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GUIDELINES FOR FATIGUE STRENGTH OF SHIP STRUCTURE

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Beijing

Brief Explanation

According to the requirements of new edition research project task of Guidelines for Fatigue Strength of Ship Structure provided by CCS (RSR12-06), the project team of Shanghai Rules & Research Institute carries out systematic application research on assessment technology of fatigue strength of ship structure, and develops edition of CCS Guidelines for Fatigue Strength of Ship Structure.

During research, we rely on technical system of current Rules for Classification of Sea-going Steel Ships and Rules for Construction of Sea-going Ships Engaged on Domestic Voyages as well as requirements for fatigue assessment, fully absorb internationally advanced hull structure fatigue strength assessment concept and method, and combine engineering application experience of 2001 and 2007 CCS Guidelines for Fatigue Strength of Ship Structure. For fatigue strength assessment of pump tower, we introduce research results of subitem "pump tower structure strength assessment and design" in Rules for Large LNG Carrier and Key Technical Research, and keep requirements for hull structural details of bulk carrier, oil tanker and container ships in the current guidelines that provide technical guidance for designer.

New Guidelines has following characteristics:

1 It adopts a load system that has more clear physical meaning and is based on equivalent design wave;

2 It adopts hot spot stress to assess fatigue strength, which improves rationality of selection of S-N curve and considers correction of mean stress more exactly;

3 It adopts corrosion correction coefficient to consider effect of corrosion on fatigue stress. Construction dimension is adopted for hull structure calculation model, which is in line with CCS current rule system and ensures general application of calculation model;

4 It establishes method for analyzing hot spot stress of complicated structural details based on finite element method, provides detailed hot spot stress selecting method, solves operational problems and satisfies rules' requirements for fatigue strength assessment to critical details;

5 It adds method for fatigue strength assessment to membrane tank LG carriers and their pump towers.

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CHAPTER 1 GENERAL

1.1 General provisions

1.1.1 The Guidelines applies to strength assessment of hull structure in cargo hold areas of sea-going steel ships, including the following ship types:

(1) non-CSR bulk carriers of 150 m and over in length;

(2) non-CSR oil tankers of 150 m and over in length;

(3) container ships of 150 m and over in length;

(4) membrane tank LNG carriers (hereinafter referred to as "LNG carriers") and their pump towers.

1.1.2 For other ships, the fatigue strength of the hull structure may be assessed in accordance with the Guidelines.

1.1.3 For ships carrying out fatigue strength assessment in accordance with the requirements of the Guidelines, their structural design, construction workmanship and quality are to comply with the requirements of CCS Rules for Classification of Sea-going Steel Ships, Rules for Construction of Sea-going Ships Engaged on Domestic Voyages and other relevant standards accepted by CCS.

1.2 Symbols

1.2.1 **Length of ship *L*** (in m) is the distance on the summer load waterline from the forward side of the stem to the after side of the rudder post, or to the center of the rudder stock if there is no rudder post. *L* is not to be less than 96%, and need not be greater than 97%, of the extreme length on the summer load waterline.

For pontoon hulls, *L* is the distance on the summer load waterline from the forward side of the fore end plate to the after side of the after end plate.

For ships without rudder stocks (such as ships provided with azimuth thrusters), *L* is 97% of the extreme length on the summer load waterline.

1.2.2 **Breadth of ship *B*** (in m) is the horizontal distance measured over the main frames at the widest part of the ship.

1.2.3 **Moulded depth *D*** (in m) is the vertical distance measured at the middle of the length *L* from top of keel to top of the deck beam at side on the uppermost continuous deck. When a rounded gunwale is arranged, the moulded depth is to be measured to the point of intersection of the continued moulded lines of the deck and side shell plating.

1.2.4 **Draught *d*** (in m) is the vertical distance measured at the middle of the length *L* from top of keel to the summer load waterline.

1.2.5 **Draught d_{LC}** (in m) is the vertical distance measured at the middle of the length *L* from top of keel to the waterline in corresponding loading condition.

1.2.6 **Block coefficient C_b** is to be determined by the following formula:

$$C_b = \frac{\nabla}{LBd}$$

where: ∇—moulded displacement in m^3 at draught corresponding to summer load waterline;

L—length of ship, in m;

B—breadth of ship, in m;

d—draught, in m.

1.2.7 **Maximum service speed *V*** means the greatest speed which the ship is designed to maintain in service at her deepest seagoing draught at the maximum propeller RPM and corresponding engine MCR (Maximum Continuous Rating).

1.2.8 Main stress and azimuth

(1) Main stresses σ_1 and σ_2 are to be determined by the following formula:

$$\sigma_1 = \frac{\sigma_x + \sigma_y}{2} + \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2} \qquad \text{N/mm}^2$$

$$\sigma_2 = \frac{\sigma_x + \sigma_y}{2} - \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2} \qquad \text{N/mm}^2$$

where: σ_x, σ_y——normal stress, in N/mm^2;

τ_{xy}——shearing stress, in N/mm^2.

(2) The included angle of main stress σ_1 and σ_2 is 90^o, and the included angle of main stress σ_1 and *X* axis is to be determined by the following formula:

$$\theta = \arctan\left(\frac{\sigma_1 - \sigma_x}{\tau_{xy}}\right) \qquad \text{rad}$$

where: σ_x, σ_1 and τ_{xy} — see (1) above.

1.2.9 Coordinate system and stress symbols

(1) Geometrical dimensions of ship are determined according to following right hand coordinate system (see Figure 1.2.9 of this Chapter):

Origin: At the intersection among the longitudinal plane of symmetry of ship, the aft end of *L* and the baseline.

X axis: longitudinal axis, positive forward.

Y axis: transverse axis, positive towards portside.

Z axis: vertical axis, positive upwards.

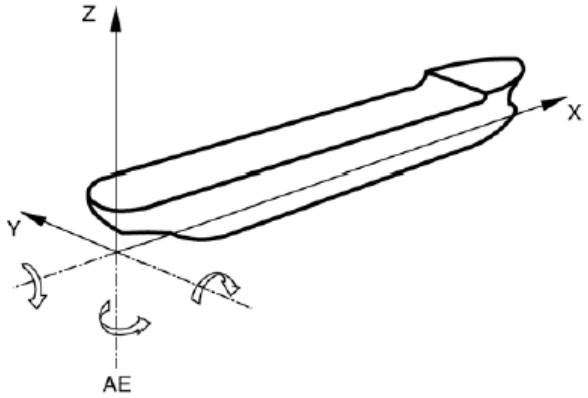


Figure 1.2.9 Reference coordinate system

(2) Definitions of positive and negative symbols of hull motion and acceleration:

Positive surge is translation in the *X*-axis direction;

Positive sway is translation in the *Y*-axis direction;

Positive heave is translation in the *Z*-axis direction;

Positive roll motion is positive rotation about *X*-axis by the right-hand rule;

Positive pitch motion is positive rotation about *Y*-axis by the right-hand rule;

Positive yaw motion is positive rotation about *Z*-axis by the right-hand rule;
Longitudinal linear acceleration of any point on the ship is positive in the *X*-axis direction;
Transverse linear acceleration of any point on the ship is positive in the *Y*-axis direction;
Vertical linear acceleration of any point on the ship is positive in the *Z*-axis direction.
(3) Definitions of stress symbols: positive for tensile stress and negative for compressive stress.

1.3 Definitions of fatigue assessment terms

1.3.1 Hot spots are locations in the structure where fatigue cracks may initiate, generally located at weld toe, weld root of partial penetration or fillet weld and free edge of plate.

1.3.2 Nominal stress σ_n (in N/mm^2) is the stress in a structural component taking into account macro-geometric effect but disregarding the stress concentration due to structural discontinuities and the presence of welds. Nominal stress may be obtained by using fine mesh FE analysis or beam theory.

1.3.3 Hot spot stress σ_h (in N/mm^2) is the stress at the hot spot taking into account the stress concentration due to structural discontinuities and presence of welded attachments but disregarding the non-linear stress peak caused by the notch at the weld toe. The hot spot stress may be obtained by multiplying the nominal stress by a Stress Concentration Factor (SCF), or directly by a very fine mesh FE analysis.

1.3.4 Stress concentration factor K_g is the ratio of hot spot stress to nominal stress, which is to be determined by the following formula:

$$K_g = \frac{\sigma_h}{\sigma_n}$$

where: σ_h—hot spot stress, in N/mm^2;
σ_n—nominal stress, in N/mm^2.

1.3.5 Hot spot stress range S_h (in N/mm^2) is stress range resulted from alternating hot spot stress of structure fatigue, which is to be determined by the following formula:

$$S_h = \left|\sigma_{\max} - \sigma_{\min}\right| \quad \text{N/mm}^2$$

where: $\sigma_{\max}$—maximum value of hot spot stress circulation, in N/mm^2;
$\sigma_{\min}$—minimum value of hot spot stress circulation, in N/mm^2.

1.3.6 Mean hot spot stress σ_m (in N/mm^2) is mean value resulted from alternating hot spot stress of structure fatigue, which is to be determined by the following formula:

$$\sigma_m = (\sigma_{\max} + \sigma_{\min})/2 \quad \text{N/mm}^2$$

where: $\sigma_{\max}$—maximum value of hot spot stress circulation, in N/mm^2;
$\sigma_{\min}$—minimum value of hot spot stress circulation, in N/mm^2.

1.3.7 Design stress range S_D (in N/mm^2) is the stress range for fatigue assessment and obtained by correction of plate thickness and correction of mean hot spot stress for hot spot stress range.

1.3.8 Critical locations are defined as the specific locations that can be prone to fatigue damage for which design improvements are provided, which are within the area by reason of stress concentration, alignment, discontinuity and corrosion will have a higher probability of failure during the life of the ship than the surrounding structures.

1.4 Fatigue damage and failure mode

1.4.1 When ships navigate at sea, the ship structures are always affected by wave forces and inertial forces resulted from ships' movements. Because both wave forces and inertial forces are continuously variable dynamic loads, they produce alternating stresses in the interior of ship structures, rending fatigue damages on ship structures.

1.4.2 Fatigue damages are one of the main damages to the ship structures. Especially for large ships and those of high tensile steel the fatigue problems are outstanding.

1.4.3 The aim of the fatigue control is to ensure that all parts of the hull structure subjected to fatigue (dynamic) loading have adequate fatigue life. Calculated fatigue lives, calibrated with the relevant fatigue damage data, may give the basis for the structural design (steel selection, scantlings and local details). Furthermore, they can form the basis for efficient inspection programs during fabrication and throughout the service life of the structure.

1.4.4 There are mainly four fatigue cracking failure modes:

(1) Fatigue crack growth from the weld toe into the base material (see Figure 1.4.4(1) of this Chapter):

In welded structures, fatigue cracking from weld toes into the base material is a frequent failure mode. The fatigue crack is initiated at small defects or undercuts at the weld toe.

In order to prevent such failure mode, the Guidelines provides method for fatigue assessment of structural welded details.

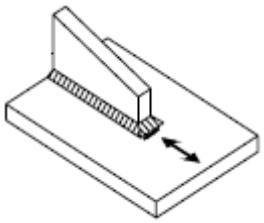


Figure 1.4.4(1)

(2) Fatigue crack growth from the weld root through the fillet weld (see Figure 1.4.4(2) of this Chapter):

Fatigue cracking from root of fillet welds with crack growth through the weld is a failure mode that can lead to significant consequences.

In order to prevent such failure mode, the Appendix of the Guidelines provides welding requirements for structural welded details at critical locations.

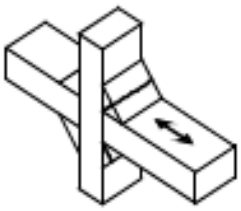


Figure 1.4.4(2)

(3) Fatigue crack growth from the weld root into the section under the weld (see Figure 1.4.4(3) of this Chapter):

Fatigue crack growth from the weld root into the section under the weld is observed during service life of structures and is also observed in laboratory fatigue testing. To avoid such failure mode, full penetration welds may be used at some critical locations where such type of cracks is liable to

occur.

In order to prevent such failure mode, the Appendix of the Guidelines provides welding requirements for structural welded details at critical locations.

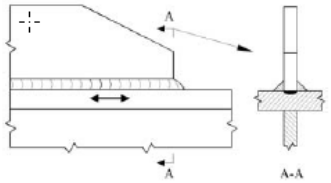


Figure 1.4.4(3)

(4) Fatigue crack growth from a free edge of non-welded details (see Figure 1.4.4(4) of this Chapter):

Fatigue cracking in the base material is a failure mode that is of concern in components with high stress cycles. Then the fatigue cracks often initiate from notches or grooves in the components or from small surface defects/irregularities.

In order to prevent such failure mode, the Guidelines provides method for fatigue assessment of non-welded structural details.

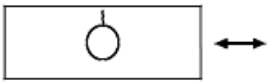


Figure 1.4.4(4)

1.5 Fatigue assessment method

1.5.1 Fatigue assessment is based upon linear cumulative damage model (Palmgren-Miner rule). Cumulative damage D is to be obtained by the following formula:

$$D = N_T \int_0^\infty \frac{f(S)}{N(S)} dS$$

where: N_T—stress total circulation cycles for structure in its design service life;

S—design stress ranges;

$f(S)$—probability density factor of long-term distribution of design stress range;

$N(S)$—number of cycles when failure of structure fatigue corresponding to design stress range S.

1.5.2 Fatigue assessment of ship structure may be carried out by means of simplified and spectrum analysis. Fatigue assessment methods in the Guidelines are based on simplified analysis.

1.5.3 The simplified fatigue analysis methods are mainly composed of following steps:

(1) fatigue load calculations;

(2) calculations of hot spot stress range;

(3) selection of design S-N curve;

(4) calculations and criteria for cumulative damage.

The flow of fatigue strength assessment of hull structure carried out by applying the Guidelines is shown in Figure 1.5.3 of this Chapter.

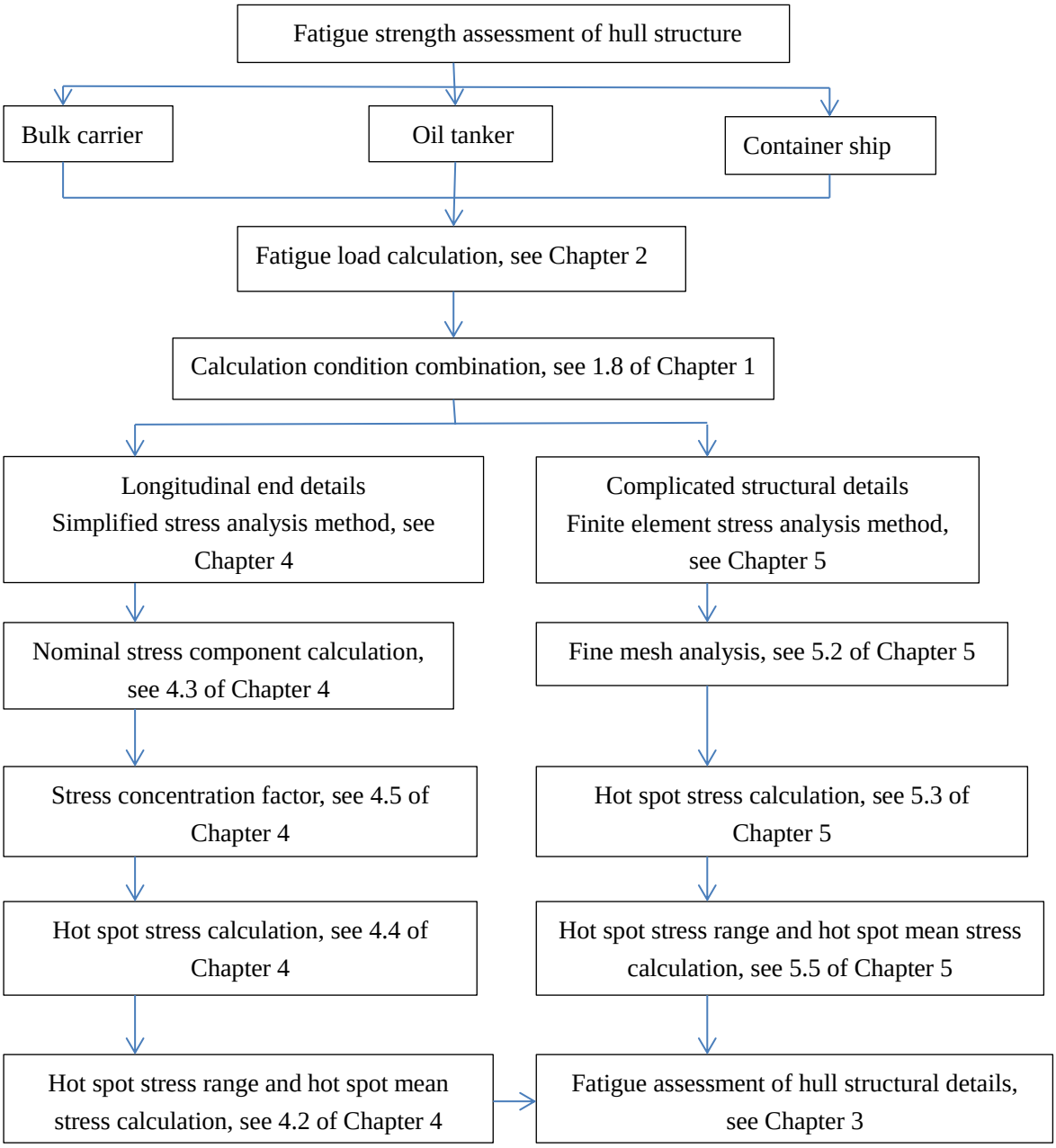


Figure 1.5.3

1.5.4 S-N curves are the basic S-N curves (see Figure 1.5.4 of this Chapter) for non-tubular joints consisting of eight curves (curves B, C, D, E, F, F_2, G and W and each shows a kind of relationship of structural details bearing alternating stress range values and the number of stress cycles), as amended by U.K. Department of Energy. Such curves are applicable to steel material of minimum yield stress less than 400 N/mm^2, and the corresponding survival probability is 97.6%.

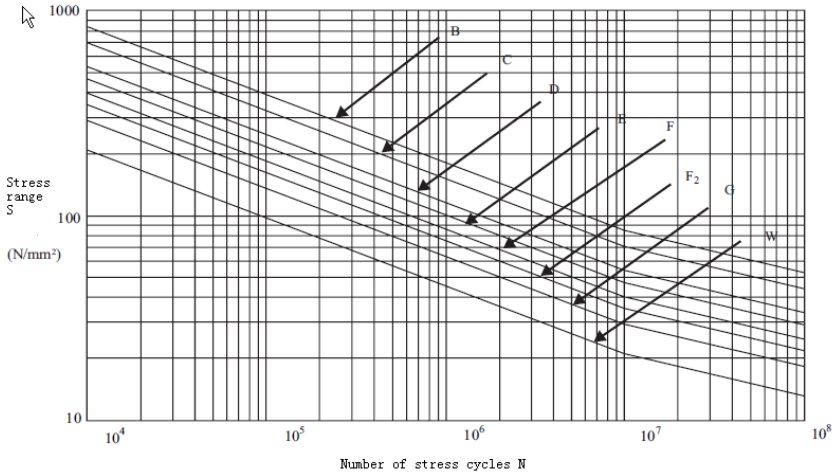


Figure 1.5.4

1.6 Corrosion correction

1.6.1 For fatigue assessment, the effect of normal corrosion wear of hull structure is to be considered. In the Guidelines, as-built scantlings are adopted for stress calculation, but hot spot stress is to be calculated by multiplying the corrosion correction factors as required below:

(1) For hull girder bending normal stress during simplified stress analysis and hot spot stress under global load case during finite element stress analysis, corrosion correction factor f_{ch} = 1.05;

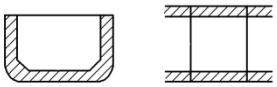
(2) For bending normal stress under lateral load during simplified stress analysis and hot spot stress under local load case during finite element stress analysis, corrosion correction factor f_{cl} = 1.1.

1.7 Loading conditions for fatigue assessment

1.7.1 Wave loads on the hull vary with draught and load distribution, and therefore, more than one loading condition need to be considered for fatigue assessment. Determination of loading condition relies on ship type, and two to three common loading and ballast conditions are usually selected as loading conditions for fatigue assessment.

1.7.2 Loading conditions for fatigue assessment of oil tanker are homogeneous full load condition and normal ballast condition. For details, see Table 1.7.2 of this Chapter.

Table 1.7.2

Loading conditions for fatigue assessment	Loading mode	Draught	Still water bending moment correction coefficient C_{SW}	Time distribution factor a
Homogeneous full load		Full load draught	0.6 (sagging)	0.425
Normal ballast		Ballast draught	0.8 (hogging)	0.425

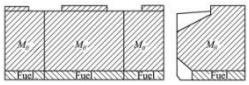
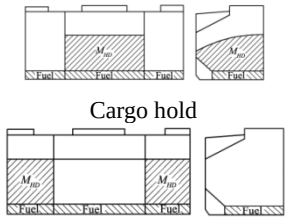
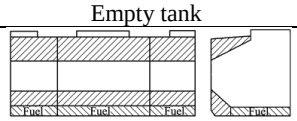
1.7.3 Loading conditions for fatigue assessment of bulk carrier are homogeneous full load condition, alternate full load condition and normal ballast condition. For details, see Table 1.7.3 of this Chapter. Definitions of relevant parameters are as follows:

M_H is actual cargo mass in a cargo hold at draught d and under homogeneous loading condition (All cargo holds are loaded with same loading ratio, and all ballast tanks are empty tanks);

M_{HD} is maximum allowable cargo mass in a cargo hold at draught d and under alternate loading condition (All cargo holds have same cargo density and loading ratio, and all ballast tanks are empty tanks);

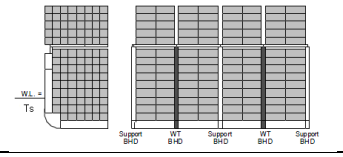
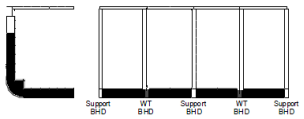
V_{FULL} is volume of cargo hold, including volume enclosed by hatch coaming of cargo hold.

Table 1.7.3

Loading conditions for fatigue assessment	Loading mode	Draught	Still water bending moment correction coefficient C_{SW}	Cargo mass of cargo hold M, in t	Density of dry bulk cargo ρ_C, in t/m^3	Time distribution factor a	
						Not alternate loading	Alternate loading
Homogenous full load		Full load draught	0.4 (sagging)	M_H	$\frac{M_H}{V_{FULL}}$	0.5	0.25
Alternate full load	 Cargo hold Empty tank	Full load draught	0.75 (hogging)	M_{HD}	Maximum cargo density allowed by design, 3.0 if not specified	--	0.25
Normal ballast		Ballast draught	0.8 (hogging)	--	--	0.35	0.35

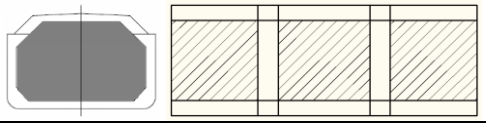
1.7.4 Loading conditions for fatigue assessment of container ship are full load condition and normal ballast condition. For details, see Table 1.7.4 of this Chapter.

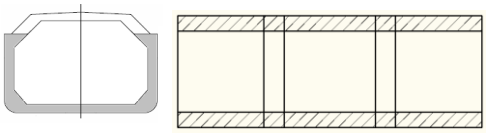
Table 1.7.4

Loading conditions for fatigue assessment	Loading mode	Draught	Still water bending moment correction coefficient C_{SW}	Time distribution factor a
Full load		Full load draught	0.9 (hogging)	0.65
Normal ballast		Ballast draught	0.8 (hogging)	0.2

1.7.5 Loading conditions for fatigue assessment of LNG carrier are homogeneous full load condition and normal ballast condition. For details, see Table 1.7.5 of this Chapter.

Table 1.7.5

Loading conditions for fatigue assessment	Loading mode	Draught	Still water bending moment correction coefficient C_{SW}	Time distribution factor a
Homogeneous full load		Full load draught	0.7 (sagging)	0.45

Normal ballast		Ballast draught	0.8 (hogging)	0.4

1.8 Calculation conditions

1.8.1 Calculation conditions are the combination of loading conditions for fatigue assessment and corresponding load cases.

1.8.2 For each loading condition for fatigue assessment, all fatigue load cases for fatigue assessment which lead to dynamic load combination are to be taken into account.

1.8.3 The predominant load case for each loading condition for fatigue assessment is defined as load case where the design stress range for the hot spot is the maximum among all load cases.

CHAPTER 2 FATIGUE LOAD

2.1 General requirements

2.1.1 This Chapter specifies loads applicable to fatigue assessment of hull structure.

2.1.2 Loads given in this Chapter include hull girder loads in still water and wave as well as lateral loads of plate.

2.1.3 Hull girder loads in still water include vertical still water bending moment, and hull girder loads in wave include vertical wave bending moment and horizontal wave bending moment.

2.1.4 Lateral loads in still water include external hydrostatic pressure and internal hydrostatic pressure induced by cargo and ballast water. Lateral loads in wave include external hydrodynamic pressure and internal inertia pressure induced by cargo and ballast water.

2.1.5 Design loads are determined by means of equivalent design wave concept, and a set of load combination factors is given for each equivalent design wave. Lateral loads in wave and hull girder loads in wave need to be combined according to load combination factors.

2.2 Parameter definitions

2.2.1 Service coefficient f_r in this Chapter is defined as follows:

f_r =1.00 for unrestricted service/open sea service;

f_r =0.90 for service category 1/greater coastal service;

f_r =0.85 for service category 2/coastal service;

f_r =0.80 for service category 3/sheltered service.

2.2.2 Probability level coefficient f_p in this Chapter is defined as follows:

$$f_P = 0.25^{\frac{1}{\xi_1}}$$

where: ξ_1 —parameter to be selected according to different load type and Table 2.2.2 of this Chapter.

Parameter ξ_1 **Table 2.2.2**

Ship motion and acceleration	$\xi_1 = 1.50 - 0.036\sqrt{L}$
Hull girder loads in wave	$\xi_1 = 1.45 - 0.036\sqrt{L}$
External hydrodynamic pressure	$\xi_1 = 1.45 - 0.036 f\sqrt{L}$

where: L—length of ship, in m;

f—factor to be calculated in accordance with the following formulae respectively:

$$f = 1 - \frac{0.08z}{d_{LCi}} \quad \text{for } z \le d_{LCi};$$

$$f = 0.92 + \frac{0.08(z - d_{LCi})}{D - d_{LCi}} \quad \text{for } z > d_{LCi}$$

where: z—Z coordinate of calculated point, in m;

d_{LCi}—draught at hull transverse section considered in corresponding loading condition, to be taken as draught at midpoint of model length in corresponding loading condition during finite element stress analysis, in m;

D—moulded depth, in m.

2.2.3 Wave coefficient C is to be calculated in accordance with the following formulae respectively:

$$C = 10.75 - \left[\frac{(300 - L)}{100}\right]^{1.5} \qquad \text{for} \quad 90\ \text{m} \le L \le 300\ \text{m}$$

$$C = 10.75 \qquad \text{for } 300\ \text{m} < L < 350\ \text{m}$$

$$C = 10.75 - \left[\frac{(L - 350)}{150}\right]^{1.5} \qquad \text{for } 350\ \text{m} \le L \le 500\ \text{m}$$

where: L—length of ship, in m.

2.3 Ship motions and accelerations

2.3.1 Ship's single degree of freedom motion is to be calculated in accordance with the following requirements:

(1) For oil tanker, LNG carrier and bulk carrier, roll encounter period T_E is to be calculated in accordance with the following formula:

$$T_E = \frac{2.3k_r}{\sqrt{GM}} \qquad \text{s}$$

where: k_r—roll radius of gyration in the loading condition considered, in m, which may be assumed according to Table 2.3.1(1) of this Chapter if no specific values available;

GM—initial metacentric height in the loading condition considered, which may be assumed according to Table 2.3.1(1) of this Chapter if no specific values available.

k_r and GM for oil tanker, LNG carrier and bulk carrier **Table 2.3.1(1)**

Loading conditions for fatigue assessment	k_r	GM
Full load condition (alternate or homogeneous loading)	0.35B	0.12B
Normal ballast condition	0.45B	0.33B

(2) For container ship, roll encounter period T_E is to be calculated in accordance with the following formula:

$$T_E = 0.5\left(T_R + \sqrt{T_R^2 - \frac{2\pi}{g}VT_R}\right) \quad \text{for} \quad T_R > \frac{2\pi}{g}V$$

$$T_E = T_R \qquad \text{for} \quad T_R \le \frac{2\pi}{g}V$$

where: T_R—roll period, in s, to be calculated according to the following formula:

$$T_R = \frac{2.2k_r}{\sqrt{GM}}$$

where: k_r—roll radius of gyration in the loading condition considered, in m, which may be assumed according to Table 2.3.1(2) of this Chapter if no specific values available;

GM—initial metacentric height in the loading condition considered, which may be assumed according to Table 2.3.1(2) of this Chapter if no specific values available;

V—maximum service speed, in Kn.

k_r and GM for container ship **Table 2.3.1(2)**

Loading conditions for fatigue assessment	k_r	GM
Full load condition	0.35B	0.07B
Normal ballast condition	0.45B	0.20B

(3) The maximum roll angle θ is to be calculated as follows, but need not be greater than 0.523 f_p rad:

$$\theta = \frac{(62.5 - 1.25T_E) f_r f_P k_b}{B + 75} \quad \text{rad}$$

where: f_r — service coefficient, see 2.2.1 of this Chapter;

f_P —probability level coefficient, see 2.2.2 of this Chapter;

k_b — coefficient, to be taken as follows:

k_b =1.2 for ships without bilge keel;

k_b =1.0 for ships with bilge keel;

k_b = 0.8 for ships with activated stabilizers;

B — breadth of ship, in m.

(4) Pitch period T_P and maximum pitch angle Φ are to be calculated as follows, and maximum pitch angle Φ need not be greater than 0.14 f_P rad:

$$T_P = 1.80\sqrt{L/10} \quad \text{s}$$

$$\Phi = 0.25 a_0 / C_b \quad \text{rad}$$

where: L — length of ship, in m;

C_b — block coefficient;

a_0 — acceleration factor, to be calculated as follows:

$$a_0 = f_r f_P \left(3\frac{C}{L} + C_V \frac{V}{\sqrt{L}}\right)$$

where: f_r — service coefficient, see 2.2.1 of this Chapter;

f_p — probability level coefficient, see 2.2.2 of this Chapter;

$C_V = \sqrt{L}/50$, not to be greater than 0.2;

L — length of ship, in m;

V — maximum service speed, in kn;

C — wave coefficient, see 2.2.3 of this Chapter.

2.3.2 Ship motion accelerations are to be calculated according to the following requirements:

(1) Roll acceleration a_{roll} is to be calculated as follows:

$$a_{roll} = \theta\left(\frac{2\pi}{T_E}\right)^2 \quad \text{rad/s}^2$$

where: θ —maximum roll angle, in rad, see 2.3.1(3) of this Chapter;

T_E —roll encounter period, in s, see 2.3.1(1) or 2.3.1(2) of this Chapter.

(2) Pitch acceleration is to be calculated as follows:

$$a_{pitch} = \Phi(\frac{2\pi}{T_P})^2 \qquad \text{rad/s}^2$$

where: Φ —maximum pitch angle, in rad, see 2.3.1(4) of this Chapter;

T_P —pitch period, in s, see 2.3.1(4) of this Chapter.

(3) Vertical acceleration a_{heave} due to heave is to be calculated as follows:

$$a_{heave} = 7a_0 / \sqrt{C_b} \qquad \text{m/s}^2$$

where: a_0 —acceleration coefficient, to be calculated according to 2.3.1(4) of this Chapter;

C_b — block coefficient.

(4) Transverse acceleration a_{sway} due to sway is to be calculated as follows:

$$a_{sway} = 3a_0 \qquad \text{m/s}^2$$

where: a_0 —acceleration coefficient, to be calculated according to 2.3.1(4) of this Chapter.

(5) Longitudinal acceleration a_{surge} due to surge is to be calculated as follows:

$$a_{surge} = 2a_0\sqrt{C_b} \qquad \text{m/s}^2$$

where: a_0 —acceleration coefficient, to be calculated according to 2.3.1(4) of this Chapter;

C_b — block coefficient.

2.3.3 Reference values of longitudinal, transverse and vertical accelerations of any point on the ship are to be calculated as follows:

(1) Longitudinal:

$$a_X = -C_{XG}g\sin\Phi + C_{XS}a_{surge} + C_{XP}a_{pitch-x} \qquad \text{m/s}^2$$

(2) Transverse:

$$a_Y = C_{YG}g\sin\theta + C_{YS}a_{sway} - C_{YR}a_{roll-y} \qquad \text{m/s}^2$$

(3) Vertical:

$$a_Z = C_{ZH}a_{heave} + C_{ZR}a_{roll-z} - C_{ZP}a_{pitch-z} \qquad \text{m/s}^2$$

where: $C_{XG}, C_{XS}, C_{XP}, C_{YG}, C_{YS}, C_{YR}, C_{ZH}, C_{ZR}, C_{ZP}$ —load combination factors defined by 2.5.3 of this Chapter;

a_{heave}, a_{sway} and a_{surge}—see 2.3.2 of this Chapter;

Φ —maximum pitch angle, in rad, see 2.3.1(4) of this Chapter;

θ —maximum roll angle, in rad, see 2.3.1(3) of this Chapter;

$a_{pitch-x}$ —longitudinal acceleration due to pitch, in m/s^2, to be calculated as follows:

$$a_{pitch-x} = a_{pitch} R \qquad \text{m/s}^2$$

a_{roll-y} —transverse acceleration due to roll, in m/s^2, to be calculated as follows:

$$a_{roll-y} = a_{roll} R \qquad \text{m/s}^2$$

a_{roll-z} —vertical acceleration due to roll, in m/s^2, to be calculated as follows:

$$a_{roll-z} = a_{roll} y \qquad \text{m/s}^2$$

$a_{pitch-z}$ —vertical acceleration due to pitch, in m/s^2, to be calculated as follows:

$$a_{pitch-z} = a_{pitch}(x - 0.45L) \qquad \text{m/s}^2$$

where: a_{roll}, a_{pitch} —see 2.3.2 of this Chapter;

$$R = z - \min(\frac{D}{4} + \frac{d_{LC}}{2}, \frac{D}{2});$$

d_{LC} —draught amidships in corresponding loading condition, in m;

D—moulded depth, in m;

L — length of ship, in m;

x, y, z —longitudinal, transverse and vertical coordinate of calculated point, in m.

2.4 Hull girder loads

2.4.1 Wave vertical bending moment and wave horizontal bending moment in this paragraph are absolute values. The symbols of wave bending moment are to be considered after combination of load combination factors in Table 2.5.3 of this Chapter. The symbol conventions for still water vertical bending moment, wave vertical bending moment and horizontal bending moment at any transverse section of the ship are shown in Figure 2.4.1 of this Chapter.

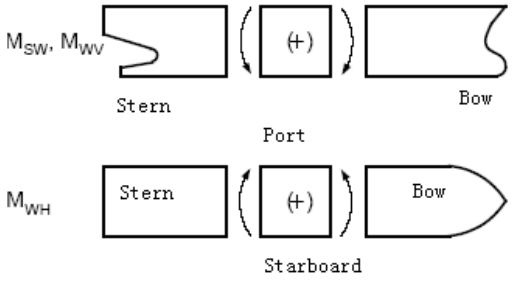


Figure 2.4.1 Symbol conventions for bending moment M_{SW}, M_{WV} and M_{WH}

2.4.2 Hull girder still water bending moment M_{SW} for fatigue analysis is to be calculated in accordance with the following formula:

$$M_{SW} = C_{SW}\overline{M}_S \qquad \text{kN m}$$

where: C_{SW}—correction coefficient of still water bending moment in corresponding loading condition, see 1.7 of Chapter 1;

$\overline{M}_S$—allowable bending moment for hull girder hogging or sagging, in kN m.

2.4.3 Vertical wave bending moment at any transverse section of the hull is to be calculated in accordance with the following formula:

(1) Hogging:

$$M_{WV,H} = 190F_M f_r f_P CL^2 BC_b 10^{-3} \qquad \text{kN m}$$

(2) Sagging:

$$M_{WV,S} = 110F_M f_r f_P CL^2 B(C_b + 0.7)10^{-3} \qquad \text{kN m}$$

where: F_M—distribution factor defined in Table 2.4.3 of this Chapter;

f_r—service coefficient, see 2.2.1 of this Chapter;

f_P—probability level coefficient, see 2.2.2 of this Chapter;

C—wave coefficient, see 2.2.3 of this Chapter;

L—length of ship, in m;

B—breadth of ship, in m;

C_b—block coefficient.

Distribution factor F_M **Table 2.4.3**

Hull section position	**Distribution factor F_M**
$0 \le x < 0.4L$	$2.5\frac{x}{L}$
$0.4L \le x \le 0.65L$	1.0
$0.65L < x \le L$	$2.86(1-\frac{x}{L})$

2.4.4 Horizontal wave bending moment at any transverse section of the hull is to be calculated in accordance with the following formula:

$$M_{WH} = (0.3+\frac{L}{2000})F_M f_r f_P CL^2 d_{LC} C_b \qquad \text{kN m}$$

where: F_M—distribution factor, see 2.4.3 of this Chapter;

f_r—service coefficient, see 2.2.1 of this Chapter;

f_P—probability level coefficient, see 2.2.2 of this Chapter;

C—wave coefficient, see 2.2.3 of this Chapter;

L—length of ship, in m;

B—breadth of ship, in m;

d_{LC}—draught amidships in corresponding loading condition, in m;

C_b—block coefficient.

2.5 Load cases

2.5.1 Load cases are composed of the following regular waves:

(1) regular waves when the vertical wave bending moment becomes maximum in head sea ("H");

(2) regular waves when the vertical wave bending moment becomes maximum in following sea ("F");

(3) regular waves when the roll motion becomes maximum ("R");

(4) regular waves when the hydrodynamic pressure at the waterline becomes maximum ("P").

2.5.2 The load cases corresponding to the equivalent design waves are defined in Table 2.5.2 of this Chapter.

Definitions of load cases **Table 2.5.2**

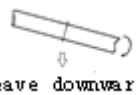
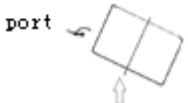
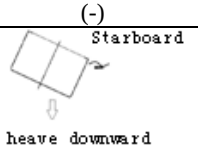
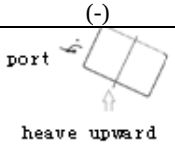
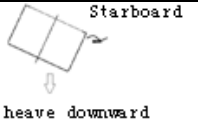
Load cases	H1	H2	F1	F2	R1P	R2P
EDW	"H"		"F"		"R"	
Heading	Head		Follow		Beam	
Weather side	-		-		Port	
Effect	Maximum bending moment		Maximum bending moment		Maximum roll	
	Sagging	Hogging	Sagging	Hogging	(+)	(-)
Motion definition			-	-		

Table 2.5.2(Continued)

Load cases	R1S	R2S	P1P	P2P	P1S	P2S
EDW	"R"		"P"		"P"	
Heading	Beam		Beam		Beam	
Weather side	Starboard		Port		Starboard	
Effect	Maximum roll		Maximum external pressure		Maximum external pressure	
	(-)	(+)	(+)	(-)	(-)	(+)
Motion definition						

2.5.3 The hull girder loads and the acceleration components to be considered in each load case are to be obtained by multiplying the reference value of each component by the relevant load combination factor LCF defined in Table 2.5.3 of this Chapter.

Load combination factor LCF **Table 2.5.3**

	LCF	H1	H2	F1	F2	R1P	R2P

	LCF	H1	H2	F1	F2	R1P	R2P
M_{WV}	C_{WV}	-1	1	$-0.75-0.2\frac{d_{LC}}{d}$	$0.75+0.2\frac{d_{LC}}{d}$	$0.1-0.2\frac{d_{LC}}{d}$	$0.2\frac{d_{LC}}{d}-0.1$
M_{WH}	C_{WH}	0	0	0	0	$1.1-\frac{d_{LC}}{d}$	$\frac{d_{LC}}{d}-1.1$
a_{surge}	C_{XS}	$0.3-0.2\frac{d_{LC}}{d}$	$0.2\frac{d_{LC}}{d}-0.3$	$-0.4\frac{d_{LC}}{d}+0.2$	$0.4\frac{d_{LC}}{d}-0.2$	0	0
a_{pitch_x}	C_{XP}	-0.9	0.9	0.1	-0.1	0	0
$gsin\Phi$	C_{XG}	$0.4\frac{d_{LC}}{d}+0.4$	$-0.4\frac{d_{LC}}{d}-0.4$	-0.15	0.15	0	0
a_{sway}	C_{YS}	0	0	0	0	$0.2-0.2\frac{d_{LC}}{d}$	$0.2\frac{d_{LC}}{d}-0.2$
a_{roll_y}	C_{YR}	0	0	0	0	1	-1
$gsin\theta$	C_{YG}	0	0	0	0	-1	1
a_{heave}	C_{ZH}	$0.8\frac{d_{LC}}{d}$ -0.15	$0.15-0.8\frac{d_{LC}}{d}$	0	0	c_{ZHR}	$-c_{ZHR}$
a_{roll_z}	C_{ZR}	0	0	0	0	1	-1
a_{pitch_z}	C_{ZP}	-0.9	0.9	0.1	-0.1	0	0

Table 2.5.3 (Continued)

	LCF	R1S	R2S	P1P	P2P	P1S	P2S
M_{WV}	C_{WV}	$0.1-0.2\frac{d_{LC}}{d}$	$0.2\frac{d_{LC}}{d}-0.1$	$0.3-0.8\frac{d_{LC}}{d}$	$0.8\frac{d_{LC}}{d}-0.3$	$0.3-0.8\frac{d_{LC}}{d}$	$0.8\frac{d_{LC}}{d}-0.3$
M_{WH}	C_{WH}	$\frac{d_{LC}}{d}-1.1$	$1.1-\frac{d_{LC}}{d}$	$0.6-0.6\frac{d_{LC}}{d}$	$0.6\frac{d_{LC}}{d}-0.6$	$0.6\frac{d_{LC}}{d}-0.6$	$0.6-0.6\frac{d_{LC}}{d}$
a_{surge}	C_{XS}	0	0	0	0	0	0
a_{pitch_x}	C_{XP}	0	0	0	0	0	0
$gsin\Phi$	C_{XG}	0	0	0	0	0	0
a_{sway}	C_{YS}	$0.2\frac{d_{LC}}{d}-0.2$	$0.2-0.2\frac{d_{LC}}{d}$	-0.95	0.95	0.95	-0.95
a_{roll_y}	C_{YR}	-1	1	0.3	-0.3	-0.3	0.3
$gsin\theta$	C_{YG}	1	-1	-0.2	0.2	0.2	-0.2
a_{heave}	C_{ZH}	c_{ZHR}	$-c_{ZHR}$	1	-1	1	-1
a_{roll_z}	C_{ZR}	-1	1	0.3	-0.3	-0.3	0.3
a_{pitch_z}	C_{ZP}	0	0	0	0	0	0

where: c_{ZHR} ——coefficient determined by ship type, to be calculated in accordance with the following formulae respectively:

$$c_{ZHR} = 0.7 - 0.4\frac{d_{LC}}{d}$$, for oil tanker, LNG carrier and bulk carrier

$$c_{ZHR} = 0.7 - 0.6\frac{d_{LC}}{d}$$, for container ship

where: L——length of ship, in m;

d_{LC} ——draught amidships in corresponding loading condition, in m;

d ——draught, in m.

2.5.4 The hull girder loads are the sum of vertical hull girder still water load and corresponding hull girder wave load multiplied by load combination factor respectively.

2.5.5 The internal loads are the sum of static pressures or forces induced by the weights carried, including those carried on decks, and of inertial pressures or forces induced by the accelerations

on these weights and calculated with load combination factors.

2.6 External pressure

2.6.1 Total sea water pressure p_{SW} at any point of the shell plating of hull is to be obtained by following formula and not to be negative:

$$p_{SW} = p_S + p_W \qquad \text{kN/m}^2$$

where: p_S —hydrostatic pressure, in kN/m^2 , see 2.6.2 of this Chapter;

p_W —hydrodynamic pressure determined according to load case, in kN/m^2, which is wave pressure equal to hydrodynamic pressure defined in 2.6.3, 2.6.4 or 2.6.5 of this Chapter, and corrected according to 2.6.6 of this Chapter.

2.6.2 For hydrostatic pressure P_S at any point of the shell plating, see Table 2.6.2 of this Chapter.

Hydrostatic pressure p_S **Table 2.6.2**

Location	Hydrostatic pressure p_S, in kN/m^2
Points at and below the waterline（$z \le d_{LCi}$）	$\rho g(d_{LCi} - z)$
Points above the waterline（$z > d_{LCi}$）	0

where: d_{LCi} —draught at hull transverse section considered in corresponding loading condition, to be taken as draught at midpoint of model length in corresponding loading condition for finite element stress analysis, in m;

z—vertical coordinate of load point, in m.

2.6.3 The hydrodynamic pressures P_H and P_F, for load cases H1, H2, F1 and F2, at any point of the shell plating below the waterline are obtained from Table 2.6.3(1) of this Chapter, and the distribution of pressure P_{F2} is schematically given in Figure 2.6.3 of this Chapter.

Hydrodynamic pressures for load cases H1, H2, F1 and F2 **Table 2.6.3(1)**

Load case	Hydrodynamic pressure, in kN/m^2
H1	$p_{H1} = -k_{aH}k_{pH}p_{HF}$
H2	$p_{H2} = k_{aH}k_{pH}p_{HF}$
F1	$p_{F1} = -k_{aF}k_{pF}p_{HF}$
F2	$p_{F2} = k_{aF}k_{pF}p_{HF}$

Note: P_{HF} in the Table is to be calculated according to the following formula:

$p_{HF} = f_h f_r f_P C\sqrt{\frac{L + \lambda - 125}{L}}(\frac{z}{d_{LCi}} + \frac{|2y|}{B_i} + 1)$; with $\frac{2y}{B_i} \le 1.0$ and z is to be taken not greater than d_{LCi}

where: f_h—factor to be calculated according to the following formula:

f_h =1.5 for load cases H1 and H2;

f_h =2.6 for load cases F1 and F2;

k_{aH} —amplitude coefficient in the longitudinal direction of the ship for load cases H1 and H2, to be calculated according to the following formulae:

$$k_{aH} = 1 + \frac{12}{C_b}\left(1 - \sqrt{\frac{|2y|}{B_i}}\right)\left|\frac{x}{L} - 0.5\right|^3 \quad \text{for} \quad 0.0 \le x/L \le 0.5;$$

$$k_{aH} = 1 + \frac{6}{C_b}\left(3 - \frac{|4y|}{B_i}\right)\left|\frac{x}{L} - 0.5\right|^3 \quad \text{for} \quad 0.5 \le x/L \le 1.0;$$

k_{aF} —amplitude coefficient in the longitudinal direction of the ship for load cases F1 and F2, to be calculated according to the following formulae:

$$k_{aF} = 1 + \left(3.5 - 2\frac{d_{LC}}{d}\right)\left(1 - \frac{|2y|}{B_i}\right)\left(1 - 5\frac{x}{L}\right) \quad \text{for} \quad 0.0 \le x/L < 0.2;$$

$$k_{aF} = 1.0 \quad \text{for} \quad 0.2 \le x/L < 0.9;$$

$$k_{aF} = 1 + 15\left(1 - \frac{|2y|}{B_i}\right)\left(\frac{x}{L} - 0.9\right) \quad \text{for} \quad 0.9 \le x/L \le 1.0;$$

k_{pH} —phase coefficient in the longitudinal direction of the ship for load cases H1 and H2, to be taken according to Table 2.6.3(2), and the intermediate values are to be obtained by direct interpolation:

k_{pH} value Table 2.6.3(2)

x/L	k_{pH}
0	$(1.0-\frac{d_{LC}}{d})+(0.5-\frac{d_{LC}}{d})\frac{\|2y\|}{B_i}$
$0.3-0.1\frac{d_{LC}}{d}$	-1.0
$0.5-0.2\frac{d_{LC}}{d}$	1.0
$0.9-0.4\frac{d_{LC}}{d}$	1.0
$0.9-0.2\frac{d_{LC}}{d}$	-1.0
1.0	-1.0

k_{pF} —phase coefficient in the longitudinal direction of the ship for load cases F1 and F2, to be taken according to Table 2.6.3(3), and the intermediate values are to be obtained by direct interpolation:

k_{pF} value **Table 2.6.3(3)**

x / L	k_{pF}
0	-0.75-0.25 $\frac{\lvert 2y \rvert}{B_i}$
0.35-0.1 $\frac{d_{LC}}{d}$	-1.0
0.5-0.2 $\frac{d_{LC}}{d}$	1.0
0.75	1.0
0.9-0.1 $\frac{d_{LC}}{d}$	-1.0
1.0	-0.5-0.5 $\frac{\lvert 2y \rvert}{B_i}$

λ —wave length, in m, to be calculated according to following formulae:

$$\lambda = C_{L1}(1+\frac{d_{LC}}{d})L \quad \text{for load cases H1and H2;}$$

$$\lambda = C_{L1}(1+\frac{2}{3}\frac{d_{LC}}{d})L \quad \text{for load cases F1 and F2;}$$

where: L—length of ship, in m;

f_r—service coefficient, see 2.2.1 of this Chapter;

f_p—probability level coefficient, see 2.2.2 of this Chapter, z is to be taken not greater than d_{LCi} for calculation;

C—wave coefficient, see 2.2.3 of this Chapter;

d_{LCi}—draught at hull transverse section considered in corresponding loading condition, to be taken as draught at midpoint of model length in corresponding loading condition for finite element stress analysis, in m;

B_i—breadth of ship of transverse section considered at waterline, to be taken as breadth of ship at midpoint of model length in corresponding loading condition for finite element stress analysis, in m;

x, y, z—longitudinal, transverse and vertical coordinate of load point respectively, in m;

C_{L1}—coefficient to be calculated according to the following formulae respectively:

C_{L1}=0.6 for oil tanker, LNG carrier and bulk carrier;

C_{L1}=0.5 for container ship;

d_{LC}—draught amidships in corresponding loading condition, in m;

d—draught, in m.

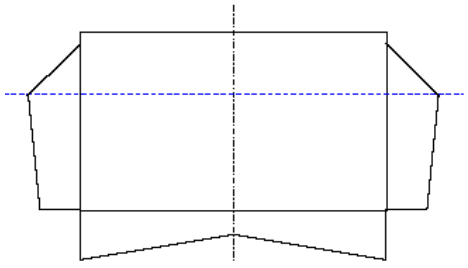


Figure 2.6.3 Distribution of hydrodynamic pressure P_{F2} amidships

2.6.4 Hydrodynamic pressure P_R, for load cases R1P, R2P, R1S and R2S, at any point of the shell plating below the waterline is to be calculated according to Table 2.6.4 of this Chapter, and pressure distribution is schematically given in Figure 2.6.4 of this Chapter.

Hydrodynamic pressure for load cases R1P, R2P, R1S and R2S Table 2.6.4

Load case	Hydrodynamic pressure, in kN/m^2
R1P	$p_{R1P} = p_{RP}$
R2P	$p_{R2P} = -p_{RP}$
R1S	$p_{R1S} = p_{RS}$
R2S	$p_{R2S} = -p_{RS}$

where: $p_{RP} = 10y\sin\theta + 0.88 f_r f_P C\sqrt{\frac{L+\lambda-125}{L}}(\frac{|2y|}{B}+1)$

$$p_{RS} = -10y\sin\theta + 0.88 f_r f_P C\sqrt{\frac{L+\lambda-125}{L}}(\frac{|2y|}{B}+1)$$

where: θ —maximum roll angle, in deg, see 2.3.1(3) of this Chapter;

f_r—service coefficient, see 2.2.1 of this Chapter;

f_p—probability level coefficient, see 2.2.2 of this Chapter;

C — wave coefficient, see 2.2.3 of this Chapter;

λ —wave length, in m, to be calculated according to following formula:

$$\lambda = \frac{g}{2\pi}T_E^2$$

y—transverse coordinate of load point, in m, port is taken as positive value;

B—breadth of ship, in m.

where: T_E—roll encounter period, in s, see 2.3.1 of this Chapter.

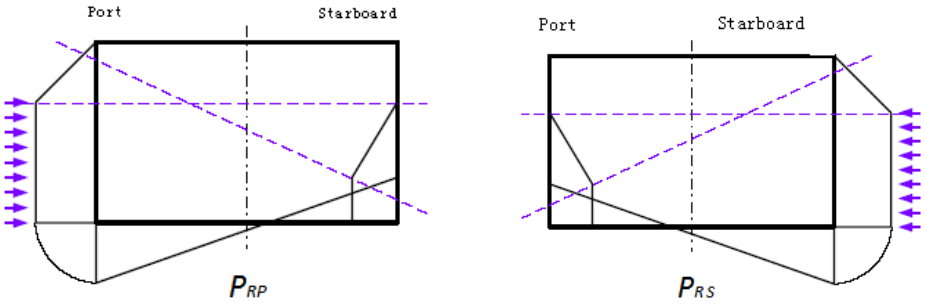


Figure 2.6.4 Distribution of P_{RP} and P_{RS} amidships

2.6.5 Hydrodynamic pressure P_P, for load cases P1P, P2P, P1S and P2S, at any point of the shell plating below the waterline is given in Table 2.6.5 of this Chapter. Distribution of pressure P_{P1} is schematically given in Figure 2.6.5 of this Chapter.

Hydrodynamic pressure for load cases P1P, P2P, P1S and P2S Table 2.6.5

Load case	Hydrodynamic pressure, in kN/m^2
P1P	$p_{P1P} = p_{PP}$
P2P	$p_{P2P} = -p_{PP}$
P1S	$p_{P1S} = p_{PS}$

P2S	$p_{P2S} = -p_{PS}$

where: $p_{PP} = 4.5 f_r f_p C \sqrt{\frac{L+\lambda-125}{L}}(2\frac{|z|}{d_{LCi}} + 3\frac{|2y|}{B})$ for $y \geq 0$

$$= 1.5 f_r f_p C \sqrt{\frac{L+\lambda-125}{L}}(2\frac{|z|}{d_{LCi}} + 3\frac{|2y|}{B}) \quad \text{for} \quad y < 0$$

$$p_{PS} = 1.5 f_r f_p C \sqrt{\frac{L+\lambda-125}{L}}(2\frac{|z|}{d_{LCi}} + 3\frac{|2y|}{B}) \quad \text{for} \quad y \geq 0$$

$$= 4.5 f_r f_p C \sqrt{\frac{L+\lambda-125}{L}}(2\frac{|z|}{d_{LCi}} + 3\frac{|2y|}{B}) \quad \text{for} \quad y < 0$$

where: λ —wave length, in m, to be calculated according to the following formula:

$$\lambda = (0.2 + C_{L2}\frac{d_{LC}}{d})L \qquad \text{m}$$

y—transverse coordinate of load point, in m;

f_r—service coefficient, see 2.2.1 of this Chapter;

f_p—probability level coefficient, see 2.2.2 of this Chapter;

C — wave coefficient, see 2.2.3 of this Chapter;

C_{L2} —coefficient to be calculated according to the following formulae:

C_{L2}=0.4 for oil tanker, LNG carrier and bulk carrier;

C_{L2}=0.15 for container ship;

d_{LC} —draught amidships in corresponding loading condition, in m;

d —draught, in m;

L —length of ship, in m.

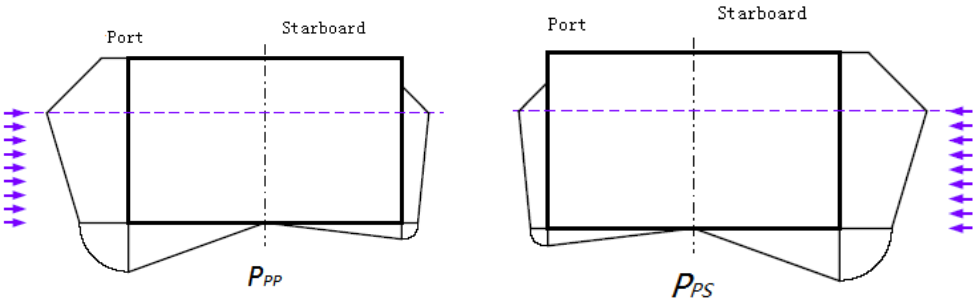


Figure 2.6.5 Distribution of P_{PP} and P_{PS} amidships

2.6.6 For each load case, hydrodynamic pressure is to be corrected according to the following requirements:

(1) For the positive hydrodynamic pressure at the waterline, hydrodynamic pressure $P_{W,C}$ at the side above waterline is to be calculated according to the following formulae (see Figure 2.6.6 of this Chapter):

$$p_{W,C} = p_{W,WL} + \rho g(d_{LCi} - z) \qquad \text{kN/m}^2\text{, for } d_{LCi} \leq z \leq h_W + d_{LCi}$$

$$p_{W,C} = 0 \qquad \text{kN/m}^2\text{, for } z \geq h_W + d_{LCi}$$

where: $p_{W,WL}$ —positive hydrodynamic pressure at the waterline for the considered load case;

d_{LCi}—draught at hull transverse section considered in corresponding loading condition, to be taken as draught at midpoint of model length in corresponding loading condition for finite element stress analysis, in m;

z—vertical coordinate of load point, in m;

$$h_W = \frac{p_{W,WL}}{\rho g}, \text{ in m}$$

where: ρ —density of sea water, to be taken as 1.025 t/m^3.

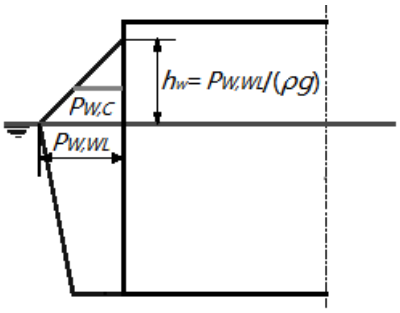
(2) For the negative hydrodynamic pressure at the waterline, hydrodynamic pressure $P_{W,C}$ below the waterline is to be calculated according to the following formula (see Figure 2.6.6 of this Chapter):

$$p_{W,C} = \max[\, p_W, \rho g(z - d_{LCi})] \qquad \text{kN/m}^2$$

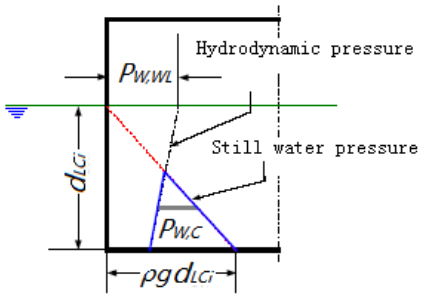
where: p_W —negative hydrodynamic pressure below waterline for load case considered;

d_{LCi}—draught at hull transverse section considered in corresponding loading condition, to be taken as draught at midpoint of model length in corresponding loading condition for finite element stress analysis, in m;

z—vertical coordinate of load point, in m.



Positive hydrodynamic pressure at the waterline



Negative hydrodynamic pressure at the waterline

Figure 2.6.6 Correction of hydrodynamic pressure

2.7 Internal pressure due to dry bulk cargo

2.7.1 The upper surface of dry bulk cargo is to be determined according to the following requirements:

(1) Where the cargo hold is loaded up to top of hatch coaming, the upper surface of dry bulk cargo is an equivalent surface to be determined in considering the same loaded cargo volume within cargo hold (relevant parameter definitions are shown in Figure 2.7.1(1) of this Chapter).

Equivalent horizontal surface of dry bulk cargo is taken at h_C above the inner bottom, and h_C is to be calculated according to the following formula:

$$h_C = h_{HPU} + h_0 \qquad \text{m}$$

where: $h_0 = \dfrac{S_A}{B_H}$, in m;

$$S_A = S_0 + \frac{V_{HC}}{l_H}, \text{ in m}$$

where: h_{HPU}—vertical distance, in m, between inner bottom and lower intersection of top side tank and side shell or inner side; if there is no top side tank, the vertical distance, in m, between inner bottom and intersection of upper deck and side shell or inner side;

S_0—shaded area, in m^2, above the lower intersection of top side tank and side shell or inner side, and up to the upper deck level, see Figure 2.7.2(1) of this Chapter; if there is no top side tank, shaded area, in m^2, above the intersection of upper deck and side shell or inner side, and up to the upper deck level;

V_{HC}—volume, in m^3, enclosed by the hatch coaming from upper deck to coaming top;

l_H—length of cargo hold, in m; if corrugated transverse bulkhead is provided, to be measured from midpoint of corrugated depth;

B_H—breadth of cargo hold at midpoint of length of cargo hold, in m.

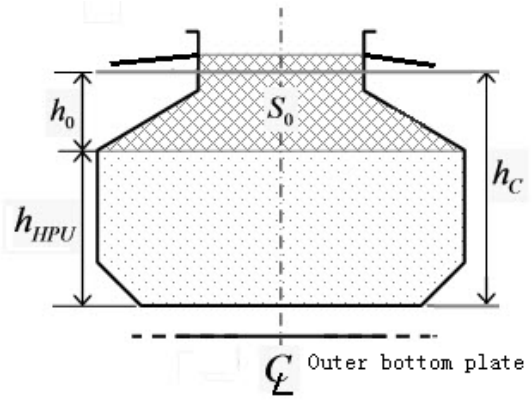


Figure 2.7.1(1) Definitions of h_C, h_0, h_{HPU} and S_0

(2) When the cargo hold is not loaded up to the upper deck, the upper surface of dry bulk cargo along hull transversely is a paraboloid (relevant parameter definitions are shown in Figure 2.7.1(2) of this Chapter). The position of upper surface is to be determined according to the volume of cargo in the cargo hold (to be taken as M / ρ_C).

Surface of dry bulk cargo is taken at h_C above the inner bottom, and h_C is to be calculated according to the following formulae:

$$h_C = h_y + h_2 + h_{HPL} \quad \text{m, for } h_2 \geq 0$$

$$h_C = h_y + h_{22} \quad \text{m, for } |y| \leq \frac{B_2}{2} \text{ and } h_2 < 0$$

$$h_C = 0 \quad \text{m, for } |y| > \frac{B_2}{2} \text{ and } h_2 < 0$$

where: h_2—distance, in m, to be calculated according to the following formula:

$$h_2 = \frac{M}{\rho_C B_H l_H} - \frac{B_H + b_{IB}}{2B_H} h_{HPL} - \frac{B_H}{6} \tan\delta + \frac{V_{TS}}{B_H \cdot l_H} \quad \text{m}$$

h_y—distance, in m, to be calculated according to the following formulae:

$$h_y = h_1(1-\frac{4y^2}{B_H^2}) \qquad \text{m, for } h_2 \geq 0$$

$$h_y = h_1(1-\frac{4y^2}{B_2^2}) \qquad \text{m, for } h_2 < 0$$

B_2—breadth of dry bulk cargo surface when h_2<0, in m, to be calculated according to the following formula:

$$B_2 = \sqrt{\frac{\frac{6}{l_H}(\frac{M}{\rho_C}+V_{TS})+\frac{3B_{IB}^2}{B_H-B_{IB}}h_{HPL}}{\tan\delta+\frac{3h_{HPL}}{B_H-B_{IB}}}} \qquad \text{m}$$

h_{22}—distance when h_2<0, in m, to be calculated according to the following formula:

$$h_{22} = h_{HPL}(\frac{B_2-B_{IB}}{B_H-B_{IB}}) \qquad \text{m}$$

h_{HPL}—vertical distance, in m, between inner bottom and upper intersection of hopper tank and side shell or inner side. h_{HPL} is to be taken equal to 0 if there is no hopper tank.

where: h_1—distance, in m, to be calculated according to the following formulae:

$$h_1 = \frac{B_H}{4}\tan\delta \qquad \text{m, for } h_2 \geq 0$$

$$h_1 = \frac{B_2}{4}\tan\delta \qquad \text{m, for } h_2 < 0$$

M—mass of cargo carried in cargo hold, in t;

V_{TS}—total volume, in m^3, of stools at bottom of transverse bulkheads within the cargo hold length ℓ_H. This volume excludes the part of hopper tank passing through the transverse bulkhead;

ρ_C —density of dry bulk cargo, in t/m^3, see 1.7.3 of Chapter 1;

B_H—breadth of cargo hold at midpoint of length of cargo hold, in m;

l_H—length of cargo hold, in m; if corrugated transverse bulkhead is provided, to be measured from midpoint of corrugated depth;

B_{IB}—breadth of inner bottom at midpoint of length of cargo hold, in m;

δ —angle of repose of cargo, to be taken as 35^o;

y—transverse coordinate of load point, in m, weather side is taken as positive value;

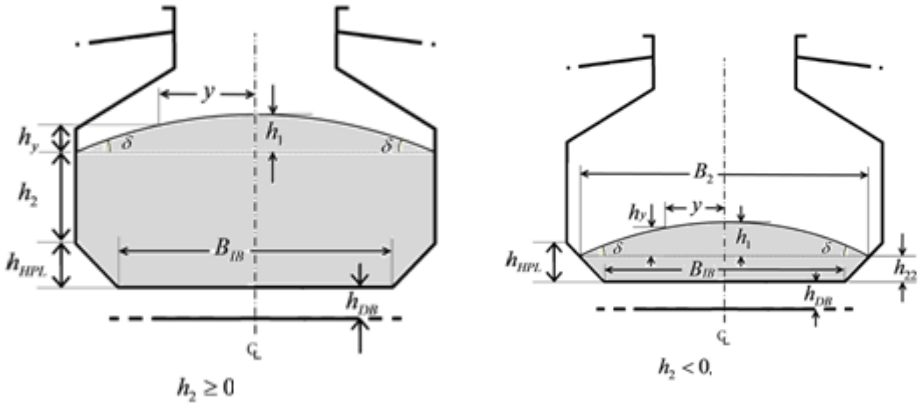


Figure 2.7.1(2) Definitions of h_y, h_1, h_2, h_{22} and h_{HPL}

2.7.2 Pressure p_{CS} of dry bulk cargo in still water is to be calculated according to the following formulae:

$$p_{CS} = \rho_C g K_C z_c \quad \text{kN/m}^2, \text{ for } z_c \geq 0$$

$$p_{CS} = 0 \quad \text{kN/m}^2, \text{ for } z_c < 0$$

where: ρ_C —density of dry bulk cargo, in t/m^3, see 1.7.3 of Chapter 1;

K_C—coefficient to be calculated according to the following formulae:

$K_C = \cos^2\alpha + \tan^2(45^\circ - 0.5\delta)\sin^2\alpha$ for inner bottom, hopper tank, transverse and longitudinal bulkheads, lower stool, vertical upper stool, inner side and side shell;

$K_C = 0$ for top side tank, upper deck and sloped upper stool;

where: α —angle, in deg, between panel considered and the horizontal plane;

δ —angle of repose of cargo, in deg, see 2.7.1(2) of this Chapter;

z_C —vertical distance, in m, from surface of dry bulk cargo to load point, to be calculated according to the following formula:

$$z_c = h_C + h_{DB} - z \quad \text{m}$$

where: h_C—vertical distance, in m, from surface of dry bulk cargo to inner bottom, see 2.7.1 of this Chapter;

h_{DB}—height of double bottom, in m;

z—vertical coordinate of load point, in m.

2.7.3 Inertia pressure p_{CW} induced by dry bulk cargo is to be calculated according to the following formulae:

$$p_{CW} = \rho_C[0.25a_X(x_G - x) + 0.25a_Y(y_G - y) + 0.5K_C a_Z z_c] \text{ kN/m}^2 \text{ for } z_c \geq 0$$

$$p_{CW} = 0 \quad \text{for } z_c < 0$$

where: ρ_C , K_C—see 2.7.1(2) of this Chapter;

a_X, a_Y, a_Z —longitudinal, transverse and vertical acceleration at the centroid of cargo hold considered, in m/s^2, see 2.3.3 of this Chapter;

x_G, y_G—longitudinal and transverse coordinate at the centroid of cargo hold considered, in m;

Z_c —see 2.7.2 of this Chapter;

x, y, z—longitudinal, transverse and vertical coordinate of load point, in m.

2.7.4 Total pressure p_C induced by dry bulk cargo is to be calculated according to the following formula and to be taken not less than zero:

$$p_C = p_{CS} + p_{CW} \qquad \text{kN/m}^2$$

where: p_{CS} —pressure of dry bulk cargo in still water, in kN/m^2, to be calculated according to 2.7.2;

p_{CW} —inertia pressure induced by dry bulk cargo, in kN/m^2, to be calculated according to 2.7.3.

2.8 Internal pressure due to liquid

2.8.1 Static pressure p_{LS} due to liquid is to be calculated according to the following formula and to be taken not less than zero:

$$p_{LS} = \rho_L g(z_{TOP} - z) \qquad \text{kN/m}^2$$

where: ρ_L —density of internal liquid, in t/m^3, to be determined according to the following requirements:

ρ_L =0.9 for cargo oil

ρ_L =0.5 for LNG

ρ_L =1.025 for ballast water

z_{TOP} —vertical coordinate of tank top with the ship in the upright position, in m;

z—vertical coordinate of load point, in m.

2.8.2 Inertia pressure p_{LW} due to liquid is to be calculated according to the following formula:

$$p_{LW} = \rho_L[a_Z(z_B - z) + f_{ull-y}a_Y(y_B - y) + f_{ull-x}a_X(x_B - x)] \qquad \text{kN/m}^2$$

where: ρ_L —density of internal liquid, in t/m^3, see 2.8.1;

x_B—X coordinate of reference point, in m;

y_B—Y coordinate of reference point, in m;

z_B—Z coordinate of reference point, in m.

Reference point is taken as the point on upper boundary of tank which makes V_j maximum:

$$V_j = (a_Z + g)(z_j - z_G) + a_Y(y_j - y_G) + a_X(x_j - x_G)$$

where: x_j, y_j, z_j—X, Y and Z coordinate of point on upper boundary of tank respectively, in m;

x_G, y_G, z_G—X, Y and Z coordinate of tank centroid respectively, in m;

$f_{ull\text{-}x}$—longitudinal filling factor, to be calculated according to the following formulae and to be taken not less than 0 but not greater than 1:

$$f_{ull-x} = 0.5 + \frac{|z_B - z|}{l_{fs}\Phi} \qquad \text{for cargo hold filled with liquid cargo}$$

$$= 1.0 \qquad \text{for other conditions}$$

$f_{ull\text{-}y}$—transverse filling factor, to be calculated according to the following formulae and to be taken not less than 0 but not greater than 1:

$$f_{ull-y} = 0.5 + \frac{|z_B - z|}{b_{top}\theta} \qquad \text{for cargo hold filled with liquid cargo}$$

$$= 1.0 \qquad \text{for other conditions}$$

a_X, a_Y, a_Z—longitudinal, transverse and vertical acceleration at the centroid of cargo hold considered, in m/s^2, see 2.3.3 of this Chapter;

x, y, z—longitudinal, transverse and vertical coordinate of load point, in m.

where: l_{fs}—length of top of compartment, in m;

b_{top}—breadth of top of compartment, in m;

Φ—maximum pitch angle, in rad, see 2.3.1(4) of this Chapter;

θ—maximum roll angle, in rad, see 2.3.1(3) of this Chapter.

2.8.3 Total pressure p_L due to liquid is to be calculated according to the following formula and to be taken not less than zero:

$$p_L = p_{LS} + p_{LW} \qquad \text{kN/m}^2$$

where: p_{LS}—static pressure due to liquid, in kN/m^2, to be calculated according to 2.8.1;

p_{LW}—inertia pressure due to liquid, in kN/m^2, to be calculated according to 2.8.2.

2.9 Loads due to container cargo

2.9.1 Assuming the cargo hold is loaded with some standard container stacking which is generally composed of TEU, container weight is taken as maximum container weight under full load condition in loading manual and height of center of gravity of stacking is taken as half of stacking height.

2.9.2 Assuming all containers within corresponding cargo hold on the hatch cover is an integral mass block, the weight of which is taken as the maximum cargo weight within corresponding cargo hold in full load condition in loading manual, and the height of center of gravity is taken as half of maximum stacking height corresponding to maximum cargo weight.

2.9.3 Load induced by container cargo is to be calculated according to the following formulae:

X direction: $W_{CX} = -m_C a_X$ kN

Y direction: $W_{CY} = -m_C a_Y$ kN

Z direction: $W_{CZ} = -f_z m_C g - m_C a_Z$ kN

where: m_C —weight of standard stacking in the cargo hold or gross weight of containers on hatch cover, in t;

a_X, a_Y, a_Z —acceleration at center of gravity of standard stacking in cargo hold or acceleration at center of gravity of container cargo on hatch cover, in m/s^2, see 2.3.3 of this Chapter;

f_z—factor of vertical static load of container cargo, to be calculated according to the following formulae:

$f_z = \cos\theta$, for R1P, R1S, R2P and R2S conditions

$= 1$, for other conditions

Where: θ —maximum roll angle, see 2.3.1 of this Chapter;

X direction load is positive forward, Y direction load is positive at port and Z direction load is positive upwards.

2.9.4 Load induced by container cargo is to be applied at container feet.

CHAPTER 3 FATIGUE ASSESSMENT

3.1 General requirements

3.1.1 In general, hull structural details at critical locations in cargo hold area are selected for fatigue strength assessment. For oil tankers, bulk carriers and container ships, structural members for check are at least to meet relevant requirements of PART TWO of Rules for Classification of Sea-going Steel Ships/Rules for Construction of Sea-going Ships Engaged on Domestic Voyage. For LNG carriers, at least the following structural members are to be checked:

(1) connection of longitudinals (bottom, side and deck) to transverse web frames;

(2) connection of longitudinals (bottom, side and deck) to transverse bulkhead;

(3) connection of hopper tank to inner bottom plate;

(4) connection of top side tank to inner shell;

(5) connection of transverse bulkhead to inner bottom plate;

(6) connection of transverse bulkhead to inner deck.

3.1.2 Total cumulative damage D of structure in its design service life is to meet the requirements of the following formula:

$$\text{Total cumulative damage} \quad D \le \frac{20}{T_D}$$

where: T_D—design fatigue life, in year.

3.1.3 The design fatigue life of hull structure is not to be less than 20 years. For bulk carriers, oil tankers and container ships, the design fatigue life is generally 20 years.

3.2 Guidance on design of hull structural details

3.2.1 Structural details designs of bulk carriers, oil tankers and container ships are given in Appendix to the Guidelines for the purpose of providing technical guidance (non-mandatory requirements) for designers in the design improvement of structural details of critical locations in order to increase structural fatigue life.

3.3 Design stress range

3.3.1 Design stress range $S_{D(k)}$ for loading condition "(k)" is to be calculated according to the following formula:

$$S_{D(k)} = \max(f_{m,i(k)} f_t S_{h,i(k)}) \qquad \text{N/mm}^2$$

where: $S_{h,i(k)}$—hot spot stress range, in N/mm^2, for load case "i" of loading condition "(k)" , see Chapter 4 or Chapter 5;

$f_{m,i(k)}$—correction factor of hot spot average stress for load case "i" of loading condition "(k)" , see 3.3.2 of this Chapter;

f_t—correction factor of plate thickness, see 3.3.3 of this Chapter.

3.3.2 Correction factor $f_{m(k)}$ for hot spot average stress for loading condition "(k)" is to be determined according to the following requirements:

(1) For welded joints

$$f_{m,i(k)} = \min\left[1.0, 0.85 + 0.3\frac{\sigma_{m,i(k)}}{C_s S_{h,i(k)}}\right] \qquad \text{for } \sigma_{m,i(k)} \geq 0$$

$$f_{m,i(k)} = \max\left[0.7, 0.85 + 0.3\frac{\sigma_{m,i(k)}}{C_s S_{h,i(k)}}\right] \qquad \text{for } \sigma_{m,i(k)} < 0$$

(2) For base material free edge

$$f_{m,i(k)} = \min\left[1.0, 0.8 + 0.4\frac{\sigma_{m,i(k)}}{C_s S_{h,i(k)}}\right] \qquad \text{for } \sigma_{m,i(k)} \geq 0$$

$$f_{m,i(k)} = \max\left[0.6, 0.8 + 0.4\frac{\sigma_{m,i(k)}}{C_s S_{h,i(k)}}\right] \qquad \text{for } \sigma_{m,i(k)} < 0$$

where: $\sigma_{m,i(k)}$—hot spot average stress, in N/mm^2, for load case "*i*" of loading condition "(*k*)";

$S_{h,i(k)}$—hot spot stress range, in N/mm^2, for load case "*i*" of loading condition "(*k*)";

C_s—coefficient to be calculated according to the following formula:

$$C_s = 1.6 + 0.0025L$$

where: L is length of ship, in m.

3.3.3 Correction factor f_t for plate thickness is to be calculated according to the following formulae:

$$f_t = 1.0 \qquad \text{for } t \leq 22$$

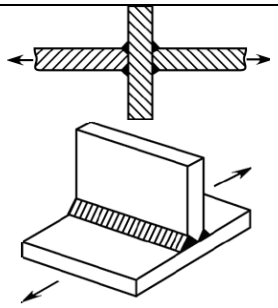
$$f_t = \left(\frac{t}{22}\right)^n \qquad \text{for } t > 22$$

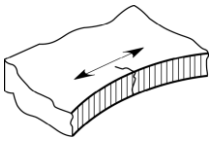
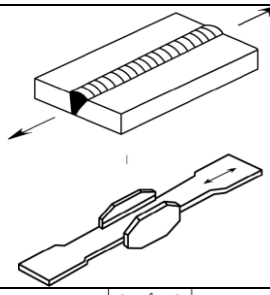
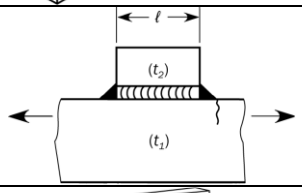
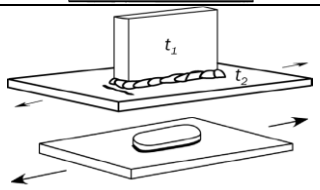
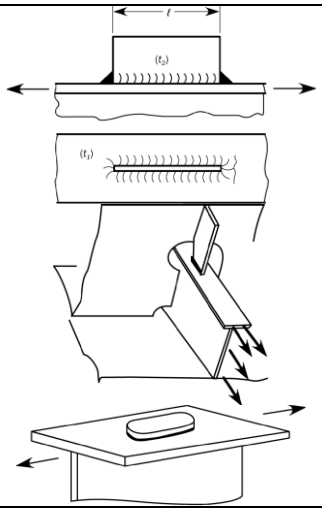
where: *n*—coefficient, see Table 3.3.3 of this Chapter;

t—plate thickness at hot spot, in mm, to be determined according to the following requirements:

For simplified stress analysis, no plate thickness correction for flat bar and bulb profile, and face plate thickness for angle bar and T-bar; for finite element stress analysis, plate thickness of structure where the crack is likely to initiate and propagate.

Table 3.3.3

Structural details	Sketches	Coefficient n
Cruciform joints, transverse T-joints, with weld perpendicular to the direction of load		0.25
Butt joints, with weld perpendicular to the		0.2

Structural details	Sketches	Coefficient n
direction of load		
Machine controlled by program or plate with flame-cut edges , with plate edge parallel to the direction of load		0.1
Plate edge which is ground smooth by machine or other means after cutting		0
Butt welds, attachments on plate edge, with weld parallel to the direction of load		0.1
Attachments on the flat bar or bulb profile, with weld parallel to the direction of load		0
Bracket welded on the plate, with weld parallel to the direction of load, doubling plates		0.2
T section face plate welded with bracket or doubling plates, with weld parallel to the direction of load		0.1

3.4 Selection of design S-N curves

3.4.1 For welded details, D curve is selected for fatigue strength assessment.

3.4.2 For base material free edge, C curve is selected for fatigue strength assessment.

3.5 Calculation of fatigue cumulative damage

3.5.1 Cumulative damage D_k of structural details for loading condition "(k)" is to be calculated according to the following formula:

$$D_k = \frac{N_D \alpha_k}{K} \frac{{S_{D(k)}}^m}{(\ln N_L)^{m/\xi_k}} \mu_k \Gamma\left(1+\frac{m}{\xi_k}\right)$$

where: N_D—total number of load cycles experienced by ship in its 20 years' service, usually to be taken as 0.65×10^8;

N_L—number of cycles for load spectrum in restoring period, to be taken as 10^2;

α_k—time distribution factor for loading condition "(k)", see 1.7 of Chapter 1 of the Guidelines;

K—factor for S-N curve, see Table 3.5.1 of this Chapter;×

$S_{D(k)}$—design stress range for loading condition "(k)", in N/mm^2;

ξ_k—Weibull shape parameter for loading condition "(k)", to be taken as 1;

$$\mu_k = 1.0 - \frac{\gamma\left(1+\frac{m}{\xi_k}, \nu_k\right) - \nu_k^{-\frac{\nabla m}{\xi_k}} \gamma\left(1+\frac{m+\nabla m}{\xi_k}, \nu_k\right)}{\Gamma\left(1+\frac{m}{\xi_k}\right)}$$

$$\nu_k = \left(\frac{S_q}{S_{D(k)}}\right)^{\xi_k} \ln N_L$$

m—inverse slope of S-N curve, to be taken as 3;

∇m—difference of inverse slope of two-slope S-N curves, to be taken as 2;

$\gamma(x,\nu)$—incomplete GAMMA function value, to be calculated according to the following formula:

$$\gamma(x,\nu) = \int_0^{\nu} u^{x-1} e^{-u} du$$

Γ—complete GAMMA function value, to be calculated according to the following formula:

$$\Gamma(x) = \int_0^{\infty} u^{x-1} e^{-u} du$$

S_q—stress amplitude values at intersection point of two-slope S-N curves, see Table 3.5.1 of this Chapter.

Table 3.5.1

S-N curve	K	S_q
C	3.464×10^{12}	70.2305
D	1.520×10^{12}	53.3680

3.5.2 Total cumulative damage of structural details is to be calculated according to the following formula:

$$D = \sum D_k$$

where: D_k—cumulative damage of structural details in each loading condition, see 3.5.1 of this Chapter.

3.6 Calculation of fatigue life

3.6.1 Structure fatigue life is to be calculated according to the following formula:

$$T_F = \frac{20}{D}$$

where: D—total cumulative damage of structural details, see 3.5.2 of this Chapter.

CHAPTER 4 SIMPLIFIED STRESS ANALYSIS

4.1 General requirements

4.1.1 Simplified stress analysis is applicable to fatigue strength assessment of connecting joints of end of longitudinals, and hot spots are in way of weld toes of connecting joints of end of longitudinals.

4.1.2 The hot spot stress ranges and hot spot mean stresses of longitudinals are to be calculated according to type and position of end connection of longitudinals and by considering stress concentration factors for different end connection type based on loading conditions specified in 1.7 of Chapter 1.

4.1.3 For simplified stress analysis, the following nominal stress components are to be considered:

(1) hull girder bending normal stress;

(2) bending normal stress of longitudinals under lateral load.

4.2 Hot spot stress ranges and hot spot mean stress based on simplified analysis

4.2.1 Hot spot stress range $S_{h,i(k)}$ for load case "*i*" of loading condition "(*k*)" is to be calculated according to the following formula:

$$S_{h,\,i(k)} = \left|\sigma_{h,i1(k)} - \sigma_{h,i2(k)}\right| \quad \text{N/mm}^2$$

where: $\sigma_{h,i1(k)}, \sigma_{h,i2(k)}$ —hot spot stress for load case "*i*" of loading condition "(*k*)", in N/mm^2, see 4.4.1 of this Chapter.

4.2.2 Hot spot mean stress for load case "*i*" of loading condition "(*k*)" is to be calculated according to the following formula:

$$\sigma_{m,\,i(k)} = \frac{\sigma_{h,i1(k)} + \sigma_{h,i2(k)}}{2} \quad \text{N/mm}^2$$

where: $\sigma_{h,i1(k)}, \sigma_{h,i2(k)}$ —hot spot stress for load case "*i*" of loading condition "(*k*)", in N/mm^2, see 4.4.1 of this Chapter.

4.3 Calculation of nominal stress components

4.3.1 Nominal stress component $\sigma_{nh,ij(k)}$ due to hull girder loads for load case "*i*" of loading condition "(*k*)" is to be calculated according to following formula:

$$\sigma_{nh,ij(k)} = \sigma_{SW,(k)} + C_{WV,ij}\sigma_{WV,ij} + C_{WH,ij}\sigma_{WH,(k)} \quad (j = 1,2) \ \text{N/mm}^2$$

where: $\sigma_{SW,(k)}$ —hull girder bending normal stress due to still water bending moment, in N/mm^2, to be calculated according to following formula:

$$\sigma_{SW,(k)} = \frac{M_{SW,(k)}(z - z_{NA})}{I_Y} \times 10^{-3} \ \text{N/mm}^2$$

$\sigma_{WV,ij}$ —hull girder bending normal stress due to vertical wave bending moment, in N/mm^2;

$$\sigma_{WV,i1} = \frac{M_{WV,S}(z - z_{NA})}{I_Y} \times 10^{-3} \qquad \text{for sagging condition;}$$

$$\sigma_{WV,i2} = \frac{M_{WV,H}(z - z_{NA})}{I_Y} \times 10^{-3} \qquad \text{for hogging condition;}$$

$\sigma_{WH,(k)}$ —hull girder bending normal stress due to horizontal wave bending moment, in N/mm^2;

$$\sigma_{WH,(k)} = \frac{M_{WH} y}{I_Z} \times 10^{-3}$$

$C_{WV,ij}$, $C_{WH,ij}$ —load combination factor of hull girder vertical wave bending moment and horizontal wave bending moment, see Table 2.5.3 of Chapter 2 of the Guidelines;

$M_{SW,(k)}$ —still water bending moment in corresponding loading condition, in kN·m;

$M_{WV,S}$, $M_{WV,H}$ —vertical wave bending moment for sagging and hogging, in kN·m;

$M_{WH,(k)}$ —horizontal wave bending moment, in kN·m;

y, *z*—transverse and vertical coordinate of calculation point, in m;

z_{NA} —vertical coordinate of neutral axis, in m;

I_Y, I_Z—inertial moment of hull section to transverse and vertical neutral axis respectively, in m^4.

4.3.2 Nominal stress component $\sigma_{nl,ij(k)}$ due to lateral load for load case "*i*" of loading condition "(*k*)" is to be calculated according to following formula:

$$\sigma_{nl,ij(k)} = \frac{C_d(\eta_{SW} P_{SW,ij(k)} + \eta_L P_{L,ij(k)} + \eta_C P_{C,ij(k)}) s l^2}{12 W_s} \left(6\left(\frac{x}{l}\right)^2 - 6\left(\frac{x}{l}\right) + 1\right) \times 10^3 \quad (j = 1,2) \qquad \text{N/mm}^2$$

where: *s*—spacing of longitudinal stiffener, in m;

l—span of longitudinal stiffener, in m, see Figure 4.3.2 of this Chapter;

x—distance from longitudinal stiffener span end to hot spot, in m, see Figure 4.3.2 of this Chapter;

W_s—section modulus, in cm^3, of stiffener with an attached plating;

C_d—relative displacement correction coefficient, to be determined according to following requirements:

C_d =1.3 bottom (inner bottom) longitudinal stiffener end details at transverse bulkhead of cargo hold;

C_d =1.2 for side (inner shell) longitudinal stiffener end details at transverse bulkhead of cargo hold;

C_d =1.15 for deck longitudinal stiffener end details at transverse bulkhead of cargo hold;

C_d =1.0 for others.

Relative displacement correction coefficient can also be determined by direct calculation.

$P_{SW,ij(k)}$, $P_{L,ij(k)}$, $P_{C,ij(k)}$—sea water pressure, liquid pressure or dry bulk cargo pressure respectively at mid span of longitudinal stiffener, in kN/m^2;

η_{SW}、η_L、η_C—coefficient for direction of lateral load pressure; when the considered pressure is applied on the stiffener side, to be taken as 1; when otherwise, to be taken as -1.

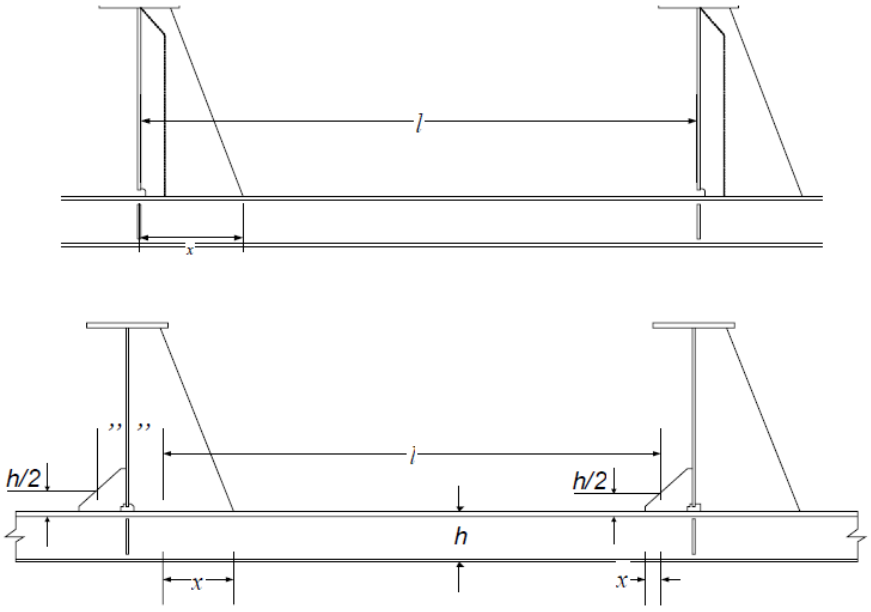


Figure 4.3.2(1) Single-hull construction

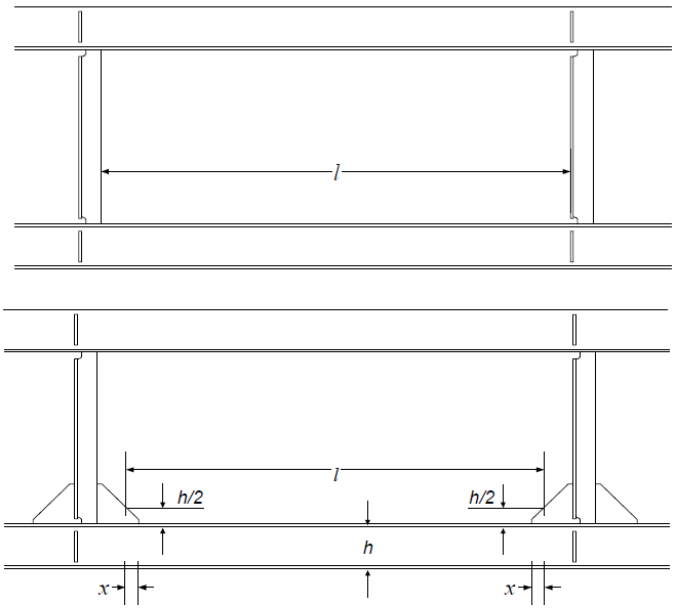


Figure 4.3.2(2) Double-hull construction

4.4 Calculation of hot spot stress

4.4.1 Hot spot stress for load case "*i*" of loading condition "(*k*)" is to be calculated according to following formula:

$$\sigma_{h,ij(k)} = C_g f_{ch} K_{gh} \sigma_{nh,ij(k)} + f_{cl} K_{gl} K_n \sigma_{nl,ij(k)} \qquad (j = 1, 2) \qquad \text{N/mm}^2$$

where: $\sigma_{nh,\ ij(k)}$—nominal stress component due to hull girder bending moment, in N/mm^2, see 4.3.1 of this Chapter;

$\sigma_{nl,\ ij(k)}$—nominal stress component due to lateral load, in N/mm^2, see 4.3.2 of this Chapter;

K_n—stress concentration factor due to unsymmetrical stiffener geometry, see 4.5.2 of this Chapter;

K_{gh}—stress concentration factor for longitudinal stiffener due to axial load, see Table 4.5.1 of this Chapter;

K_{gl}—stress concentration factor for longitudinal stiffener due to lateral load, see Table 4.5.1 of this Chapter;

f_{ch}, f_{cl}—corrosion correction factor, see 1.6.1 of Chapter 1;

C_g—panel bending correction factor, to be determined according to the following requirements:

$C_g = 1.1$ for bottom (inner bottom) longitudinal stiffener end details;

$C_g = 1.05$ for side (inner shell) longitudinal stiffener end details;

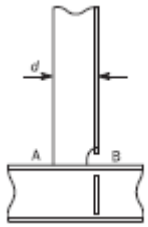
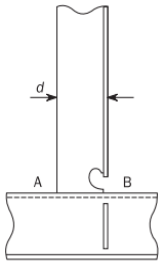
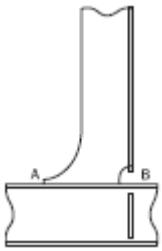
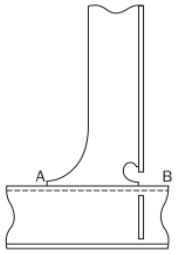
$C_g = 1.0$ for deck longitudinal stiffener end details.

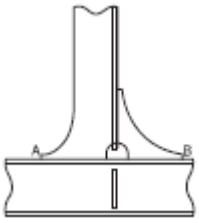
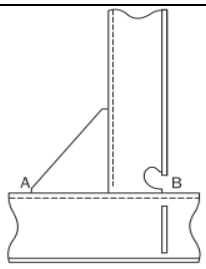
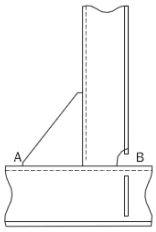
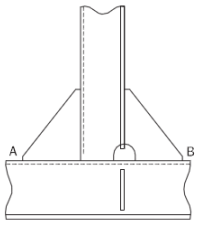
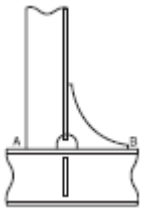
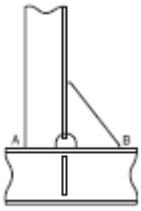
Panel bending correction factor can also be determined by direct calculation.

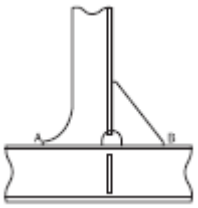
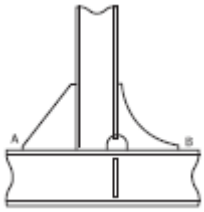
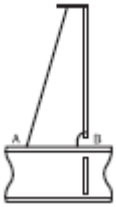
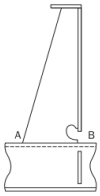
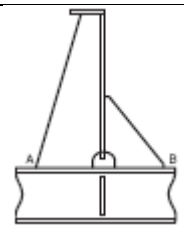
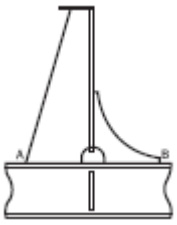
4.5 Stress concentration factors

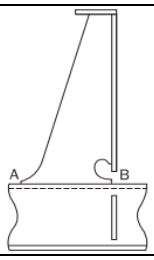
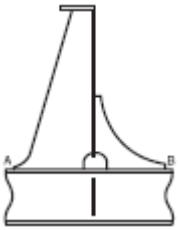
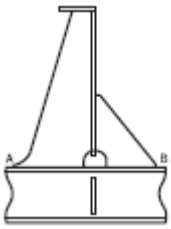
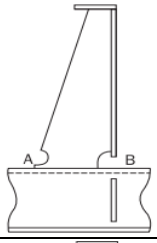
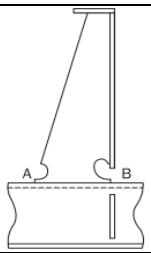
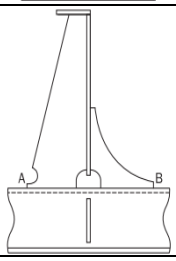
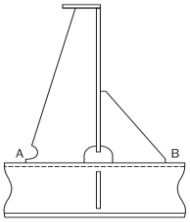
4.5.1 Stress concentration factors for longitudinal symmetrical stiffener end connections due to axial load and lateral load are shown in Table 4.5.1, and can also be determined by direct calculation.

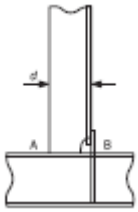
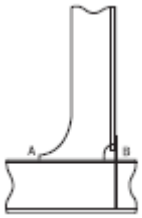
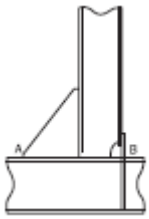
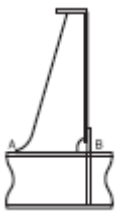
Stress concentration factors **Table 4.5.1**

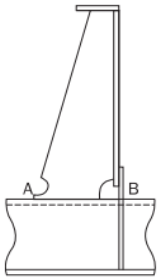
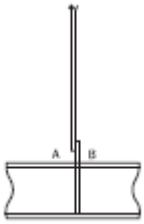
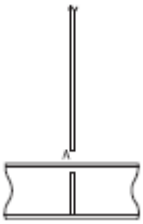
No.	Connection type	Point A		Point B	
		K_{gh}	K_{gl}	K_{gh}	K_{gl}
1		1.28 （d ≤ 150） 1.36 （150＜d ≤ 250） 1.45 （d >250）	1.40 （d ≤ 150） 1.50 （150＜d ≤ 250） 1.60 （d >250）	1.28 （d ≤ 150） 1.36 (150＜d ≤ 250) 1.45 （d >250）	1.6
2		1.28 （d ≤ 150） 1.36 （150＜d ≤ 250） 1.45 （d >250）	1.40 （d ≤ 150） 1.50 （150＜d ≤ 250） 1.60 （d >250）	1.14 （d ≤ 150） 1.24 (150＜d ≤ 250) 1.34 （d >250）	1.27
3		1.28	1.34	1.52	1.67
4		1.28	1.34	1.34	1.34

No.	Connection type	Point A		Point B	
		K_{gh}	K_{gl}	K_{gh}	K_{gl}
5		1.28	1.34	1.28	1.34
6		1.52	1.67	1.34	1.34
7		1.52	1.67	1.52	1.67
8		1.52	1.67	1.52	1.67
9		1.52	1.67	1.28	1.34
10		1.52	1.67	1.52	1.67

No.	Connection type	Point A		Point B	
		K_{gh}	K_{gl}	K_{gh}	K_{gl}
11		1.28	1.34	1.52	1.67
12		1.52	1.67	1.28	1.34
13		1.52	1.67	1.52	1.67
14		1.52	1.67	1.34	1.34
15		1.52	1.67	1.52	1.67
16		1.52	1.67	1.28	1.34
17		1.34	1.34	1.52	1.67

No.	Connection type	Point A		Point B	
		K_{gh}	K_{gl}	K_{gh}	K_{gl}
18		1.34	1.34	1.34	1.34
19		1.34	1.34	1.28	1.34
20		1.34	1.34	1.52	1.67
21		1.34	1.34	1.52	1.67
22		1.34	1.34	1.34	1.34
23		1.34	1.34	1.28	1.34
24		1.34	1.34	1.52	1.67

No.	Connection type	Point A		Point B	
		K_{gh}	K_{gl}	K_{gh}	K_{gl}
25		1. 28 ($d \leq 150$) 1.36 ($150 < d \leq 250$) 1. 45 ($d > 250$)	1. 40 ($d \leq 150$) 1.50 ($150 < d \leq 250$) 1. 60 ($d > 250$)	1. 14 ($d \leq 150$) 1.24 ($150 < d \leq 250$) 1. 34 ($d > 250$)	1. 25 ($d \leq 150$) 1.36 ($150 < d \leq 250$) 1. 47 ($d > 250$)
26		1.28	1.34	1.34	1.47
27		1.52	1.67	1.34	1.47
28		1.52	1.67	1.34	1.47
29		1.34	1.34	1.34	1.47

No.	Connection type	Point A		Point B	
		K_{gh}	K_{gl}	K_{gh}	K_{gl}
30		1.34	1.34	1.34	1.47
31		1.34	1.47	1.34	1.47
32		1.1	1.14	N/A	N/A

4.5.2 Stress concentration factors due to unsymmetrical stiffener geometry are to be calculated according to following formulae:

$$K_n = 1.03 \quad \text{for bulb steel;}$$

$$K_n = \frac{1 + \lambda\beta^2}{1 + \lambda\beta^2\psi_z} \quad \text{for others}$$

where: β —factor, to be taken as 1-2b_g/b_f;

b_g —breadth from web centerline to wing plate, in mm, see Figure 4.5.2;

b_f —breadth of wing plate, in mm;

t_f —thickness of wing plate, in mm;

h_{stf} —web height, in mm

t_w —web thickness, in mm;

t_p —thickness of attached plate, in mm;

Z—section modulus of stiffener, in cm^3;

λ —coefficient to be taken as $\dfrac{3\left(1+\dfrac{\eta}{280}\right)}{1+\dfrac{\eta}{40}}$;

ψ —coefficient to be taken as $\dfrac{h_{stf}^2 t_w}{4Z\times 10^3}$;

η —coefficient to be taken as $\dfrac{l^4}{b_f^3 t_f h_{stf}^2\left(\dfrac{4h_{stf}}{t_w^3}+\dfrac{s}{t_p^3}\right)}\times 10^{12}$。

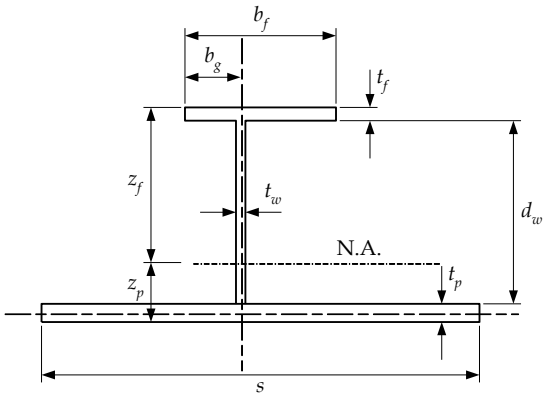


Figure 4.5.2

4.5.3 If connection types other than those given in Table 4.5.1 are adopted, fatigue strength can be assessed according to following requirements:

(1) hot spot stress is calculated directly by performing a very fine mesh finite element analysis, see Chapter 5 of the Guidelines;

(2) stress concentration factor is determined by finite element analysis, stress concentration factor K_g is to be the ratio of finite element hot spot stress to nominal stress by simplified analysis:

$$K_g = \frac{\sigma_h}{\sigma_n}$$

where: σ_h —hot spot stress, in N/mm^2;

σ_n —nominal stress, in N/mm^2.

CHAPTER 5 FINITE ELEMENT STRESS ANALYSIS

5.1 General requirements

5.1.1 The methods for finite element hot spot stress analysis are applicable to fatigue strength assessment for both welded and non-welded details, taking into account structural discontinuities due to the structural detail of the welded joint, but not taking into account the notch effect at the weld toe.

5.1.2 Fatigue strength check based on finite element stress analysis is carried out by very fine mesh analysis. These very fine mesh models may be incorporated into the global model. Alternatively, this very fine mesh analysis can be carried out by means of separate local finite element models with very fine mesh zones in conjunction with the boundary conditions obtained from a global model of the cargo holds.

5.2 Structure modeling

5.2.1 Unless otherwise specified in the Guidelines, finite element structure modeling is to comply with relevant requirements of Section 14, Chapter 1, PART TWO of CCS Rules for Classification of Sea-going Steel Ships.

5.2.2 The extent of model is to be in compliance with the following requirements:

(1) Normally, the longitudinal extent is to cover the length of 1/2 hold + 1 hold + 1/2 hold within the cargo area amidships.

(2) Considering that transverse wave loads are not symmetrical, a full-breadth model is to be required.

(3) The vertical extent is to be taken as all members within the main hull, including all the primary members on the main deck.

5.2.3 For local fine mesh sub-model, the effect of displacement boundary condition and force boundary condition on fine mesh zone hot spot stress is to be avoided. The boundary of fine mesh zone is to be taken at adjacent primary supporting members such as girders, stringers and floors in the cargo hold.

5.2.4 Finite element meshes near hot spot are to be fine enough to reflect change of stress gradient. The size of mesh is not to be greater than thickness t of stressed members at hot spot. The mesh size is to be maintained within the very fine mesh zone, extending over at least 10 elements in all directions from the hot spot position. The transition of element size between the coarser mesh and the very fine mesh zone is to be done gradually and an acceptable mesh quality is to be maintained.

5.2.5 Four-node shell elements with adequate bending and membrane properties are to be used inside the very fine mesh zone. The shell elements are to represent the mid plane and bending of the plating. Triangular elements are to be avoided where possible. Use of distorted elements (e.g. element's corner angle less than 60^{o} or greater than 120^{o}) are to be avoided. Stiffeners inside fine mesh zone are to be modeled using plate elements, and stiffeners outside fine mesh zone are to be modeled using beam elements. The geometry of the weld and construction misalignment is not required to be modeled.

5.2.6 Where stresses are to be assessed on a free edge, such as cut-outs for stiffener connections at web frames, edge of plating and hatch corners, beam elements having the same depth as the adjoining plate thickness and negligible width is to be used to obtain the required local edge stress

values.

5.3 Finite element analysis conditions

5.3.1 For finite element stress analysis, each calculation condition is based on global load case and local load case. Hot spot stress is to be obtained by stress combination of global load case and local load case and to be calculated according to following formula:

$$\sigma_C = f_{ch}\sigma_{HG} + C_{VT}f_{cl}\sigma_L \quad \text{N/mm}^2$$

where: σ_{HG} —hot spot stress for global load case, in N/mm^2;

σ_L —hot spot stress for local load case, in N/mm^2;

f_{ch}, f_{cl}—corrosion correction coefficient, see 1.6.1 of Chapter 1;

C_{VT}—ship type correction coefficient, to be determined according to following requirements:

C_{VT} =0.75 for container ship

C_{VT} =0.80 for oil tanker

C_{VT} =0.9 for bulk carrier

C_{VT} =0.95 for LNG carrier.

5.4 Boundary conditions

5.4.1 Boundary conditions for cargo hold FE model are to comply with following requirements:

(1) Boundary conditions for global load (see Table 5.4.1(1) of this Chapter)

(a) The degrees of freedom δ_x, δ_y and δ_z of each longitudinal member node for fore and aft end planes is to be linked to the independent point at neutral axis on longitudinal centerline section by means of MPC. Vertical bending moment and horizontal bending moment are to be applied on the independent point. Load combination factors for each load case are shown in Table 2.5.3, Chapter 2 of the Guidelines.

(b) The displacements of the independent point within fore and aft end planes in transverse direction, vertical direction and the rotation around longitudinal axes are restrained, i.e. $\delta_y = \delta_z = \theta_x = 0$; The displacement of the independent point within the fore end plane in longitudinal direction is restrained, i.e. $\delta_x = 0$.

Boundary conditions for global load **Table 5.4.1(1)**

Position	Displacement constraint			Rotation constraint		
	δ_x	δ_y	δ_z	θ_x	θ_y	θ_z
All longitudinal members for end planes	Link	Link	Link	-	-	-
Independent point (fore end plane)	Constraint	Constraint	Constraint	Constraint	Bending moment	-
Independent point (aft end plane)	-	Constraint	Constraint	Constraint	Bending moment	-

(2) Boundary conditions for local loads (with symmetrical loads, see Table 5.4.1(2) of this Chapter)

(a) Symmetrical conditions are applied respectively to fore and aft end planes, the displacements in longitudinal direction of nodes within the end plane and the rotations around the two coordinate axes within the end plane are restrained, i.e. $\delta_x = \theta_y = \theta_z = 0$;

(b) Vertical spring elements are to be fitted on intersection line of side shell plating/inner hull plating/longitudinal bulkhead with forward and aft bulkheads in midship cargo tanks. Elasticity coefficients for spring elements are distributed evenly and calculated according to following formula:

$$K = \frac{5GA}{6l_H n}$$

where: G—shear elastic modulus for material; for steel, G=0.792×10^5 N/mm^2;

A— shear area of side shell plating, inner hull plating or longitudinal bulkhead plate at forward and aft bulkheads, in mm^2;

l_H —length of midship cargo tank, in mm;

n—number of nodes of vertical intersections on side shell plating, inner hull plating or longitudinal bulkhead plate.

Boundary conditions for local loads (with symmetrical loads) Table 5.4.1(2)

Position	Displacement constraint			Rotation constraint		
	δ_x	δ_y	δ_z	θ_x	θ_y	θ_z
Fore and aft end planes	Constraint	-	-	-	Constraint	Constraint
Intersection of longitudinal centerline section at fore and aft transverse bulkheads with bottom	-	Constraint	-	-	-	-
Vertical intersections of side shell plating, inner hull plating and longitudinal bulkhead plate with forward and aft transverse bulkheads	-	-	Vertical spring	-	-	-

(3) Boundary conditions for local loads (with unsymmetrical loads, see Table 5.4.1(3) of this Chapter)

(a) Symmetrical conditions are applied respectively to fore and aft end planes, the displacements in longitudinal direction of nodes within the end plane and the rotations around the two coordinate axes within the end plane are restrained, i.e. $\delta_x = \theta_y = \theta_z = 0$;

(b) Transverse spring elements are to be fitted on intersections of upper deck/bottom plating/inner bottom plating with forward and aft bulkheads. Elasticity coefficients for spring elements are distributed evenly and calculated according to following formula:

$$K = \frac{5GA}{6l_H n}$$

where: G—shear elastic modulus for material; for steel, G=0.792×10^5 N/mm^2;

A—shear area of bottom plating and inner bottom plating at forward and aft bulkheads, in mm^2;

l_H—length of midship cargo tank, in mm;

n—number of nodes of horizontal intersections on bottom plating and inner bottom plating.

(c) Vertical spring elements are to be fitted on intersections of side shell plating/inner hull plating/longitudinal bulkhead with forward and aft bulkheads. Elasticity coefficients for spring elements are distributed evenly and shown in 5.4.1(2)(b) of this Chapter.

Boundary conditions for local loads (with unsymmetrical loads) Table 5.4.1(3)

Position	Displacement constraint			Rotation constraint		
	δ_x	δ_y	δ_z	θ_x	θ_y	θ_z
Fore and aft end planes	Constraint	-	-	-	Constraint	Constraint
Horizontal intersection line of upper deck, bottom plating and inner bottom plating with forward and aft transverse bulkheads	-	Transverse spring	-	-	-	-
Vertical intersection line offside shell plating, inner hull plating and longitudinal bulkhead plate with forward and aft transverse bulkheads	-	-	Vertical spring	-	-	-

5.4.2 When local fine finite element model is used, node force or nodal displacement obtained from hold model is to be applied to sub-model.

5.5 Hot spot stress ranges and hot spot mean stress based on finite element analysis

5.5.1 Hot spot stress ranges and mean stress

(1) For load case "*i*" of loading condition "(*k*)", hot spot stress ranges $S_{h,i(k)}$ is to be hot spot principal stress within $\pm 45^o$ perpendicular to the weld toe and determined according to difference of hot spot stress components for load case i_1 and load case i_2;

(2) For load case "*i*" of loading condition "(*k*)", hot spot mean stress is to be determined according to average hot spot stress components for load case i_1 and load case i_2.

5.5.2 Hot spot stress calculation for weld type nodes

(1) For general weld type nodes (such as bracket toe ends) for load case "*ij*" of loading condition "(*k*)", hot spot stress $\sigma_{ij(k)}$ (see Figure 5.5.2(1) of this Chapter) is to be calculated according to following formula:

$$\sigma_{ij(k)} = \frac{3\sigma_{ij(k),t/2} - \sigma_{ij(k),3t/2}}{2} \qquad (j = 1,2) \qquad \text{N/mm}^2$$

where: $\sigma_{ij(k),t/2}$, $\sigma_{ij(k),3t/2}$—stresses at stress read out points located at distances t/2 and 3t/2 away from the weld toe for load case "*ij*" of loading condition "(*k*)", in N/mm^2, where t is plate thickness at hot spot, in mm;

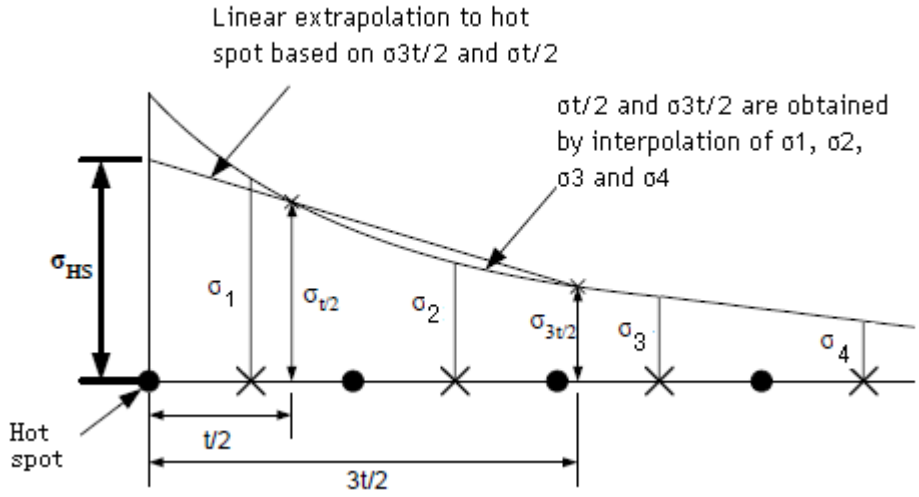


Figure 5.5.2(1) Hot spot stress of general weld type nodes

(2) Four interpolation points are selected on surface of stressed members in the vicinity of hot spots, and stress read out points are to be within 4 interpolation points. The stress of interpolation points is to be the average value of stresses at the element center points at left and right of A-A line, as shown in Figure 5.5.2(2). Stress σ at stress read out points located at distances t/2 and 3t/2 away from the weld toe is to be determined according to the stress at selected interpolation points by Lagrange's interpolation method and calculated according to following formula:

$$\sigma = C_1\sigma_1 + C_2\sigma_2 + C_3\sigma_3 + C_4\sigma_4 \qquad \text{N/mm}^2$$

where: σ_1—stress at interpolation point 1, in N/mm^2;

σ_2—stress at interpolation point 2, in N/mm^2;

σ_3—stress at interpolation point 3, in N/mm^2;

σ_4—stress at interpolation point 4, in N/mm^2;

C_1, C_2, C_3 and C_4 are to be calculated according to following formulae:

$$C_1 = \frac{(x-x_2)(x-x_3)(x-x_4)}{(x_1-x_2)(x_1-x_3)(x_1-x_4)}$$

$$C_2 = \frac{(x-x_1)(x-x_3)(x-x_4)}{(x_2-x_1)(x_2-x_3)(x_2-x_4)}$$

$$C_3 = \frac{(x-x_1)(x-x_2)(x-x_4)}{(x_3-x_1)(x_3-x_2)(x_3-x_4)}$$

$$C_4 = \frac{(x-x_1)(x-x_2)(x-x_3)}{(x_4-x_1)(x_4-x_2)(x_4-x_3)}$$

where: x—distance from stress read out point to weld toe, in mm;

x_1 —distance from interpolation point 1 to weld toe, in mm;

x_2 —distance from interpolation point 2 to weld toe, in mm;

x_3 —distance from interpolation point 3 to weld toe, in mm;

x_4 —distance from interpolation point 4 to weld toe, in mm.

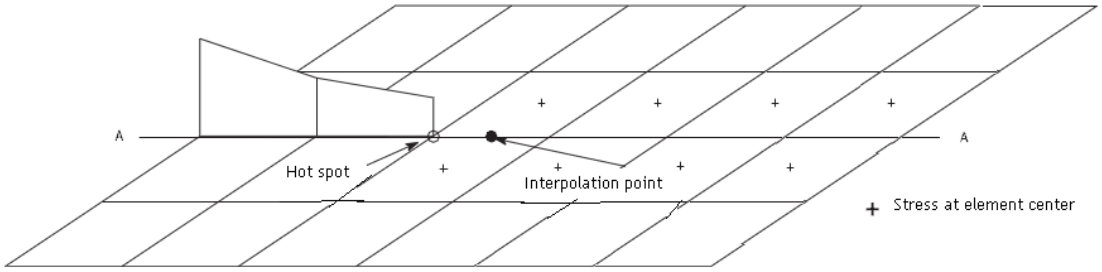


Figure 5.5.2(2) Method for obtaining stress at interpolation points

5.5.3 Hot spot stress calculation for cruciform weld type nodes

(1) For cruciform weld type nodes (such as weld type hopper knuckle, horizontal girder root, lower stool and inner bottom knuckle), as shown in Figure 5.5.3(1), for load case "*ij*" of loading condition "(*k*)" , stress $\sigma_{ij(k)}$ at hot spot is to be the stress in way of element intersection line x_{shift} and obtained by linear interpolation of stress at adjacent interpolation points on the intersection line, as shown in Figure 5.5.3(2).

Stress read out position x_{shift} is to be calculated according to following formula:

$$x_{shift} = \frac{t}{2} + x_{wt} \quad \text{mm}$$

where: t—thickness of plate at hot spot, in mm;

x_{wt} —length of weld toe, in mm, not greater than $t/2$.

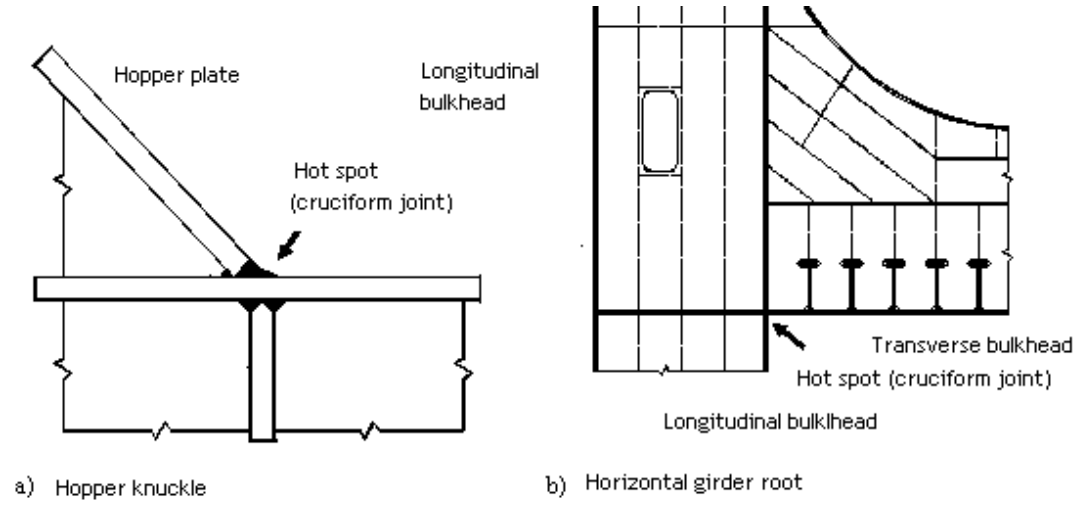


Figure 5.5.3(1) Cruciform weld type nodes

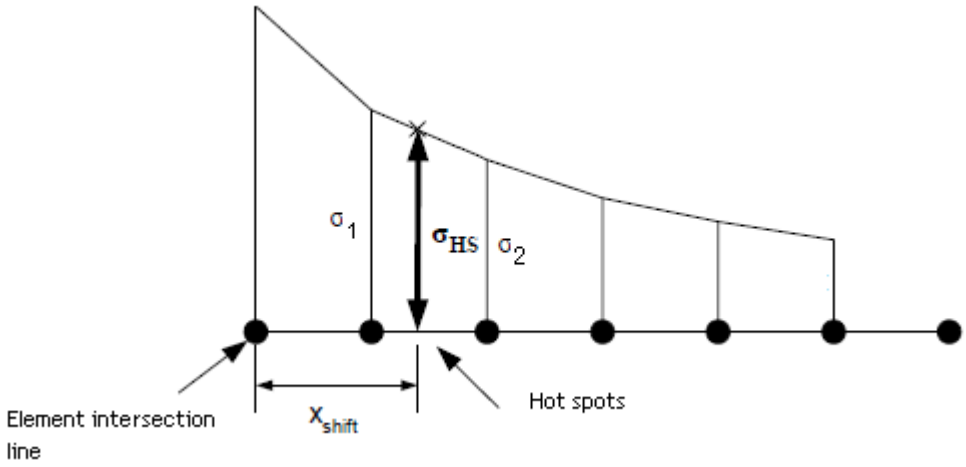


Figure 5.5.3(2) Stress interpolation value of cruciform weld type hot spots

(2) The stress of adjacent interpolation points is obtained by average element midpoint stress at left and right sides of A-A line. Element midpoint stress is to be calculated according to following formula:

$$\sigma_{ij(k)}(x) = (\sigma_{ij(k),membrane}(x) + 0.6 f_{1d}\sigma_{ij(k),bending}(x)) \times \beta \qquad (j = 1,2) \quad \text{N/mm}^2$$

where: $\sigma_{ij(k),bending}(x)$—bending stress, in N/mm^2, to be calculated according to following formula:

$$\sigma_{ij(k),bending}(x) = \sigma_{ij(k),surface}(x) - \sigma_{ij(k),membrance}(x) \qquad (j = 1,2) \quad \text{N/mm}^2$$

$\sigma_{ij(k),surface}(x)$—surface stress within 45° perpendicular to weld toe, in N/mm^2, including membrane stress and bending stress;

$\sigma_{ij(k),membrance}(x)$—membrane stress, in N/mm^2;

f_{1d}—factor, to be determined according to following requirements:

f_{1d}=1 for plate subject to local lateral load;

f_{1d}=0 for plate not subject to local lateral load.

β—plate angle correction factor, to be calculated according to following formulae:

$$\beta = 1.07 - 0.15\frac{x_{wt}}{t} + 0.22\left(\frac{x_{wt}}{t}\right)^2 \quad \text{for} \quad \alpha = 135°$$

$$\beta = 1.09 - 0.16\frac{x_{wt}}{t} + 0.36\left(\frac{x_{wt}}{t}\right)^2 \quad \text{for} \quad \alpha = 120°$$

$$\beta = 1.09 + 0.036\frac{x_{wt}}{t} + 0.27\left(\frac{x_{wt}}{t}\right)^2 \quad \text{for} \quad \alpha = 90°$$

Plate angle correction factors for other angles are to be determined by linear interpolation.

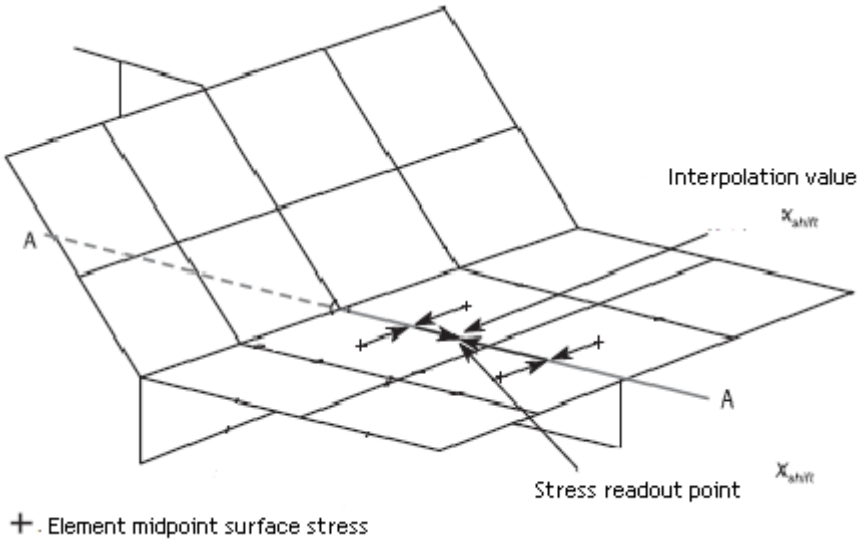


Figure 5.5.3(2) Determination of stress at interpolation points

5.5.4 For fatigue assessment of free edge of plate, a beam element is to be used to obtain the fatigue stress range. The stress range is to be based on axial and bending stress in the beam element. The beam element is to have the same depth as the connecting plate thickness while the in-plane width is negligible.

5.6 Requirements for finite elements of typical details

5.6.1 Hopper knuckle welded connection

(1) The modeling requirements in this subparagraph are applicable to the modeling of bilge hopper lower-knuckle and upper-knuckle welded connections.

(2) Where a separate local finite element model is used, the minimum extent of the local model is to be according to the following:

① Longitudinally, the model is to cover two web frame spaces (i.e. one web frame space extending either side of the transverse web frame of interest). Transverse web frames at the end of the local model need not be represented in the local model;

② Vertically, the model is to extend from the baseline to the lower stringer in the double side water ballast tank for tankers and double skin bulk carriers. For single skin bulk carriers, the model is to extend from the baseline to the top of the hopper ballast tank. Where a fatigue assessment is also carried out for the upper knuckle connection, the model is to be extended to four longitudinal spaces above the lower stringer in the double side ballast tank;

③ Transversely, the model is to extend from the ship side to 4 longitudinal spaces inboard of the double bottom side girder.

(3) Any scarfing brackets on the web frame adjoining the inner bottom plating, the first longitudinal stiffeners away from the knuckle hot spot as well as any carlings and brackets offset from the main frames are to be modeled explicitly using shell elements. Longitudinal stiffeners further away from the knuckle may be modeled by beam elements. The inner bottom plate ‘overhang’ outboard of the girder is to be modeled using shell elements up to the extent of the scarfing bracket. Away from the scarfing bracket in longitudinal direction, the inner bottom plate ‘overhang’ may be modeled using line elements of equivalent the area. Any perforations, such as

cut-outs for cabling, pipes and access that are within one stiffener space from the knuckle point are to be modeled explicitly.

(4) Figures 5.6.1(1) to (5) show typical local finite element models of the hopper knuckle connection and close-up views of mesh zone.

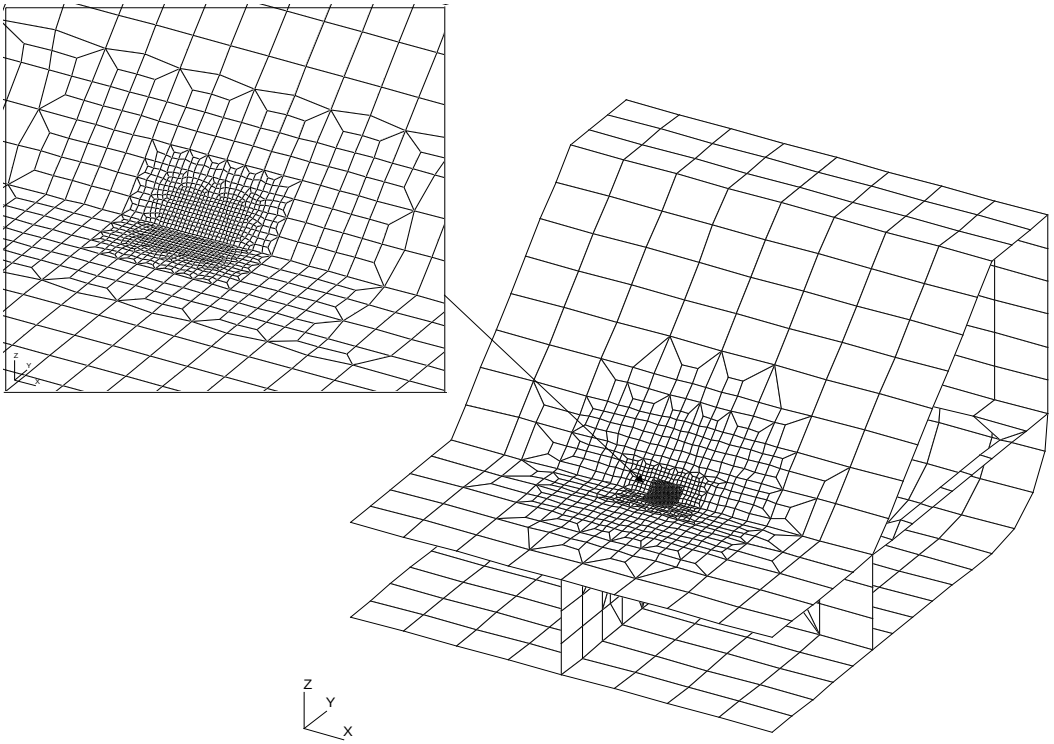


Figure 5.6.1(1) Finite element fine mesh model of hopper knuckle

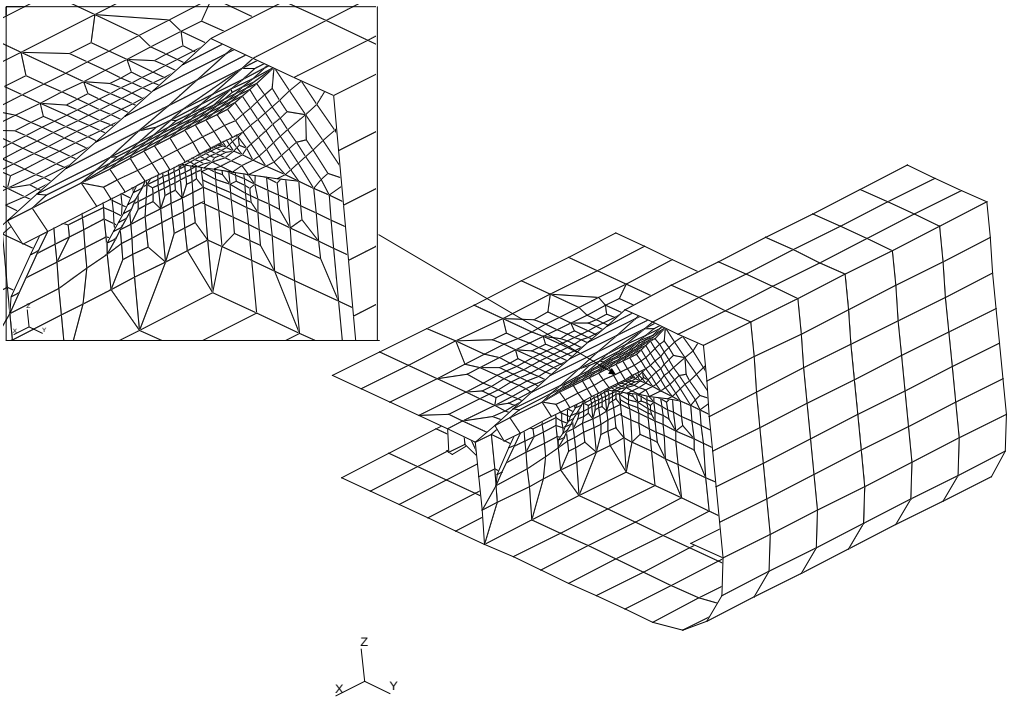


Figure 5.6.1(2) Finite element fine mesh model of hopper knuckle

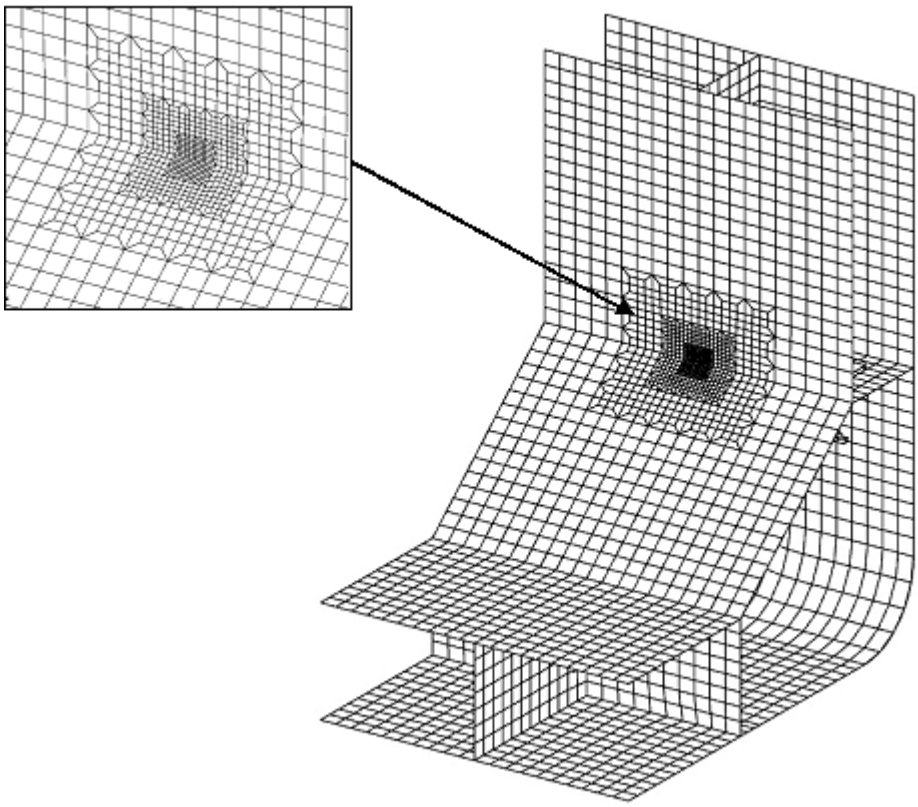


Figure 5.6.1(3) Finite element fine mesh model of hopper knuckle

5.6.2 Lower stool – inner bottom connection

(1) The modeling requirements in this subparagraph are applicable to the connection between lower stool and inner bottom knuckle.

(2) Where a separate local finite element model is used, the minimum extent of the local model is as follows:

① Vertically, from the bottom shell to a level at least 2 m above the inner bottom or up to the connection of the corrugation to the upper shelf plate of the lower stool, whichever is greater;

② The local model is to be extended transversely to the nearest diaphragm web in the lower stool on each side of the fine mesh zone (i.e. to the adjacent double bottom girder). The end diaphragms need not be modeled;

③ Longitudinally, the model is to cover one floor space aft of the aft lower stool – inner bottom connection and one floor space forward of the forward lower stool – inner bottom connection.

(3) Diaphragm webs, brackets inside the lower stool and stiffeners on the stool plates are to be modeled at their actual positions within the extent of the local model. Shell elements are to be used for modeling of diaphragms and brackets. The first vertical or horizontal stiffeners on the lower stool plate and the first longitudinal stiffeners on the inner bottom are to be represented by shell elements, other stiffeners may be represented by beam elements. Figure 5.6.2 shows a typical finite element model of the lower stool - inner bottom connection.

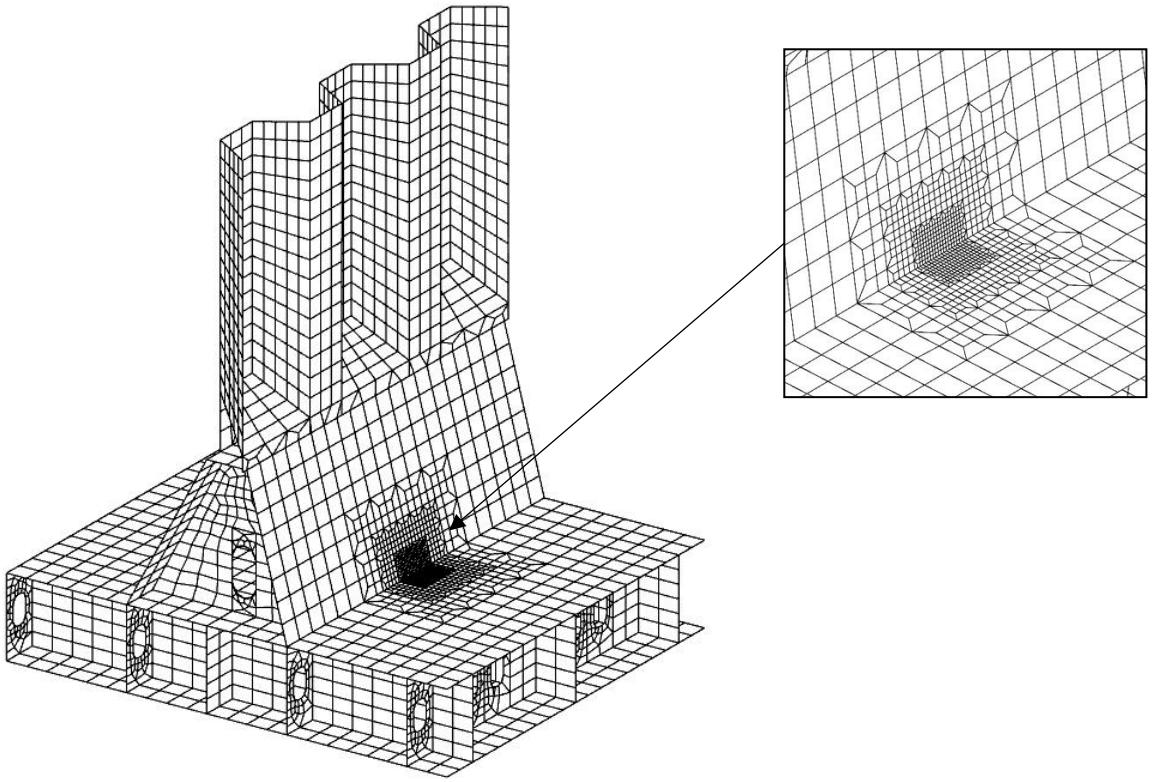


Figure 5.6.2 Connection between inner bottom and lower stool plate

5.6.3 Lower stool – corrugated bulkhead connection

(1) The modeling requirements in this subparagraph are applicable to the connection between lower stool knuckle and corrugated bulkhead.

(2) Where a separate local finite element model is used, the minimum extent of the local model is as follows:

① Vertically, from the bottom of the lower stool to a level at least 2 m above the upper shelf plate of the lower stool;

② The local model is to be extended transversely to the nearest diaphragm web in the lower stool on each side of the fine mesh zone (i.e. to the adjacent double bottom girder). The end diaphragms need not be modeled.

③ Longitudinally, the model is to cover one floor space aft of the aft lower stool – inner bottom connection and one floor space forward of the forward lower stool – inner bottom connection.

(3) Diaphragm webs, brackets inside the lower stool and stiffeners on the stool plates are to be modeled at their actual positions within the extent of the local model. Shell elements are to be used for modeling of diaphragms and bracket. The first vertical or horizontal stiffeners on the lower stool plate are to be represented by shell elements, other stiffeners may be represented by beam elements. Figure 5.5.3 shows a typical finite element model of the lower stool - corrugated bulkhead connection..

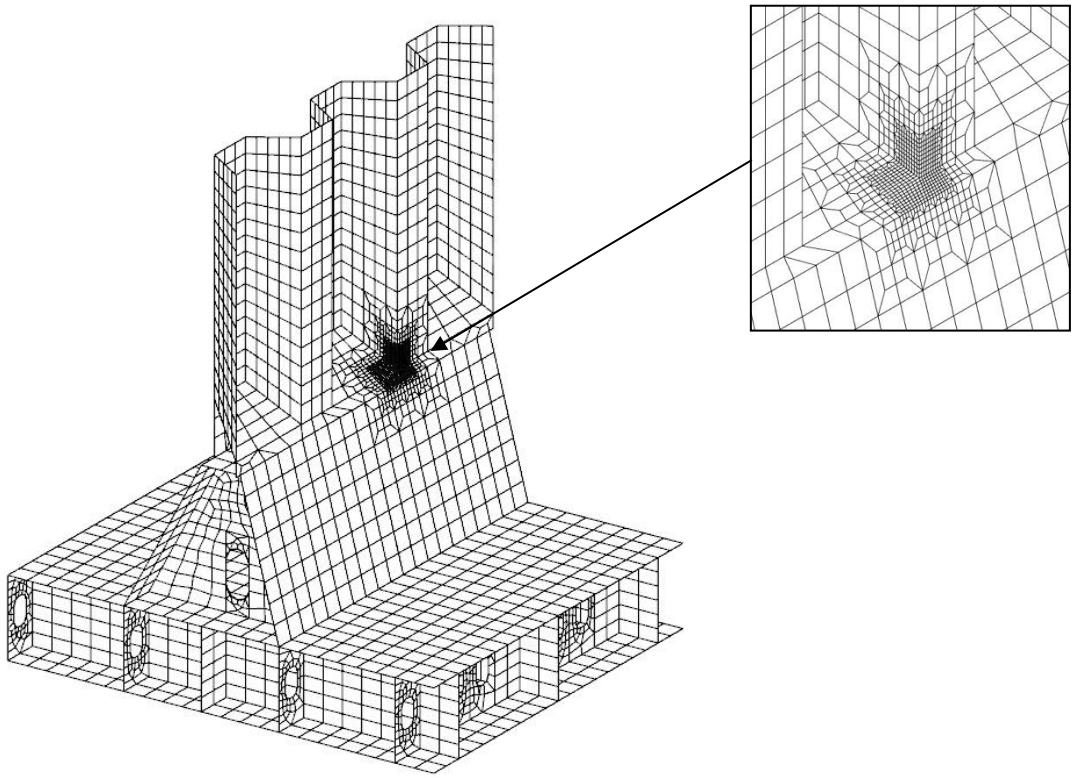


Figure 5.6.3 Connection between corrugated bulkhead and lower stool

5.6.4 Side frame bracket to hopper sloping plate connections

(1) The modeling requirements in this subparagraph are applicable to the side frame to hopper sloping plate bracket connections.

(2) Shell elements are to be used for modeling the side frame bracket, hopper tank sloping plate and adjacent stiffeners. Figure 5.6.4 shows a typical finite element model of the side frame bracket to hopper sloping plate connection.

(3) Where a separate local finite element model is used, the minimum extent of the local model is to be according to the following:

① Longitudinally, the model is to cover two web frame spaces (i.e. one web frame space extending either side of the bracket connection of interest). Transverse web frames at the end of the local model need not be represented in the local model;

② Vertically, the model is to extend from the baseline to the bottom of the topside tank sloping plate;

③ Transversely, the model is to extend from the ship side to the adjacent double bottom side girder.

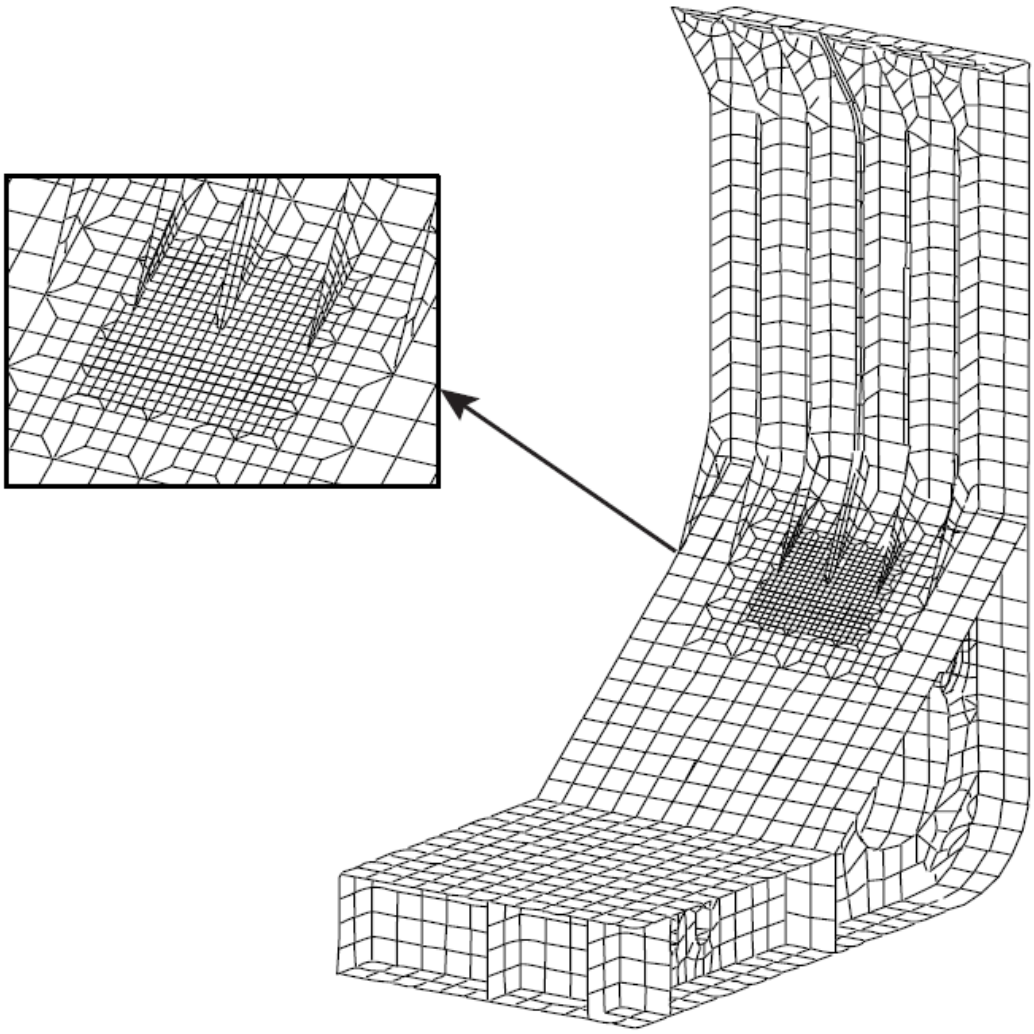


Figure 5.6.4 Side frame bracket to hopper sloping plate connections

5.6.5 Side frame bracket to the upper sloping / flat bottom wing tank connections

(1) The modeling requirements in this subparagraph are applicable to the side frame bracket to upper sloping/flat bottom wing tank connections.

(2) Shell elements are to be used for modeling the side frame bracket, upper sloping or flat bottom plate and adjacent stiffeners. Figure 5.6.5 shows a typical finite element model of the side frame toe end to hopper sloping plate connection.

(3) Where a separate local finite element model is used, the minimum extent of the local model is to be according to the following:

① Longitudinally, the model is to cover two web frame spaces (i.e. one web frame space extending either side of the bracket connection of interest). Transverse web frames at the end of the local model need not be represented in the local model;

② Vertically, the model is to extend from the deck level to the top of the hopper sloping plate;

③ Transversely, the model is to extend from the ship side to the hatch coaming corresponding to the upper sloping wing tank.

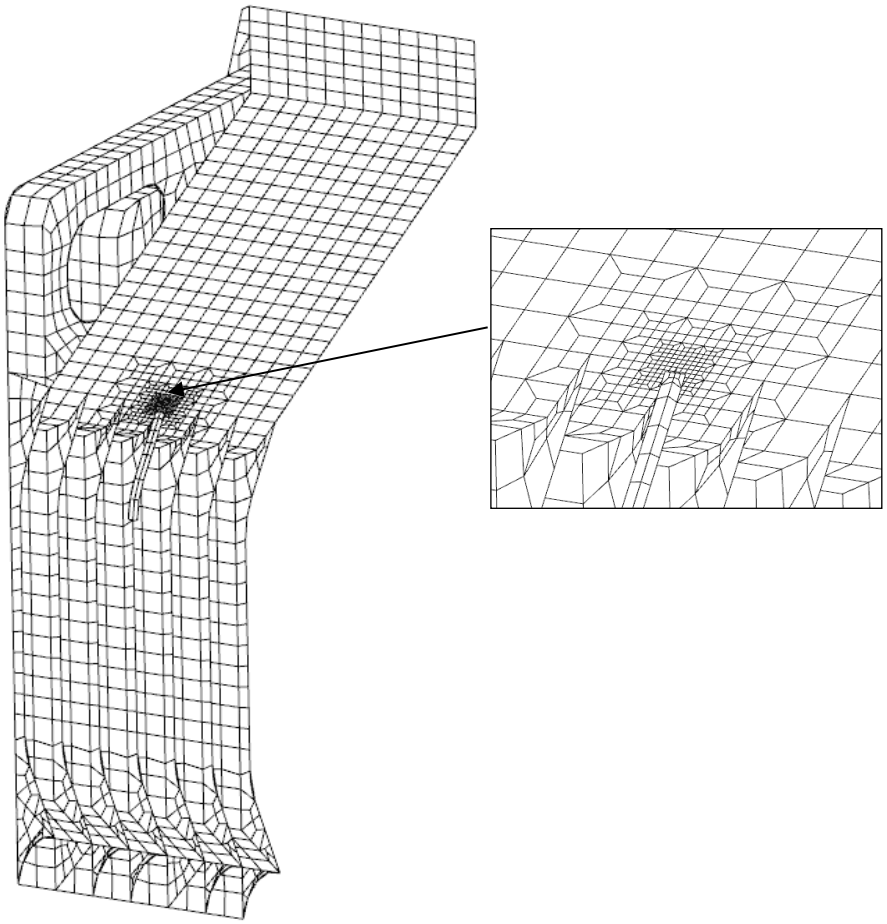


Figure 5.6.5 Side frame bracket to the upper sloping / flat bottom wing tank connections

5.6.6 Hatch coaming end bracket to the deck plating connection

(1) The modeling requirements in this subparagraph are applicable to hatch coaming end bracket to the deck plating connection.

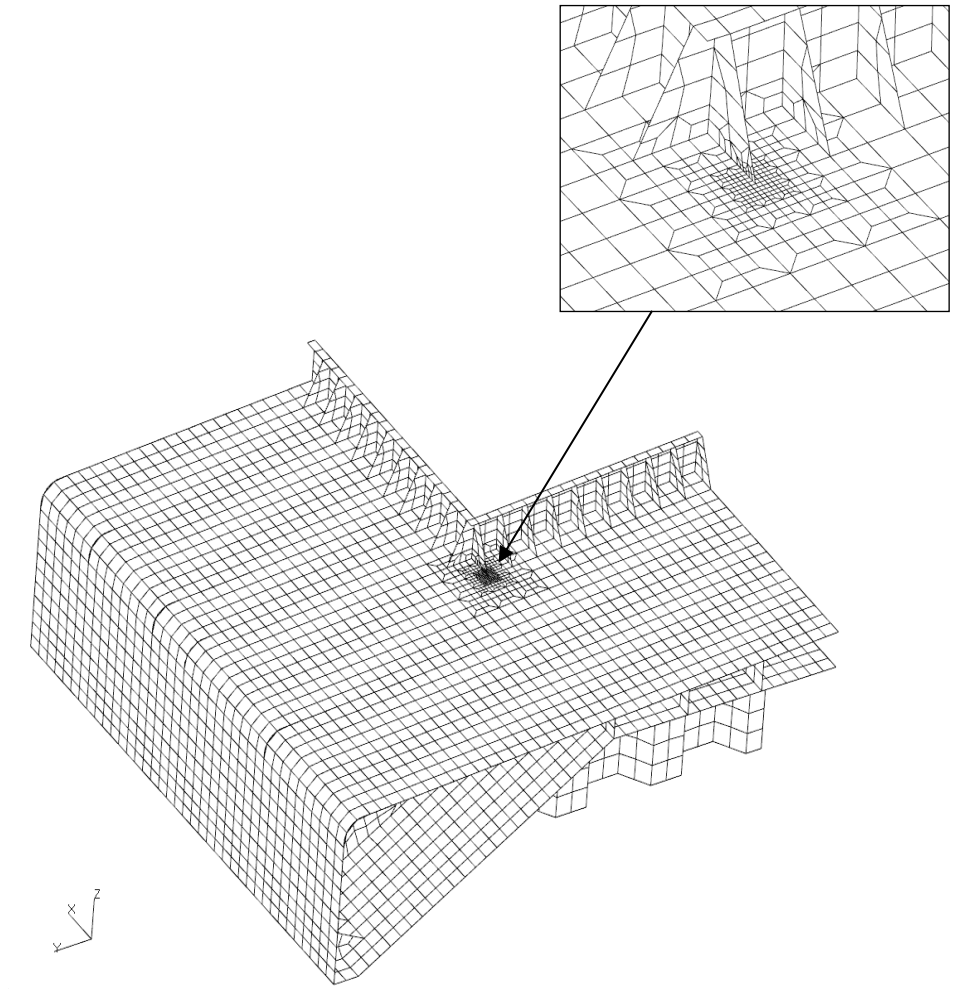
(2) Where a separate local finite element model is used, the minimum extent of the local model is to be according to the following:

① Transversely, over the half-breadth of the ship;

② Longitudinally, from the midpoint of the compartment to the adjacent cargo hold up to and including the full width of the cross deck;

③ Vertically, from the top plate of coaming to the intersection of the topside tank sloping plate with the side or inner side shell.

(3) The primary supporting members and coaming stays are to be represented by shell finite elements. Figure 5.6.6 shows a typical FE model of the toe connection of a longitudinal hatch coaming end bracket to the deck plating.



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Figure 5.6.6 Hatch coaming end bracket to the deck plating connection

CHAPTER 6 FATIGUE STRENGTH OF PUMP TOWER

6.1 General provisions

6.1.1 This Chapter is applicable to fatigue strength assessment of pump tower structure of membrane tank LNG carrier.

6.1.2 Where not covered in this Chapter, the requirements of Chapter 5 of CCS Guidelines for Survey of Membrane Tank LNG Carriers are to be complied with.

6.1.3 For fatigue strength assessment of pump tower structure, the No.2 cargo tank close to the bow is to be taken as the target tank for sloshing load calculation.

6.1.4 Fatigue strength assessment process of pump tower structure is as shown in Figure 6.1.4 of this Chapter.

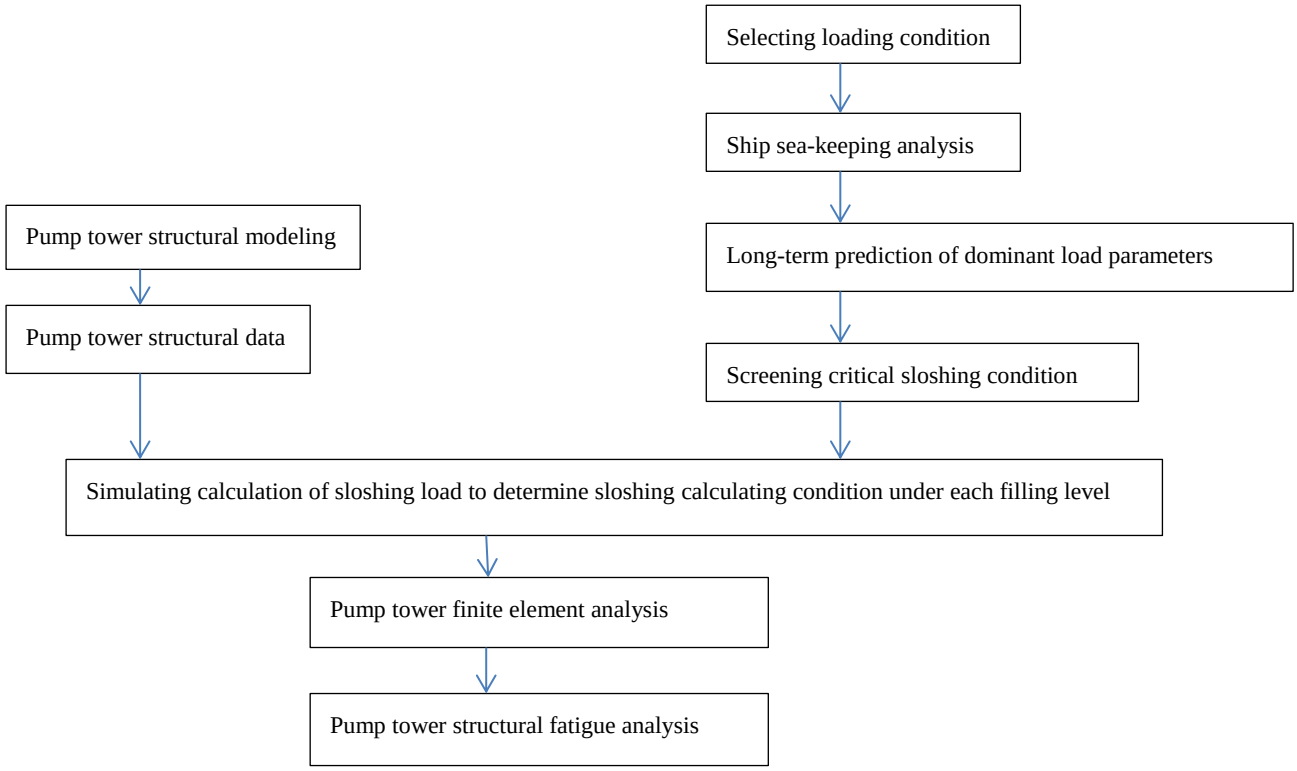


Figure 6.1.4 Pump tower fatigue analysis process

6.2 Loading conditions and filling level

6.2.1 Two loading conditions set in Table 6.2.1 of this Chapter are to be selected as the calculation conditions used for ship sea-keeping analysis. For full load condition, filling level not less than 50%*h* in 6.2.2 of this Chapter is to be used. For ballast condition, filling level less than 50%*h* in 6.2.2 of this Chapter is to be used.

Loading conditions for sea-keeping analysis Table 6.2.1

No.	Loading condition	Draught
1	Full load condition	Summer load line draught
2	Ballast condition	Ballast draught at arrival

6.2.2 In addition to all filling levels in the loading manual, 5%*h*, 10%*h*, 70%*h* and 95%*h* are to be selected as standard filling levels under consideration. Where additional filling levels are required, detailed data of filling level and service time proportion under each filling level are to be provided by the designer.

6.2.3 If service time proportion under each filling level is not provided by the designer, even distribution may be assumed.

6.3 Ship sea-keeping analysis

6.3.1 Ship sea-keeping analysis based on equivalent design wave approach is mainly used for:

(1) obtaining response amplitude operators (RAO) of dominant load parameters to determine critical sloshing condition;

(2) obtaining Weibull shape parameter of dominant load parameters to determine long-term distribution of fatigue stress;

(3) determining long-term prediction value of dominant load parameters for calculating sloshing load.

6.3.2 Equivalent design wave approach

(1) For unrestricted service, the long-term distribution of wave loads is calculated by combining the short-term predictions into the long-term predictions based on the existing information on wave statistics, in which the extreme value of certain probability level of exceedance is taken;

(2) A method of short-term extreme value prediction is used for the specific service. At a given probability level, the sea condition corresponding to the highest wave height is to be obtained, and the short-term extreme values are calculated based on this sea condition;

(3) For fatigue analysis, the probability level of wave long-term extreme prediction value is 10^{-4}.

6.3.3 Dominant load parameters

(1) For transverse motion, roll motion (i.e. roll angle) and transverse acceleration are taken;

(2) For longitudinal motion, pitch motion (i.e. pitch angle) and longitudinal acceleration are taken.

6.3.4 Environmental data

(1) For unrestricted service, the North Atlantic wave data used are taken from the Wave Scatter Diagram of North Atlantic in IACS Rec.No34, and two-parameter Bretschneider spectrum function is recommended;

(2) For specific service, a specific wave scatter diagram for this area is generally used. A JONSWAP function is used for the wave spectrum.

6.4 Sloshing conditions

6.4.1 General provisions

Sloshing conditions are based on different wave heading angle and wave encounter frequency. Each filling level includes a set of critical sloshing conditions, and the most critical sloshing condition under this filling level can be selected.

6.4.2 Determination of critical sloshing condition

(1) The following three principles are to be complied with in determining the critical sloshing condition:

① RAO is in the vicinity of maximum value;

② the encounter period is in proximity to the sloshing motion period;

③ the wave heading angle is within the range of maximum effects.

(2) Based on the above principles, conditions for determining a critical sloshing condition are indicated in Table 6.4.2 of this Chapter.

Conditions for determining a critical sloshing condition **Table 6.4.2**

Motion	Formula for the conditions	Remarks
Transverse motion	$\left\|T_y - T_e\right\| < 0.3T_y$	T_y and T_e are natural period of tank transverse motion and wave encounter period respectively
	$\mathrm{RAO}(\beta,\omega) > 0.7\max\left[\mathrm{RAO}(\beta,\omega)\right]$	RAO is corresponding to the dominant load parameter
	$60^0 \le \beta \le 90^0$	Taking into account beam sea
Longitudinal motion	$\left\|T_x - T_e\right\| < 0.3T_x$	T_y and T_e are natural period of tank transverse motion and wave encounter period respectively
	$\mathrm{RAO}(\beta,\omega) > 0.7\max\left[\mathrm{RAO}(\beta,\omega)\right]$	RAO is corresponding to the dominant load parameter
	$0^0 \le \beta \le 30^0$	Taking into account head sea

6.4.3 Calculating sloshing condition

(1) According to sloshing motion period under each filling level, most critical sloshing condition under each filling level is obtained at maximum pump tower force in positive direction and reverse direction respectively;

(2) Calculation condition for pump tower fatigue analysis is to be based on most critical sloshing condition under each filling level.

6.5 Finite element analysis of pump tower structure

6.5.1 Structural modeling

Finite element structural model and boundary condition of pump tower structure are to comply with relevant requirements of Section 5, Chapter 5 of CCS Guidelines for Survey of Membrane Tank LNG Carriers.

6.5.2 Fatigue load

(1) Sloshing load

The liquid velocity and acceleration along the centerline of the pump tower can be obtained by means of the direct calculation of sloshing motion. The sloshing-induced force on the pump tower, i.e. Morison force $\vec{F}_M$, is calculated by the following formula:

$$\vec{F}_M = \frac{1}{2}\rho C_d \vec{U}(z)\left|\vec{U}(z)\right| D + \frac{\pi}{4}\rho C_m \vec{a}(z) D^2 \qquad \text{N/m}$$

where: ρ—fluid density, in kg/m^3;

$U(z)$—liquid velocity in the pump tower pipe centerline normal to the member, in m/s;

$a(z)$—liquid acceleration in the pump tower pipe centerline normal to the member, in m/s^2;

D—diameter of transverse section of pump tower, in m;

C_d—drag coefficient of Morison, normally taken as 1.2;

C_m—inertia coefficient of Morison, normally taken as 2.0.

The change of Morison force along the length and vertical direction of the member is to be taken into account in loading the FE model. The combined Morison force $\vec{F}_l$ acting on a structural member of the length of l is:

$$\vec{F}_l = \int_0^l \left[\frac{1}{2} \rho C_d \vec{U}(z) \left| \vec{U}(z) \right| D + \frac{\pi}{4} \rho C_m \vec{a}(z) D^2 \right] dl \qquad \text{N}$$

(2) Inertial forces

The impact of ship motion and gravity are to be considered in the FE model. Inertia accelerations of pump tower are given by:

$$\begin{cases} a_x = \ddot{\xi}_1 - (y_C - y_G)\ddot{\theta}_3 + (z_C - z_G)\ddot{\theta}_2 - g\theta_2 \\ a_y = \ddot{\xi}_2 + (x_C - x_G)\ddot{\theta}_3 - (z_C - z_G)\ddot{\theta}_1 + g\theta_1 \\ a_z = \ddot{\xi}_3 - (x_C - x_G)\ddot{\theta}_2 + (y_C - y_G)\ddot{\theta}_1 - g \end{cases}$$

where: a_x, a_y and a_z——inertia accelerations of the pump tower along X, Y and Z axes, in m/s^2;

x_C, y_C and z_C——three dimensional coordinates of the point considered, in m;

x_G, y_G and z_G——three dimensional coordinates of the ship's center of gravity, in m.

6.5.3 Finite element analysis

Each sloshing calculating condition corresponds to two sets of positive and reverse direction sloshing loads. Two sets of loads are loaded on pump tower structure finite element model respectively, and inertia loads at the same direction are superimposed at the same time. Nominal stress on each pole section of pump tower tubular joints is obtained by static analysis calculation.

6.6 Fatigue analysis

6.6.1 The design fatigue life of pump tower of membrane tank LNG carrier is not to be less than 20 years.

6.6.2 Fatigue strength of each tubular joint in pump tower structure is to be checked. Typical tubular joints include thick pipe and thin pipe. The thick pipe is the chord while the thin one is the brace (including horizontal brace and sloping brace).

6.6.3 Hot spot stress of tubular joints

Hot spot stress of tubular joints can be calculated according to stress concentration factor after nominal stress is obtained. For each checked section, 8 positions are selected for hot spot stress calculation, as shown in Figure 6.6.3 of this Chapter.

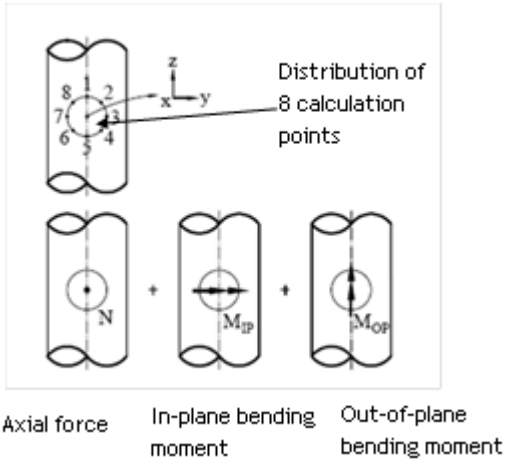


Figure 6.6.3 Distribution of hot spot stress calculation points

The hot spot stress combination of above 8 calculation points can be obtained by following formulae:

$$\sigma_1 = SCF_A\sigma_x - SCF_I\sigma_{my}$$

$$\sigma_2 = SCF_A\sigma_x - \frac{1}{2}\sqrt{2}SCF_I\sigma_{my} + \frac{1}{2}\sqrt{2}SCF_O\sigma_{mz}$$

$$\sigma_3 = SCF_A\sigma_x + SCF_O\sigma_{mz}$$

$$\sigma_4 = SCF_A\sigma_x + \frac{1}{2}\sqrt{2}SCF_I\sigma_{my} + \frac{1}{2}\sqrt{2}SCF_O\sigma_{mz}$$

$$\sigma_5 = SCF_A\sigma_x + SCF_I\sigma_{my}$$

$$\sigma_6 = SCF_A\sigma_x + \frac{1}{2}\sqrt{2}SCF_I\sigma_{my} - \frac{1}{2}\sqrt{2}SCF_O\sigma_{mz}$$

$$\sigma_7 = SCF_A\sigma_x - SCF_O\sigma_{mz}$$

$$\sigma_8 = SCF_A\sigma_x - \frac{1}{2}\sqrt{2}SCF_I\sigma_{my} - \frac{1}{2}\sqrt{2}SCF_O\sigma_{mz}$$

where: SCF_A, SCF_I and SCF_O—stress concentration factor of tubular joints, to be taken according to Table 6.6.5 of this Chapter;

σ_x, σ_{my} and σ_{mz} —nominal axial stress, nominal in-plane bending stress and nominal out-of-plane bending stress on each circular pipe element respectively, in N/mm^2.

6.6.4 Design stress range

(1) Hot spot stress range of tubular joints is to be calculated according to following formula:

$$S_{h,i(k)} = \left|\sigma_{i(k)} - \sigma'_{i(k)}\right| \qquad \text{N/mm}^2$$

where: $\sigma_{i(k)}$ —hot spot stress of ith point under positive direction sloshing load and sloshing

condition "(k)" considered, in N/mm^2;

$\sigma'_{i(k)}$ —hot spot stress of ith point under reverse direction sloshing load and sloshing condition "(k)"considered, in N/mm^2.

(2) Design stress range $S_{D(k)}$ under sloshing calculating condition "(k)" is to be calculated according to following formula:

$$S_{D(k)} = \max(S_{h,i(k)}) \qquad \text{N/mm}^2$$

6.6.5 Tubular joint stress concentration factor

Tubular joint stress concentration factor *SCF* is calculated according to parameter formula in Table 6.6.5 of this Chapter.

Tubular joint stress concentration factor formula **Table 6.6.5**

Type of tubular joint		α	Axial load SCF_A	In-plane bending moment SCF_I	Out-of-plane bending moment SCF_O
Chord SCF_{chord}	K	1.0	αA	$2/3A$	$3/2A$
	T&Y	1.7			
Brace SCF_{brace}			$1.0+0.375(1+\sqrt{\eta/\mu}\cdot \text{SCF}_{\text{chord}}) \geq 1.8$		

where: $A = 1.8\sqrt{\gamma}\eta\sin\theta$.

6.6.6 Fatigue damage of pump tower tubular joints

(1) The accumulative damage of pump tower tubular joints under sloshing calculating condition "(k)" is to be calculated according to following formula:

$$D_k = \frac{N_D \alpha_k}{K} \frac{S_{D(k)}{}^m}{(\ln N_L)^{m/\xi_k}} \mu_k \Gamma\left(1+\frac{m}{\xi_k}\right)$$

where: α_k —time distribution factor under loading condition "(k)", see 6.2.2 and 6.2.3 of this Chapter;

$S_{D(k)}$ —design stress range, see 6.6.4(2);

N_L —circulation cycle for load spectrum in restoring period, to be taken as 10^4;

K—factor for S-N curve, to be taken as $10^{12.146}$;

ξ_k —Weibull shape parameter for sloshing calculating condition "(k)", to be calculated according to 6.3 of this Chapter:

$$\mu_k = 1.0 - \frac{\gamma\left(1+\frac{m}{\xi_k}, \nu_k\right) - \nu_k^{-\frac{\nabla m}{\xi_k}} \gamma\left(1+\frac{m+\nabla m}{\xi_k}, \nu_k\right)}{\Gamma\left(1+\frac{m}{\xi_k}\right)}$$

$$\nu_k = \left(\frac{S_q}{S_{D(k)}} \right)^{\xi_k} \ln N_L$$

S_q—stress amplitude values at intersection point of two-slope S-N curves, $S_q = 52.63$ MPa，if plate thickness is more than 25mm, S_q is to be corrected:

$$S_q = 52.63 \Big/ \left(\frac{t}{25} \right)^n \quad \text{MPa}$$

n—correction factor，when $SCF \le 10, n = 0.25$; when $SCF > 10$， $n = 0.3$;

For other symbols, see 3.5.1, Chapter 3 of the Guidelines.

(2) Total accumulative damage of pump tower tubular joints is to be calculated according to following formula:

$$D = \sum D_k$$

where: D_k—accumulative damage of pump tower tubular joints under each sloshing condition considered, see (1).

6.6.7 Fatigue life calculation

Fatigue life of pump tower tubular joints is to be calculated according to following formula:

$$T_F = \frac{20}{D}$$

where: D—total accumulative damage of pump tower tubular joints, see 6.6.6(2) of this Chapter.

APPENDIX HULL STRUCTURAL DETAILS OF BULK CARRIERS, OIL TANKERS AND CONTAINER SHIPS

All contents of Appendix 3 of CCS Guidelines for Fatigue Strength of Ship Structure, 2007 are kept.