筒体屈曲计算技术规程

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目录

1.未加劲筒体（柱体）屈曲

1.1 输入参数

筒体屈曲的输入参数如下表所示：

第一步	内力输入	加载应力侧应力侧输入参数	设计轴向力KN	Nsd	-20000	压力为负
		一定输负数	设计弯矩KN*m	Msd	-100000	
			设计扭矩KN*m	Tsd	100000	
			设计剪力KN	Qsd	4500	
			设计周向压力Mpa	Psd	-0.02	外压力取负值，水压为外压力
第二步	圆筒尺寸（应力侧）		半径	r	3500	mm
			壁厚	t	66	mm
			屈服强度	fy	345	Mpa
	圆筒尺寸（抗力侧）		厚度t	66	mm	
			模量E	206000	Mpa	
			长度L	100000	mm	L对于筒形基础应该是无支长度，所以会随时变换，取泥面和顶盖距离的一半
			泊松比v	0.3		
			半径r	3500	mm	

1.2 等效应力计算

1.2.1 纵向膜应力计算

依据 DNV-RP-C202-2017 中第 2.2.2 节，筒体（柱体）的纵向膜应力可根据下式计算，其中式（2.2.2）为轴应力，式（2.2.3）为弯曲膜应力，式（2.2.1）为纵向总膜应力：

2.2.2 Longitudinal membrane stress

If the simple beam theory is applicable, the design longitudinal membrane stress may be taken as:

$$\sigma_{x,Sd} = \sigma_{a,Sd} + \sigma_{m,Sd} \tag{2.2.1}$$

where $\sigma_{a,Sd}$ is due to uniform axial force and $\sigma_{m,Sd}$ is due to bending.

For a cylindrical shell without longitudinal stiffeners:

$$\sigma_{a,Sd} = \frac{N_{Sd}}{2\pi rt} \tag{2.2.2}$$

$$\sigma_{m,Sd} = \frac{M_{1,Sd}}{\pi r^2 t}\sin\theta - \frac{M_{2,Sd}}{\pi r^2 t}\cos\theta \tag{2.2.3}$$

1.2.2 切应力计算

依据 DNV-RP-C202-2017 中第 2.2.3 节，筒体（柱体）的切应力可根据下式计算，其中式（2.2.6）为扭转切应力，式（2.2.7）为剪切应力，式（2.2.5）为总

切应力：

2.2.3 Shear stresses

If simple beam theory is applicable, the membrane shear stress may be taken as:

$$\tau_{Sd} = \left|\tau_{T,Sd} + \tau_{Q,Sd}\right| \tag{2.2.5}$$

where $\tau_{T,Sd}$ is due to the torsional moment and $\tau_{Q,Sd}$ is due to the overall shear forces.

$$\tau_{T,Sd} = \frac{T_{Sd}}{2\pi r^2 t} \tag{2.2.6}$$

$$\tau_{Q,Sd} = -\frac{Q_{1,Sd}}{\pi r t}\sin\theta + \frac{Q_{2,Sd}}{\pi r t}\cos\theta \tag{2.2.7}$$

where the signs of the torsional moment and the shear forces must be reflected. Circumferential and longitudinal stiffeners are normally not considered to affect τ_{Sd}.

1.2.3 环向膜应力计算

依据 DNV-RP-C202-2017 中第 2.2.4 节，筒体（柱体）的环向膜应力可根据下式计算：

2.2.4 Circumferential membrane stress

For an unstiffened cylinder the circumferential membrane stress may be taken as:

$$\sigma_{h,Sd} = \frac{p_{Sd} r}{t} \tag{2.2.8}$$

1.2.4 等效应力计算

依据 DNV-RP-C202-2017 中第 3.2 节，筒体（柱体）的总等效应力可根据下式计算：

$$\sigma_{j,Sd} = \sqrt{\left(\sigma_{a,Sd} + \sigma_{m,Sd}\right)^2 - \left(\sigma_{a,Sd} + \sigma_{m,Sd}\right)\sigma_{h,Sd} + \sigma_{h,Sd}{}^2 + 3\tau_{Sd}{}^2} \tag{3.2.3}$$

$$\sigma_{a0,Sd} = \begin{cases} 0 & if\ \sigma_{a,Sd} \geq 0 \\ -\sigma_{a,Sd} & if\ \sigma_{a,Sd} < 0 \end{cases} \tag{3.2.4}$$

$$\sigma_{m0,Sd} = \begin{cases} 0 & if\ \sigma_{m,Sd} \geq 0 \\ -\sigma_{m,Sd} & if\ \sigma_{m,Sd} < 0 \end{cases} \tag{3.2.5}$$

$$\sigma_{h0,Sd} = \begin{cases} 0 & if\ \sigma_{h,Sd} \geq 0\text{, internal net pressure} \\ -\sigma_{h,Sd} & if\ \sigma_{h,Sd} < 0\text{, external net pressure} \end{cases} \tag{3.2.6}$$

$\sigma_{a,Sd}$ = design axial stress in the shell due to axial forces (tension positive), see equation (2.2.2)

$\sigma_{m,Sd}$ = design bending stress in the shell due to global bending moment (tension positive), see equation (2.2.3)

$\sigma_{h,Sd}$ = design circumferential stress in the shell due to external pressure (tension positive), see equation (2.2.8), (2.2.9), or (2.2.14)
For ring stiffened cylinders only stresses midway between rings shall be used.

τ_{Sd} = design shear stress in the shell due to torsional moments and shear force, see equation (2.2.5).

1.3 弹性屈曲强度限值计算

1.3.1 各类型屈曲限值计算（轴压、弯曲、剪切、水压）

未加加劲肋的壳体屈曲可根据下式计算：

值得注意的是，计算不同类型的屈曲（轴压、弯曲、剪切、水压）需要采用不同的ψ、ξ、ρ值，计算得到f_{Ea}、f_{Em}、f_{Eh}、$f_{E\tau}$。

3.4.2 Shell buckling

The characteristic buckling strength of unstiffened circular cylinders is calculated from [3.2]. The elastic buckling strength of an unstiffened circular cylindrical shell is given by:

$$f_E = C\frac{\pi^2 E}{12\left(1-\nu^2\right)}\left(\frac{t}{l}\right)^2 \tag{3.4.1}$$

The reduced buckling coefficient may be calculated as:

$$C = \psi\sqrt{1+\left(\frac{\rho\xi}{\psi}\right)^2} \tag{3.4.2}$$

The values for ψ, ξ and r are given in Table 3-2 for the most important load cases.
The curvature parameter Z is defined as:

$$Z_l = \frac{l^2}{rt}\sqrt{1-\nu^2} \tag{3.4.3}$$

For long cylinders the solutions in Table 3-2 will be pessimistic. Alternative solutions are:

— Torsion and shear force

If $\frac{l}{r} > 3.85\sqrt{\frac{r}{t}}$ then the elastic buckling strength may be calculated as:

$$f_{E\tau} = 0.25E\left(\frac{t}{r}\right)^{3/2} \tag{3.4.4}$$

— Lateral/hydrostatic pressure

If $\frac{l}{r} > 2.25\sqrt{\frac{r}{t}}$ then the elastic buckling strength may be calculated as:

$$f_{Eh} = 0.25E\left(\frac{t}{r}\right)^2 \tag{3.4.5}$$

Table 3-2 Buckling coefficients for unstiffened cylindrical shells, mode a) shell buckling

	ψ	ξ	ρ
Axial stress	1	$0.702\,Z_l$	$0.5\left(1+\frac{r}{150t}\right)^{-0.5}$
Bending	1	$0.702\,Z_l$	$0.5\left(1+\frac{r}{300t}\right)^{-0.5}$

	ψ	ξ	ρ
Torsion and shear force	5.34	$0.856\, Z_l^{3/4}$	0.6
Lateral pressure[1)]	4	$1.04\sqrt{Z_l}$	0.6
Hydrostatic pressure[2)]	2	$1.04\sqrt{Z_l}$	0.6
NOTE 1: Lateral pressure coefficient ψ = 4, accounts for lateral pressure on the cylinder shell only. NOTE 2: Hydrostatic pressure, ψ = 2, accounts for the effect of the lateral pressure on the cylinder shell and the end cap (i.e. axial stresses due to pressure on the end cap shall not be included in the calculation of axial stress, σ_a).			

1.3.2 壳体特征屈曲强度计算

依据 DNV-RP-C202-2017 中第 3.2 节，筒体（柱体）的壳体特征屈曲强度可根据下式计算：

3.2 Characteristic buckling strength of shells

The characteristic buckling strength of shells is defined as:

$$f_{ks} = \frac{f_y}{\sqrt{1+\bar{\lambda}_s^4}} \tag{3.2.1}$$

where:

$$\bar{\lambda}_s^2 = \frac{f_y}{\sigma_{j,Sd}}\left[\frac{\sigma_{a0,Sd}}{f_{Ea}} + \frac{\sigma_{m0,Sd}}{f_{Em}} + \frac{\sigma_{h0,Sd}}{f_{Eh}} + \frac{\tau_{Sd}}{f_{E\tau}}\right] \tag{3.2.2}$$

1.3.3 壳体设计屈曲强度计算

依据 DNV-RP-C202-2017 中第 3.1 节，筒体（柱体）的壳体设计屈曲强度可根据下式计算：

$$f_{ksd} = \frac{f_{ks}}{\gamma_M} \tag{3.1.2}$$

The characteristic buckling strength, f_{ks}, is calculated in accordance with [3.2].

The material factor, γ_M, is given as:

$$\begin{aligned} \gamma_M &= 1.15 && for\ \overline{\lambda}_s < 0.5 \\ \gamma_M &= 0.85 + 0.60\overline{\lambda}_s && for\ 0.5 \le \overline{\lambda}_s \le 1.0 \\ \gamma_M &= 1.45 && for\ \overline{\lambda}_s > 1.0 \end{aligned} \tag{3.1.3}$$

Shell structures may be subjected to global column buckling. Evaluation of global column buckling is found in [3.8].

1.4 屈曲判断

依据 DNV-RP-C202-2017 中第 3.1 节，筒体（柱体）的壳体屈曲判断可根据下式计算：

3.1 Stability requirement

The stability requirement for shells subjected to one or more of the following components:

— axial compression or tension
— bending
— circumferential compression or tension
— torsion
— shear

is given by:

$$\sigma_{j,Sd} \le f_{ksd} \tag{3.1.1}$$

2.设置纵向加劲肋的筒体的加劲肋之间的面板屈曲

2.1 输入参数

筒体屈曲的输入参数如下表所示：

22	内力输入	加载应力侧应力侧输入参数	设计轴向力KN	Nsd	-24767	压力为负
23		一定输负数	设计弯矩KN*m	Msd	-1252.51	
24			设计扭矩KN*m	Tsd	0	
25			设计剪力KN	Qsd	3738.69	
26			设计周向压力Mpa	Psd	-0.033	外压力取负值，水压为外压力
27			半径	r	7000	mm
28			壁厚	t	30	mm
29	加劲肋参数		加劲肋腹板厚度	tw	25	mm
30			加劲肋腹板高度	hw	200	hw<9.5tw（mm）
31			加劲肋翼缘厚度	tf	0	mm
32			加劲肋翼缘宽度	bf	0	mm
33			纵向加劲肋间距	s	1300	mm,L应大于S.且s小于3（r/t）^0.5
34			纵向加强劲的横截面积	A	5000	mm^2
35			等效厚度	te	33.84615385	mm
36			屈服强度	fy	345	Mpa
37	圆筒尺寸（抗力侧）		厚度t	30	mm	
38			模量E	206000	Mpa	
39			长度1	8000	mm	L对于筒形基础应该是无支长度，所以会随时变换，取泥面和顶盖距离的一半，L应大于S.
40			泊松比v	0.3		
41			半径r	7000	mm	

2.2 等效应力计算

该节等效应力计算按照 1.2 节进行，但是在计算轴向膜应力和弯曲膜应力时，应使用等效厚度 te 代替筒体厚度 t，参考依据为 DNV-RP-C202-2017 中式（2.2.4）：

For a cylindrical shell with longitudinal stiffeners it is usually permissible to replace the shell thickness by the equivalent thickness for calculation of longitudinal membrane stress only:

$$t_e = t + \frac{A}{s} \tag{2.2.4}$$

2.3 弹性屈曲强度限值计算

2.3.1 各类型屈曲限值计算（轴压、剪切、水压）

加加劲肋的壳体的加劲肋间面板屈曲可根据下式计算：

值得注意的是，计算不同类型的屈曲（轴压、弯曲、剪切、水压）需要采用不同的ψ、ξ、ρ值，计算得到f_{Ea}、f_{Eh}、$f_{E\tau}$。

3.3.2 Shell buckling

The characteristic buckling strength is calculated from [3.2].

The elastic buckling strength of curved panels with aspect ratio l/s > 1 is given by:

$$f_E = C\frac{\pi^2 E}{12\left(1-\nu^2\right)}\left(\frac{t}{s}\right)^2 \tag{3.3.1}$$

A curved panel with aspect ratio l/s < 1 may be considered as an unstiffened circular cylindrical shell with length equal to l, see [3.4.2].

The reduced buckling coefficient may be calculated as:

$$C = \psi\sqrt{1+\left(\frac{\rho\xi}{\psi}\right)^2} \tag{3.3.2}$$

The values for ψ, ξ and r are given in Table 3-1 for the most important load cases.

Table 3-1 Buckling coefficient for unstiffened curved panels, mode a) shell buckling

	ψ	ξ	ρ
Axial stress	4	$0.702\,Z_s$	$0.5\left(1+\frac{r}{150t}\right)^{-0.5}$
Shear stress	$5.34+4\left(\frac{s}{l}\right)^2$	$0.856\sqrt{\frac{s}{l}}Z_s^{3/4}$	0.6
Circumferential compression	$\left[1+\left(\frac{s}{l}\right)^2\right]^2$	$1.04\frac{s}{l}\sqrt{Z_s}$	0.6

The curvature parameter Z_s is defined as:

$$Z_s = \frac{s^2}{rt}\sqrt{1-\nu^2} \tag{3.3.3}$$

2.3.2 壳体特征屈曲强度和设计屈曲强度计算

按照 1.3.2 节和 1.3.3 节进行，值得注意的是，该部分计算没有弯曲引起的壳体屈曲限值f_{Em}，因此需要计算总纵向膜应力。

$$\bar{\lambda} = \frac{f_y}{\sigma_{j,sd}}\left[\frac{\sigma_{x0,sd}}{f_{Ea}} + \frac{\sigma_{h0,sd}}{f_{Eh}} + \frac{\tau_{sd}}{f_{E\tau}}\right]$$

2.4 屈曲判断

屈曲判断与 1.4 节相同。

3.带纵向加劲肋的筒体整体屈曲

3.1 输入参数

带加劲肋的筒体整体屈曲的输入参数如下表所示，由于第二章中计算也是带加劲肋的计算，因此本节输入参数全部关联第二章中输入参数。

在计算有效壳体宽度 Se 时，需要用到特征屈曲强度f_{ks}，如果壳体屈曲强度采用本章的表格计算得到的f_{ks}，会涉及到循环计算的问题，因此此处的f_{ks}关联第一章。（出于保守考虑）

依据 DNV-RP-C202-2017 中 3.6.3.3 节，有效壳体宽度 Se 可根据下式计算：

3.6.3.3 Effective shell width

The effective shell width, s_e, may be calculated from:

$$\frac{s_e}{s} = \frac{f_{ks}}{\sigma_{j,Sd}}\frac{|\sigma_{x,Sd}|}{f_y} \qquad (3.6.7)$$

形心计算公式如下：

$$y_{se} = \frac{t \times se \times \frac{t}{2} + h_w \times t_w \times (t + \frac{h_w}{2}) + t_f b_f \times (t + h_w + \frac{t_f}{2})}{t \times se + h_w \times t_w + t_f b_f}$$

惯性矩计算公式如下：

$$
\begin{aligned}
Z_{sef} = {} & \frac{S_e t^3}{12} + \cancel{AX^2}\; S_e \times t \times \left(y_{se} - \frac{t}{2}\right)^2 \\
& + \frac{t_w h_w^3}{12} + t_w h_w \times \left(y_{se} - \left(t + \frac{h_w}{2}\right)\right)^2 \\
& + \frac{b_f\, \cancel{h_w}\, t_f^3}{12} + b_f t_f \times \left(y_{se} - \left(t + h_w + \frac{t_f}{2}\right)\right)^2
\end{aligned}
$$

	C	D	E	F	G	H
22	内力输入	加载应力侧应力侧输入参数	设计轴向力KN	Nsd	-24767	压力为负
23		一定输负数	设计弯矩KN*m	Msd	-1252.51	
24			设计扭矩KN*m	Tsd	0	
25			设计剪力KN	Qsd	3738.69	
26			设计周向压力Mpa	Psd	-0.033	外压力取负值，水压为外压力
27			半径	r	7000	mm
28			壁厚	t	30	mm
29	加劲肋参数		加劲肋腹板厚度	tw	25	mm
30			加劲肋腹板高度	hw	200	
31			加劲肋翼缘厚度	tf	0	mm
32			加劲肋翼缘宽度	bf	0	mm
33			纵向加劲肋间距	s	1300	mm
34			有效壳体宽度Se	Se	688.4600641	$\frac{s_e}{s} = \frac{f_{ks}}{\sigma_{j,Sd}} \frac{\lvert\sigma_{x,Sd}\rvert}{f_y}$ (3.6.7)
35			包括有效壳板宽度se的纵向加劲肋截面形心	y_{se}	37.41383175	$y_{se} = \frac{t \times S_e \times \frac{t}{2} + h_w \times t_w \times (t + \frac{h_w}{2}) + t_f b_f \times (t + h_w + \frac{t_f}{2})}{t \times S_e + h_w \times t_w + t_f b_f}$
36			包括有效壳板宽度se的纵向加劲肋截面惯性矩	I_{sef}	71452748.56	$Z_{sef} = \frac{S_e t^3}{12} + \cancel{AX^2}\, S_e \times t \times (y_{se} - \frac{t}{2})^2 + \frac{t_w h_w^3}{12} + t_w h_w \times (y_{se} - (t + \frac{h_w}{2}))^2 + \frac{b_f \cancel{h_w} t_f^3}{12} + b_f t_f \times (y_{se} - (t + h_w + \frac{t_f}{2}))^2$
37			纵向加强劲的横截面积	A	5000	mm^2
38			等效厚度	te	33.84615385	mm
39			屈服强度	fy	345	Mpa
40	圆筒尺寸（抗力侧）		厚度t	30	mm	
41			模量E	206000	Mpa	
42			长度l	8000	mm	L对于筒形基础应该是无支长度，所以会随时变换
43			泊松比v	0.3		
44			半径r	7000	mm	
45						

3.2 等效应力计算

该节等效应力计算按照 1.2 节进行，但是在计算轴向膜应力和弯曲膜应力时，应使用等效厚度 te 代替筒体厚度 t，参考依据为 DNV-RP-C202-2017 中式（2.2.4）：

For a cylindrical shell with longitudinal stiffeners it is usually permissible to replace the shell thickness by the equivalent thickness for calculation of longitudinal membrane stress only:

$$t_e = t + \frac{A}{s} \tag{2.2.4}$$

3.3 弹性屈曲强度限值计算

3.3.1 各类型屈曲限值计算（轴压、弯曲、剪切、水压）

未加加劲肋的壳体屈曲可根据下式计算：

值得注意的是，计算不同类型的屈曲（轴压、弯曲、剪切、水压）需要采用不同的ψ、ξ、ρ值，计算得到f_{Ea}、f_{Eh}、$f_{E\tau}$。

3.6.3.2 Elastic buckling strength

The elastic buckling strength of longitudinally stiffened cylindrical shells is given by:

$$f_E = C\frac{\pi^2 E}{12(1-\nu^2)}\left(\frac{t}{l}\right)^2 \quad (3.6.3)$$

The reduced buckling coefficient may be calculated as:

$$C = \psi\sqrt{1+\left(\frac{\rho\xi}{\psi}\right)^2} \quad (3.6.4)$$

The values for ψ, ξ and ρ are given in Table 3-3 for the most important load cases.

Table 3-3 Buckling coefficients for stiffened cylindrical shells, mode b) panel stiffener buckling

	ψ	ξ	ρ
Axial stress	$\frac{1+\alpha_C}{1+\frac{A}{s_e t}}$	$0.702Z_l$	0.5
Torsion and shear stress	$5.34+1.82\left(\frac{l}{s}\right)^{4/3}\alpha_C^{1/3}$	$0.856\,Z_l^{3/4}$	0.6
Lateral Pressure	$2\left(1+\sqrt{1+\alpha_C}\right)$	$1.04\sqrt{Z_l}$	0.6

where:

$$Z_l = \frac{l^2}{rt}\sqrt{1-\nu^2} \quad (3.6.5)$$

$$\alpha_C = \frac{12(1-\nu^2)I_{sef}}{st^3} \quad (3.6.6)$$

A = area of one stiffener, exclusive shell plate

I_{sef} = moment of inertia of longitudinal stiffener including effective shell width s_e, see equation (3.6.7)

3.3.2 壳体特征屈曲强度和设计屈曲强度计算

按照 1.3.2 节和 1.3.3 节进行，值得注意的是，该部分计算没有弯曲引起的壳

体屈曲限值f_{Em}，因此需要计算总纵向膜应力。

$$\bar{\lambda} = \frac{f_y}{\sigma_{j,sd}}\left[\frac{\sigma_{x0,sd}}{f_{Ea}} + \frac{\sigma_{h0,sd}}{f_{Eh}} + \frac{\tau_{sd}}{f_{E\tau}}\right]$$

3.4 屈曲判断

屈曲判断与 1.4 节相同。

4.整体柱状屈曲

4.1 构造要求（判断是否需要考虑柱状屈曲）

依据 DNV-RP-C202-2017 中第 3.8.1 节，判断筒体（柱体）是否需要考虑柱状屈曲，可通过下式进行计算：

3.8.1 Stability requirement

The column buckling strength should be assessed if

$$\left(\frac{kL_C}{i_C}\right)^2 \geq 2.5\frac{E}{f_y} \tag{3.8.1}$$

where:

k = effective length factor

L_C = total cylinder length

i_C = $\sqrt{I_C/A_C}$= radius of gyration of cylinder section

I_C = moment of inertia of the complete cylinder section (about weakest axis), including longitudinal stiffeners/internal bulkheads if any

A_C = cross-sectional area of complete cylinder section; including longitudinal stiffeners/internal bulkheads if any.

构造要求表格如下，表中参数关联第一章的表格：

构造要求				
输入参数	筒体半径	r	3500	mm
	筒体直径	D	7000	mm
	筒体壁厚	t	66	mm
	弹性模量	E	206000	Mpa
	钢材屈服强度	fy	345	Mpa
	有效长度系数	k	2	规范中未给出: 1. 筒体结构一定不会出现柱状屈曲; 2. 可按照悬臂结构考虑，去k=2。
	总筒体长度	Lc	100000	mm
中间参数	筒体截面惯性矩	Ic	8.63723E+12	mm4
	截面面积	Ac	1437002.16	mm2
	转动惯量半径	ic	2451.650261	mm
		(k*Lc/ic)^2	6654.921839	
		2.5*E/fy	1492.753623	
输出参数	是否应该评估柱屈	$\left(\frac{kL_C}{i_C}\right)^2 \ge 2.5\frac{E}{f_y}$	NG	0代表不需要验证，1代表需要验证

4.2 整体柱状屈曲强度验算

4.2.1 柱体屈曲强度

依据 DNV-RP-C202-2017 中第 3.8.2 节，柱体屈曲强度可根据下式计算：

3.8.2 Column buckling strength

The characteristic buckling strength, f_{kc}, for column buckling may be defined as:

$$f_{kc} = \left[1.0 - 0.28\bar{\lambda}^2\right] f_{ak} \qquad for\ \bar{\lambda} \le 1.34 \tag{3.8.5}$$

$$f_{kc} = \frac{0.9}{\bar{\lambda}^2} f_{ak} \qquad for\ \bar{\lambda} > 1.34 \tag{3.8.6}$$

where:

$$\bar{\lambda} = \sqrt{\frac{f_{ak}}{f_E}} = \frac{kL_c}{\pi i_c}\sqrt{\frac{f_{ak}}{E}} \tag{3.8.7}$$

In the general case equation (3.1.1) shall be satisfied. Hence f_{ak} may be determined (by iteration of equations (3.1.1) to (3.2.6)) as maximum allowable $\sigma_{a0,Sd}$ ($\sigma_{a,Sd}$) where the actual design values for $\sigma_{m,Sd}$, $\sigma_{h,Sd}$ and τ_{Sd} have been applied.

For the special case when the shell is an unstiffened shell the following method may be used to calculate f_{ak}.

$$f_{ak} = \frac{b + \sqrt{b^2 - 4ac}}{2a} \tag{3.8.8}$$

$$a = 1 + \frac{f_y^2}{f_{Ea}^2} \tag{3.8.9}$$

$$b = \left(\frac{2f_y^2}{f_{Ea} f_{Eh}} - 1\right)\sigma_{h,Sd} \tag{3.8.10}$$

$$c = \sigma_{h,Sd}^2 + \frac{f_y^2 \sigma_{h,Sd}^2}{f_{Eh}^2} - f_y^2 \tag{3.8.11}$$

$$f_{akd} = \frac{f_{ak}}{\gamma_M} \tag{3.8.12}$$

$\sigma_{h,Sd}$ = design circumferential membrane stress, see equations (2.2.8) or (2.2.9), tension positive

f_y = yield strength

γ_M = material factor, see equation (3.1.3)

f_{Ea}, f_{Eh} = elastic buckling strengths, see [3.4].

4.2.2 欧拉屈曲强度和柱体屈曲设计强度

依据 DNV-RP-C202-2017 中第 3.8.1 节，柱体屈曲设计强度和欧拉屈曲强度可根据下式计算：

$$f_{Ei} = \frac{\pi^2 E I_{c,i}}{\left(k_i L_{c,i}\right)^2 A_c}, i = 1.2 \tag{3.8.3}$$

$$f_{kcd} = \frac{f_{kc}}{\gamma_M} \tag{3.8.4}$$

γ_M = material factor, see equation (3.1.3)

f_{kc} = characteristic column buckling strength, see equation (3.8.5) or (3.8.6).

4.2.3 整体屈曲强度验算

依据 DNV-RP-C202-2017 中第 3.8.1 节，整体柱体屈曲强度验算计算方法如下：

The stability requirement for a shell-column subjected to axial compression, bending and circumferential compression is given by:

$$\frac{\sigma_{a0,Sd}}{f_{kcd}} + \frac{1}{f_{akd}}\left[\left(\frac{\sigma_{m1,Sd}}{1-\frac{\sigma_{a0,Sd}}{f_{E1}}}\right)^2 + \left(\frac{\sigma_{m2,Sd}}{1-\frac{\sigma_{a0,Sd}}{f_{E2}}}\right)^2\right]^{0.5} \le 1.0 \quad (3.8.2)$$

where:

$\sigma_{a0,Sd}$ = design axial compression stress, see equation (3.2.4)

$\sigma_{m,Sd}$ = maximum design bending stress about given axis, see equation (2.2.3)

f_{akd} = design local buckling strength, see [3.8.2]

f_{kcd} = design column buckling strength, see equation (3.8.4)

f_{E1}, f_{E2} = Euler buckling strength found from equation (3.8.3):

5.纵向加劲肋构造要求

依据 DNV-RP-C202-2017 中第 3.10.2 节，纵向加劲肋构造要求如下：

3.10.2 Longitudinal stiffeners

The geometric proportions of longitudinal stiffeners should comply with the requirements given below (see Figure 1-2 for definitions):

— flat bar longitudinal stiffeners:

$$h \le 0.4 t_w \sqrt{\frac{E}{f_y}} \quad (3.10.6)$$

— flanged longitudinal stiffeners:

$$h \le 1.35 t_w \sqrt{\frac{E}{f_y}} \quad (3.10.7)$$

If the requirements in equations (3.10.6) and (3.10.7) are not satisfied, the characteristic material resistance f_r shall be taken as f_T (where f_T is calculated in accordance with [3.9]).

$$b_f \le 0.4 t_f \sqrt{\frac{E}{f_y}} \quad (3.10.8)$$