Guidance
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China Classification Society

Guidelines for Fatigue Strength Assessment Based on Fracture Mechanics Methodology

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Beijing

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Section 1 General

1.1 Application

1.1.1 The Guidelines specify the fatigue strength assessment of hull structure based on fracture mechanics methodology. The load is typically calculated by means of the equivalent design wave method or the spectral analysis method. The Guidelines are applicable to ships that are subject to fatigue strength assessment based on fracture mechanics methodology defined according to rules or guidelines set forth by China Classification Society (hereinafter referred to as CCS), and also applicable to ships for which class notations as specified in Section 1 [1.1.2] are voluntarily applied, or ships for which CCS deems it necessary to consider the effects of crack growth.

1.1.2 Upon the completion of the fatigue strength assessment in accordance with the Guidelines and compliance with the requirements, a class notation FFM (XX,YY) will be appended, where XX refers to the environmental conditions (e.g. NA for North Atlantic, which scatter diagram defined according to IACS Rec.34), and YY refers to the design life (in year).

1.1.3 For ships subject to fatigue strength assessment in accordance with the Guidelines, their structural design, construction procedure and construction quality shall meet the requirements of the *Rules for Classification of Sea-going Steel Ships* or the *Rules for Materials and Welding* of CCS or other relevant standards accepted by CCS.

1.2 Definition

1.2.1 Initial defect

It refers to slag inclusions and porosity generated in the smelting and manufacturing procedure of actual structures, tool marks and grooves generated during processing, cracks, incomplete penetration, porosity, undercuts, overburning and slag inclusions generated during welding, shrinkage cavities and looseness in castings, as well as stress corrosion cracks and fatigue cracks generated during the use of the structure in different environments. The types of defects include through thickness cracks, edge cracks, embedded cracks and surface cracks. The specific schematic diagram of each type is shown in Section 3, [3.3].

1.2.2 Fatigue stress range spectrum

It refers to a stress range spectrum consisting of fatigue stress ranges that meet the requirements of the distribution function, where each value serves as the stress range for the prediction calculation of detail fatigue crack growth.

1.2.3 Equivalent Design Wave methodology

The calculation of the fatigue stress range spectrum is based on the Equivalent Design Wave method, such as the stress range calculation method given in Part 9-1, Chapter 9of the *Rules for Classification of Sea-going Steel Ships,* or the *Guidelines for Fatigue Strength of Ship Structure* of CCS.

1.2.4 Spectral Analysis methodology

Fatigue stress range spectrum calculation is based on the Spectral Analysis methodology, such as the stress range calculation method given in the *Guidelines for Spectrum Based Fatigue Assessment of Hull Structure* of CCS.

1.2.5 Failure Assessment Diagram Method (FAD)

It refers to a method for assessing the integrity of structures containing planar defects, for which all possible failure modes, from brittle fracture to plastic collapse, are considered. The calculation methods are described in Section 6.

1.2.6 Nominal stress

It refers to stress calculated in a structural, only taking into account the geometric effect of the structure, but disregarding the stress concentration due to structural discontinuity and welds. Tensile stress is positive and compressive stress is negative.

1.3 Symbols

1.3.1 $\Delta\sigma_n$: Nominal stress range, in N/mm^2; the variation range of alternating stress resulting in structural fatigue, calculated by the following formula:

$$\Delta\sigma_n = \sigma_{\max} - \sigma_{\min}$$

Where:

$\sigma_{\max}$: Algebraic maximum in a nominal stress cycle, in N/mm^2;

$\sigma_{\min}$:Algebraic minimum in a nominal stress cycle, in N/mm^2.

1.3.2 σ_{ref}: Reference stress, in N/mm^2, used in the FAD to assess the stress resulting in plastic fracture of the structure, calculated according to Section 6 Table 6.4.1.

1.3.3 σ_{mean}: Mean nominal stress, N/mm^2, calculated by the following formula:

$$\sigma_{mean} = \frac{\sigma_{\max} + \sigma_{\min}}{2}, \quad \text{N/mm}^2.$$

1.3.4 K: Stress intensity factor, in MPa$\sqrt{m}$, reflecting the physical quantity of elastic stress field strength at crack tip, in relation to crack type, crack size, geometric size of structure and stress magnitude, as described in Section 3, [3.3].

1.3.5 ΔK: Stress intensity factor range, in MPa$\sqrt{m}$, the difference between the maximum and minimum stress intensity factors in an alternating stress cycle, as described in Section 2, [2.3].

1.3.6 ΔK_{eq0}: Equivalent stress intensity factor range, in MPa$\sqrt{m}$, taking into account the influence of load (stress) ratio.

1.3.7 R: Load (stress) ratio, referring to the ratio of the minimum stress to the maximum stress in a fatigue load (stress) cycle.

1.3.8 ΔK_{th0}: Threshold stress intensity factor range, in MPa$\sqrt{m}$, characterizing the critical point at which crack growth occurs, i.e. when the value is greater than this threshold, crack propagates; otherwise, crack does not propagate. For hull structures steels, the recommended threshold is 2 MPa$\sqrt{m}$.

1.3.9 C :Material constant in fatigue crack growth law, taken as the Paris Law's parameter. The recommend value for steel is followed

C=1.65×10^{-11}.

1.3.10 m:Material constant in fatigue crack growth law, taken as the Paris Law's parameter. The recommend value for steel is m=3.

1.3.11 K_{IC}: Plane strain fracture toughness, in MPa $\sqrt{\text{m}}$. Under plane strain conditions, the threshold stress intensity factor for the unstable growth of Mode I (i.e. opening mode) cracks in steel shall comply with relevant provisions in Part 1, Chapter 2 of the *Rules for Materials and Welding* of CCS.

1.3.12 da/dN: Crack growth rate, in m/cycle, a physical quantity describing the crack growth speed and the amount of crack growth in each cycle.

1.3.13 K_r: Fracture parameter, the ratio of stress intensity factor to fracture toughness, as described in Section 6, [6.3].

1.3.14 L_r:Plastic collapse parameter, a measure of the appropriated stresss level and to be controlled by plastic collapse consideration, as described in Section 6, [6.4].

1.3.15 N_{total}: Total number of cycles, the total number of fatigue load cycles during the design fatigue life.

1.3.16 N_F: Failure number of cycles, the number of fatigue load cycles experienced before the fatigue failure of the structure.

1.3.17 R_{eH}: Material yield strength, in N/mm^2, which shall comply with the requirements in Part 2, Chapter 1, Section 3 of the *Rules for Classification of Sea-going Steel Ships* of CCS.

1.3.18 R_m: Material tensile strength, in N/mm^2, which shall comply with relevant provisions in Part 1, Chapter 3 of the *Rules for Materials and Welding* of CCS.

Note: For the constants in 1.3.8-1.3.10, if other values are used, they shall be approved by CCS.

1.4 Fatigue Failure Mode

1.4.1 The Guidelines mainly describe the following two fatigue crack failure modes:

(1) Fatigue cracks initiating from small defects or undercuts at the weld toe and propagating into the base material;

(2) Fatigue cracks initiating from the edge of a non-welded details (cut, groove or small surface defect/irregularity in structure)

1.5 Fatigue Assessment Methodology

1.5.1 The theoretical basis for fatigue assessment is the unique curve model of crack growth rate equation based on fracture mechanics methodology, and the specific calculation method is described in Section 2, [2.3.1].

1.5.2 For fatigue assessment, the equivalent design wave method or spectral analysis method is used for different detail positions respectively, as described in Section 2, [2.2].

1.6 Fatigue Loading Conditions

1.6.1 When the assessment is performed using the Equivalent Design Wave method, the loading conditions and fraction of time in each loading condition for fatigue assessment shall comply with the relevant requirements of the *Rules for Classification of Sea-Going Steel Ships* or the *Guidelines for Fatigue Strength of Ship Structure* of CCS.

1.6.2 When the assessment is performed using the Spectral Analysis method, the loading conditions and fraction of time in each loading condition for fatigue assessment shall comply with the relevant requirements of the *Rules for Classification of Sea-going Steel Ships* or the *Guidelines for Spectrum Based Fatigue Assessment of Hull Structure* of CCS.

1.7 Fatigue Load Cases

1.7.1 The load cases for fatigue assessment by the Equivalent Design Wave method shall comply with the relevant requirements of the *Rules for Classification of Sea-Going Steel Ships* or the *Guidelines for Fatigue Strength of Ship Structure* of CCS.

1.7.2 The load cases for fatigue assessment by the Spectral Analysis method shall comply with the relevant requirements of the *Rules for Classification of Sea-Going Steel Ships* or the *Guidelines for Spectrum Based Fatigue Assessment of Hull Structure* of CCS.

Section 2 Fatigue Evaluation

2.1 General

2.1.1 The fatigue strength assessment in the Guidelines is based on the calculation of fatigue crack growth and the failure assessment principles. The fatigue stress (range) used in the calculation is the nominal stress (range).

2.1.2 The calculated fatigue life T_F is to comply with the following formula:

$T_F \geqslant T_{DF}$

where:

T_{DF} : Design fatigue life, in year.

2.1.3 The design fatigue life T_{DF} of the hull structure shall be in accordance with the *Rules for Classification of Sea-Going Steel Ships*, the *Guidelines for Fatigue Strength of Ship Structure* or the *Guidelines for Spectrum Based Fatigue Assessment of Hull Structure* of CCS.

2.2 Structural details to be assessed

2.2.1 The Guidelines apply to the fatigue assessment of weld toes and free edges of base material, and the assessment details are as specified in Part 9-1, Chapter 9 of the *Rules for Classification of Sea-Going Steel Ships*, the *Guidelines for Fatigue Strength of Ship Structure* or the *Guidelines for Spectrum-based Fatigue Assessment of Hull Structure*.

2.3 Unique Crack Growth Rate Curve Model

2.3.1 The crack growth law is the Unique Crack Growth Rate Curve Model expressed as follows:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C\left[\left(\Delta K_{eq0}\right)^m - \left(\Delta K_{th0}\right)^m\right]$$

where:

C : Crack growth constant;

m : Crack growth constant;

ΔK_{th0} : Threshold stress intensity factor range;

ΔK_{eq0} : Equivalent stress intensity factor range, calculated by the followingformula:

$$\Delta K_{eq0} = M_R \Delta K$$

ΔK : Stress intensity factor range, calculated by the following formula:

$$\Delta K = K_{\max} - K_{\min}, \quad \mathrm{MPa}\sqrt{\mathrm{m}}$$

M_R : Correction factor of load (stress) ratio, calculated by the following formula:

$$M_R = \begin{cases} (1-R)^{-\beta_1} & (R<0) \\ (1-R)^{-\beta} & (0 \le R < 0.5) \\ \left(1.05-1.4R+0.6R^2\right)^{-\beta} & (0.5 \le R < 1) \end{cases}$$

R :Load (stress) ratio, calculated by the following formula:

$$R = \frac{K_{\min} + K_{res}}{K_{\max} + K_{res}}$$

$K_{\min}$: The minimum stress intensity factor, in MPa$\sqrt{m}$, calculated according to Section 3, [3.3];

$K_{\max}$: The maximum stress intensity factor, in MPa$\sqrt{m}$, calculated according to Section 3, [3.3];

K_{res} : Stress intensity factor of residual stress, in MPa$\sqrt{m}$, calculated according to Section 3, [3.3];

β, β_1: Parameters depending on materials and service environment, taken as:

β=0.3, β_1=0.7;

Note: When other values are used, they shall be approved by CCS.

2.4 Fatigue Stress Range Spectrum

2.4.1 The load for the calculation of fatigue crack growth is obtained from a stepped stress range spectrum, and the standard stepped stress range spectrum is calculated by the following formula:

$$\frac{\Delta\sigma_i}{\Delta\sigma_{\max}} = \left(1 - \frac{\lg N_i}{\lg N_{total}}\right)^{1/\xi}$$

where:

$\Delta\sigma_{\max}$: The maximum design fatigue stress range corresponding to the total number of cycles N_{total};

N_i : Number of stress range cycles of stress range spectrum block i;

$\Delta\sigma_i$: Fatigue stress range corresponding to the number of cycles N_i;

ξ : Weibull distribution shape parameter, with reference to Part 2 of the *Rules for Classification of Sea-Going Steel Ships* or the *Guidelines for Fatigue Strength of Ship Structure* of CCS;

N_{total} : Total number of fatigue load cycles.

2.5 Failure Assessment Methodology

2.5.1 The failure assessment calculation for structural details, taking into account initial defects, is used of Failure Assessment Diagram (hereinafter referred to as FAD).

2.5.2 A typical FAD is shown in Fig. 2.5.2, with the plastic collapse parameter L_r plotted on the abscissa and the fracture coefficient K_r on the ordinate. The failure assessment curve divides the assessment diagram into two areas: safe and unsafe. If the assessment point on the fatigue crack growth curve is below the failure assessment curve, it indicates that the structure containing cracks is safe; otherwise, it is unsafe.

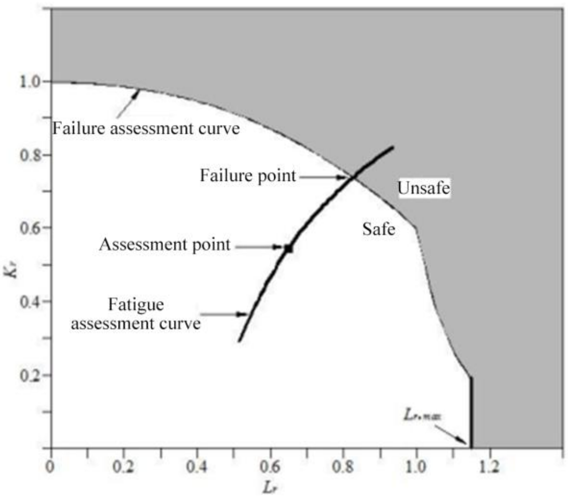


Fig. 2.5.2 Typical Failure Assessment Diagram

2.5.3 The calculation method of failure assessment curve is calculated according to Section 6, [6.3].

2.5.4 The calculation methods of fracture and plastic collapse factors for fatigue crack growth are given in Section 6, [6.3] and [6.4].

2.5.5 The intersection of the failure assessment curve and fatigue crack growth curve is the failure point of the structural detail, and the corresponding number of load cycles in the fatigue stress range is the number of failure cycles N_F.

2.6 Fatigue Life Calculation

2.6.1 The fatigue failure life of structure shall be calculated by the following formula:

$$T_F = \frac{N_F}{N_{total}} \cdot T_{DF}$$

where:

T_{DF} :Design fatigue life, in year;

N_F : Total number of fatigue cycles before failure;

N_{total} : Total number of fatigue load cycles within the design fatigue life T_{DF}.

2.7 Fatigue Crack Growth Assessment Procedure

2.7.1 Fatigue crack growth calculation and failure assessment calculation mainly consist of the following steps.

Step 1: Determination of initial parameters

Geometric sizes of details: plate thickness and width, with parameters defined according to Section 3, [3.3];

Equivalent initial defect size of detail: with parameters defined according to Section 3, [3.1.2];

Material properties: fracture toughness, yield strength and tensile strength, with parameters defined according to Section 1, [1.3.11], [1.3.17] and [1.3.18];

Material crack growth constant: with parameters defined according to Section 1, [1.3.8]-[1.3.10].

Step 2: Generation of fatigue stress range spectrum

(1) For the Equivalent Design Wave method, the long-term probability distribution for the calculation of stress

range is taken as Weibull distribution function, with parameters defined according to Section 4;

(2) For the Spectral Analysis method, the short-term probability distribution for the calculation of stress range is taken as Rayleigh distribution function, with parameters defined according to Section 5;

The stepped spectrum blocks of fatigue stress range and the corresponding number of cycles are generated according to the probability distribution function of stress range.

Step 3: Normalization of initial defect size and calculation of stress intensity factor

Calculate the stress intensity factor (range) at the fatigue hot spot of the structure by equivalent normalization of initial defects defined according to Section 3.

Step 4: Calculation of fatigue crack growth

Calculate the increment d*a* for each cyclic load calculated according to Section 2.

Step 5: Failure assessment

Construct the FAD by calculating the failure assessment curve and fatigue crack growth curve; determine whether the crack exceeds the failure criterion based on the failure conditions defined according to Section 6: If the failure criterion is satisfied, the calculation ends; otherwise, repeat the calculation defined according to Steps 3 to 5.

2.7.2 The procedure for the calculation of fatigue crack growth is shown in Fig. 2.7.2. The calculation method of equivalent stress intensity factor range in the flowchart is defined according to Section 2.3 "Equivalent Stress Intensity Factor Range ΔK_{eq0}".

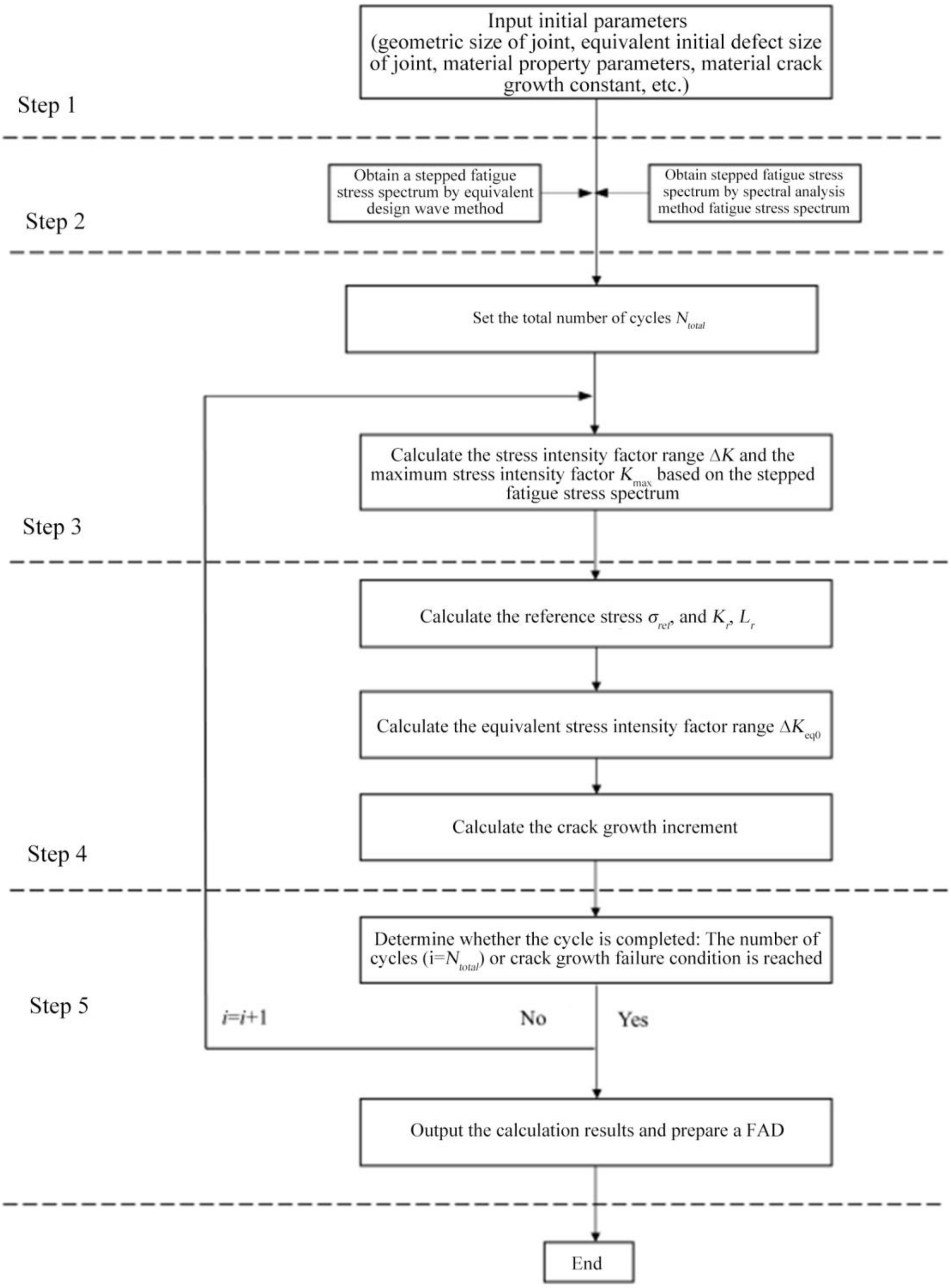


Fig. 2.7.2 Flowchart for Fatigue Crack Growth Assessment Procedure

Section 3 Initial Defect Size Characterizations and Stress Intensity Factor Solutions

3.1 General

3.1.1 In the Guidelines, it is assumed that structural details actually have initial defects during the procedure of metallurgical fabrication, machining and welding.

3.1.2 For newly built ships, the modes of cracks related to initial defects include edge cracks and surface cracks. The crack size can be determined based on the results from conventional nondestructive testing methods. The sizes of initial cracks shown in Table 3.1.2 may be used during the design stage or at the unavailability of reliable detection data.

Fitted Initial Crack Sizes for absence of Non-Destructive Testing Table 3.1.2

Crack Type	Crack Size, m	
Edge Crack	a=0.1x10^{-3}	-
Surface Crack	a=0.5x10^{-3}	$2c$=10x10^{-3}

Note: For edge cracks, a is the crack length;

For surface cracks, a is the crack depth and c is the half of the crack length.

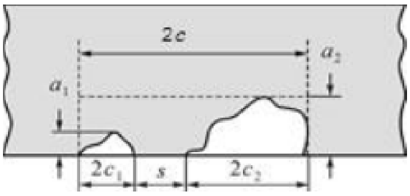
3.1.3 For ships in operation, the modes and sizes of cracks related to initial cracks shall be determined based on the nondestructive testing results, and the equivalent size shall be simplified as specified in Section 3, [3.2] . The embedded crack is simplified as an elliptical crack, and the surface crack is simplified as a semi-elliptical crack.

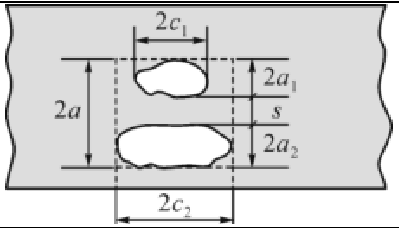
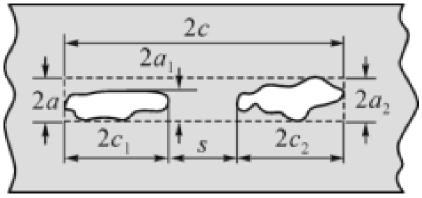
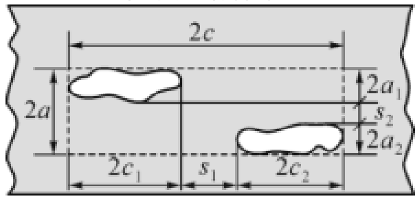
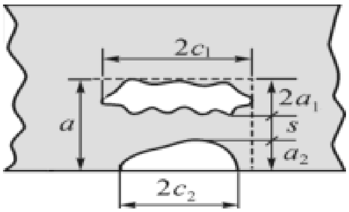
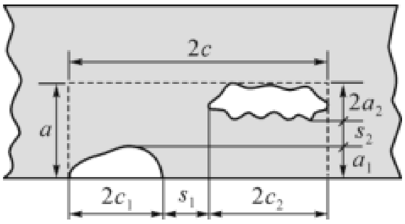
3.1.4 The base material in this Section refers to flat steel plate subjected to uniform tensile stress, and the crack mode under consideration is Mode I crack, also known as opening crack. For this mode of crack, the crack tip opens under the applied stress perpendicular to the crack plane, and the crack grows in a direction perpendicular to the stress.

3.2 Interaction Rules for Coplanar Cracks

3.2.1 Coplanar cracks refer to multiple cracks existing on the same plane. For two or more coplanar cracks, interaction shall be carried out according to the criteria shown in Table 3.2.1.

Interaction Rules for Coplanar Cracks Table 3.2.1

	Schematic Cracks	Criteria for Interaction	Effective Dimensions after Interaction
1	Coplanar surface cracks  	$s \leq \max(0.5a_1, 0.5a_2)$ a_1/B and/or $a_2/B \leq 0.5$ $s \leq \max(a_1, a_2)$ a_1/B and $a_2/B > 0.5$	$a = \max(a_1, a_2)$ $2c = 2c_1 + 2c_2 + s$
2	Coplanar embedded cracks(interaction in thickness direction)	$s \leq a_1 + a_2$	$2a = 2a_1 + 2a_2 + s$ $2c = \max(2c_1, 2c_2)$

			
3	Coplanar embedded cracks(interaction in width direction) 	$s \le \max(a_1, a_2)$	$2a = \max(2a_1, 2a_2)$ $2c = 2c_1 + 2c_2 + s$
4	Coplanar embedded cracks(interaction in thickness and width direction) 	$s_1 \le \max(a_1, a_2)$ $s_2 \le a_1 + a_2$	$2c = 2c_1 + 2c_2 + s_1$ $2a = 2a_1 + 2a_2 + s_2$
5	Coplanar surface cracks(interaction in thickness direction) 	$s \le a_1 + a_2$	$a = 2a_1 + a_2 + s$ $2c = \max(2c_1, 2c_2)$
6	Coplanar surface cracks(interaction in thickness and width direction) 	$s_1 \le \max(0.5a_1, a_2)$ $s_2 \le a_1 + a_2$	$a = a_1 + 2a_2 + s_2$ $2c = 2c_1 + 2c_2 + s_1$

3.3 Stress Intensity Factor Solutions

3.3.1 This section contains stress intensity factor solutions for a range of crack types that include through-thickness crack, edge crack, embedded crack and surface crack at weld toes. It is also given the stress intensity factor solutions for surface crack under welding residual stress at weld toe.t is given the stress intensity factor solutions for surface crack under welding residual stress at weld toe.

3.3.2 The stress intensity factor *K* of the through thickness crack on plate under uniform tension is calculated by the following formula:

$$K = \sigma_n \sqrt{\pi a} Y(a) \quad \text{MPa}\sqrt{\text{m}}$$

where:

σ_n : Nominal stress, in N/mm^2;

a : Half of crack length, in m, as shown in Fig. 3.3.2;

Y(a) : Calculated by the following formula:

$$Y(a)=\left(1-0.25\left(\frac{2a}{w}\right)^2+0.06\left(\frac{2a}{w}\right)^4\right)\sqrt{\sec(\pi a/w)}$$

W : Width of plate, in m, as shown in Fig. 3.3.2.

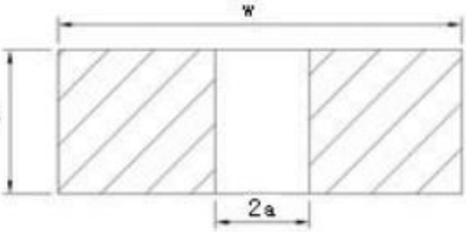


Fig. 3.3.2 Through-thickness Crack(t: thickness of plate, in m)

3.3.3 The stress intensity factor *K* of the free edge crack on plate under uniform tension is calculated by the following formula:

$$K=Y(a)\sigma_n\sqrt{\pi a}\quad \mathrm{MPa}\sqrt{\mathrm{m}}$$

where:

σ_n : Nominal stress, in N/mm^2;

a : Crack length, in m, as shown in Fig. 3.3.3;

Y(a) : Calculated by the following formula:

$$Y(a)=\left[1.12-0.231(\frac{a}{w})+10.55(\frac{a}{w})^2-21.72(\frac{a}{w})^3+30.39(\frac{a}{w})^4\right]$$

w : Width of plate, in m, as shown in Fig. 3.3.3.

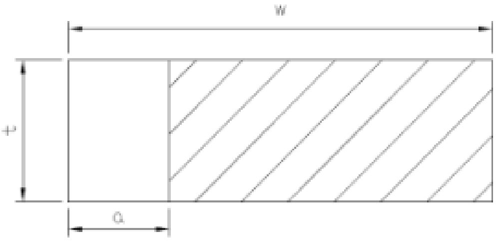


Fig. 3.3.3 Edge Crack(t: thickness of plate, in m)

3.3.4 The stress intensity factor *K* of the embedded crack on plate under uniform tension is calculated by the following formula:

$$K=F\left(\frac{a}{c},\frac{a}{t'},\frac{c}{w},\theta\right)\frac{\sqrt{\pi a}\sigma_n}{\Phi}\quad \mathrm{MPa}\sqrt{\mathrm{m}}$$

where:

σ_n : Nominal stress, in N/mm^2;

a :Half crack length of minor axis, in m, as shown in Fig. 3.3.4;

Φ : Calculated according to Appendix 1, [1.1.1] ;

$F\left(\frac{a}{c},\frac{a}{t'},\frac{c}{w},\theta\right)$: Calculated according to Appendix 1, [1.1.1];

c : Half crack length of major axis, in m, as shown in Fig. 3.3.4;

t' : Equivalent thickness, in m, calculated by the following formula:

$t'=2a+2p$

p : Distance from minor axis plane of crack to plate plane, in m, as shown in Fig. 3.3.4;

w : Width of plate, in m, as shown in Fig. 3.3.4;

θ : Eccentric angle of ellipse, in radian.

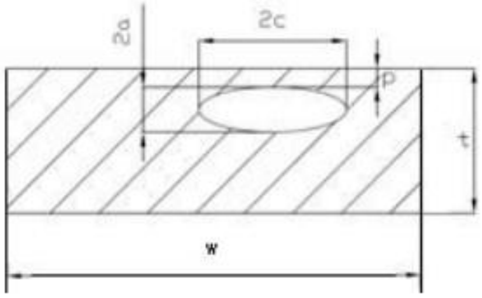


Fig. 3.3.4 Embedded Cracks (*t*: thickness of plate, in m)

Note: The calculation method in this Section is based on the assumption that embedded cracks are elliptical, and crack parameters shall meet the following conditions:

$0 \le a/2c \le 1$， $2c/w < 0.5$, $-\pi < \varphi \le \pi$， and at $0 \le a/2c \le 0.1$, $(a/t') < 0.625\,(0.6+a/c)$

3.3.5 The stress intensity factor K of the surface crack at the weld toe is calculated by the following formula:

$$K = \left(M_K^T\sigma_m + M_K^B H\sigma_b\right)\frac{\sqrt{\pi a}}{\Phi}F\left(\frac{a}{c},\frac{a}{t'},\frac{c}{w},\theta\right) \quad \mathrm{MPa}\sqrt{\mathrm{m}}$$

where:

σ_m : Nominal membrane stress, in N/mm^2;

σ_b : Nominal bending stress, in N/mm^2;

H : Calculated according to Appendix 1, [1.1.2];

A : Crack depth, in m, as shown in Fig. 3.3.5(1);

Φ :Calculated according to Appendix 1, [1.1.2];

$F\left(\frac{a}{c},\frac{a}{t'},\frac{c}{w},\theta\right)$: Calculated according to Appendix 1, [1.1.2];

c : Half crack length of major axis, in m, as shown in Fig. 3.3.5(1);

t : Plate thickness, in m, as shown in Fig. 3.3.5(1);

w : Plate width, in m, as shown in Fig. 3.3.5(1);

θ : Eccentric angle of ellipse, in radian;

M_K^T : Stress intensity magnification factor of welded structure under tensile stress;

M_K^B : Stress intensity magnification factor of welded structure under bending stress;

When the defect or crack is located in a local stress concentration area, refer to Fig. 3.3.5 (2);

M_K^T, M_K^B shall be calculated by the following formula:

$$M_K^{T(B)} = \begin{cases} v\left(\dfrac{a}{t}\right)^u & (M_K^T > 1.0) \\ 1 & (M_K^T \leq 1.0) \end{cases}$$

v, u: as shown in Table 3.3.5.

L : Length of weld toe, in m, as shown in Fig. 3.3.5(2).

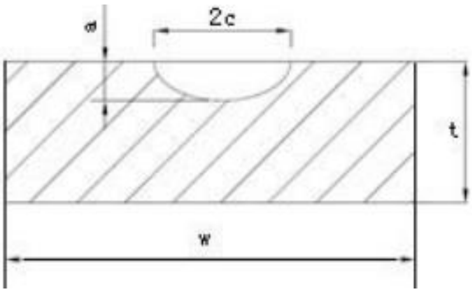


Fig. 3.3.5(1) Surface Crack

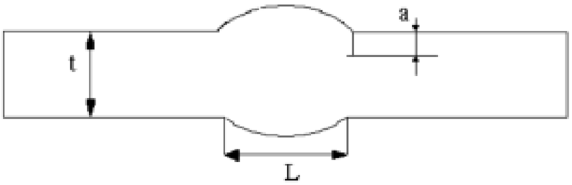


Fig. 3.3.5(2) Butt Weld

Values of v and u for axial and bending loading Table 3.3.5

Type of Load	L/t	a/t	v	u
Axial	$\leqslant 2$	$\leqslant 0.05(L/t)^{0.55}$ $>0.05(L/t)^{0.55}$	$0.51(L/t)^{0.27}$ 0.83	-0.31 $-0.15(L/t)^{0.46}$
	>2	$\leqslant 0.073$ >0.073	0.615 0.83	-0.31 -0.20
Bending	$\leqslant 1$	$\leqslant 0.03(L/t)^{0.55}$ $>0.03(L/t)^{0.55}$	$0.45(L/t)^{0.21}$ 0.68	-0.31 $-0.19(L/t)^{0.21}$
	>1	$\leqslant 0.03$ >0.03	0.45 0.68	-0.31 -0.91

Note: The calculation method in this Section is based on the assumption that the surface crack is semi-elliptical, and the crack parameters shall meet the following conditions:

$0 \leqslant a/c \leqslant 1.0$, $0 \leqslant a/t \leqslant 1.0$, $2c/w \leqslant 0.5$, $0 \leqslant \phi \leqslant \pi$

3.3.6 The stress intensity factor K_{res} for welding residual stresses at the weld toe is calculated by the following formula:

$$K_{res} = F\left(\frac{a}{c}, \frac{a}{t'}, \frac{c}{w}, \theta\right)\frac{\sqrt{\pi a}\sigma_{res}}{\Phi} \quad \text{MPa}\sqrt{\text{m}}$$

where:

σ_{res} : Welding residual stress, in N/mm^2, calculated by the following formula:

$$\sigma_{res} = 0.3R_{eH}$$

R_{eH} : Yield strength of material, in N/mm^2.

Other symbols are defined in Section 3, [3.3.5] .

Section 4 Equivalent Design Wave Methodology

4.1 General

4.1.1 The Equivalent Design Wave method is applicable for the fatigue assessment of typical details in hull structures, where the initial cracks are generally found at the weld toe of welded detail or at the free edge of plate.

4.1.2 The fatigue stress range for the Equivalent Design Wave method is determined according to the fatigue-related requirements in the *Rules for Classification of Sea-Going Steel Ships* or the *Guidelines for Fatigue Strength of Ship Structure*.

4.1.3 Appropriate stress intensity factors are selected for the calculation of crack propagation according to the typical detail connection form and position.

4.2 Fatigue Stress Range Spectrum

4.2.1 The Guidelines recommend the method of determining the fatigue stress range spectrum based on the long-term distribution function of fatigue stress range. Other methods of determining the fatigue stress range spectrum shall be approved by CCS.

4.2.2 A stepped stress range spectrum following the distribution is generated using the shape parameter ξ and scale parameter q of Weibull distribution. The stress range value of each spectrum block is taken as the stress range $\Delta\sigma_n$ for calculating the fatigue life with respect to the crack growth of structure, and the maximum and minimum stresses are $\sigma_{max}=\Delta\sigma_n/2+\sigma_{mean}$ and $\sigma_{min}=\Delta\sigma_n/2+\sigma_{mean}$ respectively.

4.2.3 The probability density function of the long-term distribution of stress range is represented by a two-parameter Weibull distribution, and its probability density is calculated by the following formula:

$$f_{Weibull}\left(\Delta\sigma\right)=\frac{\xi}{q}\left(\frac{\Delta\sigma}{q}\right)^{\xi-1}\exp\left[-\left(\frac{\Delta\sigma}{q}\right)^{\xi}\right] \qquad 0\le\Delta\sigma<+\infty$$

where:

$\Delta\sigma$: Stress range, in N/mm^2;

ξ : Weibull distribution shape parameter, with reference to Part 2 of the *Rules for Classification of Sea-Going Steel Ships* or the *Guidelines for Fatigue Strength of Ship Structure* of CCS;

q : Equivalent scale parameter of Weibull distribution, calculatedby the following formula:

$$q=\frac{\Sigma\alpha_k q_k}{\Sigma\alpha_k}$$

a_k : Fraction of time of loading condition k, as described in Section 1, [1.6.1];

q_k : Weibull distribution scale parameter of loading condition k, calculated by the following formula:

$$q_k=\frac{\Delta\sigma_{n,k}}{\left(\ln n_k\right)^{1/\xi}}$$

$\Delta\sigma_{n,k}$: Nominal stress range of loading condition *k* corresponding to 10^{-8} probability level of exceedance, in N/mm^2;

n_k : Number of load cycles under loading condition *k* corresponding to 10^{-8} probability level of exceedance, calculated by the following formula:

$$n_k = \alpha_k \times N_{total}$$

N_{total}: Total number of fatigue load cycles within the design fatigue life, with reference to the *Rules for Classification of Sea-Going Steel Ships* or the *Guidelines for Fatigue Strength of Ship Structure* of CCS.

4.3 Stress Range

4.3.1 The fatigue design stress range $\Delta\sigma_{n,k}$ for loading condition *k* shall be calculated by the following equation:

$$\Delta\sigma_{n,k} = \max(\Delta\sigma_{n,ik}) \quad \text{N/mm}^2$$

where:

$\Delta\sigma_{n,ik}$: Nominal stress range under load case *i* in loading condition *k*, in N/mm^2.

4.3.2 The fatigue nominal stress range $\Delta\sigma_{n,ik}$ under load case *i* in loading condition *k* shall be calculated by the following formula:

$$\Delta\sigma_{n,ik} = \left|\sigma_{n,i1k} - \sigma_{n,i2k}\right| \quad \text{N/mm}^2$$

where:

$\sigma_{n,i1k}$,$\sigma_{n,i2k}$: Nominal stress under load case *i* in loading condition *k*, in N/mm^2. '1' and '2' represent load cases *i*1 and *i*2 respectively.

4.3.3 Under load case *i* in loading condition *k*, the mean fatigue stress is calculated by the following formula:

$$\sigma_{mean,ik} = \frac{\sigma_{n,i1k} + \sigma_{n,i2k}}{2} \quad \text{N/mm}^2$$

Where:

$\sigma_{n,i1k}$,$\sigma_{n,i2k}$: Nominal stress under load case *i* in loading condition *k*, in N/mm^2. '1' and '2' denote load cases *i*1 and *i*2 respectively.

Section 5 Spectral Analysis Methodology

5.1 General

5.1.1 The provisions of this Section apply to the calculation of fatigue strength for load calculation by Spectral Analysis method.

5.1.2 For hydrodynamic and finite element analysis requirements not specified in this Section, such as operating loads, hot spot stress interpolation methods, etc., reference is made to the *Guidelines for Spectrum Based Fatigue Assessment of Hull Structure* or the *Guidelines for Fatigue Strength of Ship Structure*.

5.1.3 The calculation procedure of spectral analysis method is shown in Fig. 5.1.3.

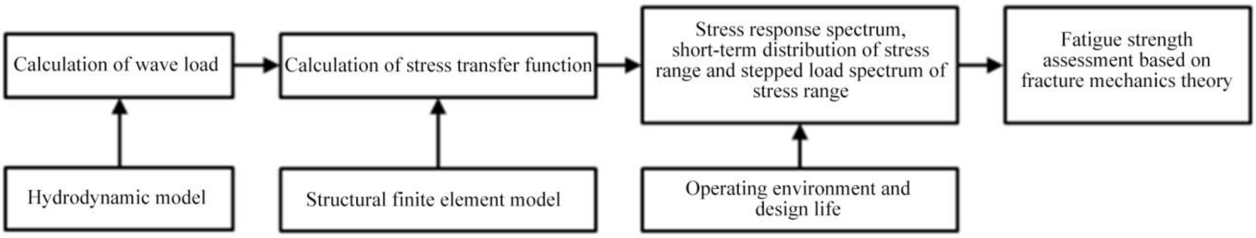


Fig. 5.1.3 Flowchart for Spectral Analysis Procedure

5.2 Hydrodynamic Analysis

5.2.1 The mass model for hydrodynamic analysis shall be able to accurately reflect the mass distribution characteristics of a real ship, where the total mass, center-of-gravity position shall be consistent with the target loading conditions. The hydrodynamic model shall simulate the shape of a real ship as much as possible. The displacement volume and buoyancy center position of the hydrodynamic model shall be consistent with the target loading conditions. The mesh shall be so arranged that the wet surface is kept smooth enough and evenly distributed as far as possible, and the number of meshes shall be sufficient to ensure the accuracy of calculation results. For relevant requirements, refer to Appendix A [3.1.4] in Chapter 1, Part 9 of the *Rules for Classification of Sea-Going Steel Ships* of CCS.

5.2.2 The software used for hydrodynamic analysis shall be approved by CCS.

5.3 Finite Element Analysis

5.3.1 For local structures requiring fatigue analysis, a local three-dimensional fine finite mesh element model can be established. The displacement results obtained from the three-dimensional coarse mesh finite element analysis of the whole ship are applied to the boundary detail of the model for separate analysis as forced displacement boundary conditions, or the fine model can be directly embedded in the whole ship model for analysis. Specific requirements are given in Section 3 of the *Guidelines for Spectrum Based Fatigue Assessment of Hull Structure*.

5.3.2 The amplitudes of motion and dynamic responses of the hull loaded are described using the real part and imaginary part methods. The stress amplitude of the first principal stress at the target detail under unit regular waves for each loading condition, wave frequency and heading angle is taken as the transfer function of that loading condition, wave frequency and heading angle.

5.4 Fatigue Stress Range Spectrum

5.4.1 Wave loads shall be determined using Spectral Analysis method, as described in the *Guidelines for Spectrum Based Fatigue Assessment of Hull Structure*.

5.4.2 It is advisable to use the wave scatter diagrams recommended by IACS. For ships operating on specific routes, the use of other wave condition scatter diagrams shall be approved by CCS.

5.4.3 The wave frequency and wave heading angle shall be selected in accordance with the following:

(1) The wave frequency is 0.1~1.8 rad/s, and the step size is 0.1 rad/s;

(2) The wave heading angle includes 0°, 30°, 60°, 90°, 120°, 150°, 180°, 210°, 240°, 270°, 300° and 330°;

(3) The speed is 75% of the maximum service speed.

5.4.4 The fatigue stress range spectrum block and corresponding number of cycles are obtained based on the Rayleigh distribution function of short-term distribution of fatigue stress range. The value of stress range of each spectrum block is used as the stress range $\Delta\sigma_n$ for the calculation of fatigue life with respect to the crack growth of structure, and the maximum and minimum stresses are $\sigma_{max}=\Delta\sigma_n/2+\sigma_s$ and $\sigma_{min}=-\Delta\sigma_n/2+\sigma_s$ respectively (σ_s is the structural stress generated by static load).

5.4.5 The two-parameter Pierson-Moskowitz spectrum (hereinafter referred to as P-M spectrum) is used for the wave power spectrum, and the probability density function is expressed as follows:

$$G_\eta(\omega, H_s, T_z) = \frac{H_s^2}{4\pi}\left(\frac{2\pi}{T_z}\right)^4 \omega^{-5} \exp\left(-\frac{1}{\pi}\left(\frac{2\pi}{T_z}\right)^4 \omega^{-4}\right)$$

where:

ω : Wave frequency, in rad/s;

H_s : Significant wave height, in m;

T_z : Average zero-crossing period, in s.

5.4.6 The short-term distribution response spectrum of the stress range is expressed as follows:

$$G_\sigma(\omega, H_s, T_z, \theta) = \left|H_\sigma(\omega, \theta)\right|^2 G_\eta(\omega, H_s, T_z)$$

where :

θ : Wave heading angle, in deg;

$H_\sigma(\omega,\theta)$: Stress response transfer function.

5.4.7 The probability density function of the short-term distribution of the stress range is represented by a Rayleigh distribution function, and its probability density is calculated by the following formula:

$$f_\sigma(\sigma) = \frac{\Delta\sigma}{4m_0}\exp\left(-\frac{\Delta\sigma^2}{8m_0}\right) \qquad 0 \le \Delta\sigma < +\infty$$

where:

$\Delta\sigma$:Stress range, in N/mm^2;

m_0 : Spectral moment, calculated according to 5.4.8.

5.4.8 The average zero-crossing rate v of the fatigue stress range, i.e. the average number of average zero-crossings with a positive slope per unit time, is calculated by the following formula:

$$\nu = \frac{1}{2\pi}\sqrt{\frac{m_2}{m_0}}$$

where:

m_0 and m_2: Spectral moment, calculated by the following formula:

$$m_n = \int_0^{+\infty} \omega^n \cdot G_\sigma(\omega, H_s, T_z, \theta) d\omega$$

5.4.9 The long-term distribution of stress range is piecewise continuous, expressed as a weighted combination of short-term distributions, and its distribution function is calculated by the following formula:

$$F_{\Delta\sigma}(\Delta\sigma) = \frac{\sum_{n=1}^{N_n}\sum_{i=1}^{N_s}\sum_{j=1}^{N_h} \nu_{nij} \cdot p_n \cdot p_i \cdot p_j \cdot F_{\Delta\sigma_{nij}}(\Delta\sigma)}{\sum_{n=1}^{N_n}\sum_{i=1}^{N_s}\sum_{j=1}^{N_h} \nu_{nij} \cdot p_n \cdot p_i \cdot p_j}$$

where:

$F_{\Delta\sigma nij}(\Delta\sigma)$: Short-term distribution of stress range under the nth loading condition and ith sea condition and jth heading, as described in Section 5, [5.4.7];

N_n : Number of loading conditions;

N_s : Number of sea conditions;

N_h : Number of headings;

P_n : Proportion of nth loading condition in the design life;

$$0.85 \le \sum_{n=1}^{n=N_n} p_n \le 1$$

Pi : Probability of occurrence of ith sea condition;

Pj : Probability of occurrence of j th heading;

ν_{nij} : Average zero-crossing rate of stress alternating response under nth loading and ith sea condition and jth heading.

5.5 Fatigue Stress Range Spectrum Procedure

Step 1: Hydrodynamic analysis

Establish a hydrodynamic model of the target ship under selected loading conditions, including wet surface area model and mass model. Refer to Section 5, [5.2] for the requirements of the hydrodynamic model. Calculate the motion and dynamic response of the hull under various loading conditions, wave frequencies and heading angles. Refer to Section 5, [5.4] for the input parameters and speeds required for the calculation of motion and wave load response of the ship.

Step 2: Finite element calculation

Establish a finite element model of the target ship, including structure model and mass model. Refer to Section 5, [5.3.1] for requirements on finite element models;

Calculate the stress transfer function of target detail under various loading conditions, wave frequencies and heading angles. Refer to Section 5, [5.3.2] for the requirements for finite element stress calculation.

Step 3: Fatigue spectral analysis

Obtain the short-term probability distribution function of stress range under specific loading condition, wave frequency and heading angle from the sea wave scatter diagram defined according to Section 5, [5.4.8], based on the transfer function;

Step 4: Fatigue stress range spectrum

Obtain the fatigue stress range spectrum defined according to Section 2, [2.4].

Step 5: Fatigue life calculation

Calculate the fatigue life defined according to Section 2, [2.7].

Section 6 Failure Assessment Methodology

6.1 General

6.1.1 The FAD can be used to evaluate all possible failure behaviors of structures containing planar cracks, from brittle fracture to plastic collapse, taking into account the influence of fracture toughness and plastic failure resistance on the safety assessment of structures containing cracks.

6.1.2 The assessment is performed using a generic failure assessment curve that applies to materials without significant yield terrace characteristics on the stress-strain curve.

6.1.3 The failure assessment procedure is shown in Fig. 6.1.3:

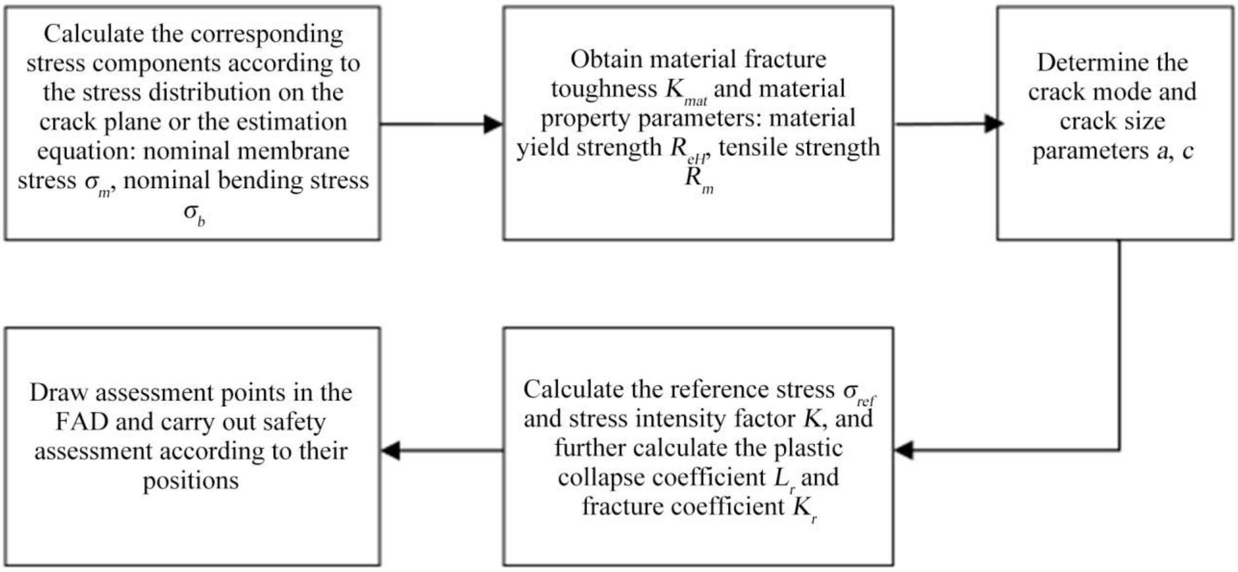


Fig. 6.1.3 Flowchart for Failure Assessment

where:

σ_m : Nominal membrane stress, taken as the fatigue nominal stress in this Guidelines, in N/mm^2;

σ_b : Nominal bending stress, in N/mm^2;

K_r : Fracture parameter;

L_r : Plastic collapse parameter;

σ_{ref} : Reference stress, in N/mm^2;

K_{mat} : Material fracture toughness of steel, MPa$\sqrt{m}$, taken as the plane strain fracture toughness K_{IC} of steel.

6.2 Failure Assessment Line

6.2.1 The failure assessment curve is expressed as follows:

$$\begin{cases} f\left(L_r\right)=\left(1+0.5L_r^2\right)^{-0.5}\left[0.3+0.7exp\left(-\mu L_r^6\right)\right] & L_r\leq 1 \\ f\left(L_r\right)=\ f\left(L_r\ =1\right)L_r^{\frac{(\eta-1)}{(2\eta)}} & 1<L_r\leq L_{r,\max} \\ f\left(L_r\right)=0 & L_r>L_{r,\max} \end{cases}$$

where:

L_r : Plastic collapse parameter, as described in Section 6, [6.4];

$L_{\mathrm{r,max}}$: *The* maximum plastic collapse parameter, calculated by the following formula:

$$L_{r,\max}=\frac{R_{eH}+R_m}{2R_{eH}}$$

R_{Eh} : Material yield strength, in N/mm^2;

R_m : Material tensile strength, in N/mm^2.

$$\mu=\min(0.001\frac{E}{R_{eH}},0.6)$$

$$\eta=0.3(1-\frac{R_{eH}}{R_m})$$

6.3 Fracture Parameter for Fatigue Crack Growth

6.3.1 The fracture parameter K_{r} for fatigue crack growth is calculated by the following formula:

$$K_r=\frac{K_I}{K_{mat}}=\frac{K_I^p+K_I^s}{K_{mat}}+\rho$$

where:

K_I^p : Stress intensity factor, in MP$\sqrt{m}$, calculated from primary stress (nominal stress);

K_I^s : Stress intensity factor, in MP$\sqrt{m}$, calculated from secondary stress (welding residual stress);

ρ : Plasticity correction factor, calculated by the following formula:

$$\begin{cases} \rho_1=0.1\left[K_I^S\left(\frac{L_r}{K_I^P}\right)\right]^{0.714}-0.007\left[K_I^S\left(\frac{L_r}{K_I^P}\right)\right]^2+0.00003\left[K_I^S\left(\frac{L_r}{K_I^P}\right)\right]^5 & K_I^S\left(\frac{L_r}{K_I^P}\right)<5.2 \\ \rho_1=0.25 & K_I^S\left(\frac{L_r}{K_I^P}\right)\geq 5.2 \end{cases}$$

$$\begin{cases} \rho=\rho_1 & L_r\leq 0.8 \\ \rho=4\rho_1\left(1.05-L_r\right) & 0.8<L_r<1.05 \\ \rho=0 & L_r\geq 1.05 \end{cases}$$

6.4 Plastic Collapse Parameter for Fatigue Crack Propagation

6.4.1 The plastic collapse parameter L_r for crack growth is calculated by the following formula:

$$L_r = \frac{\sigma_{ref}}{\sigma_{fs}}$$

where:

σ_{ref} : Reference stress, in N/mm^2, as shown in Table 6.4.1;

σ_{fs} : Flow strength of the material at the crack, in N/mm^2, taken as the yield strength R_{eH} of the material.

Reference stress $\boldsymbol{\sigma_{ref}}$ solutions, in N/mm^2 **Table 6.4.1**

S/N	Crack Type	Reference Stress σ_{ref}
1	Through-thickness crack	$\sigma_{ref} = \dfrac{\sigma_b + \left(\sigma_b{}^2 + 9\sigma_m^2\right)^{0.5}}{3\left(1 - \dfrac{2a}{w}\right)}$
2	Edge crack	$\sigma_{ref} = \dfrac{\sigma_b + \left(\sigma_b{}^2 + 9\sigma_m^2\right)^{0.5}}{3\left(1 - \dfrac{a}{w}\right)}$
3	Surface crack	$\sigma_{ref} = \dfrac{\sigma_b + \left[\sigma_b{}^2 + 9\sigma_m^2\left(1-\alpha''\right)^2\right]^{0.5}}{3\left(1-\alpha''\right)^2}$ $\begin{cases} \alpha'' = (a/t)/\{1+(t/c)\} & (w \geq 2(c+t)) \\ \alpha'' = (2a/t)(c/w) & (w < 2(c+t)) \end{cases}$
4	Embedded crack	$\sigma_{ref} = \dfrac{\sigma_b + 3\sigma_m\alpha'' + \left[\left(\sigma_b + 3\sigma_m\alpha''\right)^2 + 9\sigma_m^2\left\{\left(1-\alpha''\right)^2 + 4\left(\dfrac{p\alpha''}{t}\right)\right\}\right]^{0.5}}{3\left\{\left(1-\alpha''\right)^2 + 4\left(\dfrac{p\alpha''}{t}\right)\right\}}$

In the table:

a : half-length of through thickness crack, length of side crack, depth of surface crack and half-length of embedded crack respectively, in m;

w : plate width, in m;

c: half-length of crack, in m;

t: plate thickness, in m;

p: distance from embedded crack to plate surface, in m, as shown in Section 3, Fig. 3.3.4;

σ_m: nominal membrane stress, in N/mm^2;

σ_b: nominal bending stress, in N/mm^2.

Appendix 1 Stress Intensity Factor for Typical Crack

1.1 Stress Intensity Factor for Embedded Elliptical Crack

The stress intensity factor *K* for embedded elliptical crack is calculated by the following formula:

$$K = F\left(\frac{a}{c},\frac{a}{t'},\frac{c}{w},\theta\right)\frac{\sqrt{\pi a}\sigma_n}{\Phi} \quad \text{MPa}\sqrt{\text{m}}$$

where:

σ_n : Nominal stress, in N/mm^2;

$$\Phi = \begin{cases} \left[1+1.464\left(a/c\right)^{1.65}\right]^{1/2} & \left(0 \le a/2c \le 0.5\right) \\ \left[1+1.464\left(c/a\right)^{1.65}\right]^{1/2} & \left(0.5 < a/2c \le 1\right) \end{cases}$$

$$F_e\left(\frac{a}{c},\frac{a}{t'},\frac{c}{w},\theta\right) = \left[M_1 + M_2\left(\frac{2a}{t'}\right)^2 + M_3\left(\frac{2a}{t'}\right)^4\right] g f_\theta f_w$$

$$M_1 = \begin{cases} 1 & \left(0 \le a/2c \le 0.5\right) \\ \sqrt{c/a} & \left(0.5 \le a/2c \le 1\right) \end{cases}$$

$$M_2 = \frac{0.05}{0.11+\left(a/c\right)^{3/2}}$$

$$M_3 = \frac{0.29}{0.23+\left(a/c\right)^{3/2}}$$

$$g = 1 - \left[\frac{\left(2a/t'\right)^4\left\{2.6-\left(4a/t'\right)\right\}^{0.5}}{1+4\left(a/c\right)}\right]\left|\cos\theta\right|$$

$$f_\theta = \begin{cases} \left[\left(a/c\right)^2\cos^2\theta + \sin^2\theta\right]^{1/4} & \left(0 \le a/2c \le 0.5\right) \\ \left[\left(c/a\right)^2\sin^2\theta + \cos^2\theta\right]^{1/4} & \left(0.5 < a/2c \le 1\right) \end{cases} \qquad \theta = \begin{cases} 0 & \text{at the crack length tip} \\ \pi/2 & \text{at the crack depth tip} \end{cases}$$

$$f_w = \left[\sec\left(\frac{\pi c}{w}\sqrt{\frac{2a}{t'}}\right)\right]^{1/2}$$

t' : Equivalent thickness, in m.

1.2 Stress Intensity Factor for Surface Crack at Weld Toe

The crack stress intensity factor *K* for surface crack at weld toe shall be calculated by the following formula:

$$K = \left(M_K^T\sigma_m + M_K^B H\sigma_b\right)\frac{\sqrt{\pi a}}{\Phi}F\left(\frac{a}{c},\frac{a}{t},\frac{c}{w},\theta\right) \quad \text{MPa}\sqrt{\text{m}}$$

where:

$$\Phi = \left[1.0 + 1.464 \left(\frac{a}{c} \right)^{1.65} \right]^{1/2}$$

$$F(\frac{a}{c}, \frac{a}{t}, \frac{c}{w}, \theta) = \left[M_1 + M_2 \left(\frac{a}{t} \right)^2 + M_3 \left(\frac{a}{t} \right)^4 \right] g f_\theta f_w$$

$$M_1 = 1.13 - 0.09(a / c)$$

$$M_2 = -0.54 + 0.89 / (0.2 + a / c)$$

$$M_3 = 0.5 - 1 / (0.65 + a / c) + 14(1 - a / c)^{24}$$

$$f_\theta = \left[\sin^2 \theta + (a / c)^2 \cos^2 \theta \right]^{1/4}$$

$$g = 1 + \left[0.1 + 0.35 \left(a / t \right)^2 \right] \left(1 - \sin \varphi \right)^2$$

$$f_w = \left[\sec \left(\frac{\pi}{2} \frac{2c}{W} \sqrt{\frac{a}{t}} \right) \right]^{1/2}$$

$$H = H_1 + (H_2 - H_1) \sin^p \theta$$

$$H_1 = 1 - 0.34(a / t) - 0.11(a / c)(a / t)$$

$$H_2 = 1 + G_1 (a / t) + G_2 (a / t)^2$$

$$G_1 = -1.22 - 0.12 \left(a / c \right)$$

$$G_2 = 0.55 - 1.05 \left(a / c \right)^{0.75} + 0.47 \left(a / c \right)^{1.5}$$

$$p = 0.2 + a / c + 0.6(a / t)$$

σ_m : Nominal membrane stress, in N/mm^2;

M_K^T :Stress intensity magnification factor of welded structure under tensile stress;

M_K^B :Stress intensity magnification factor of welded structure under bending stress;