单桩疲劳损伤计算及SCF计算技术规程

中国能源建设集团山西省电力勘测设计院有限公司

目录

1.疲劳设计安全系数（DFF）与材料侧安全系数（γ_m）

1.1 疲劳设计安全系数（DFF）

依据《DNVGL-ST-0126-2018 Support structures for wind turbines》中表 4-18，疲劳设计安全系数在不同区域（大气区、浪溅区、浸没区）的取值如下表所示：

Table 4-18 Required S-N curves and design fatigue factors - DFF

Location	*Accessibility for inspection and repair of initial fatigue and coating damages* [2]	*S-N curve* [5]	*Minimum DFF* [6]
Atmospheric zone	No	In air for coated surfaces free corrosion for surfaces protected by corrosion allowance, only [4]	3
	Yes		1
Upper splash zone (above MWL) [1]	No	Combination of in air and free corrosion curves [3] [4]	3
	Yes		2
Lower splash zone (below MWL) [1]	No	In seawater for surfaces with cathodic protection Free corrosion for surfaces protected by corrosion allowance, only [4]	3
	Yes		2
Submerged zone	No	In seawater for surfaces with cathodic protection Free corrosion for surfaces protected by corrosion allowance, only [4]	3
	Yes		2
Scour zone	No		3
Below scour zone	No	In seawater	3

Note:

1) Splash zone definition according to DNVGL-RP-0416.
2) If the designer considers the steel surface accessible for inspection and repair of initial fatigue damage and coating, this shall be documented through qualified procedures for these activities. See also [4.16] and Sec.9.
3) The basic S-N curve for unprotected steel in the splash zone is the curve marked free corrosion. The basic S-N curve for coated steel is the curve marked in air. It is acceptable to carry out fatigue life calculations in the splash zone based on accumulated damage for steel considering the probable coating conditions throughout the design life – intact, damaged and repaired. The coating conditions shall refer to an inspection and repair plan as specified in Sec.9.
4) When free corrosion S-N curves are applied in design, the full benefit of potential grinding of welds as outlined in [4.13.5] cannot be expected and therefore may not be taken into account. The effect of free corrosion on a ground weld may be accounted for by downgrading the S-N curve one class and applying the S-N curves for in seawater for free corrosion.
5) Shear keys within grouted connections may be designed assuming S-N curves marked in air.
6) According to the chosen DFF, an inspection program according to [9.3] will be required.

对上表进行总结，内容如下：

疲劳设计安全系数表 DFF *DNV-St-126*			
位置	是否便于检查或维修	S-N 曲线	DFF
大气区	No	空气中	3
	Yes		2 or 1
浪溅区	No	在空气	3

		中和自由腐蚀的结合	
	Yes		2
浸没区	No	海水中	3
	Yes		2
冲刷区	No		3
冲刷区以下	No		3

1.2 材料侧安全系数（γ m）

依据 DNV-0126 中 4.7.1.3 节，结构钢材料安全系数可按下表取值：

表 1-1 结构钢材料安全系数（依据 DNV-0126 4.7.1.3）

材料系数	ULS	ALS	SLS
γ_{M0}	1.10	1.00	1.00
γ_{M1}	1.10	1.00	1.00
γ_{M2}（螺栓）	1.25	1.00	1.00

依据《DNVGL-ST-0126-2018 Support structures for wind turbines》中表 4-19，DFF 与材料侧安全系数γm 的对应关系如下表所示：

Table 4-19 Material factors - γ_m

DFF	γ_m
1	1.0
2	1.15
3	1.25

值得注意的是，DFF 与γm 不同时考虑。

2.应力集中系数（SCF）计算

2.1 等厚度对接焊缝 SCF 计算（板的对接）

依据《DNVGL-RP-C203-Fatigue design of offshore steel structures》中 3.1.2

节规定，等厚度对接焊缝的应力集中系数 SCF 可通过下式进行计算：

3.1.2 Stress concentration factors for butt welds

The eccentricity between welded plates with a similar thickness may be accounted for in the calculation of stress concentration factor. The following formula applies for a butt weld in an unstiffened plate or for a pipe butt weld with a large radius:

$$SCF = 1 + \frac{3(\delta_m - \delta_0)}{t} \qquad (3.1.1)$$

where

δ_m is eccentricity (misalignment) and t is plate thickness, see Figure 3-8.

δ_0 = 0.1 t is misalignment inherent in the S-N data for butt welds and analysis procedure for plated structures with an expected fabrication tolerance that is lower than that allowed in fabrication specification and as used in design; see also Table 3-1. See DNVGL-OS-C401 for fabrication tolerances.

其中 $\delta_0 = 0.1t$，δ_m的取值规定如下（依据《DNVGL-RP-C203-Fatigue design of offshore steel structures》中表 3-1）：

Table 3-1 Recommended values of δ_0 for butt welds in different types of structures

Structural detail	*As welded*	*Ground flush*
Plated structures	0.10t*	0.05t*
Tubular girth welds in structures	0.05t	0
Girth welds in tethers	0	0
Girth welds in pipelines and risers	0	0
* where the tolerance is known, the actual value should be used for calculation of SCF with δ_0 = 0.05t for plated structures and δ_0 = 0 for ground welds		

注意：对于单桩 D 曲线，取值为 0.05t。

2.2 不等厚度对接焊缝 SCF 计算（板的对接）

依据《DNVGL-RP-C203-Fatigue design of offshore steel structures》中 3.1.2 节规定，不等厚度对接焊缝（板对接）的应力集中系数 SCF 可通过下式进行计算，具体规定如下：

The stress concentration for the weld between plates with different thickness in a plate field on the side of the thickness transition may be derived from the following formula:

$$SCF = 1 + \frac{6(\delta_m + \delta_t - \delta_0)}{t\left[1 + \frac{T^{1.5}}{t^{1.5}}\right]} \qquad (3.1.2)$$

where

δ_m = maximum misalignment

δ_t = ½ (T- t) eccentricity due to change in thickness.
Note: This applies also at transitions sloped as 1:4.

δ_0 = 0.1 t is misalignment inherent in the S-N data for butt welds and analysis procedure for plated structures with an expected fabrication tolerance that is lower than that allowed in fabrication specification and as used in design; see also Table 3-1. See DNVGL-OS-C401 for fabrication tolerances.

T = thickness of thicker plate

t = thickness of thinner plate

2.3 不等厚度对接焊缝 SCF 计算（圆管对接）

依据《DNVGL-RP-C203-Fatigue design of offshore steel structures》中 3.3.7.3 节规定，不等厚度对接焊缝（圆管对接）的应力集中系数 SCF 可通过下式进行计算，具体规定如下：

The following equation for calculation of SCF at tubular butt welds with eccentricities can be used:

$$\mathrm{SCF} = 1 + \frac{6(\delta_t + \delta_m - \delta_0)}{t} \frac{1}{1 + \left(\frac{T}{t}\right)^{\beta}} e^{-\alpha} \qquad (3.3.5)$$

where

$$\alpha = \frac{1.82L}{\sqrt{Dt}} \cdot \frac{1}{1 + \left(\frac{T}{t}\right)^{\beta}}$$

δ_0 = 0.05 t is misalignment inherent in the S-N data and analysis procedure for as welded butt welds (not for ground connections).

D = Outer tubular diameter as defined in Figure 3-8

$$\beta = 1.5 - \frac{1.0}{\log\left(\frac{D}{t}\right)} + \frac{3.0}{\left(\log\left(\frac{D}{t}\right)\right)^2}$$

This formula also takes into account the length over which the eccentricity is distributed: L, see Figure 3-11 and Figure 3-8. The stress concentration is reduced as L is increased and or D is reduced. It is noted that for small L and large D the last formula provides stress concentration factors that are close to that of the simpler formula for plates.

2.4 交叉节点 SCF 计算

依据《DNVGL-RP-C203-Fatigue design of offshore steel structures》中 3.1.3 节规定，交叉节点的应力集中系数 SCF 可通过下式进行计算，具体规定如下：

3.1.3 Stress concentration factors for cruciform joints

The stress concentration factor for cruciform joint at plate thickness t_i may be derived from the following formula:

$$\mathrm{SCF} = 1 + \frac{6 t_i^{2} (\delta - \delta_0)}{l_i \left(\frac{t_1^3}{l_1} + \frac{t_2^3}{l_2} + \frac{t_3^3}{l_3} + \frac{t_4^3}{l_4} \right)} \tag{3.1.4}$$

where

δ = (δ_m + δ_t) is the total eccentricity

δ_0 = 0.15 t_i is misalignment embedded in S-N data for cruciform joints and analysis procedure when including effect of fabrication tolerances. See DNVGL-OS-C401 for fabrication tolerances.

t_i = thickness of the considered plate (i = 1, 2)

l_i = length of considered plate (i = 1, 2)

The other symbols are defined in Figure 3-1.

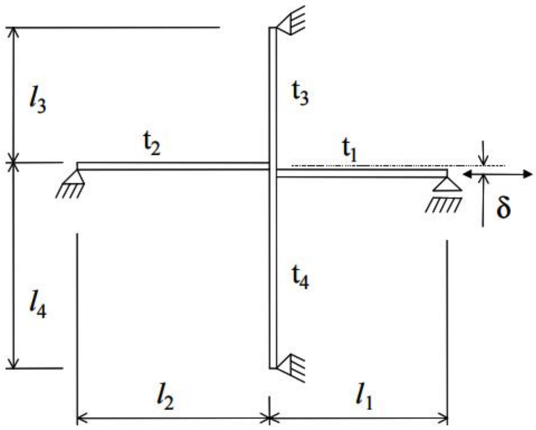


Figure 3-1 Cruciform joint

2.5 圆管与圆锥的 SCF 计算

依据《DNVGL-RP-C203-Fatigue design of offshore steel structures》中 3.1.3 节规定，圆管与圆锥的应力集中系数 SCF 可通过下式进行计算，具体规定如下：

3.3.9 Stress concentration factors for conical transitions

The stress concentration at each side of unstiffened tubular-cone junction can be estimated by the following equations (the SCF shall be used together with the stress in the tubular at the junction for both the tubular and the cone side of the weld):

$$SCF = 1 + \frac{0.6t\sqrt{D_j(t+t_c)}}{t^2}\tan\alpha \tag{3.3.12}$$

for the tubular side

$$SCF = 1 + \frac{0.6t\sqrt{D_j(t+t_c)}}{t_c^2}\tan\alpha \tag{3.3.13}$$

for the cone side

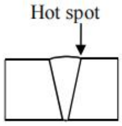
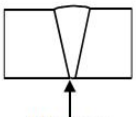
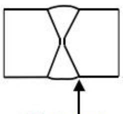
where

D_j = cylinder diameter at junction (D_S, D_L)
t = tubular member wall thickness (t_S, t_L)
t_c = cone thickness
α = the slope angle of the cone (see Figure 3-15)

2.6 形状不对称的（管线，小直径管道）焊接坡口 SCF 计算

依据《DNVGL-RP-C203-Fatigue design of offshore steel structures》中 2.10.1 节规定，形状不对称的（管线，小直径管道）焊接坡口应力集中系数 SCF 可通过下式进行计算，具体规定如下：

Table 2-5 Classification of welds in pipelines

Description		*Tolerance requirement (mean hi/lo-value)*	*S-N curve*	*Thickness exponent k*	*SCF*
Welding	*Geometry and hot spot*				
Single side	Hot spot 		D	0.15	Eq. (2.10.1)
Single side	 Hot spot	$\delta_m \leq 1.0$ mm	E	0.00	Eq. (2.10.4)
		$1.0 \text{ mm} < \delta_m \leq 2.0$ mm	F	0.00	
		$2.0 \text{ mm} < \delta_m \leq 3.0$ mm	F1	0.00	
Double side	 Hot spot		D	0.15	Eq. (2.10.1)
Ground weld outside and inside			C	0.00	Eq. (2.10.1) for outside and Eq. (2.10.4) for inside

The width of the girth welds in the root in pipelines and risers may be larger than that shown in Figure 3-8 and may also be narrower on the outside to reduce the welding volume and increase fabrication efficiency. A more typical weld section through a girth weld is shown in Figure 2-16. For this geometry the stress due to local bending is less for the root than for the weld toe (weld cap). The local bending stress at the weld toe due to axial misalignment, δ_m, and membrane stress, σ_m, can be expressed as:

$$\sigma_{bt} = \frac{3\delta_m}{t} e^{-\sqrt{t/D}} \sigma_m \tag{2.10.2}$$

The width of the weld at the root in Figure 2-16 is L_{Root}. Then the bending stress in the pipe wall at the transition from the weld to the base material at the root can be obtained from the linearized moment in Figure 2-16 as:

$$\sigma_{br} = \frac{3\delta_m L_{Root}}{t L_{Cap}} e^{-\sqrt{t/D}} \sigma_m \tag{2.10.3}$$

Thus, for the weld root the effect of axial misalignment can be included by the following *SCF* for the weld root:

$$SCF_{Root} = 1 + \frac{3\delta_m L_{Root}}{t L_{Cap}} e^{-\sqrt{t/D}} = 1 + (SCF_{Cap} - 1)\frac{L_{Root}}{L_{Cap}} \tag{2.10.4}$$

where

SCF_{Cap} is defined by equation (2.10.1).

If knowledge about the weld shape is missing, one may put L_{Root} equal L_{Cap} in equation (2.10.4) such that it reduces to that of equation (2.10.1). The background for this equation is presented in /103/.

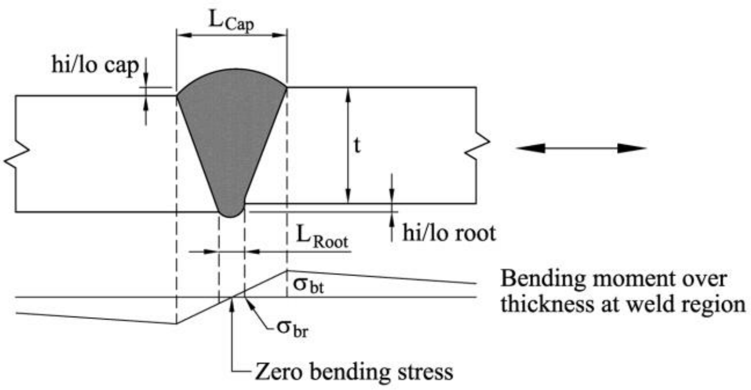


Figure 2-16 Stress distribution due to axial misalignment at single-sided welds in tubular members

2.7 桶体开圆孔的 SCF 计算

依据《DNVGL-RP-C203-Fatigue design of offshore steel structures》中 3.3.8 节规定，桶体开孔的应力集中系数 SCF 可通过下式进行计算，具体规定如下：

3.3.8 Stress concentration factors for stiffened shells

The stress concentration at a ring stiffener can be calculated as

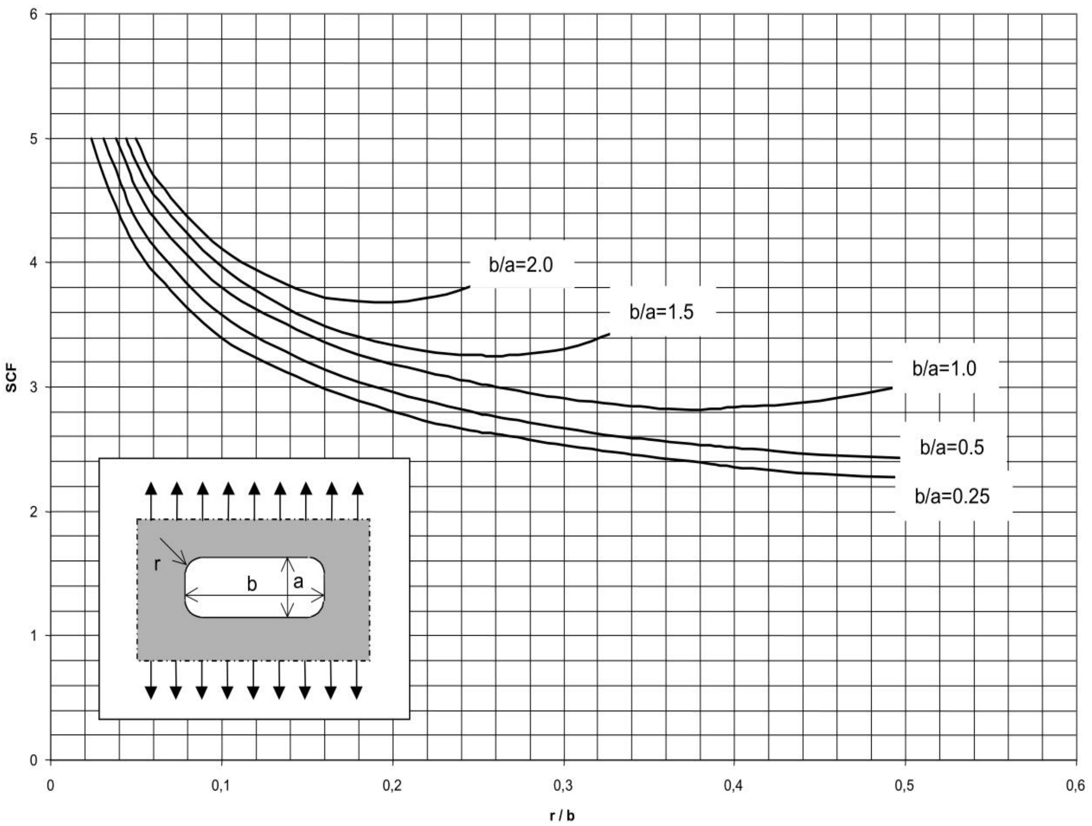
$$
\begin{aligned}
&SCF = 1 + \frac{0.54}{\alpha} \text{ for the outside of the shell} \\
&SCF = 1 - \frac{0.54}{\alpha} \text{ for the inside of the shell} \\
&\alpha = 1 + \frac{1.56t\sqrt{rt}}{A_r}
\end{aligned}
\tag{3.3.11}
$$

where

A_r = area of ring stiffener without effective shell

r = radius of shell measured from centre to mean shell thickness

t = thickness of shell plating



3.疲劳损伤系数计算

3.1 计算依据与公式

依据 DNVGL-RP-C203 中 2.4.3 节，疲劳强度可规定如下：

The fatigue strength of welded joints is to some extent dependent on plate thickness. This effect is due to the local geometry of the weld toe in relation to thickness of the adjoining plates. See also effect of profiling on thickness effect in [7.2]. It is also dependent on the stress gradient over the thickness. See [F.5], Commentary. The thickness effect is accounted for by a modification of the stress range such that the design S-N curve for thickness larger than the reference thickness reads:

规范翻译：焊接接头的疲劳强度在一定程度上取决于板厚。这种影响源于焊趾的局部几何形状与相邻板厚的关系。参见[7.2]中关于轮廓对厚度影响的讨论。此外，它还受到厚度方向上应力梯度的影响。参见[F.5]的注释。厚度影响通过调整应力范围来考虑，使得对于大于参考厚度的设计 S-N 曲线为：

$$\log N = \log\bar{a} - m\log(\Delta\sigma(\frac{t}{t_{ref}})^{k})$$

$$\log N = \log\bar{a} - m\log(（\gamma_{m} \times SCF \times \sigma）(\frac{t}{t_{ref}})^{k})$$

其中：m—S-N 曲线的负逆斜率，根据选择曲线，在表 1-1 中取值；

loga —对数 N 轴的截距，根据选择曲线，在表 1-1 中取值；

t_{ref} —参考厚度，对于非管状焊接，焊接连接（管状接头除外）的参考厚度为 25 毫米。对于管状接头，参考厚度为 16 毫米。螺栓的参考厚度 tref=25 毫米;

	非管状节点 mm	管状节点 mm	螺栓 mm
参考厚度 tref	25	16	25

t—裂缝最有可能增加的厚度，取板厚度；

k—疲劳强度的厚度指数，根据选择曲线，在表 1-1 中取值；

Δσ—为应力幅值，取等效疲劳荷载下的有效应力值。

对过渡段选用 DNVGL-C203 中的表 1-1 进行疲劳计算，如下表和下图所示。注：（由于过渡段处于空气中，所以取空气中的 S-N 曲线）

3.2 参考 S-N 曲线表

依据 DNVGL-RP-C203 中 2.4.4 节~2.4.6 节中内容，S-N 曲线参数选取如下：（注：过渡段处于空气中因此只选用空气中的 S-N 曲线，如涉及到其他部位，可按需选取其他曲线）

（1）空气中的 S-N 曲线

表 1-1 空气中 S-N 曲线参数表

S-N curve	$N \le 10^7$ cycles		$N > 10^7$ cycles $\log \bar{a}_2$ $m_2 = 5.0$	Fatigue limit at 10^7 cycles (MPa) *)	Thickness exponent k	Structural stress concentration embedded in the detail (S-N class), see also equation (2.3.2)
	m_1	$\log \bar{a}_1$				
B1	4.0	15.117	17.146	106.97	0	
B2	4.0	14.885	16.856	93.59	0	
C	3.0	12.592	16.320	73.10	0.05	
C1	3.0	12.449	16.081	65.50	0.10	
C2	3.0	12.301	15.835	58.48	0.15	
D	3.0	12.164	15.606	52.63	0.20	1.00
E	3.0	12.010	15.350	46.78	0.20	1.13
F	3.0	11.855	15.091	41.52	0.25	1.27
F1	3.0	11.699	14.832	36.84	0.25	1.43
F3	3.0	11.546	14.576	32.75	0.25	1.61
G	3.0	11.398	14.330	29.24	0.25	1.80
W1	3.0	11.261	14.101	26.32	0.25	2.00
W2	3.0	11.107	13.845	23.39	0.25	2.25
W3	3.0	10.970	13.617	21.05	0.25	2.50

*) see also [2.11]

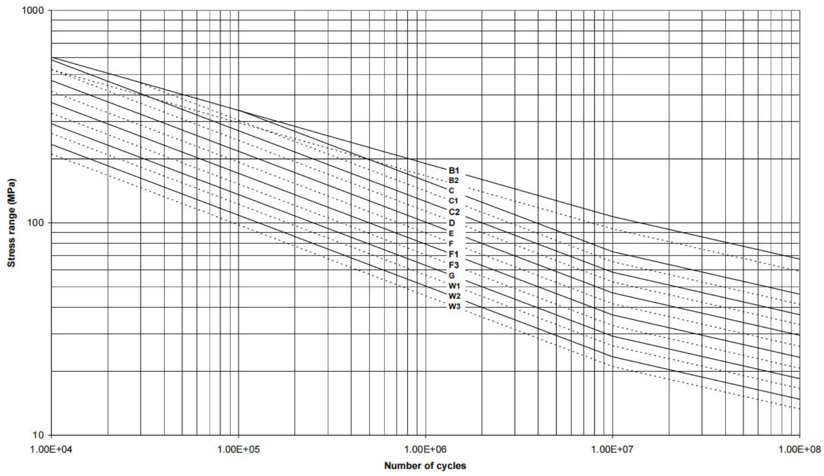


图 1-1 空气中 S-N 曲线图

（2）阴极保护下海水环境中的 S-N 曲线

表 1-2 阴极保护下海水环境中的 S-N 曲线参数表

S-N curve	$N \le 10^7$ cycles		$N > 10^7$ cycles $\log \bar{a}_2$ $m_2 = 5.0$	Fatigue limit at 10^7 cycles (MPa) *)	Thickness exponent k	Structural stress concentration embedded in the detail (S-N class), see also equation (2.3.2)
	m_1	$\log \bar{a}_1$				
B1	4.0	15.117	17.146	106.97	0	
B2	4.0	14.885	16.856	93.59	0	
C	3.0	12.592	16.320	73.10	0.05	
C1	3.0	12.449	16.081	65.50	0.10	
C2	3.0	12.301	15.835	58.48	0.15	
D	3.0	12.164	15.606	52.63	0.20	1.00
E	3.0	12.010	15.350	46.78	0.20	1.13
F	3.0	11.855	15.091	41.52	0.25	1.27
F1	3.0	11.699	14.832	36.84	0.25	1.43
F3	3.0	11.546	14.576	32.75	0.25	1.61
G	3.0	11.398	14.330	29.24	0.25	1.80
W1	3.0	11.261	14.101	26.32	0.25	2.00
W2	3.0	11.107	13.845	23.39	0.25	2.25
W3	3.0	10.970	13.617	21.05	0.25	2.50

*) see also [2.11]

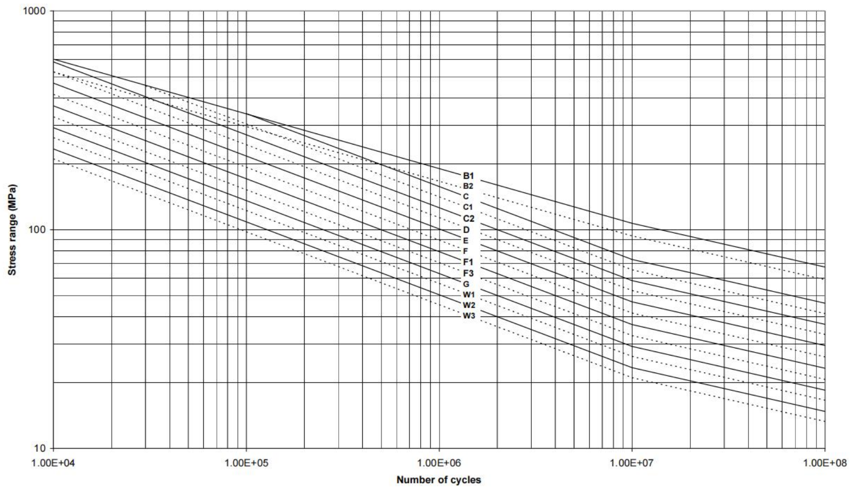


图 1-2 阴极保护下海水环境中的 S-N 曲线图

（2）管节点的 S-N 曲线

表 1-3 管节点的 S-N 曲线参数表

Environment	m_1	$\log \bar{a}_1$	m_2	$\log \bar{a}_2$	*Fatigue limit at 10^7 cycles (MPa)*)*	*Thickness exponent k*
Air	$N \le 10^7$ cycles		$N > 10^7$ cycles			
	3.0	12.48	5.0	16.13	67.09	0.25
Seawater with cathodic protection	$N \le 1.8 \cdot 10^6$ cycles		$N > 1.8 \cdot 10^6$ cycles			
	3.0	12.18	5.0	16.13	67.09	0.25
Seawater free corrosion	3.0	12.03	3.0	12.03	0	0.25
*) see also [2.11]						

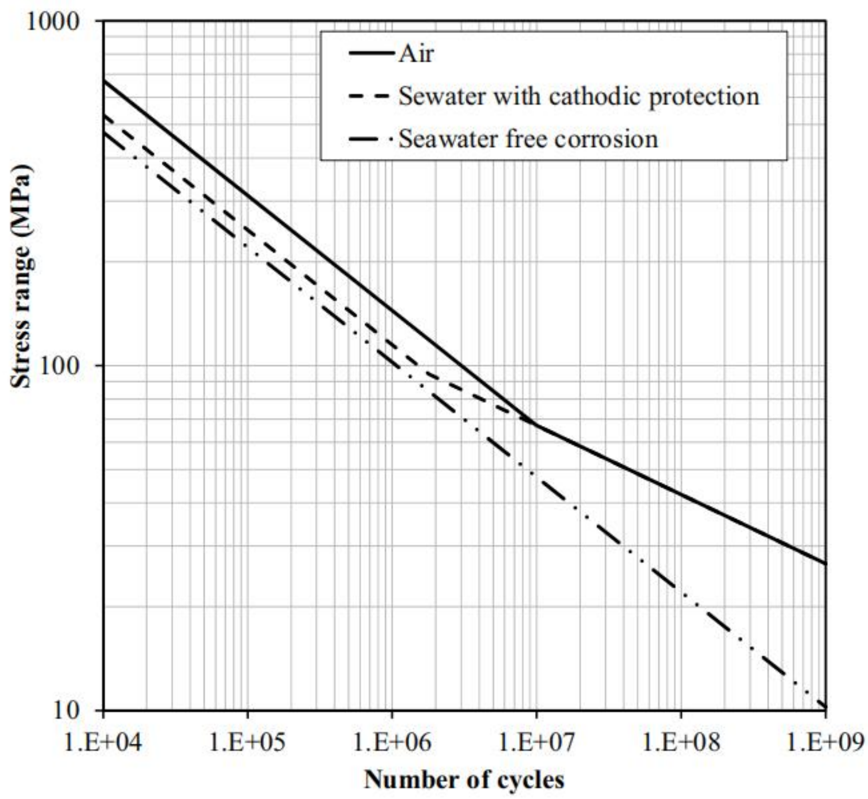


图 1-3 管节点的 S-N 曲线图