a) Meridional membrane stress:

$$\sigma_{m,m}(\Delta q) = \frac{E_b\cdot\left(e_p^*\right)^2}{2\,w^3\cdot C_f}\cdot\Delta q \tag{14.5.6-1}$$

b) Meridional bending stress:

$$\sigma_{\mathrm{m,b}}(\Delta q)=\frac{5\,E_b\cdot e_{\mathrm{p}}^{*}}{3\,w^2\cdot C_{\mathrm{d}}}\cdot\Delta q \tag{14.5.6-2}$$

14.5.6.2 Calculation of the total stress range due to cyclic displacement

$$\sigma_{\mathrm{eq}}=0{,}7\cdot\left[\sigma_{\mathrm{m,m}}(P)+\sigma_{\mathrm{m,b}}(P)\right]+\left[\sigma_{\mathrm{m,m}}(\Delta q)+\sigma_{\mathrm{m,b}}(\Delta q)\right] \tag{14.5.6-3}$$

14.5.6.3 Calculation of the allowable number of cycles

14.5.6.3.1 General

The specified number of cycles N_{spe} shall be stated as consideration of the anticipated number of cycles expected to occur during the operating life of the bellows. The allowable number of cycles N_{alw}, as calculated in this subclause, shall be at least equal to N_{spe} : $N_{\mathrm{alw}} \geq N_{\mathrm{spe}}$.

The allowable number of cycles given by the following formulae includes a reasonable safety margin (factor 3 on cycles and 1,25 on stresses) and represents the maximum number of cycles for the operating condition considered.

Therefore an additional safety factor should not be applied: an overly conservative estimate of cycles can necessitate a greater number of convolutions and result in a bellows more prone to instability.

If the bellows is submitted to different cycles of displacement, such as those produced by start-up or shutdown, their cumulative damage shall be calculated using Miner's rule for cumulative fatigue (see 18.5.6).

NOTE Use of specific fatigue curves established by a manufacturer will be covered later and specific requirements to be applied will be set-up in Annex K.3.

14.5.6.3.2 Austenitic steel and other similar materials

This following formula applies to as-formed bellows made of austenitic steel, nickel-chromium-iron and nickel-iron-chromium alloys.

The allowable number of cycles is given by (see Figure 14.5.6-1):

— If $\dfrac{E_0}{E_b}\sigma_{\mathrm{eq}} \geq 1080$ MPa:

$$N_{\mathrm{alw}}=\left[\frac{9283{,}3}{\dfrac{E_0}{E_b}\sigma_{\mathrm{eq}}-372{,}3}\right]^{3{,}4} \tag{14.5.6-4}$$

where σ_{eq} is expressed in MPa.

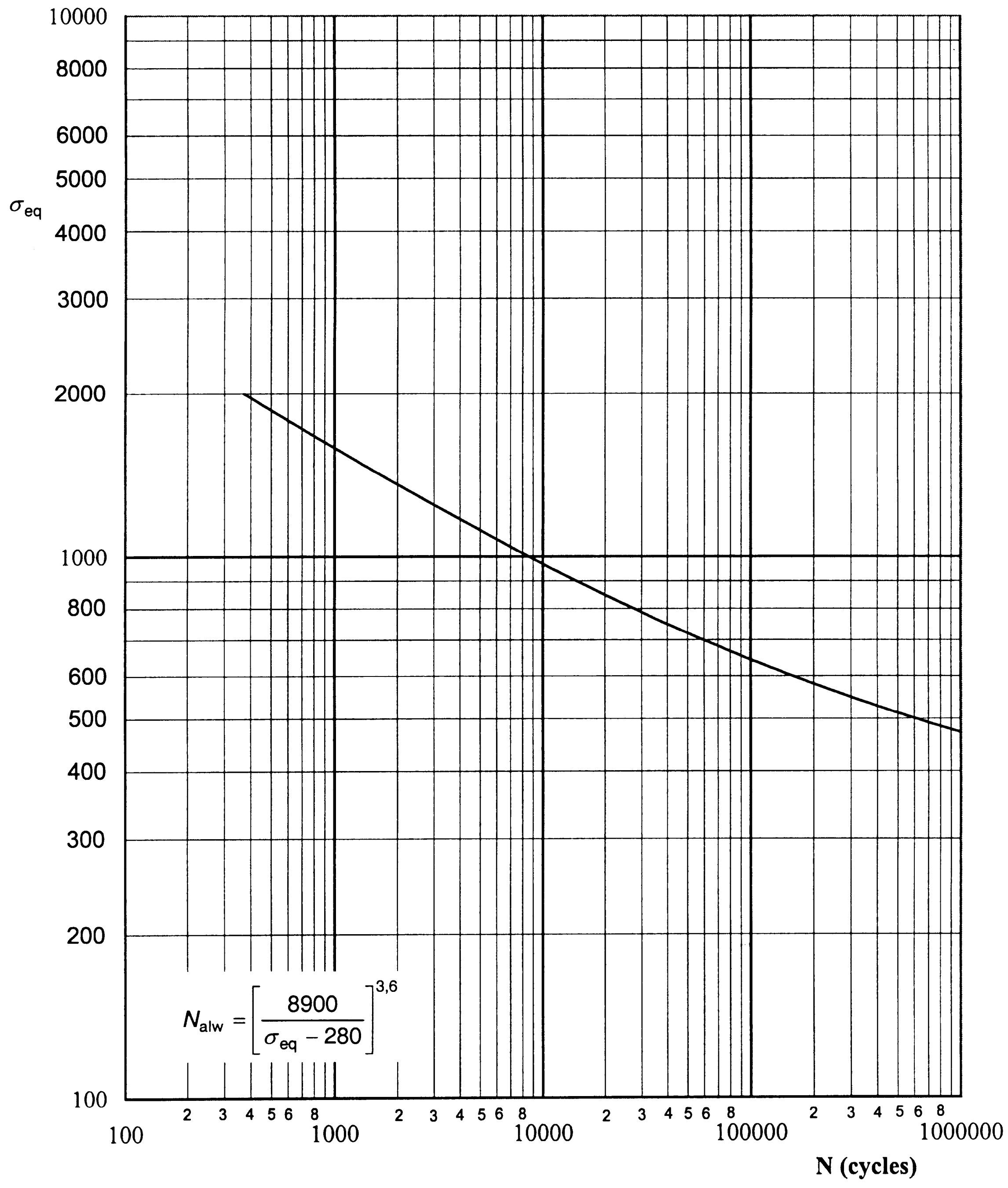
— If $\dfrac{E_0}{E_b}\sigma_{\mathrm{eq}} < 1080$ MPa:

$$N_{\text{alw}} = \left[\frac{10259,4}{\dfrac{E_0}{E_b}\sigma_{\text{eq}} - 297,9} \right]^{3,4} \qquad 14.5.6\text{-}5)$$

where σ_{eq} is expressed in MPa.

— If $\dfrac{E_0}{E_b}\sigma_{\text{eq}} \leq 297,9$ MPa: $N_{\text{alw}} = 10^6$ cycles shall be used.

The curve and the equations are only valid for: $370 \leq N_{\text{alw}} \leq 10^6$



Key
X number of cycles *N*
Y σ_{eq} in MPa

Figure 14.5.6-1 — Fatigue curve at room temperature (E_b=E_0) for unreinforced as-formed bellows

14.5.6.3.3 Ferritic steel

The fatigue design curves of 18.10 or 18.11, as appropriate, shall be used.

14.5.7 Axial rigidity

The theoretical axial rigidity of a bellows comprising N convolutions may be evaluated by the following equation:

$$K_b = \frac{F}{N \cdot \Delta q} = \frac{\pi}{2\left(1 - v_b^2\right)} \cdot E_b \cdot \frac{n_\mathrm{p}}{N} \cdot D_\mathrm{m} \cdot \left(\frac{e_\mathrm{p}^*}{w}\right)^3 \cdot \frac{1}{C_\mathrm{f}} \qquad (14.5.7\text{-}1)$$

where F is the applied axial force and $N \cdot \Delta q$ the corresponding axial displacement of the bellows.

This equation is valid only in the elastic range.

NOTE Outside this range lower values can be used, based on manufacturer's experience or representative test results (see K.1).

14.5.8 U-shaped convolutions circumferentially welded at their crest or root

14.5.8.1 Scope

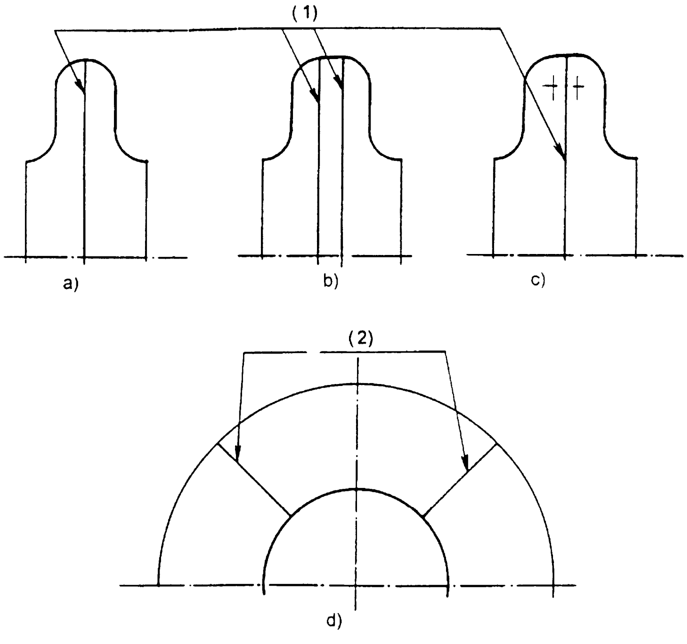
This subclause applies to unreinforced U-shaped bellows of single ply fabricated from two symmetrical half-convolutions joined by a circumferential butt weld:

— either directly (Figure 14.5.8-1a);

— or by means of a cylindrical shell (Figure 14.5.8-1b);

— or by means of a straight part obtained by forming (Figure 14.5.8-1c).

Each of the half-convolutions may be of one single seamless element (Figures 14.5.8-1a and 14.5.8-1b), or formed from several elements joined by meridional butt welding (Figure 14.5.8-1d).



Key

(1) circumferential welds

(2) meridional welds

Figure 14.5.8-1 — Circumferential welds in U-shaped expansion bellows

14.5.8.2 Design

Rules of 14.5.1 to 14.5.7 apply with the following additional requirements.

a) The two half convolutions may have a short cylindrical part, of length m_i at the root and m_e at the crest (see Figure 14.5.8-2), in order to facilitate the welding. The length m_i or m_e shall comply with:

$m_i \le 0{,}2\sqrt{D_m \cdot e}$ $\qquad$ $m_e \le 0{,}2\sqrt{D_m \cdot e}$

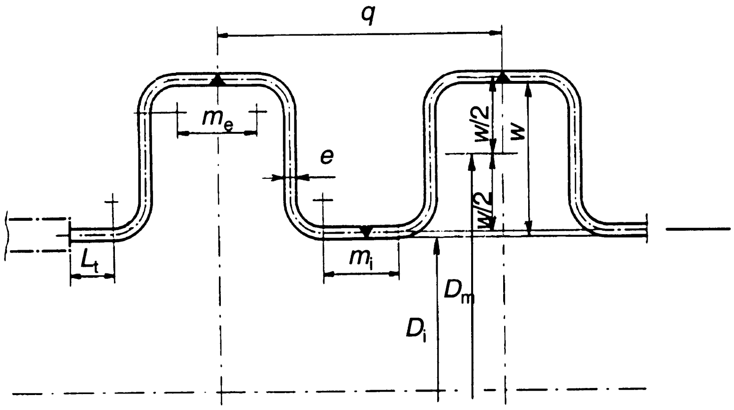


Figure 14.5.8-2 — Convolutions with a cylindrical part

b) In 14.5.3.3, Equations (14.5.3-3) and (14.5.3-4) giving $\sigma_{\theta,E}(P)$ and $\sigma_{\theta,I}(P)$ are replaced by equations:

$$\sigma_{\theta,E}(P) = \frac{1}{2} \cdot \frac{(q - m_i) \cdot D_m + m_e \cdot w + (L_t + m_i / 2) \cdot (D_i + e)}{A + e^{*}(m_e + L_t + m_i / 2)} \cdot P \qquad (14.5.8\text{-}1)$$

$$\sigma_{\theta,I}(P) = \frac{1}{2} \cdot \frac{(q - m_i) \cdot D_m + m_e \cdot w + m_i \cdot (D_i + e)}{A + e^{*}(m_e + m_i)} \cdot P \qquad (14.5.8\text{-}2)$$

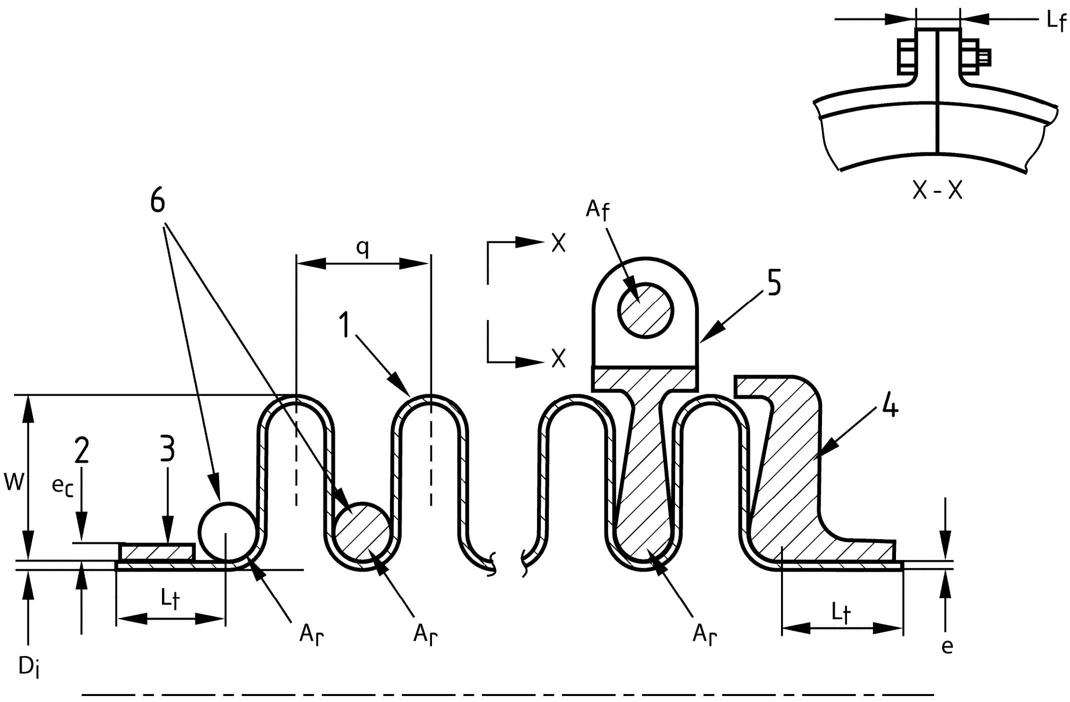
c) In 14.5.6.2 : σ_{eq} obtained from Equation (14.5.6-3) shall be multiplied by a coefficient 2.

14.6 U-shaped reinforced bellows

14.6.1 Purpose

This subclause applies to bellows that have nominally U-shaped convolutions with rings to reinforce the bellows against internal pressure.

Each convolution consists of a sidewall and two tori of the same radius (at the crest and root of the convolution), in the neutral position, so that the convolution profile presents a smooth geometrical shape as shown in Figure 14.6.1-1.



Key

(1) convolution
(2) end tangent
(3) reinforcing collar
(4) end equalizing ring
(5) equalizing ring
(6) reinforcing rings

Figure 14.6.1-1 — U-shaped reinforced bellows

The following symbols apply in addition to those listed in Clause 4 and 14.3.

A_f is the cross sectional metal area of one reinforcing fastener, see Figure 14.6.1-1;

A_r is the cross sectional metal area of one bellows reinforcing ring member, see Figure 14.6.1-1;

C_r is the convolution height factor for reinforced bellows, given by Equation 14.6.3-11;

E_f is the modulus of elasticity of reinforcing fastener material at design temperature;

E_r is the modulus of elasticity of reinforcing ring member material at design temperature;

H is the resultant total internal pressure force acting on the bellows and reinforcement, given by Equation (14.6.3-12);

f_f is the allowable stress of reinforcing fastener material at design temperature;

f_r is the allowable stress of reinforcing ring member material at design temperature;

R is the ratio of the internal pressure force resisted by the bellows on the internal pressure force resisted by the reinforcement, given by Equation (14.6.4-3).

14.6.2 Conditions of applicability

The following conditions of applicability apply in addition to those listed in 14.4.

a) A variation of 10 % between the crest convolution radius r_{ic} and the root convolution radius r_{ir} shall be permitted (see Figure 14.5.1-2 for definitions of r_{ic} and r_{ir}).

b) The torus radius shall be such that:

$r_{\mathrm{i}} \geq 3\, e_{\mathrm{p}}$

where $r_{\mathrm{i}} = \dfrac{r_{\mathrm{ic}} + r_{\mathrm{ir}}}{2}$.

c) The off-set angle of the sidewalls, α, in the neutral position shall be such that:

$-15 \leq \alpha \leq +15$ degrees (see Figure 14.5.1-2).

d) The convolution height shall be such that: $w \leq \dfrac{D_{\mathrm{i}}}{3}$.

14.6.3 Determination of intermediate quantities

The following formulae are used in the determination of the intermediate factors.

$$e = n_{\mathrm{p}} e_{\mathrm{p}} \tag{14.6.3-1}$$

$$D_{\mathrm{c}} = D_{\mathrm{i}} + 2\, e + e_{\mathrm{c}} \tag{14.6.3-2}$$

$$D_{\mathrm{m}} = D_{\mathrm{i}} + w + e \tag{14.6.3-3}$$

$$e_{\mathrm{p}}^{*} = e_{\mathrm{p}} \sqrt{\frac{D_{\mathrm{i}}}{D_{\mathrm{m}}}} \tag{14.6.3-4}$$

$$e^{*} = n_{\mathrm{p}} e_{\mathrm{p}}^{*} \tag{14.6.3-5}$$

$$k = \min \left[\left(\frac{L_{\mathrm{t}}}{1{,}5\, \sqrt{D_{\mathrm{i}} e_{\mathrm{p}}}} \right) \ ; \ (1{,}0) \right] \tag{14.6.3-6}$$

$$A = e^{*} \left[2\, w + (\pi - 2)(2 r_{\mathrm{i}} + e) \right] \tag{14.6.3-7}$$

$$C_1 = \frac{2 r_{\mathrm{i}} + e}{w} \tag{14.6.3-8}$$

$$C_2 = \frac{2 r_{\mathrm{i}} + e}{1{,}1\, \sqrt{D_{\mathrm{m}} e_{\mathrm{p}}^{*}}} \tag{14.6.3-9}$$

$$q = 4 r_{\mathrm{i}} + 2e \tag{14.6.3-10}$$

$$C_{\mathrm{r}} = 0{,}3 - \left(\frac{100}{1048 P^{1{,}5} + 320} \right)^2 \tag{14.6.3-11}$$

where P is expressed in MPa

$$H = P D_{\mathrm{m}} q \tag{14.6.3-12}$$

$$R_1 = \frac{AE_b}{A_r E_r} \tag{14.6.3-13}$$

$$R_2 = \frac{AE_b}{D_m}\left(\frac{L_f}{A_f E_f} + \frac{D_m}{A_r E_r}\right) \tag{14.6.3-14}$$

14.6.4 Stresses due to internal pressure

14.6.4.1 End tangent

The circumferential membrane stress due to pressure:

$$\sigma_{\theta,t}(P) = \frac{1}{2}\left[\frac{(D_i + e)^2 L_t E_b k}{e(D_i + e)L_t E_b + e_c D_c L_c E_c k}\right] P \tag{14.6.4-1}$$

shall comply with:

$$\sigma_{\theta,t}(P) \le f$$

14.6.4.2 Collar

The circumferential membrane stress due to pressure:

$$\sigma_{\theta,c}(P) = \frac{1}{2}\left[\frac{D_c^2 L_t E_c k}{e(D_i + e)L_t E_b + e_c D_c L_c E_c k}\right] P \tag{14.6.4-2}$$

shall comply with:

$$\sigma_{\theta,c}(P) \le f_c$$

14.6.4.3 Bellows convolutions

a) The circumferential membrane stress due to pressure:

$$\sigma_\theta = \frac{H}{2A}\left(\frac{R}{R+1}\right) \tag{14.6.4-3}$$

shall comply with: $\sigma_\theta \le f$

where

$R=R_1$ for integral reinforcing ring members, given by Equation (14.6.3-12);

$R=R_2$ for reinforcing ring members joined by fasteners, given by Equation (14.6.3-13).

NOTE In the case of reinforcing members that are made in sections, and joined by fasteners in tension, this equation assumes that the structure used to retain the fastener does not bend in order to permit the reinforcing member to expand diametrically. In addition, the end reinforcing members must be restrained against the longitudinal annular pressure load of the bellows.