

Guidelines on Fatigue Design Assessment of Ship Structures

2021



IRCLASS
Indian Register of Shipping

History of Revision/Updates

- First publication: March 2021

Guidelines for
Fatigue Assessment of Ship Structures
2021

Contents

Sections

1. General Principles

- 1.1 Application
- 1.2 Definitions
- 1.3 Assumptions
- 1.4 Types of environment
- 1.5 Corrosion model
- 1.6 Fatigue failure modes
- 1.7 Methodology
- 1.8 Loads
- 1.9 Loading Conditions
- 1.10 Reference Co-ordinate System

2. Fatigue Evaluation

- 2.1 Fatigue analysis methodology
- 2.2 Acceptance criteria
- 2.3 Reference stresses for fatigue assessment
- 2.4 S-N Curves
- 2.5 Fatigue damage calculation
- 2.6 Weld improvement methods

3. Simplified Stress Analysis

- 3.1 General
- 3.2 Fatigue approach for longitudinal end connections
- 3.3 Axial and bending stress
- 3.4 Global Axial Stress
- 3.5 Local bending stress
- 3.6 Stress due to relative displacements of primary supporting members
- 3.7 Stress concentration factor

4. Finite Element Stress Analysis

- 4.1 General
- 4.2 Type of details
- 4.3 FE model
- 4.4 FE modelling for hot spot stress calculation
- 4.5 Hot spot stress for ordinary details different from web-stiffened cruciform joints
- 4.6 Hot spot stress for web-stiffened cruciform joint
- 4.7 Limitations of hot spot stress approach
- 4.8 Method for hot spot stress extraction

Appendix – A Detail Design Standard

Abbreviations:

<i>AP</i>	<i>: Aft perpendicular</i>
<i>BL</i>	<i>: Base line</i>
<i>CG</i>	<i>: Centre of gravity</i>
<i>CL</i>	<i>: Centre line</i>
<i>FE</i>	<i>: Finite element</i>
<i>FEM</i>	<i>: Finite Element Method</i>
<i>FP</i>	<i>: Forward perpendicular</i>
<i>LCB</i>	<i>: Longitudinal centre of buoyancy</i>
<i>LCF</i>	<i>: Longitudinal centre of flotation</i>
<i>LCG</i>	<i>: Longitudinal centre of gravity</i>
<i>P-M spectrum</i>	<i>: Pierson–Moskowitz spectrum</i>
<i>TCG</i>	<i>: Transverse centre of gravity</i>
<i>VCG</i>	<i>: Vertical centre of gravity</i>
<i>FAS</i>	<i>: Fatigue Assessment based on simplified approach</i>

Section 1

General Principles

1.1 Application

1.1.1 These guidelines provide a methodology and procedures to perform fatigue analysis for steel ships in accordance with the *IRS Rules and Regulations for the Construction and Classification of Steel Ships* (hereinafter referred to, as the Rules). These Guidelines are to be used in conjunction with the *Guidelines on Structural Assessment of Ships based on Finite Element Method*, IRS-G-DES-05.

1.1.2 The additional class notation **FDA (Fatigue Design Assessment)** will be assigned to vessels where a fatigue design assessment has been carried out in accordance with the relevant requirements of the Rules and these Guidelines for unrestricted service. **FDA** notation is mandatory for ships of length greater than or equal to 150 m and may be optionally applied for ships of length greater than 90 m. If fatigue assessment is carried out for a number of years >25 and/ or restricted service, then the class notation **FDA (N, specific area of operation)**, would be assigned; where 'N' denotes the number of years.

1.1.3 These guidelines provide a simplified fatigue analysis procedure. The reference stress for fatigue may be evaluated using Prescriptive (Simplified beam theory) method or using the Finite Element (FE) method.

1.1.4 Fatigue assessment of ships with non-conventional shapes or with restricted service notation will be specially considered.

1.1.5 Fatigue assessment is performed for ship's structural details to prevent the following types of fatigue failure:

- Fatigue cracks initiating from the toe of the weld and propagating into the plate.
- Fatigue cracks initiating from free edge of non-welded details.

1.1.6 The structural details to be checked for fatigue assessment by simplified stress analysis are given in Section 3 and by finite element stress analysis are given in Section 4. Additional specific details may be requested to be checked on a case-by-case basis by IRS.

1.1.7 The fatigue strength assessment indicated in these guidelines is applicable for steel material with specified minimum yield stress less than or equal to 390 [N/mm²]. For steel with specified minimum yield stress value higher than 390 [N/mm²] and for steels with improved fatigue performance, the S-N curves are to be specially considered on case to case basis.

1.2 Definitions

1.2.1 *Fatigue damage ratio*: Ratio of the number of applied stress cycles and the corresponding number of stress cycles to failure at constant stress range.

1.2.2 *Fatigue life*: Total time corresponding to the number of stress cycles required to cause fatigue failure of the component. The fatigue life is generally expressed in terms of number of years.

1.2.3 *Fatigue stress*: Fatigue stress is the stress including corrections, for e.g. mean stress, thickness effect, surface finishing and material factor, relevant for fatigue assessment purpose, i.e.:

- Hot spot stress for welded details
- Local stress at free plate edge

1.2.4 Hot spots: Hot spots are locations in the structure where fatigue cracks may initiate due to the combined effect of nominal structural stress fluctuation and stress concentration effects due to the weld geometry.

Hot spots may be located at:

- Weld toe.
- Weld root of partial penetration or fillet weld.

1.2.5 Hot spot stress: Hot spot stress is a local stress at the weld toe 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. It is the value of stress on the surface at the hot spot also known as geometric stress or structural stress.

- The hot spot stresses to be considered correspond to the two principal stresses on the surface plating at the weld toe. The first principal stress acts within $\pm 45^\circ$, perpendicular to the weld and the second principal stress acts outside $\pm 45^\circ$. Refer Fig.1.2.1.
- The hot spot stress is to be obtained by multiplying the nominal stress by a Stress Concentration Factor (SCF), according to Section 3 or directly by a very fine mesh FE analysis, according to Section 4.

1.2.6 Local stress at free edge: Local stress at free edge is the stress at the plate free edge derived using finite element analysis according to Section 4, Cl. 4.2.4.

1.2.7 Load case: Load case is the state of the ship subjected to a combination of loads.

1.2.8 Local notch: A local notch is a localized geometric feature, such as the weld toe, which causes stress concentration. The local notch does not modify the structural stress but generates a non-linear stress peak.

1.2.9 Macro-geometric discontinuity: A global discontinuity, the effect of which is usually not taken into account in structural details, such as large openings, a curved part in a beam, a bend in a flange, and eccentricity in lap joints etc.

1.2.10 Macro-geometric effect: A stress raising effect due to macro-geometry in the vicinity of the welded joint, but not due to the welded joint itself.

1.2.11 Membrane stress: Average normal stress across the thickness of a plate or shell.

1.2.12 Nominal stress: Nominal stress is a general stress in a structural component taking into account macro-geometric effect including effective breadth of flanges but disregarding the stress concentration due to structural discontinuities and the presence of welds. Nominal stress is to be obtained either using coarse or fine mesh FE analysis, as required in Section 4 or using analytical calculation based on beam theory with effective breadth of flanges included, as required in Section 3. Refer Fig. 1.2.1.

1.2.13 Notch stress: Notch stress is a peak stress in a notch such as the root of a weld or the edge of a cut-out. This peak stress takes into account the stress concentrations due to the presence of structural geometry and notches. Refer Fig.1.2.1.

1.2.14 *Palmgren-Miner rule*: Method for estimating fatigue life under variable amplitude loading from the constant amplitude S-N curve. Often referred to as Miner's rule. Fatigue failure is expected when the Miner sum reaches unity.

1.2.15 *S-N curve*: Graphical presentation of the dependence of fatigue life (N) on fatigue strength (S).

1.2.16 *Stress cycle*: A part of a stress history containing a stress maximum and a stress minimum.

1.2.17 *Stress range*: The difference between stress maximum and stress minimum in a stress cycle.

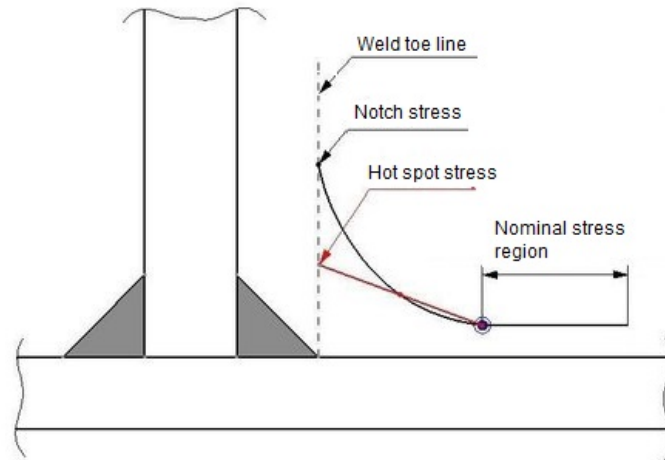


Fig. 1.2.1: Stress Definitions

1.3 Assumptions

1.3.1 The following assumptions are made in the fatigue assessment:

- A linear cumulative damage model, i.e. Palmgren-Miner's Rule is used in connection with the design S-N curves with 97.7% probability of survival.
- Design fatigue life, T_{DF} , is taken not less than 25 years.
- Rule quasi-static wave induced loads are based on North Atlantic wave environment. They are determined at 10^{-2} probability level of exceedance.
- Net thickness approach is used but FE analysis can be gross scantling also, based on stress correction factor (Cl. 1.5.2).
- Type of stress used for crack initiating at the weld toe is the hot spot stress. Type of stress used for crack initiating at free edge of non-welded details is local stress at free edge.
- Long term distribution of stress range of a structural detail is assumed to follow a two-parameter Weibull distribution. Weibull shape parameter ξ is equal to 1 and the fatigue stress range $\Delta\sigma_{FS}$ is given at the reference probability level of exceedance equal to 10^{-2} .
- The acceptance criteria for fatigue checking are the total fatigue damage D to be less than or equal to 1 for the design fatigue life.

1.4 Types of environment

1.4.1 Two types of environment are considered for the fatigue detail conditions:

- in air environment
- in corrosive environment without protection

1.5 Corrosion model

1.5.1 The effects of corrosive environment on fatigue life are taken into account by means of:

- Net thicknesses approach

The net thickness, t_{net} , of a structural element is required for structural strength in compliance with the design basis. This approach clearly separates the net thickness from the thickness added to address the corrosion that is likely to occur during the operation phase of the ship.

In the “Net thickness Approach”, the required gross scantling is obtained by adding the net scantling obtained from the structural strength requirement to the total corrosion addition as defined below.

$$t_{gross_required} = t_{net_required} + t_c$$

The total corrosion addition, t_c in [mm], for both sides of the structural member is obtained by the following formula:

$$t_c = t_{c1} + t_{c2} + t_{res}$$

where,

- | | | |
|------------------|---|---|
| t_{c1}, t_{c2} | = | Corrosion addition, in [mm], on each of the two sides of the considered structural member, as defined in Table 1.5.1.1. |
| t_{res} | = | Reserve thickness, taken as 0.5[mm], also to be applied in non-corrosive environment and for stainless steel and aluminium to account for possible thickness reductions, e.g. wear and tear, grinding or under tolerance thickness. |

The fatigue assessment methods prescribed are to be assessed by applying the corrosion addition specified in Table 1.5.1.2 to the offered gross scantlings, t_{gr_off} . Half of the applied corrosion addition specified in Table 1.5.1.2 is to be deducted from both sides of the structural members being considered.

The gross offered thickness, t_{gr_off} is the gross thickness, in [mm], provided at the newbuilding stage, which is obtained by deducting any thickness for voluntary addition from the as-built thickness, as follows:

$$t_{gr_off} = t_{as_built} - t_{vol_add}$$

where,

- | | | |
|-----------------|---|--|
| t_{as_built} | = | As-built thickness, in [mm], taken as the actual thickness provided at the new building stage. |
| t_{vol_add} | = | Thickness for voluntary addition, in [mm], taken as the thickness voluntarily added as the owner’s extra margin or builder’s extra margin for corrosion wastage in addition to t_c . |

- S-N curves.

The basic design S-N curves for corrosive environment are considered to represent the fatigue capacity of material. (Refer Section 2).

Table 1.5.1.1: Corrosion addition for one side of a structural member

Sl. No.	Compartment Type	Structural Member	Corrosion Addition (tc1 or tc2)	
			General	Special case
1	Tanks for Ballast water ¹⁾ /Sea water	All members ⁷⁾	1.00	1.25 ²⁾
2	Tanks for Cargo Oil ¹⁾ and Slop Tank	All members	1.00	1.25 ²⁾
3	Tanks for Liquid Chemical	All members	1.00	
4	Tanks for fuel oil, lube oil	All members	0.50	1.00 ²⁾
5	Tanks for Brine, Urea, Bilge Tank, Drain Storage, Chain Locker	Face plates of PSM's	1.00	
		Other members	1.00	
6	Tanks for fresh water	All members	0.50	
7	Other tanks - cargo tanks only intended to carry fresh water, fuel oil, lube oil, RSW or mud.	All members	0.50	
8	Dry Bulk Cargo ³⁾	General	1.00	
		Inner bottom plating		
		Sloping stool plate of hopper tanks and lower stool	1.50	-
		Transverse bulkhead plating		
		Brackets, Frames, ordinary stiffeners and primary supporting members	1.00	1.5 ⁴⁾
9	Containers and General cargo hold	All members in hold	1.00	
10	Accommodation spaces ⁵⁾	All members	0.00	
11	Void, dry spaces and other category spaces not mentioned above ⁶⁾ .	All members	0.50	-
12	Stainless steel and aluminium (independent of compartment type)	All members	0.00	
13	External Surfaces	All members	0.50	-

(1) Ballast tank: also includes combined ballast and cargo oil tanks but does not include cargo oil tanks which may carry ballast according to Regulation 18 of MARPOL 73/78 as amended.

(2) This minimum corrosion addition is applied in the area within 1.5[m] below the top of the tank. This is applied to ballast or liquid cargo tanks with exposed weather deck as the tank top.

(3) Dry bulk cargo hold includes holds intended for the carriage of dry bulk cargoes, which may carry oil or water ballast.

(4) This minimum corrosion addition is applied in the area within 1.5[m] above the bottom of hold, e.g. inner bottom. The bottom of hold is defined as the lowest horizontal boundaries of the hold.

(5) When not covered by any sheeting, AC Room, galleys, technical areas and crew staircases are to be considered as "other compartments"

(6) Applicable for the spaces containing membrane or independent cargo tanks of gas carriers. Also applicable for semi-enclosed compartments, e.g. open ro-ro spaces.

(7) 0.5 [mm] is to be added to the plate surface exposed to ballast for the plate boundary between water ballast and heated cargo oil tanks or heated fuel/lube oil tanks/slop tanks. 0.3[mm] is to be added to each surface of the web and face plate of a stiffener in a ballast tank and attached to the boundary between water ballast and heated cargo oil tanks or heated fuel/lube oil tanks/slop tanks. Heated oil tanks are defined as tanks/slop tanks arranged with any form of heating capability (the most common type is heating coils).

(8) Dry bulk cargo carriers refers to the cargo holds of vessels with class notations BC-A, BC-B, BC-C or Ore Carrier. For single skin bulk carriers of length > 150[m], $t_{cmin} = 3.5$ [mm].

Table 1.5.1.2: Applied corrosion addition for Fatigue assessment

Structural requirement	Property/analysis type	Applied corrosion addition for structural assessment
Fatigue assessment (simplified stress analysis)	Hull girder section properties Local supporting member	0.5 t_c
Fatigue assessment (Finite Element Stress analysis)	Very fine mesh Finite Element model	0 ¹⁾²⁾
1) For ships with class notation ESP , 0.5 t_c is to be applied. Otherwise, gross offered thickness to be applied. 2) Refer Cl.1.5.2.2 when carrying out the Finite element method.		

1.5.2 Stress correction factor, f_c

1.5.2.1 The global stress is less affected by the corrosion than the local stress due to the probabilistic nature of corrosion, which gives less average corrosion on a global level compared to at a local level. The corrosion allowances are typically higher for local stress calculation than for global stress calculation.

1.5.2.2 For simplified beam model based on net scantlings t_{n50} , (refer Table 1.5.1.2), the correction factor f_c only applies to the global stresses. When using a global FE model based on net or gross offered scantlings (refer Table 1.5.1.2), the same correction factor applies to both the global and local stresses, i.e. directly on the stress. The correction factor should be taken as:

- Prescriptive fatigue strength assessment
 - $f_c = 1.0$ for local plate and stiffener bending based on t_{n50}
 - $f_c = 0.95$ for hull girder stresses based on t_{n50}
- FE based fatigue strength assessment
 - $f_c = 1.0$ for stresses based on t_{gr_off}
 - $f_c = 0.95$ for stresses based on t_{n50}

Since FE models may be based on either t_{n50} or t_{gr_off} , the notation t is used for the thickness in relation to FE analysis. However, prescriptive assessment should be based on t_{n50} .

1.6 Fatigue failure modes

1.6.1 The following fatigue crack failure modes are generally observed in the ship structure for welded or cut edge details:

- Fatigue cracks initiating from the weld toe into the base material - weld toe failure
- Fatigue cracks initiating from the weld root and propagating into the plate section under the weld - weld root failure
- Fatigue cracks initiating from the weld root and propagating through the weld throat.
- Fatigue cracks initiating from surface irregularity or notch at the free edge into the base material - cut edge failure

1.7 Methodology

1.7.1 Simplified stress analysis

Procedure based on simplified stress analysis, (Section 3), is used to determine the hot spot stress at weld toe of longitudinal stiffener end connections. Nominal stresses are calculated by using analytical method based on beam theory according to Section 3 Cl. 3.4, 3.5 and 3.6. Hot spot stresses are obtained by multiplying nominal stresses by stress concentration factors (SCF) of the considered detail according to Section 3, Cl. 3.7

1.7.2 Finite element stress analysis

Procedure based on finite element stress analysis, (Section 4), is used to determine hot spot stress at weld toe of specified structural details, from very fine mesh models.

The hot spot stress is generally highly dependent on the finite element model used for representing the structure.

General procedure for the calculation of hot spot stress at weld toe for any welded details except for web stiffened cruciform joints is given in Section 4, Cl. 4.5. Procedure for the calculation of hot spot stress at the flange connections for web stiffened cruciform joints is given in Section 4, Cl. 4.6. Calculation of local stress for non-welded area is provided in Section 4, Cl. 4.5.4.

1.7.3 A simple flowchart of fatigue strength assessment approaches used is shown in Fig. 1.7.1. The finite element based fatigue analysis procedure is elaborated in a flowchart given in Fig. 1.7.2. Fig. 1.7.3 indicates fatigue analysis procedure based on the beam theory approach.

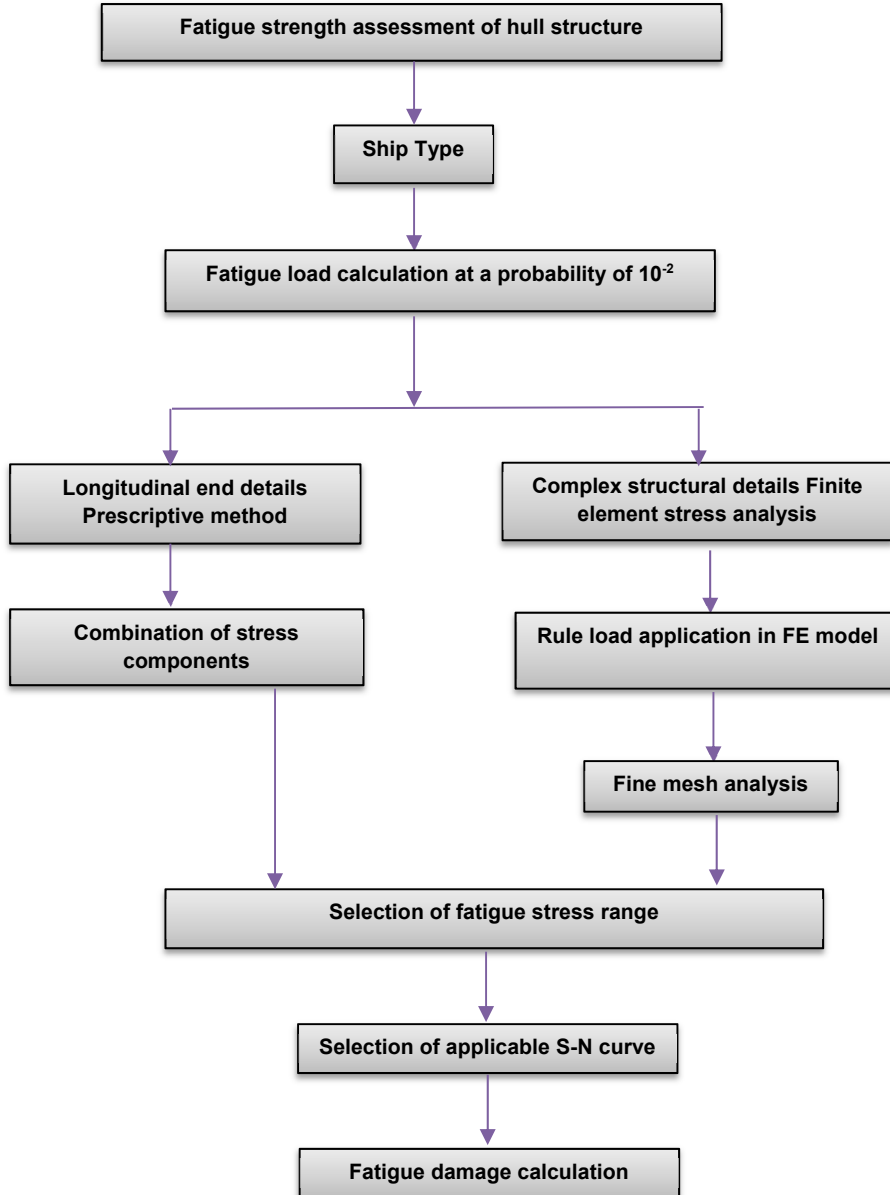


Fig. 1.7.1: Flow chart for fatigue strength assessment of hull structure

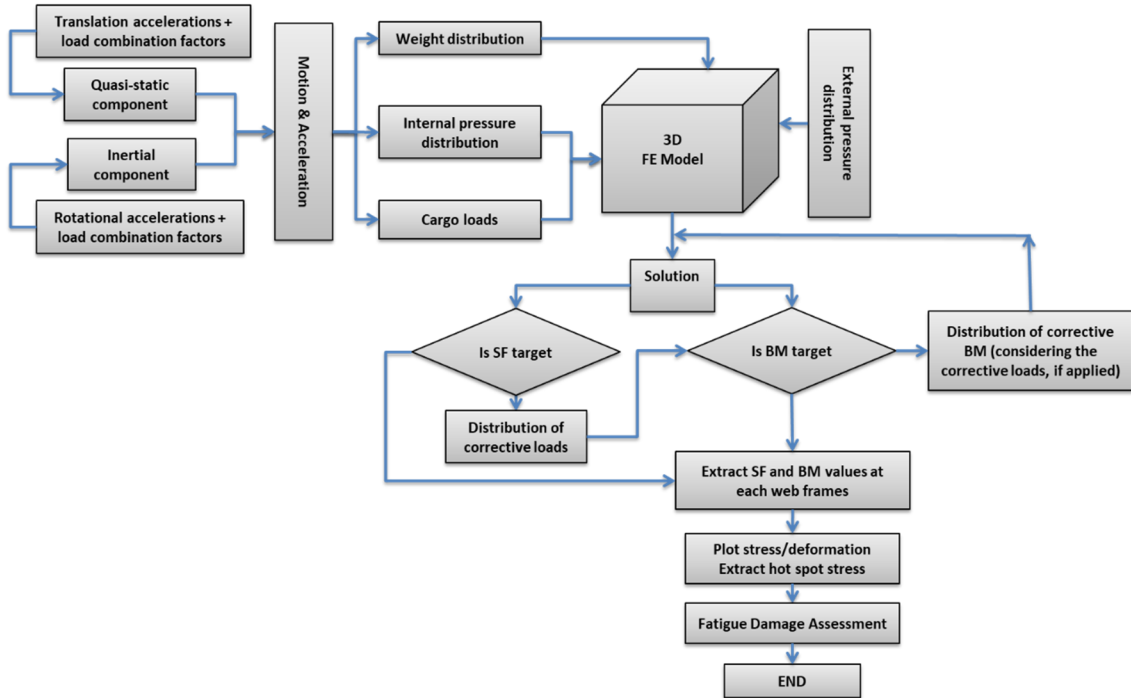


Fig. 1.7.2: Procedure for simplified fatigue using FEM

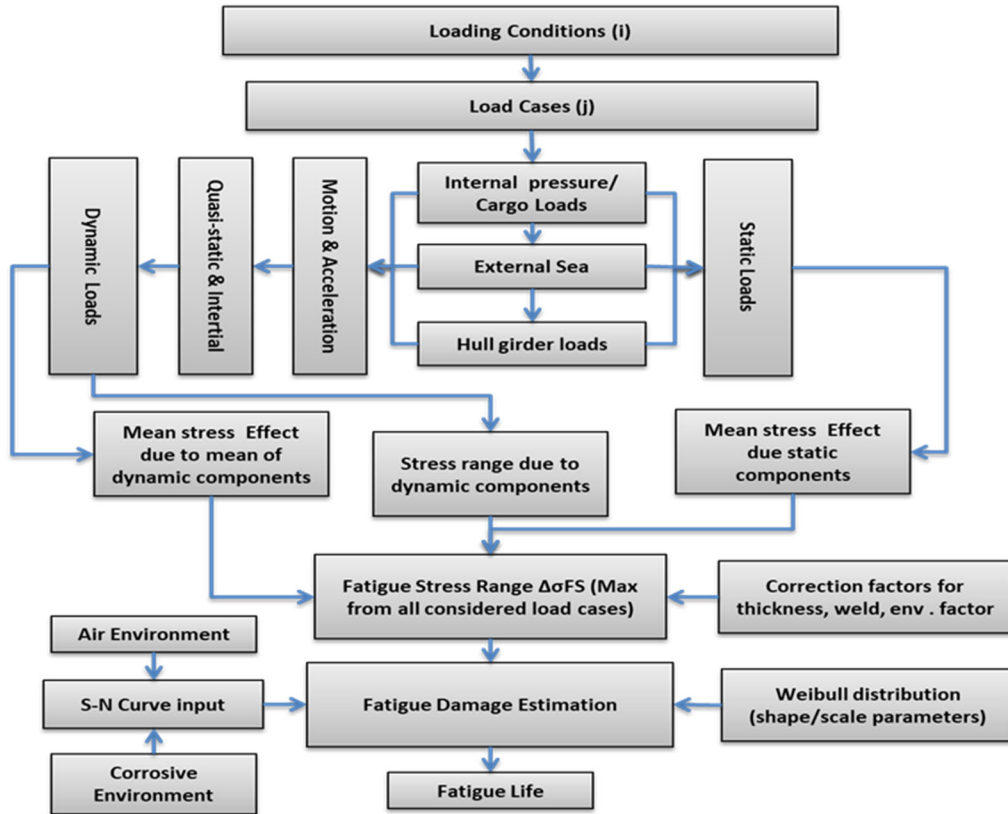


Fig. 1.7.3: Procedure for simplified fatigue using beam theory

1.8 Loads

1.8.1 The loads induced in static and dynamic condition are to be considered for fatigue analysis of ship structures which are given below:

- Hull girder loads (bending moments, torsion moment)
- Local loads (wave pressure, inertia and quasi-static loads)

1.8.2 The loads for fatigue analysis are calculated from IRS rules Part 3 Chapter 4, applying appropriate load reduction factors f_p , used in the prescriptive calculations as given in Section 3.

1.8.3 The following loads are not considered for fatigue analysis in these guidelines:

- dynamic loads resulting from main engine or propeller induced vibratory forces
- dynamic loads due to natural hull girder vibration (springing response)
- dynamic loads due to wave induced hull girder vibrations
- transient loads such as thermal stresses.
- low cycle loads such as cargo variations (cargo loading and unloading) or impact loads such as slamming, sloshing in partially filled tanks

1.9 Loading Conditions

1.9.1 Fatigue analyses are to be carried out for representative loading conditions according to the ship's intended operations.

1.9.2 For novel ship types for which standard loading conditions are generally not defined, the selection of loading conditions is to be performed in consultation with IRS.

1.9.3 Parameters related to a particular loading condition are denoted with a (j) subscript in these guidelines.

1.9.4 The loading conditions to be considered for some specific ship types and corresponding fraction of time for each loading condition, $\alpha(j)$, are defined in Table 1.9.1. These values are to be used if designers has not specified any values, for corresponding loading conditions.

Table 1.9.1: Standard values for loading conditions to be used for the fatigue analysis		
Vessel type	Full load condition	Normal/partial ballast condition
Tanker	0.5	0.5
Bulk carrier and dry Cargo ship ²⁾	0.5	0.5
MPV/ general dry cargo ship ⁴⁾	0.6 ³⁾	0.4 ³⁾
Liquefied gas carriers	0.5	0.5
Container ships	0.75 ¹⁾	0.25
Ore Carrier ²⁾	0.5	0.5
Passenger Ship ⁵⁾	0.75	0.25
RO-RO ⁵⁾	0.75	0.25
Others ⁶⁾	--	--

1) Two loading conditions, a minimum and maximum hogging condition, is to be checked separately. The lowest fatigue life from the two loading conditions is representative of the calculated fatigue life. For each loading condition, the ballast tank is to be considered as full (to the tank top) 70% and empty 30% of the time, and the fatigue damage is to be calculated as the sum of these two contributions.
2) Applicable for ore carrier, bulk carrier and dry cargo ships except MPV/general dry cargo ships having a long centre cargo hold.
3) For each loading condition, the ballast tank shall be considered as full (to the tank top) 30% and empty 70% of the time, and the fatigue damage shall be calculated as the sum of these two contributions for each loading condition. In the partial condition with empty ballast tanks, bulk cargo pressures should be considered for the hold filled with 70% of the maximum cargo mass and a density of $\rho_c = 1.0$.
4) Applicable for MPV/general dry cargo ships having a long centre cargo hold.
5) Values used when global FE analysis is required. Prescriptive assessment of longitudinal end connections is not required for passenger vessels.
6) Other ships will be specifically considered.

1.10 Reference Co-ordinate System

1.10.1 The ship geometry, motion, accelerations and loads are defined with respect to right handed coordinate system are, as shown in **Error! Reference source not found.** 1.10.1.

1.10.2 The sign conventions (Refer Fig. 1.10.2) for hull girder loads are as follows:

- The vertical bending moments M_{sw} and M_{wv} are positive when they induce tensile stresses in the strength deck (hogging bending moment) and negative when they induce tensile stresses in the bottom (sagging bending moment).
- The vertical shear forces Q_{sw} , Q_{wv} are positive in the case of downward resulting forces acting aft of the transverse section and upward resulting forces acting forward of the transverse section under consideration.
- The horizontal bending moment M_{wh} is positive when it induces tensile stresses in the starboard side and negative when it induces tensile stresses in the port side.
- The torsional moment M_{wt} is positive in the case of resulting moment acting aft of the transverse section following negative rotation around the X-axis, and of resulting moment acting forward of the transverse section following positive rotation around the X-axis.

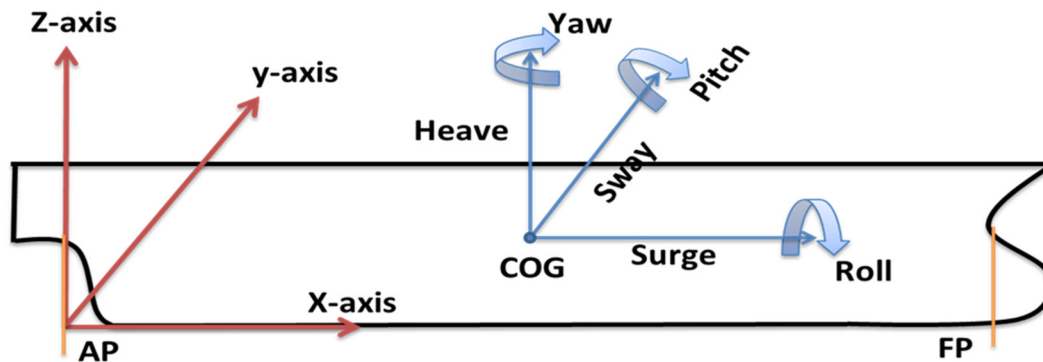


Fig. 1.10.1: Reference coordinate system

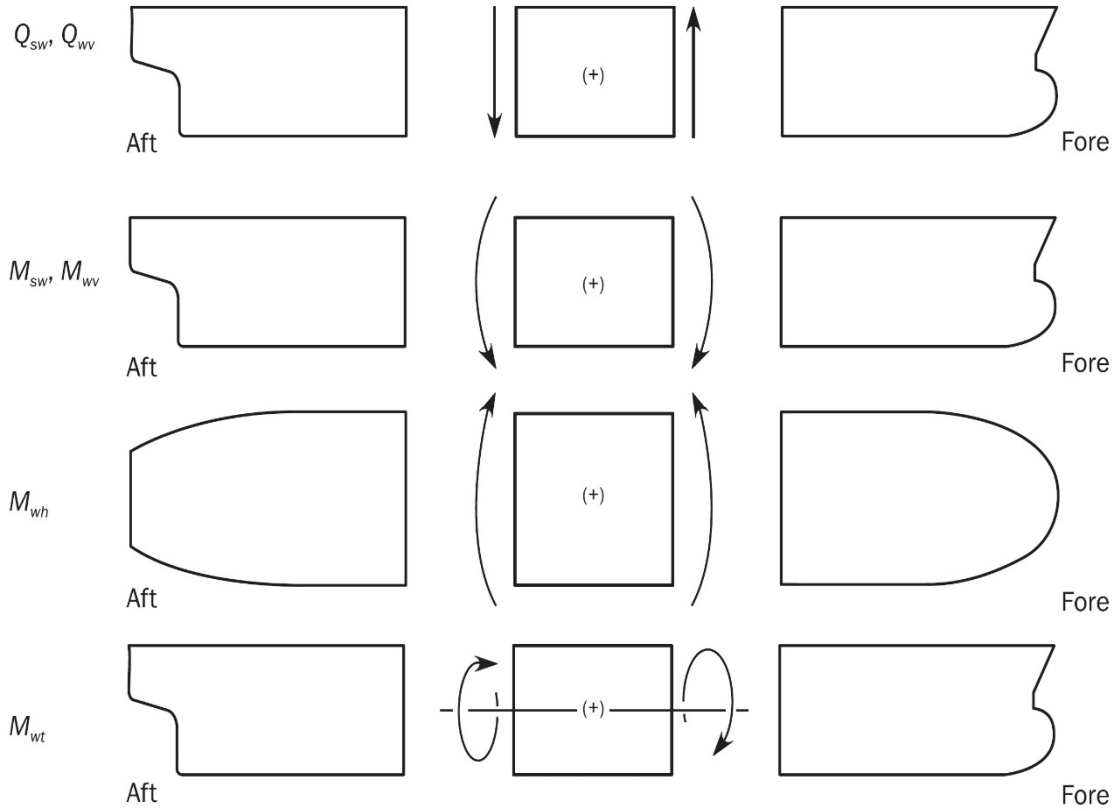


Fig. 1.10.2: Sign convention for hull girder loads

Section 2

Fatigue Evaluation

2.1 Fatigue analysis methodology

2.1.1 General

In general, assessment of the fatigue strength of structural members includes the following steps:

- a) Calculation of stress ranges, according to Sec. 2.3.
- b) Selection of the design S-N curve, according to Sec. 2.4.
- c) Calculation of the cumulative damage and the fatigue life calculation, according to Sec. 2.5
- d) Check the acceptance criteria as per Sec. 2.2

2.1.2 Cumulative damage

The fatigue assessment of the structure is based on the application of the Palmgren-Miner rule by estimating the linear cumulative fatigue damage D taken as:

$$D = \sum_{i=1}^{n_{tot}} \frac{n_i}{N_i}$$

where:

- | | | |
|-----------|---|--|
| n_i | = | Number of cycles at stress range $\Delta\sigma_i$. |
| N_i | = | Number of cycles to failure at stress range $\Delta\sigma_i$. |
| n_{tot} | = | Total number of stress range blocks. |
| i | = | Stress range block index. |

As the long-term stress range distribution of a structural detail in a ship can be described by a two-parameter Weibull distribution, fatigue damage can be obtained by means of a closed form equation, as given in Sec. 2.5.

2.2 Acceptance criteria

The design fatigue life, T_{DF} , is to be 25 years, unless a higher value is specified by the designer.

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

$$T_F \geq T_{DF}$$

- | | | |
|----------|---|--|
| T_{DF} | = | Design fatigue life, in year, specified by the designer, but not to be taken less than 25 years. |
| T_F | = | Fatigue life, in year, calculated according to Cl. 2.5.5. |

2.3 Reference stresses for fatigue assessment

2.3.1 Fatigue stress

The fatigue stress for each loading condition is defined in Cl. 2.3.2 for welded joints and in Cl. 2.3.3 for base material free edge.

2.3.2 Welded joints

For welded joints, the fatigue stress $\Delta\sigma_{FS(j)}$, in $[N/mm^2]$, corrected for mean stress effect, thickness effect and warping effect, is taken as:

- For simplified stress analysis:

$$\Delta\sigma_{FS,(j)} = f_{\text{mean},(j)} \cdot f_{\text{warp}} \cdot f_{\text{thick}} \cdot \Delta\sigma_{HS,(j)}$$

- For FE analysis:
- (a) For web-stiffened cruciform joints:

$$\Delta\sigma_{FS,(j)} = f_{ws} \cdot f_s \cdot \max(\Delta\sigma_{FS1,(j)}, \Delta\sigma_{FS2,(j)})$$

- (b) For other joints:

$$\Delta\sigma_{FS,(j)} = \max(\text{SideL}, \text{SideR}) [\max(\Delta\sigma_{FS1,(j)}, \Delta\sigma_{FS2,(j)})]$$

where:

f_{ws}	=	Correction factor for the effect of stress gradient along weld line
	=	0.96
f_s	=	Correction factor for the effect of supporting member
	=	0.95
$\Delta\sigma_{HS,(j)}$	=	Hot spot stress range, in [N/mm ²], due to dynamic loads for loading condition (j) given in Section 3, Cl. 3.9.1.
$\Delta\sigma_{FS1,(j)}$	=	Fatigue stress range, in [N/mm ²], due to the principal hot spot stress range $\Delta\sigma_{HS1,(j)}$
	=	$\Delta\sigma_{FS1,(j)} = f_{\text{mean}1,(j)} \cdot f_{\text{material}} \cdot f_{\text{thick}} \cdot f_c \cdot f_e \cdot \Delta\sigma_{HS1,(j)}$
$\Delta\sigma_{FS2,(j)}$	=	Fatigue stress range, in [N/mm ²], due to the principal hot spot stress range $\Delta\sigma_{HS2,(j)}$
	=	$\Delta\sigma_{FS2,(j)} = 0.9 \cdot f_{\text{mean}2,(j)} \cdot f_{\text{material}} \cdot f_{\text{thick}} \cdot f_c \cdot f_e \cdot \Delta\sigma_{HS2,(j)}$
SideL, SideR	=	Left and right side respectively of the line A-A as shown in Section 4, Cl. 4.5, Fig. 4.5.4 and Fig. 4.5.5.
$f_{\text{mean}1,(j)}$	=	Correction factor for mean stress effect given in Cl. 2.3.4.
$f_{\text{mean}2,(j)}$	=	Correction factor for mean stress effect given in Cl. 2.3.4.
f_{warp}	=	Correction factor due to warping effect, taken as:
	=	1.07 for the deck longitudinal stiffener of bulk carrier, the closest to the longitudinal hatch coaming in way of the hatch corner as shown in Fig. 2.3.1, except $f_{\text{warp}} = 1.0$ when OST is not the dominant load case for all loading conditions.
	=	1.04 for following deck longitudinal stiffeners of bulk carrier, except $f_{\text{warp}} = 1.0$ when OST is not the dominant load case for all loading conditions.
	•	The closest stiffener to the longitudinal hatch coaming at one web frame away from the hatch corner, in way of the hatch opening as shown in Fig. 2.3.1,
	•	The second closest stiffener away from the longitudinal hatch coaming in way of the hatch corner as shown in Fig. 2.3.1,
	=	1.0 for the other cases.

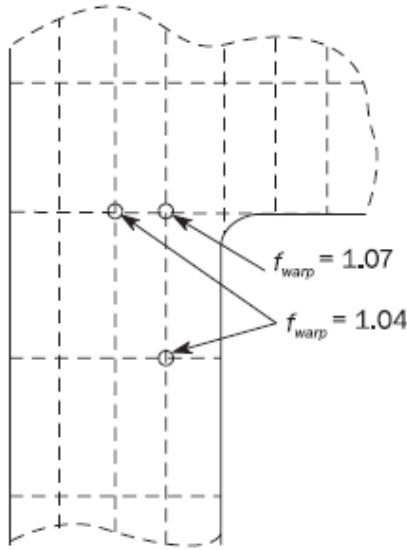


Fig. 2.3.1: Warping effect on deck longitudinal stiffeners of bulk carrier

$\Delta\sigma_{HS1,(j)}$ = Principal hot spot stress ranges, in $[N/mm^2]$, due to dynamic loads for loading condition (j) which acts within $\pm 45^\circ$ of the perpendicular to the weld toe, determined in Section 4, Cl. 4.5.4 and Section 4, Cl. 4.6.2(d) for the two types of shell elements (4-node or 8-node).

$\Delta\sigma_{HS2,(j)}$ = Principal hot spot stress ranges, in $[N/mm^2]$, due to dynamic loads for loading condition (j) which acts outside $\pm 45^\circ$ of the perpendicular to the weld toe, determined in Section 4, Cl. 4.5.4 and Section 4, Cl. 4.6.2(d) for the two types of shell elements (4-node or 8-node).

2.3.3 Base material free edge

For base material free edge, the fatigue stress range, $\Delta\sigma_{FS,(j)}$ in $[N/mm^2]$, is taken as the local stress range at free edge, $\Delta\sigma_{BS,(j)}$, as defined in Section 1, Cl. 1.2.6 with correction factors:

$$\Delta\sigma_{FS,(j)} = K_{sf} \cdot f_{material} \cdot f_{mean,(j)} \cdot f_{thick} \cdot f_c \cdot \Delta\sigma_{BS,(j)}$$

where:

- K_{sf} = Surface finishing factor for base material given in Cl. 2.4.2.2.
- $f_{material}$ = Correction factor for material strength, given in Cl. 2.3.6.
- $\Delta\sigma_{BS,(j)}$ = Local stress range, in $[N/mm^2]$, due to dynamic loads for loading condition (j).

2.3.4 Mean stress effect

2.3.4.1 Correction factor for mean stress effect The mean stress correction factor to be considered for each principal hot spot stress range of welded joint, $\Delta\sigma_{HS1,i(j)}$, or for local stress range at free edge, $\sigma_{BS,i1(j)}$, is taken as:

- For welded joint:

$$f_{mean,(j)} = \begin{cases} \min \left[1.0, 0.9 + 0.2 \frac{\sigma_{mcor,(j)}}{2\Delta\sigma_{HS,(j)}} \right] & \text{for } \sigma_{mcor,(j)} \geq 0 \\ \max \left[0.3, 0.9 + 0.8 \frac{\sigma_{mcor,(j)}}{2\Delta\sigma_{HS,(j)}} \right] & \text{for } \sigma_{mcor,(j)} < 0 \end{cases}$$

- For material:

$$f_{\text{mean,(j)}} = \begin{cases} \min \left[1.0, 0.8 + 0.4 \frac{\sigma_{\text{mcor,(j)}}}{2\Delta\sigma_{\text{BS,(j)}}} \right] & \text{for } \sigma_{\text{m,cor,(j)}} \geq 0 \\ \max \left[0.3, 0.8 + \frac{\sigma_{\text{mcor,(j)}}}{2\Delta\sigma_{\text{BS,(j)}}} \right] & \text{for } \sigma_{\text{m,cor,(j)}} < 0 \end{cases}$$

where,

$$\sigma_{\text{mcor,(j)}} = \begin{cases} \sigma_{\text{mean,(j)}} & \text{for } \sigma_{\text{max}} \leq R_{\text{eEq}} \\ R_{\text{eEq}} - \sigma_{\text{max}} + \sigma_{\text{mean,(j)}} & \text{for } \sigma_{\text{max}} > R_{\text{eEq}} \end{cases}$$

$$\sigma_{\text{max}} = \begin{cases} \max, (j)(\Delta\sigma_{\text{HS,(j)}} + \sigma_{\text{mean,(j)}}) & \text{for welded joint} \\ \max, (j)(\Delta\sigma_{\text{BS,(j)}} + \sigma_{\text{mean,(j)}}) & \text{for base material} \end{cases}$$

$$R_{\text{eEq}} = \max(315, \sigma_y)$$

$$\sigma_{\text{mean,(j)}} = \text{Fatigue mean stress, in [N/mm}^2\text{], for base material calculated according to Cl. 2.3.4.2 or for welded joint calculated according to Cl. 2.3.4.3 or 2.3.4.4, as applicable.}$$

2.3.4.2 Mean stress for base material free edge

The fatigue mean stress for base material free edge, $\sigma_{\text{mean,(j)}}$, in [N/mm²], due to static and dynamic loads for loading condition (j) is calculated by the following formula based on local stress:

$$\sigma_{\text{mean,(j)}} = \sigma_{\text{BS,(j)}}$$

2.3.4.3 Mean stress for simplified stress analysis

The fatigue mean stress to be considered for welded joint assessed by the simplified stress analysis is to be obtained from Section 3, Cl. 3.3.5.

2.3.4.4 Mean stress for FE analysis

The fatigue mean stresses for welded joint due to static and dynamic loads, $\sigma_{\text{mean,(j),pX}}$ and $\sigma_{\text{mean,(j),pY}}$, in [N/mm²], for loading condition (j), belonging to the two principal hot spot stress range directions, pX and pY, is calculated by the following formula based on hot spot stress components as defined in Section 4, Cl. 4.5.3, 4.6.2(d) and 4.5.5:

$$\sigma_{\text{mean,(j),pX}} = \frac{(\sigma_{\text{HS,(j)}})_{\text{xx}} + (\sigma_{\text{HS,(j)}})_{\text{yy}}}{2} + \frac{(\sigma_{\text{HS,(j)}})_{\text{xx}} - (\sigma_{\text{HS,(j)}})_{\text{yy}}}{2} \cdot \cos 2\theta + (\sigma_{\text{HS,(j)}})_{\text{xy}} \cdot \sin 2\theta$$

$$\sigma_{\text{mean,(j),pY}} = \frac{(\sigma_{\text{HS,(j)}})_{\text{xx}} + (\sigma_{\text{HS,(j)}})_{\text{yy}}}{2} - \frac{(\sigma_{\text{HS,(j)}})_{\text{xx}} - (\sigma_{\text{HS,(j)}})_{\text{yy}}}{2} \cdot \cos 2\theta - (\sigma_{\text{HS,(j)}})_{\text{xy}} \cdot \sin 2\theta$$

θ = Angle between the direction x of the element coordinate system and the principal direction pX of the principal hot spot stress range coordinate system (Section 4, Cl. 4.5.3, 4.6.2(d) and 4.5.5). The direction x of the element coordinate system is defined as the normal to the weld toe.

The one of the two mean stresses $\sigma_{\text{mean,(j),pX}}$ and $\sigma_{\text{mean,(j),pY}}$ which has a principal stress direction with an absolute value less than 45° is defined as $\sigma_{\text{mean1,(j)}}$, belonging to $\sigma_{\text{HS1,(j)}}$. The other mean stress is defined as $\sigma_{\text{mean2,(j)}}$ belonging to $\sigma_{\text{HS2,(j)}}$.

2.3.5 Thickness effect

2.3.5.1 General

Plate thickness primarily influences the fatigue strength of welded joints through the effect of geometry of the weld, and through-thickness stress distribution. The correction factor, f_{thick} , for plate thickness effect is taken as:

$$f_{thick} = 1 \quad \text{for } t_{eff} \leq 22[\text{mm}]$$

$$f_{thick} = \left(\frac{t_{eff}}{22}\right)^n \quad \text{for } t_{eff} > 22[\text{mm}]$$

where

- n = Thickness exponent given in Table 2.3.5 and Table 2.4.2.2 respectively for welded and non-welded joints. n is to be selected according to the considered stress direction. For this selection, $\Delta\sigma_{HS1}$ and $\Delta\sigma_{HS2}$ are considered perpendicular and parallel to the weld respectively.
- t_{eff} = Effective thickness of welds. If values not specified t_{n50} to be used.
- t_{n50} = Net thickness of the considered member in way of the hot spot for welded joints or base material free edge [mm].

2.3.5.2 For simplified stress analysis, the net thickness to be considered for stiffeners is as follows:

- Flat bar and Bulb profile: no thickness factor correction,
- Angle bar and T-bar: flange net thickness

2.3.5.3 For FE analysis, the effective thickness to be considered is the thickness of the member where the crack is likely to initiate and propagate.

- For 90° attachments, i.e. cruciform welded joints, transverse T-joints and plates with transverse attachment, the thickness to be considered is to be taken as:

$$t_{eff} = \min\left(\frac{d}{2}, t_1\right)$$

where

- d = Toe distance [mm], as shown in Fig. 2.3.5, taken as:

$$d = t_2 + 2\ell_{leg}$$

- t_1 = Thickness [mm], of the continuous plate as shown in Fig. 2.3.5.
- t_2 = Thickness [mm], of the transverse attach plate where the hot spot is assessed, as shown in Fig. 2.3.5.
- ℓ_{leg} = Fillet weld leg length [mm].

When post-weld treatment methods are applied to improve the fatigue life of considered welded joint, the thickness exponent is provided in Sec. 2.6.

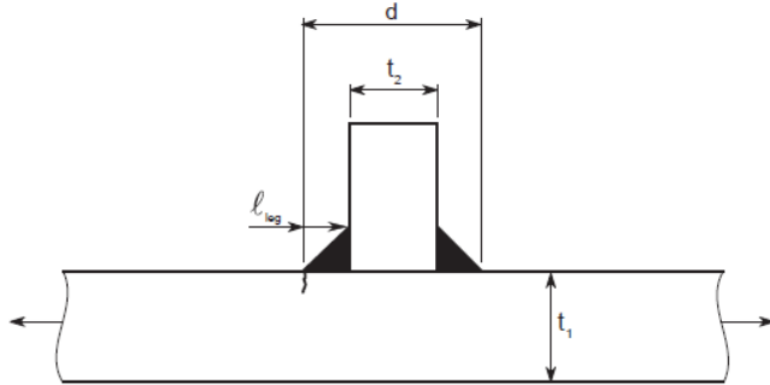
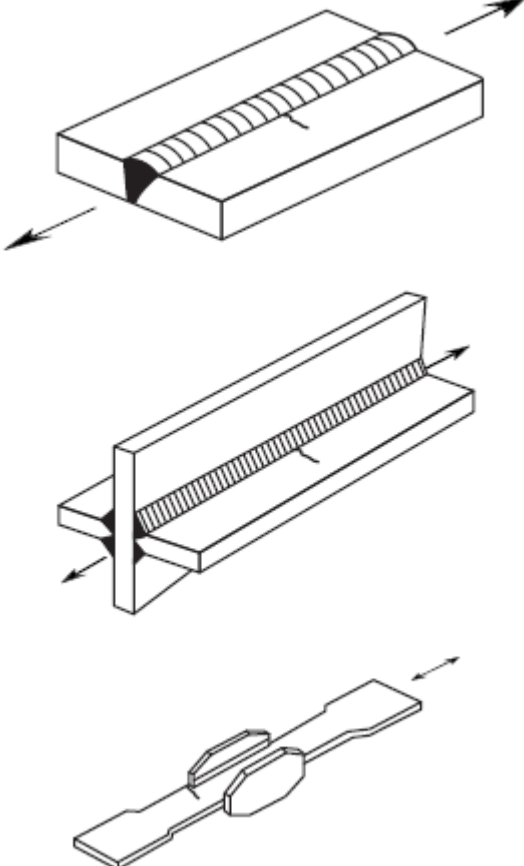
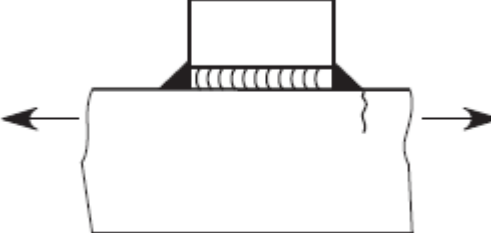
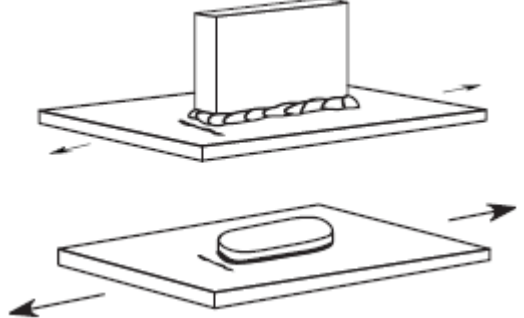
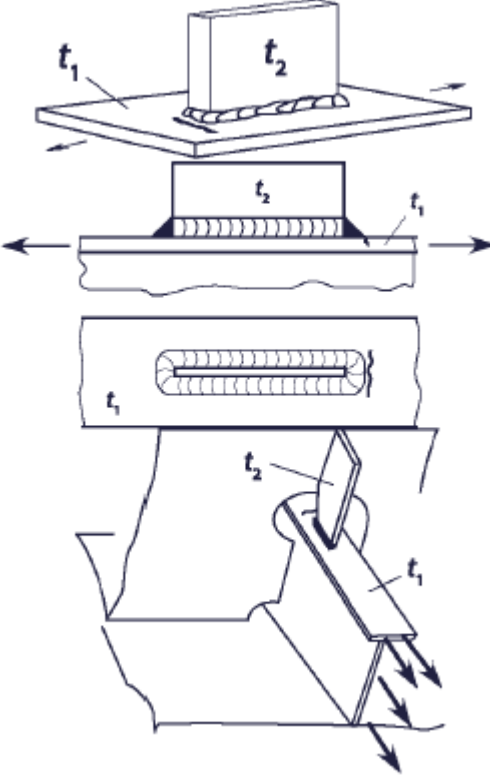


Fig. 2.3.5: Toe distance for cruciform welded joints, transverse T-joints and plates with transverse attachment

Table 2.3.5: Welded joints: thickness exponents				
Sl. No	Joint category description	Geometry	Condition	n
1	Cruciform joints, transverse T-joints, plates with transverse attachments		As-welded	0.25
			Weld toe treated by post-weld improvement method	0.2
2	Transverse butt welds		As-welded	0.2
			Ground flush or weld toe treated by post-weld improvement method	0.1
3			Any	0.1

	Longitudinal welds or attachments to plate edges		Weld toe treated by post-weld improvement method	0.1
4	Longitudinal attachments on the flat bar or bulb profile		Any	0.0
			Weld toe treated by post-weld improvement method ⁽¹⁾	0.0
5	Longitudinal attachments and doubling plates		As welded	0.2
			Weld toe treated by post-weld improvement method	0.1
6	Longitudinal attachments and doubling plates		As-welded $t_2 \geq 0.33 t_1$ else	0.1 0.0

	supported longitudinally		Weld toe treated by post-weld improvement method ⁽¹⁾	0
(1) No benefit applicable for post-weld treatment of longitudinal end connections				

2.3.5.4 For base material

The thickness effect is not considered for base material and free plate edges assuming good workmanship practice (S-N curve B and C) and when adequate protective measures are taken against wear, tear and corrosion, e.g. from friction from cargo or cargo handling appliances.

2.3.6 Material factor

2.3.6.1 Welded joints

For welded joints, the fatigue strength is independent on the steel yield strength. So, the correction factor for material strength, f_{material} , is taken as 1.

2.3.6.2 Non welded details

For non-welded details such as cut plate edges, the fatigue strength increases together with the yield stress of the base material. The fatigue stress range, $\Delta\sigma_{\text{FS,(j)}}$, needs to be corrected for material strength, f_{material} , taken as:

$$f_{\text{material}} = \frac{1200}{965 + \sigma_y}$$

2.3.7 Environmental factor

The environmental factor is a correction factor representing the ratio of the stress range based on the vertical wave bending moment from a specific trade and the North Atlantic wave environment. For prescriptive loads, the following environmental factors are used

- $f_e = 0.8$ for worldwide wave environment
- $f_e = 1.0$ for North Atlantic wave environment.

Note:

If hydrodynamic analysis is carried out using a scatter diagram, the environmental factor to be taken as 1.0.

2.4 S-N Curves

2.4.1 Design S-N curves

2.4.1.1 Unless supported by direct measurements, the U.K. HSE (previously DEn) Basic S-N Curves are to be used for determining the fatigue life.

2.4.1.2 The fatigue assessment for welded joints and base material is based on use of S-N curves which are obtained from fatigue tests. The design S-N curves are established at two standard deviations below the mean S-N curves corresponding to 50% of probability of survival for relevant experimental data. Design S-N curves given in Table 2.4.1.1 and Table 2.4.1.2 correspond to a probability of survival of 97.7%.

2.4.1.3 S-N curve scope of application

These S-N curves are applicable to steels with minimum yield strength less than 400 [N/mm²]. For steels with higher yield strength, data obtained from an approved test program are to be used.

2.4.1.4 In-air environment

The basic design curves in-air environment shown in Fig. 2.4.1.1 are represented by linear relationships between log ($\Delta\sigma$) and log (N) as follows:

$$\log N = \log(K_2) - m \cdot \log(\Delta\sigma)$$

where

$$\log(K_2) = \log(K_1) - 2 \cdot \log(\delta)$$

- K_1 = Constant related to mean S-N curve, as given in Table 2.4.1.1
- K_2 = Constant related to design S-N curve, as given in Table 2.4.1.1
- δ = Standard deviation of log (N), as given in Table 2.4.1.1
- m = Inverse slope of the design S-N curve, as given in Table 4.2.1.1 for in-air environment and in Table 2.4.1.2 for corrosive environment.
The inverse slope for S-N curves in-air environment changes from m to $m+2$ at $N = 10^7$ cycles.
- $\Delta\sigma_q$ = Stress range at $N = 10^7$ cycles related to design S-N curve, in N/mm², as given in Table 2.4.1.1

Table 2.4.1.1: Basic S-N curve data, in-air environment

Class	K_1		m	Standard deviation δ	K_2	Design stress range at 10^7 cycles	Design stress range at 2×10^6 cycles
	K_1	$\log_{10} K_1$		$\log_{10} \delta$		$\Delta\sigma_q$ [N/mm ²]	[N/mm ²]
B	2.343E15	15.3697	4.0	0.1821	1.01E15	100.2	149.9
C	1.082E14	14.0342	3.5	0.2041	4.23E13	78.2	123.9
D	3.988E12	12.6007	3.0	0.2095	1.52E12	53.4	91.3
E	3.289E12	12.5169	3.0	0.2509	1.04E12	47.0	80.4
F	1.726E12	12.2370	3.0	0.2183	0.63E12	39.8	68.1
F2	1.231E12	12.0900	3.0	0.2279	0.43E12	35.1	59.9
G	0.566E12	11.7525	3.0	0.1793	0.25E12	29.2	50.0
W	0.368E12	11.5662	3.0	0.1846	0.16E12	25.1	43.1

2.4.1.5 Corrosive environment

The basic design curves for corrosive environment shown in Fig. 2.4.1.2 are represented by linear relationships between $\log(\Delta\sigma)$ and $\log(N)$ as follows:

$$\log N = \log(K_2) - m \cdot \log(\Delta\sigma)$$

- N = Predicted number of cycles to failure under stress range $\Delta\sigma$.
- K_2 = Constant related to design S-N curve, as given in Table 2.4.1.2

Table 2.4.1.2: Basic S-N curve data, corrosive environment			
Class	m	K_2	Design stress range at 2×10^6 Cycles [N/mm²]
B_{Corr}	4.0	5.05E14	126.1
C_{Corr}	3.5	2.12E13	101.6
D_{Corr}	3.0	7.60E11	72.4
E_{Corr}	3.0	5.18E11	63.7
F_{Corr}	3.0	3.16E11	54.0
$F2_{Corr}$	3.0	2.15E11	47.6
G_{Corr}	3.0	1.24E11	39.6
W_{Corr}	3.0	7.86E11	34.0

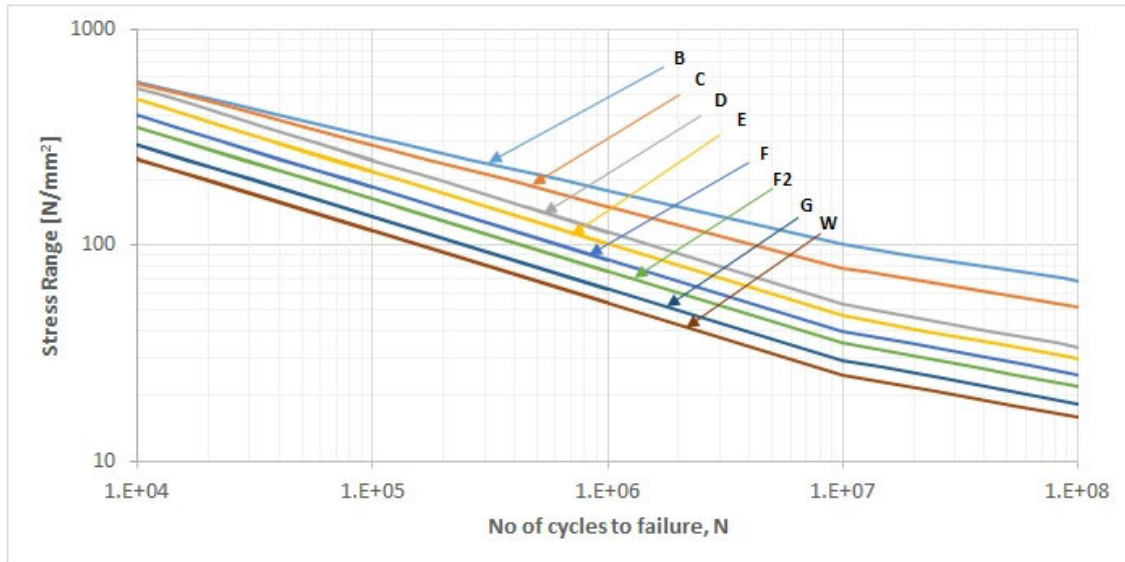


Figure 2.4.1.1: Basic design S-N curves, in-air environment

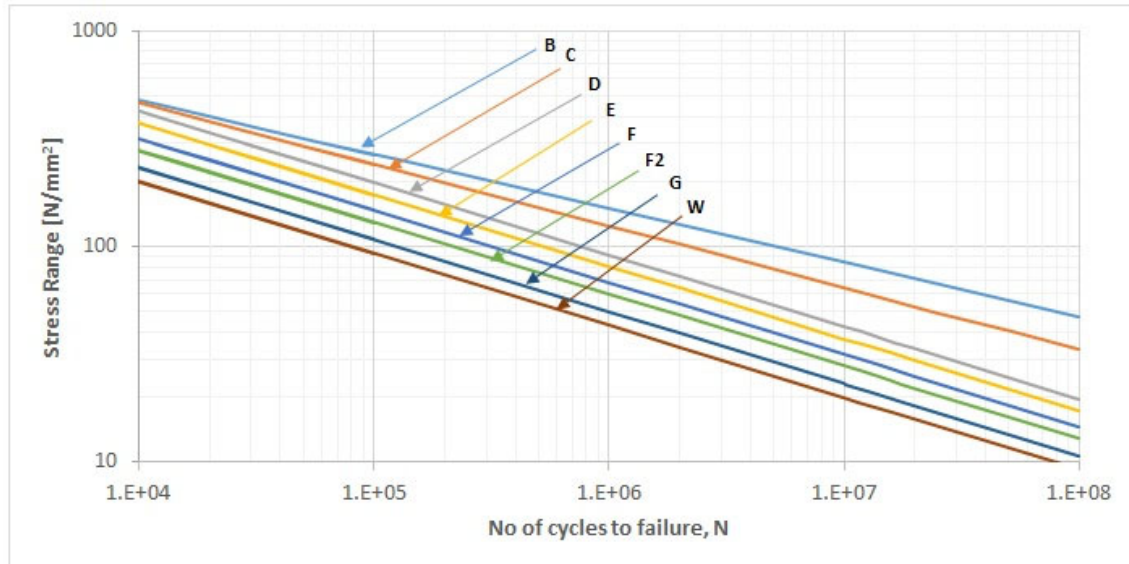


Figure 2.4.1.2: Basic design S-N curves, corrosive environment

2.4.2 Selection of S-N curves

2.4.2.1 General

The HSE S-N Curves for non-tubular joints consist of eight curves, as shown in Table 2.4.1.1 identified by B, C, D, E, F, F2, G and W categories. These curves give the relationship between the nominal stress range and the number of constant amplitude load cycles to failure. Each curve represents a class of welded details depending upon:

- The geometrical arrangement of the detail,
- The direction of the fluctuating stress relative to the detail
- The method of fabrication and inspection of the detail.

The Table 2.4.2.1 provide the summary of details based on above factors. More information can be referred from the UK HSE (1984).

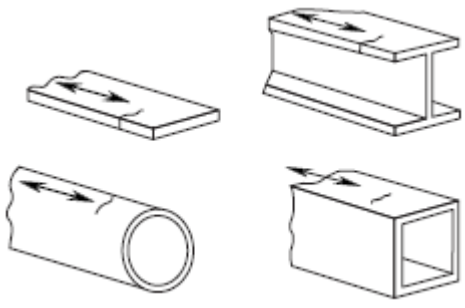
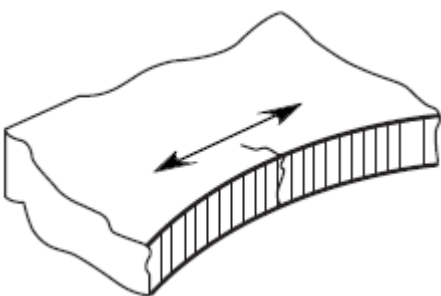
Table 2.4.2.1: Welded Joint Classification for SN curve

SN curve category for Joint Classification	Description ^[1]
Category B	1) Parent metal in the as-rolled condition with no flame-cut edges or with flame-cut edges ground or machined 2) Full penetration butt welds with the weld cap ground flush with the surface and with the weld proved to be free from defects by NDT.
Category C	1) Parent material in the as-rolled condition with automatic flame-cut edges and ensured to be free from cracks. 2) Butt or fillet welds made by an automatic submerged or open arc process and with no stop-start positions within their length. 3) With the weld cap ground flush with the surface and with the weld proved to be free from significant defects by NDT.
Category D	1) As C(2) but with stop-start positions within the length 2) With the welds made either manually or by an automatic process other than submerged arc and in flat position
Category E	1) Intermittent fillet welds

Category F	<ol style="list-style-type: none"> 1) Welds made on a permanent backing strip between plates of equal width and thickness or tapered with a maximum slope of 1/4. 2) Parent material (of the stressed member) or ends of butt or fillet welded attachments (parallel to the direction of applied stresses) on stressed members: <ul style="list-style-type: none"> - attachment length $l \leq 150$[mm] - edge distance $d \geq 10$[mm] 3) Parent metal of cruciform or T Joints made with full penetration welds and with any undercut at the corners of the member ground out 4) Parent metal at the toe of weld connection of web stiffeners to girder flanges: edge distance $d \geq 10$[mm]. 5) As E(1) but adjacent to cut-outs.
Category F2	<ol style="list-style-type: none"> 1) Parent material (of the stressed member) or ends of butt or fillet welded attachments (parallel to the direction of applied stresses) on stressed members: <ul style="list-style-type: none"> - attachment length $l > 150$[mm] - edge distance $d \geq 10$[mm] 2) As F(3) with partial penetration or fillet welds with any undercut at the corners of the member ground out. Parent metal of load-carrying fillet welds transverse to the direction of stresses (member X): edge distance $d \geq 10$[mm]
Category G	<ol style="list-style-type: none"> 1) Parent material (of the stressed member) at toes or ends of butt or fillet welded attachments on or within 10 mm of edges or corners. 2) Parent metal of load-carrying fillet welds transverse to the direction of stresses (member X): edge distance $d < 10$[mm] 3) Parent metal of load-carrying fillet welds parallel to the direction of stresses, with the weld end on plate edge (member Y). 4) Parent metal at the toe of weld connection of web stiffeners to girder flanges: edge distance $d < 10$ mm
<p>¹ For additional guidance also refer, Offshore Installations – Guidance on Design, Construction and Certification: Health & Safety Executive, UK.</p>	

2.4.2.2 Surface finishing factor

The S-N curve C is applicable to most of non-welded locations taking into account the likelihood of some notching from corrosion, wear and tear in service with surface finishing factor as given in Table 2.4.2.2. Higher surface finishing quality may be applied in using S-N curve B as given in Table 2.4.2.2, provided adequate protective measures are taken against wear, tear and corrosion and finite element analysis according to Section 4.3 and 4.4 is carried out.

Table 2.4.2.2: Non-welded joints: thickness exponent and surface finishing factor						
Joint configuration, fatigue crack location and stress direction	Edge cutting process	Edge treatment	Surface finishing	n	K_{sf}	S-N Curve
Base material, Rolled or extruded plates and sections as well as seamless pipes. No surface or rolling defects	N/A	N/A	No surface nor roll defect ^{(1) (2)}	0	0.94	B
						
Cut edges						
	Machine cutting e.g. by a thermal process or sheared edge cutting	Cutting edges chamfered or rounded by means of smooth grinding, groove direction parallel to the loading direction	Smooth surface free of cracks and notches ^{(1) (2)}	0.1	1.00	B
		Cutting edges broken or rounded	Smooth surface free of cracks and notches ^{(1) (2)}	0.1	1.07	B
		No edge treatment	Surface free of cracks and severe notches (inspection procedure) ^{(1) (2)}	0.1	1.00	C
	Manually thermally cut e.g. by flame cutting	No edge treatment	Surface free of cracks and severe notches (inspection procedure) ^{(1) (2)}	0.1	1.24	C

- (1) Stress increase due to geometry of cut-outs to be considered.
(2) Fine mesh FE analysis according to Section 4.3 and 4.4.

2.5 Fatigue damage calculation

2.5.1 General

2.5.1.1 The design fatigue life is divided into a number of time periods due to different loading conditions and due to limitation of the corrosion protection.

2.5.1.2 It is assumed that the corrosion protection (i.e. coating system) is only effective for a limited number of years during which the structural details are protected, i.e. in-air environment. During the remaining part of the design life as specified in Table 2.5.1, the structural details are unprotected i.e. exposed to corrosive environment.

The elementary fatigue damage, given in 2.5.2, is the damage accumulated during a specific loading condition (j) associated with a specific environmental condition either protected condition, i.e. in-air environment, or unprotected condition, i.e. corrosive environment.

The combined fatigue damage, given in 2.5.3, is the combination of damage accumulated for a specific loading condition (j) for the in-air and corrosive environment time.

Total fatigue damage, given in 2.5.4, is the sum of the combined fatigue damages obtained for all loading conditions.

2.5.2 Elementary fatigue damage

The elementary fatigue damage for each fatigue loading condition (j) is to be calculated independently for both protected in-air environment and unprotected corrosive environment, based on the fatigue stress range obtained for the predominant load case and calculated based on a closed form formulation as follows:

$$D_{E(j)} = \frac{\alpha_{(j)} \cdot N_D}{K_2} \frac{\Delta\sigma_{FS,(j)}^m}{(\ln N_R)^{m/\xi}} \cdot \mu_{(j)} \cdot \Gamma\left(1 + \frac{m}{\xi}\right)$$

where:

N_D = Total number of wave cycles experienced by ship during the design fatigue life, taken as:

$$N_D = \frac{31.557 \times 10^6 (f_0 T_D)}{4 \log L}$$

f_0 = Factor taking into account time in seagoing operations excluding time in loading and unloading, repairs, etc. taken as 0.85.

$\alpha_{(j)}$ = Fraction of time in each loading condition given in in Section 1.

$\Delta\sigma_{FS,(j)}$ = Fatigue stress range at the reference probability level of exceedance of 10^{-2} , in [N/mm²].

N_R = Number of cycles corresponding to the reference probability of exceedance of $10^{-2} = 100$.

ξ = Weibull shape parameter, = 1.

$\Gamma(x)$ = Complete Gamma function.

K_2 = Constant of the design S-N curve, as given in Sec. 2.4 for in-air environment and for corrosive environment.

$\mu_{(j)}$ = Coefficient taking into account the change of inverse slope of the S-N curve, m,

- For in-air environment:

$$\mu_{(j)} = 1 - \frac{\left\{ \gamma\left(1 + \frac{m}{\xi}, v_{(j)}\right) - v_{(j)}^{-\Delta m/\xi} \cdot \gamma\left(1 + \left(\frac{m + \Delta m}{\xi}\right), v_{(j)}\right) \right\}}{\Gamma\left(1 + \frac{m}{\xi}\right)}$$

$$v_{(j)} = \left(\frac{\Delta\sigma_q}{\Delta\sigma_{FS,(j)}} \right)^\xi \ln N_R$$

- For corrosive environment:

$\mu_{(j)}$ = 1.0

$\gamma(a, x)$ = Incomplete Gamma function.

$\Delta\sigma_q$ = Stress range, in [N/mm²], corresponding to the intersection of the two segments of design S-N curve at $N = 10^7$ cycles, as given in Sec. 2.4.

Δm = Change in inverse slope of S-N curve at $N=10^7$ cycles, = 2

2.5.3 Combined fatigue damage

The combined fatigue damage in protected in-air environment and unprotected corrosive environment for each loading condition (j) is to be calculated as follows:

$$D_{(j)} = D_{E,air(j)} \cdot \frac{T_D - T_C}{T_D} + D_{E,corr(j)} \cdot \frac{T_C}{T_D}$$

where:

$D_{E,air(j)}$ = The elementary fatigue damage for in-air environment for loading condition (j) given in Cl. 2.5.2.

$D_{E,corr(j)}$ = The elementary fatigue damage for corrosive environment for loading condition (j) as calculated in Cl. 2.5.2.

T_C = Time in corrosive environment, in years, according to Table 2.5.1.

T_D = Design life, in years, to be taken as 25 years.

Table 2.5.1: Time in corrosive environment, T_C	
Location of weld joint or structural detail	Time in corrosive environment T_C, in years
Water ballast tank	10
Oil cargo tank	
Lower part1) of cargo hold for dry bulk cargo	
Cargo hold for dry bulk cargo except lower part 1)	5
Void spaces	5
Fuel oil tanks	5
Cofferdam	

Dry cargo holds	
Hull external surfaces	
Other areas	5
1) Lower part including inner bottom and other structure with a height of 1.5[m] above the inner bottom.	

2.5.4 Total fatigue damage

The total fatigue damage for all applicable loading conditions is calculated as follows:

$$D = \sum_{j=1}^{n_{LC}} D_{(j)}$$

where:

$D_{(j)}$ = Combined fatigue damage for each applicable loading condition, as given in Cl. 2.5.3.

2.5.5 Fatigue life calculation

The fatigue life, T_F , is taken as:

$$T_F = \frac{T_D}{D_{air}} \text{ if } \frac{T_D}{D_{air}} \leq (T_D - T_C)$$

$$T_F = T_D - T_C + \left(\frac{T_D}{D_{air}} - T_D + T_C \right) \frac{D_{air}}{D_{corr}} \text{ otherwise}$$

where:

D_{air} = Total fatigue damage for all loading conditions in-air environment taken as:

$$D_{air} = \sum_{j=1}^{n_{LC}} D_{E,air(j)}$$

D_{corr} = Total fatigue damage for all loading conditions in corrosive environment taken as:

$$D_{corr} = \sum_{j=1}^{n_{LC}} D_{E,corr(j)}$$

2.6 Weld improvement methods

2.6.1 General

Post-weld fatigue strength improvement methods are to be considered as a supplementary means of achieving the required fatigue life, and subjected to quality control procedures. The benefit from post-weld treatment can only be applied for corrosion free condition and may only be considered provided that a protective coating is applied after the post-weld treatment and maintained during the design life time.

2.6.2 Limitation of the benefit of post-weld treatment

For structural details where the benefit of post-weld treatment is applicable, the calculated fatigue life at the design stage for the considered structural detail excluding the post-weld treatment effects, is not to be less than $T_{DF}/1.47$.

2.6.3 The calculated fatigue life at design stage excluding post-weld treatment effects is not to be less than 25 years.

2.6.4 Post-weld treatment at fabrication stage

There is one basic post-weld treatment method considered in these guideline to improve fatigue strength at the fabrication stage, i.e. weld geometry control and defect removal method by burr grinding.

2.6.5 Weld toe

The post-weld improvement method is applied to the weld toe to increase its fatigue life. The possibility of failure initiation at other locations is always to be considered. If the failure is shifted from the weld toe to the root by applying post-weld treatment, there may be no significant improvement in the overall fatigue performance of the joint. Improvements of the weld root cannot be expected from treatment applied to weld toe. A brief description of the method and the degree of improvement which can be achieved is given in Cl. 2.6.6.

2.6.6 Weld toe burr grinding

2.6.6.1 The weld may be machined using a burr grinding tool to produce a favorable shape to reduce stress concentrations and remove defects at the weld toe, see Fig. 2.6.6.1. In order to eliminate defects, such as intrusions, undercuts and cold laps, the material in way of the weld toe is to be removed. The depth of grinding is to be at least 0.5 [mm] below the bottom of any visible undercut. The total depth of the burr grinding is not to be greater than the lesser of 2 [mm] and of 7% the local gross thickness of the machined plate. Any undercut not complying with this requirement is to be repaired by an approved method.

2.6.6.2 To avoid introducing a detrimental notch effect due to small radius grooves, the burr diameter is to be scaled to the plate thickness at the weld toe being ground. The diameter is to be in the 10 to 25 [mm] range for application to welded joints with plate thickness from 10 to 50 [mm]. The resulting root radius of the groove is to be no less than $0.25t_{as-built}$. The weld throat thickness and leg length after burr grinding must comply with the rule requirements or any increased weld sizes as indicated on the approved drawings. The inspection procedure is to include a check of the weld toe radius, the depth of burr grinding, and confirmation that the weld toe undercut has been removed completely.

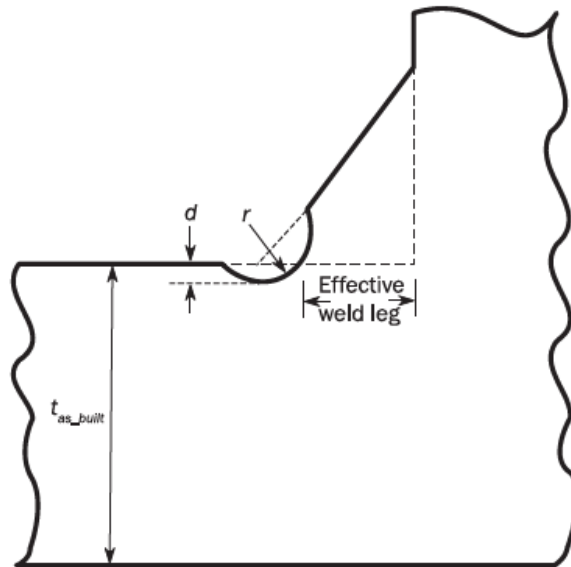


Fig. 2.6.6.1: Details of ground weld toe geometry

2.6.7 Fatigue improvement factor

The benefit of burr grinding corresponds to an increase in fatigue strength by a factor of 1.3 (i.e. a reduction of the effective stress range by 1.3), reducing the damage in air to

$$\frac{D_{\text{air}}}{2.2}$$

Where D_{air} is the Fatigue damage in air as given in 2.5.5.

2.6.8 Applicability

The application of post-weld improvement and fatigue improvement factor provided is subject to the following:

- The weld type complies with Cl. 2.6.9.
- The weld improvement is effective or valid in improving the fatigue strength of structural details under high cycle fatigue conditions and do not apply to low-cycle fatigue conditions, i.e. when $N \leq 5 \times 10^4$, where N is the number of life cycles to failure.
- Unless otherwise specifically stated, the fatigue improvement factor is to be used for welds, joining steel plates which are between 6 and 50 [mm] thick.
- This improvement can only be achieved in a corrosion free condition and may only be considered provided that a suitable protective coating is applied after the post-weld treatment and maintained during the design life time. Hot spots are to be protected from corrosive environment.
- Fatigue improvement factor is to be applied to as-welded transverse butt welds, as-welded T-joint and cruciform welds and as-welded longitudinal attachment welds excluding longitudinal end connections.
- In way of areas prone to mechanical damage, fatigue improvement may occur only if if these are adequately protected.
- Treatment of inter-bead toes is required for large multi-pass welds as shown in Fig. 2.6.8.
- The yard is to provide the list of details and their locations on the ship for which the post-weld treatment has been applied.

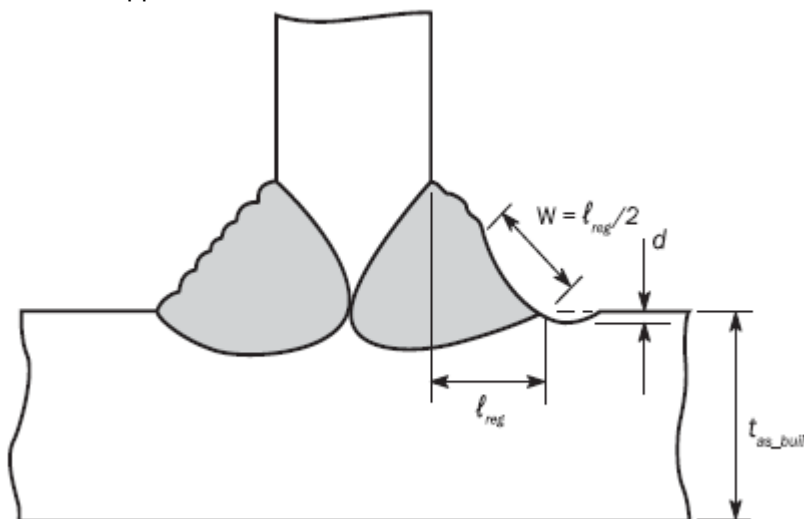


Fig. 2.6.8: Extent of weld toe burr grinding to remove inter-bead toes on weld face
(l_{reg} : Weld leg length, W : Width of groove, d : Depth of grinding to be between 0.5 and 1[mm])

2.6.9 Weld type for post-weld treatment

When weld improvements are planned, full or partial penetration welds with a minimum root face according to IRS rules, Part 3, Chapter 17 are to be used to mitigate or to eliminate the possibility of cracking at the weld root.

Section 3

Simplified Stress Analysis

3.1 General

3.1.1 This section provides the procedure for fatigue strength of the longitudinal stiffener end connections. The type of stresses considered in the analysis are explained in Section 2.3 to 2.6.

3.2 Fatigue approach for longitudinal end connections

3.2.1 The determination of the longitudinal stiffener end connections hot spot stress is based on:

- Nominal stresses from beam theory.
- Stress concentration factors for the different longitudinal end connections as given in Section 3.7
- Loading conditions specified in Section 1.

3.2.2 The longitudinal stiffener end connection types are described in Cl. 3.7.2.

3.3 Axial and bending stress

3.3.1 General

3.3.1.1 This sub-section deals with the assessment of fatigue induced by the axial and bending modes (Fig. 2.3.1) in way of longitudinal stiffener connections to primary members.

3.3.1.2 The simplified stress analysis aims at evaluating the hot spot stress at the flange of longitudinal stiffener connections with primary supporting members. The longitudinal stiffener is considered as a beam subjected to:

- axial loads induced by hull girder bending, and
- local bending induced by lateral pressure.

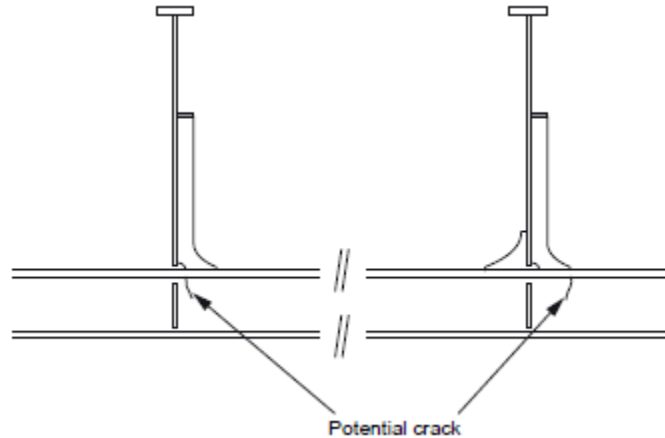


Fig. 3.3.1: Areas of potential cracks in longitudinal stiffener web due to bending mode

3.3.2 Effect of primary structure distortion

The hot spot stress ranges and hot spot mean stresses in way of each end connection of longitudinal stiffener, as shown in Fig. 3.5.1 are to be evaluated at the flange at following locations:

- a) Transverse webs or floors other than those located at transverse bulkhead including swash bulkhead of cargo hold or in way of stool, such that additional hot spot stress due to the relative displacement is not to be considered.
- b) Transverse webs or floors located at transverse bulkhead including swash bulkhead of cargo hold or in way of stool, such that additional hot spot stress due to the relative displacement are to be considered.

3.3.3 Stress concentration factors

Stress concentration factors due to unsymmetrical stiffener geometry according to Cl. 3.7.1 and due to the stiffener end connection geometry at two potential hot spots (point 'A' and 'B') according to Cl. 3.7.2 are to be applied.

For each hot spot of each connection, two geometric stress concentration factors (K_a and K_b) are defined, for both the axial stress and the bending stress respectively. The end connections given in Cl. 3.7.2 are based on typical joint geometry under axial and lateral loadings. When a structural detail is different from those shown in Table 3.7.2, a finite element analysis is to be used to demonstrate the adequacy of the detail in terms of fatigue strength, according to Cl. 3.7.3.

3.3.4 Hot spot stress range

The hot spot stress range, in $[N/mm^2]$, due to dynamic loads for loading condition (j) is obtained from the following formula:

$$\Delta\sigma_{HS,(j)} = |(\sigma_{GD,(j)} + \sigma_{LD,(j)} + \sigma_{dD,(j)})|$$

where:

- | | | |
|-------------------|---|--|
| $\sigma_{GD,(j)}$ | = | Stresses due to global hull girder wave bending moments, in $[N/mm^2]$, as defined in Cl. 3.4.1(a). |
| $\sigma_{LD,(j)}$ | = | Stresses due to local dynamic pressure, in $[N/mm^2]$, as defined in Cl. 3.5.1(a). |
| $\sigma_{dD,(j)}$ | = | Stresses due to relative displacement in wave, in $[N/mm^2]$, as defined in Cl. 3.5.5. |

3.3.5 Hot spot mean stress

The hot spot mean stress, in [N/mm²], due to static and dynamic loads for loading condition (j) is obtained from the following formula:

$$\sigma_{\text{mean,(j)}} = \sigma_{\text{GS,(j)}} + \sigma_{\text{LS,(j)}} + \sigma_{\text{dS,(j)}} + \sigma_{\text{mGD,(j)}} + \sigma_{\text{mLD,(j)}} + \sigma_{\text{mdD,(j)}}$$

where:

$\sigma_{\text{GS,(j)}}$	=	Stress due to still water hull girder bending moment, in [N/mm ²], as defined in Cl. 3.4.1(b).
$\sigma_{\text{LS,(j)}}$	=	Stress due to local static pressure, in [N/mm ²], as defined in Cl. 3.5.1(b).
$\sigma_{\text{dS,(j)}}$	=	Stress due to relative displacement in still water, in [N/mm ²], as defined in Cl. 3.5.6.
$\sigma_{\text{mLD,(j)}}$	=	Mean stress due to local dynamic pressure, in [N/mm ²], as defined in Cl. 3.5.1(a).
$\sigma_{\text{mGD,i(j)}}$	=	Mean stress due to global wave bending moment, in [N/mm ²], as defined in Cl.3.4.1(a).
$\sigma_{\text{mdD,i(j)}}$	=	Mean stress due to relative displacement in wave, in [N/mm ²], as defined in Cl. 3.5.5.

3.4 Global Axial Stress

3.4.1 Hull girder bending stress

(a) Stress due to hull girder wave bending moments

The hull girder hot spot stress, in [N/mm²], for considered loading condition (j) is obtained from the following formula:

$$\sigma_{\text{GD,(j)}} = f_p \cdot f_c \cdot K_a \cdot \left(\frac{M_{\text{wv}}}{I_{y-n50}} (z - z_n) - \frac{M_{\text{wh}}}{I_{z-n50}} \cdot y \right) 10^{-3}$$

where:

M_{wv}	=	Vertical wave bending moment, in [kN-m], at the hull girder load calculation point of the considered longitudinal position for the loading condition (j) as given IRS rule Part 3, Chapter 5, section [2].
M_{wh}	=	Horizontal wave bending moment, in [kNm], at the hull girder load calculation point of the considered longitudinal position for the loading condition (j) as given IRS rule Part 3, Chapter 5, section [3].
f_p	=	Load reduction factor taken as: = 0.3
(j)	=	Suffix which denotes loading condition:
I_{y-n50}	=	Net vertical hull girder moment of inertia, at the longitudinal position being considered [m ⁴].
I_{z-n50}	=	Net horizontal hull girder moment of inertia, at the longitudinal position being considered [m ⁴].
y	=	Transverse coordinate of the load calculation point under consideration [m].
z	=	Vertical coordinate of the load calculation point under consideration [m].
z_n	=	Distance from the baseline to the horizontal neutral axis [m].

K_a = Geometrical stress concentration factor for stress due to axial load given in 3.7.2.

(b) Stress due to still water hull girder bending moment

The hull girder hot spot stress due to still water bending moment [N/mm²], in loading condition (j) is obtained from the following formula:

$$\sigma_{GS,(j)} = \frac{f_c \cdot K_a \cdot \beta_{(j)} \cdot M_{sw} \cdot (z - z_n)}{I_{y-n50}} 10^{-3}$$

where:

M_{sw} = Permissible still water vertical bending moment [kNm], at the hull girder load calculation point of the considered longitudinal position.

$\beta_{(j)}$ = Fraction of permissible still water vertical bending moment, for loading condition (j) as given below in Table 3.4.1.

Table 3.4.1: Fraction of permissible still water vertical bending moments, $\beta_{(j)}$		
Vessel type	Full load condition	Normal/partial ballast condition
Tanker	0.6 in sagging condition	0.8 in hogging condition
Bulk carrier and dry Cargo ship ¹⁾	0.4 in sagging condition	0.8 in hogging condition ²⁾
MPV/ general dry cargo ship ³⁾	1.0 in sagging condition	1.0 in hogging condition
Liquefied gas carriers	0.7 in sagging condition	0.8 in hogging condition
Container ships	0.90 in hogging condition	0.8 in hogging condition
Ore Carrier ¹⁾	1.0 in sagging condition	1.0 in hogging condition
Passenger Ship ⁴⁾	--	1.0 in hogging condition
RO-RO ⁴⁾	--	1.0 in hogging condition
Others ⁵⁾	--	
1) Applicable for ore carrier, bulk carrier and dry cargo ships except MPV/general dry cargo ships having a long centre cargo hold.		
2) In alternate condition it is taken as 0.75.		
3) Applicable for MPV/general dry cargo ships having a long centre cargo hold.		
4) Values used when global FE analysis is required. Prescriptive assessment of longitudinal end connections is not required for passenger vessels.		
5) Other ships shall be specifically considered.		

3.5 Local bending stress

3.5.1 Stress due to stiffener bending

(a) Stress due to dynamic pressure

The hot spot stress, in [N/mm²], due to local dynamic pressure for loading condition (j) is obtained from the following formula:

$$\sigma_{LD(j)} = \frac{K_b \cdot K_n \cdot s \cdot \ell_{bdg}^2 \cdot f_p (\eta_w \cdot f_{NL} \cdot P_{W,(j)} + \eta_{ld} \cdot P_{ld,(j)} + \eta_{bd} \cdot P_{bd,(j)}) \left(1 - \frac{6X_e}{\ell_{bdg}} + \frac{6X_e^2}{\ell_{bdg}^2}\right)}{12Z_{eff-n50}}$$

where:

- $P_{W,(j)}$ = Dynamic wave pressure, at the mid span [kN/m²], for loading condition (j) as given IRS rule Part 3, Chapter 4, section[3].
- $P_{ld,ik(j)}$ = Dynamic liquid tank pressure, at the mid span [kN/m²], for loading condition (j) as given IRS rule Part 3, Chapter 4, section[3].

Pressure acting on both sides of the stiffener, i.e. applied on the attached plate on stiffener side or on opposite side to the stiffener, could be simultaneously considered if relevant in the loading condition.

For the deck longitudinal stiffeners of bulk carriers, no internal pressure from the topside tank is considered.

- $P_{bd,(j)}$ = Dynamic dry bulk cargo pressure at the mid span [kN/m²], i for loading condition (j) as given IRS rule Part 3, Chapter 4, section[3].
- $\eta_w, \eta_{ld}, \eta_{bd}$ = Pressure normal coefficients, taken as:
= 1 when the considered pressure is applied on the stiffener side,
= -1 otherwise.
- f_{NL} = Correction factor for the non-linearity of the wave pressure taken as:

$$f_{NL} = 1 \text{ for } z > T_{LC} + 2h_w$$

$$f_{NL} = 2.5 \frac{z - T_{LC}}{h_w} - 4 \text{ for } T_{LC} + 1.8h_w < z \leq T_{LC} + 2h_w$$

$$f_{NL} = 0.5 \frac{z - T_{LC}}{h_w} - 0.4 \text{ for } T_{LC} + 1.1h_w < z \leq T_{LC} + 1.8h_w$$

$$f_{NL} = 0.4 \text{ for } T_{LC} + 1.2h_w < z \leq T_{LC} + 1.6h_w$$

$$f_{NL} = 0.7 - 0.25 \frac{z - T_{LC}}{h_w} \text{ for } T_{LC} + 0.6h_w < z \leq T_{LC} + 1.2h_w$$

$$f_{NL} = 1 - 0.75 \frac{z - T_{LC}}{h_w} \text{ for } T_{LC} - 0.2h_w < z \leq T_{LC} + 0.6h_w$$

$$f_{NL} = 0.1875 \frac{z - T_{LC}}{h_w} + 1.1875 \text{ for } T_{LC} - h_w < z \leq T_{LC} - 0.2h_w$$

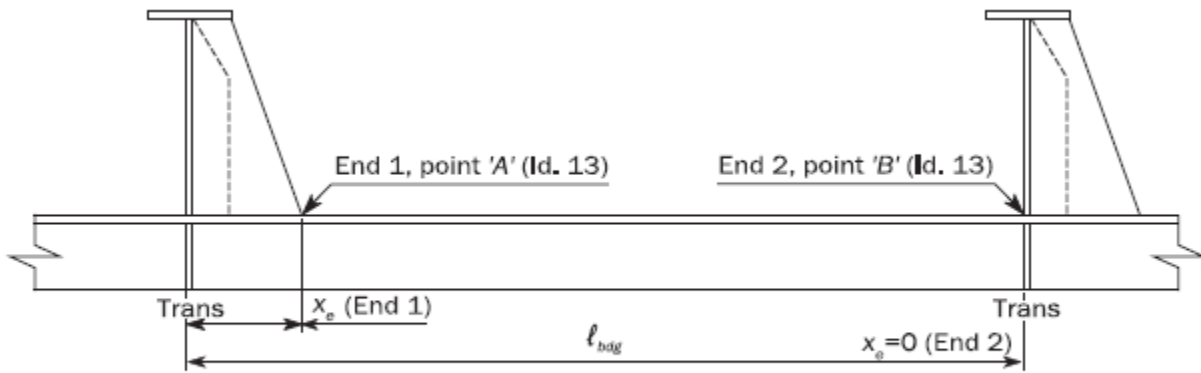
$$f_{NL} = 1 \text{ for } z \leq T_{LC} - h_w$$

- h_w = Water head equivalent to the pressure at waterline, in [m].
- X_e = Distance, in [m], to the hot spot from the closest end of the span ℓ_{bdg} , as defined in Fig. 3.5.1.
- $Z_{eff-n50}$ = Net section modulus [cm³], of the considered stiffener calculated considering an effective breadth b_{eff} of attached plating and taken at the stiffener flange.
- b_{eff} = Effective breadth [mm], of attached plating specified at the ends of the span and in way of end brackets and supports, taken as:

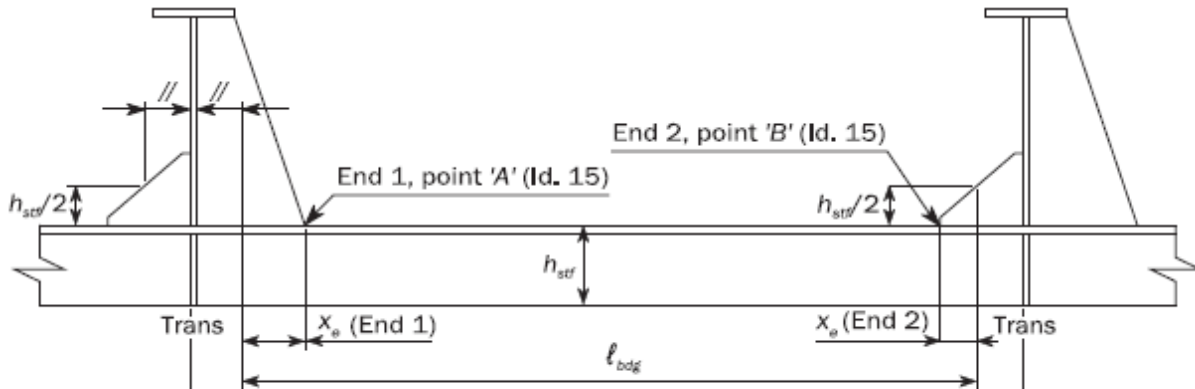
$$b_{\text{eff}} = s \cdot \min \left(\frac{1.04}{1 + \frac{\left(\frac{\ell_{\text{bdg}}}{s} \left(1 - \frac{1}{\sqrt{3}} \right) \cdot 10^3 \right)^{1.35}}{3}}; 1.0 \right) \text{ for } \frac{\ell_{\text{bdg}}}{s} \left(1 - \frac{1}{\sqrt{3}} \right) \cdot 10^3 \geq 1$$

$$b_{\text{eff}} = 0.26 \ell_{\text{bdg}} \left(1 - \frac{1}{\sqrt{3}} \right) \cdot 10^3 \text{ for } \frac{\ell_{\text{bdg}}}{s} \left(1 - \frac{1}{\sqrt{3}} \right) \cdot 10^3 < 1$$

- K_b = Geometrical stress concentration factor for stress due to lateral pressure given in 3.7.2.
- K_n = Stress concentration factor due to unsymmetrical stiffener geometry, as defined in 3.7.1.
- ℓ_{bdg} = Effective bending span of stiffener [m].
- s = Stiffener spacing [m].



Supported by free flange transverses



Supported by free flange transverses

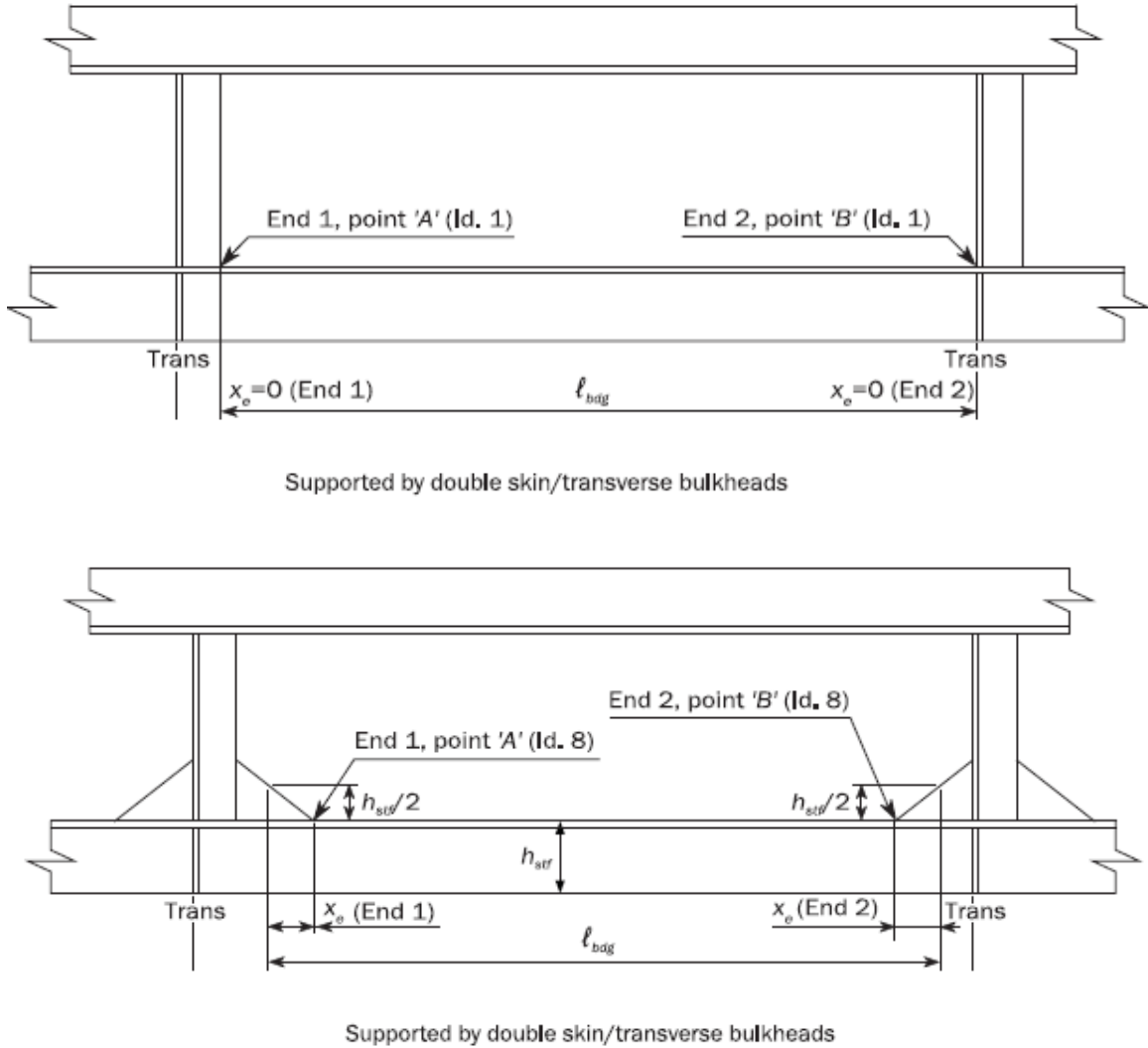


Figure 3.5.1: Definition of effective span and X_e for hot spot

(b) Stress due to static pressure

The hot spot stress due to local static pressure [N/mm²], for loading condition (j) is obtained from the following formula:

$$\sigma_{LS(j)} = \frac{K_b \cdot K_n \cdot s \cdot \ell_{bdg}^2 \cdot (\eta_s \cdot P_{S(j)} + \eta_{ls} \cdot P_{LS(j)} + \eta_{bs} \cdot P_{BS(j)}) \left(1 - \frac{6X_e}{\ell_{bdg}} + \frac{6X_e^2}{\ell_{bdg}^2} \right)}{12Z_{eff-n50}}$$

where:

- $P_{S(j)}$ = Static external pressure [kN/m²], in loading condition (j) as given IRS rule Part 3, Chapter 4, section [3].
- $P_{LS(j)}$ = Static liquid tank pressure [kN/m²], in loading condition (j) as given IRS rule Part 3, Chapter 4, section [3].

Pressure acting on both sides could be simultaneously considered if relevant in the loading condition.

$P_{bs(j)}$	=	Static dry bulk cargo pressure [kN/m ²], in loading condition (j) as given IRS rule Part 3, Chapter 4, section [3].
$\eta_S, \eta_{ls}, \eta_{bs}$	=	Pressure normal coefficients, taken as:
	=	1 when the considered pressure is applied on the stiffener side,
	=	-1 otherwise.

3.6 Stress due to relative displacements of primary supporting members

3.6.1 The additional hot spot stress due to the relative displacement of primary supporting members is to be considered for longitudinal stiffener end connections fitted on transverse web frames or floors located:

- in way of plane transverse bulkheads (including swash bulkheads in cargo holds), or
- in way of transverse stools and cofferdam bulkheads.

3.6.2 The relative displacement is defined as the lateral displacement of the longitudinal measured at the frame forward (Fwd) or afterward (Aft) relative to the displacement at the transverse bulkhead (or restrained frame).

3.6.3 Displacement of primary supporting members

The displacement of primary supporting members is to be evaluated using a FE model. The displacement of a primary supporting member is the displacement of the point located at the intersection of the stiffener flange, the stiffener web and the supporting member web. This displacement is measured along the line defined by the intersection between the stiffener web and the primary supporting member web in the non-deformed state of the finite element model.

3.6.4 Sign convention

Where the stress at the hot spot location, i.e. at the flange of longitudinal at the transverse bulkhead (or restrained frame), due to relative displacement is in tension, the sign of the relative displacement is positive.

3.6.5 Stress due to relative displacement derived using FE method

The relative displacement stress can be calculated based on relative displacement derived from FE analysis. If the relative displacement is derived from FE analysis, the local rotation at the position of the hot spot needs to be accounted for.

The stress due to relative displacement, in [N/mm²], for both locations 'a' and 'f' is to be calculated directly using the following expression:

$$\sigma_{dD,(j)} = \begin{cases} K_b \cdot \sigma_{dFwd-a,(j)} + K_b \cdot \sigma_{dAft-a,(j)} & \text{for location "a"} \\ K_b \cdot \sigma_{dFwd-f,(j)} + K_b \cdot \sigma_{dAft-f,(j)} & \text{for location "f"} \end{cases}$$

where:

a, f	=	Suffix which denotes the location as indicated in Fig. 3.6.5.
Aft, Fwd	=	Suffix which denotes the direction, afterward (Aft) or forward (Fwd), from the transverse bulkhead as shown in Fig. 3.6.5.
K_b	=	Stress concentration factor due to bending for the location 'a' or 'f' which may correspond to points 'A' or 'B' as defined in Table 3.7.2.
$\sigma_{dFwd-a,(j)}, \sigma_{dAft-a,(j)}, \sigma_{dFwd-f,(j)}, \sigma_{dAft-f,(j)}$	=	Additional stress at location 'a' and 'f', in [N/mm ²], due to the relative displacement between the transverse bulkhead including swash bulkhead or floors in way of stool and the forward (Fwd) and afterward (Aft) transverse web or floor of loading condition (j), taken as:

$$\sigma_{dFwd-a,(j)} = \frac{3.9 \delta_{Fwd,(j)} \cdot EI_{Aft-n50} \cdot I_{Fwd-n50}}{Z_{Aft-n50} \cdot \ell_{Fwd} (\ell_{Aft} I_{Fwd-n50} + \ell_{Fwd} I_{Aft-n50})} \left(1 - 1.15 \frac{|X_{eAft}|}{\ell_{Aft}} \right) 10^{-5}$$

$$\sigma_{dAft-a,(j)} = \left[\frac{3.9 \delta_{Aft,(j)} \cdot EI_{Aft-n50} \cdot I_{Fwd-n50}}{Z_{Aft-n50} \cdot I_{Aft} (\ell_{Aft} I_{Fwd-n50} + \ell_{Fwd} I_{Aft-n50})} \left(1 - 1.15 \frac{|X_{eAft}|}{\ell_{Aft}} \right) - \frac{0.9 \delta_{Aft,(j)} \cdot EI_{Aft-n50} |X_{eAft}|}{Z_{Aft-n50} \ell_{Aft}^3} \right] 10^{-5}$$

$$\sigma_{dFwd-f,(j)} = \left[\frac{3.9 \delta_{Fwd,(j)} \cdot EI_{Aft-n50} \cdot I_{Fwd-n50}}{Z_{Fwd-n50} \cdot I_{Fwd} (\ell_{Aft} I_{Fwd-n50} + \ell_{Fwd} I_{Aft-n50})} \left(1 - 1.15 \frac{|X_{eFwd}|}{\ell_{Fwd}} \right) - \frac{0.9 \delta_{Fwd,(j)} \cdot EI_{Fwd-n50} |X_{eFwd}|}{Z_{Fwd-n50} \ell_{Fwd}^3} \right] 10^{-5}$$

$$\sigma_{dAft-f,(j)} = \frac{3.9 \delta_{Aft,(j)} \cdot EI_{Aft-n50} \cdot I_{Fwd-n50}}{Z_{Fwd-n50} \cdot \ell_{Aft} (\ell_{Aft} I_{Fwd-n50} + \ell_{Fwd} I_{Aft-n50})} \left(1 - 1.15 \frac{|X_{eFwd}|}{\ell_{Fwd}} \right) 10^{-5}$$

- $I_{Aft-n50}, I_{Fwd-n50}$ = Net moment of inertia, in [cm⁴], of forward (Fwd) and afterward (Aft) longitudinal.
- $Z_{Aft-n50}, Z_{Fwd-n50}$ = Net section modulus of forward (Fwd) and afterward (Aft) stiffener, in [cm³].
- ℓ_{Aft}, ℓ_{Fwd} = Span, in [m], of forward (Fwd) and afterward (Aft) longitudinal, as shown in Fig. 3.6.5.
- X_{eAft}, X_{eFwd} = Distance, in [m], as shown in Fig. 3.5.1, to the hot spot in location 'a' or 'f' from the closest end of ℓ_{Fwd} and ℓ_{Aft} respectively.
- $\delta_{Aft,(j)}, \delta_{Fwd,(j)}$ = Relative displacement in the direction perpendicular to the attached plate, in [mm], between the transverse bulkhead (including swash bulkhead or floor in way of stools) and the forward (Fwd) or afterward (Aft) transverse web (or floor) as shown in Fig. 3.6.5.

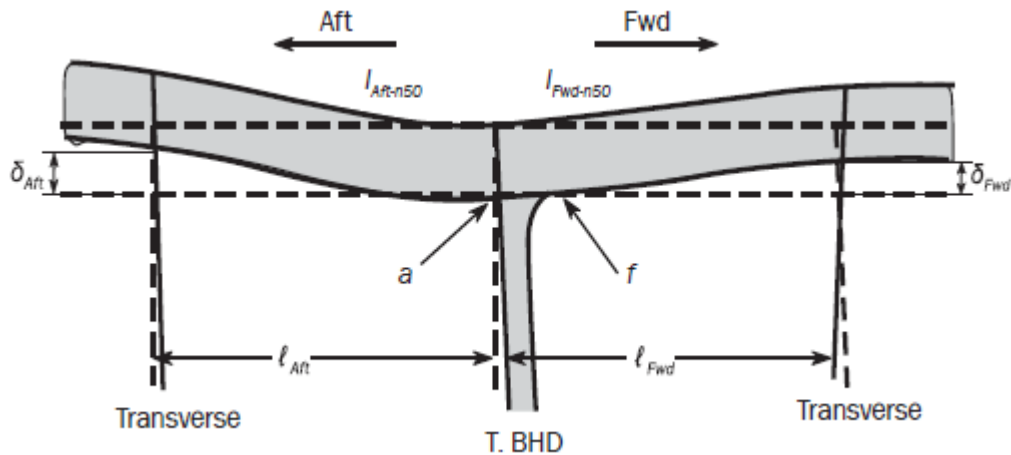


Fig. 3.6.5: Definition of the relative displacement (example of the side longitudinal)

3.6.6 Stress due to relative displacement in still water

The additional hot spot stress, in [N/mm²], in still water, due to the relative displacement is to be obtained according to Cl. 3.6.5, replacing dynamic local stress σ_{LD} and dynamic pressure with static local stress σ_{LS} and static pressure.

3.7 Stress concentration factor

3.7.1 Unsymmetrical stiffener

- (a) The stress concentration factor K_n for unsymmetrical flange of built-up and rolled angle stiffeners under lateral load, calculated at the web's mid-thickness position, as shown in Fig. 3.7.1(a), is to be taken as:

$$K_n = \frac{1 + \lambda \beta^2}{1 + \lambda \beta^2 \Psi_z}$$

where,

$$\lambda = \frac{3 \left(1 + \frac{\eta}{280} \right)}{1 + \frac{\eta}{40}}$$

$$\eta = \frac{\ell_{bdg}^4 \cdot 10^{12}}{b_{f-n50}^3 \cdot t_{f-n50} \cdot h_{stf-n50}^2 \cdot \left(\frac{4 \cdot h_{stf-n50}}{t_{w-n50}^3} + \frac{S}{t_{p-n50}^3} \right)}$$

$$\beta = 1 - \frac{2b_{g-n50}}{b_{f-n50}} \text{ for built - up profiles}$$

$$\beta = 1 - \frac{t_{w-n50}}{b_{f-n50}} \text{ for rolled angle profiles}$$

- b_{g-n50} = Eccentricity of the stiffener equal to the distance from flange's edge to web's centreline, in [mm], as shown in Fig. 3.7.1(b).
 b_{f-n50} = Net breadth of flange, in [mm], as shown in Fig. 3.7.1(b).
 t_{f-n50} = Net flange thickness, in [mm], as shown in Fig. 3.7.1(b).
 $h_{stf-n50}$ = Net stiffener height, including face plate, in [mm], as shown in Fig. 3.7.1(b).
 t_{w-n50} = Net web thickness, in [mm], as shown in Fig. 3.7.1(b).
 h_{w-n50} = Net web's height stiffener, in [mm], as shown in Fig. 3.7.1(b).
 t_{p-n50} = Net thickness of attached plating, in [mm], as shown in Fig. 3.7.1(b).
 Ψ_z = Coefficient given as:

$$\Psi_z = \frac{h_{w-n50}^2 t_{w-n50}}{4Z_{n50}} 10^{-3}$$

- Z_{n50} = Net section modulus, in [cm³], of stiffener with an attached plating breadth equal to the stiffener spacing.

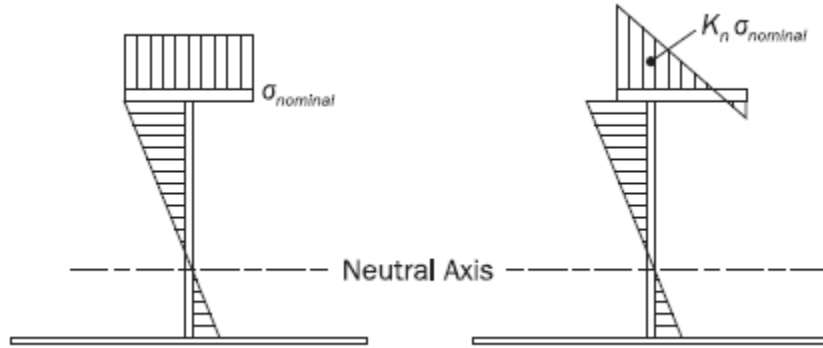


Fig. 3.7.1(a): Bending stress in stiffener with symmetrical and unsymmetrical flange

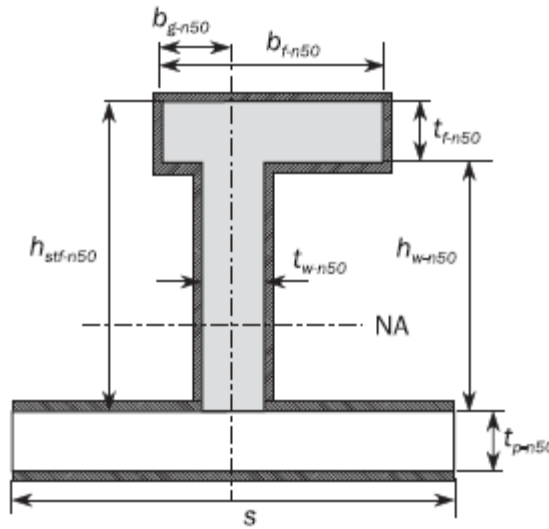


Fig. 3.7.1(b): Stiffener - Net scantling

(b) Bulb profiles

For bulb profiles K_n factor is to be calculated using the equivalent built-up profile as shown in Fig. 3.7.1(c). The flange of the equivalent built-up profile is to have the same properties as the bulb flange, i.e. same cross sectional area and moment of inertia about the vertical axis and neutral axis position. For HP bulb profiles, examples of the equivalent built up profile dimensions are listed in Table 3.7.1.

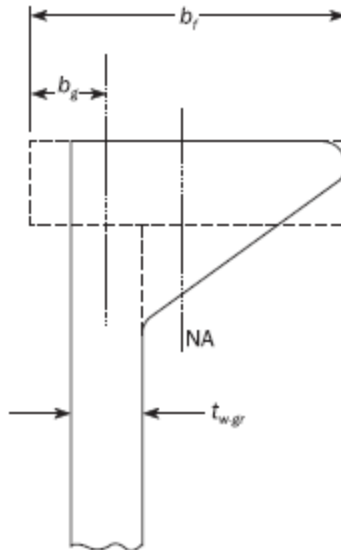


Figure 3.7.1(c): Bulb profile and equivalent built-up profile

Table 3.7.1: HP equivalent built-up profile dimensions				
HP-bulb		Equivalent built-up flange in gross thickness		
Height (mm)	Gross web thickness, t_{w-gr} (mm)	b_f (mm)	t_{f-gr} (mm)	b_g (mm)
200	9 – 13	$t_{w-gr} + 24.5$	22.9	$(t_{w-gr} + 0.9)/2$
220	9 – 13	$t_{w-gr} + 27.6$	25.4	$(t_{w-gr} + 1.0)/2$
240	10 – 14	$t_{w-gr} + 30.3$	28.0	$(t_{w-gr} + 1.1)/2$
260	10 – 14	$t_{w-gr} + 33.0$	30.6	$(t_{w-gr} + 1.3)/2$
280	10 – 14	$t_{w-gr} + 35.4$	33.3	$(t_{w-gr} + 1.4)/2$
300	11 – 16	$t_{w-gr} + 38.4$	35.9	$(t_{w-gr} + 1.5)/2$
320	11 – 16	$t_{w-gr} + 41.0$	38.5	$(t_{w-gr} + 1.6)/2$
340	12-17	$t_{w-gr} + 43.3$	41.3	$(t_{w-gr} + 1.7)/2$
370	13-19	$t_{w-gr} + 47.5$	45.2	$(t_{w-gr} + 1.9)/2$
400	14-19	$t_{w-gr} + 51.7$	49.1	$(t_{w-gr} + 2.1)/2$
430	15-21	$t_{w-gr} + 55.8$	53.1	$(t_{w-gr} + 2.3)/2$

3.7.2 Longitudinal stiffener end connections

(a) The stress concentration factors K_a and K_b are given in Table 3.7.2 for end connection of stiffeners subjected to axial and lateral loads. The values given in Table 3.7.2 for soft toe are valid provided that toe geometry complies with the requirements given in 3.7.2(e). The stress concentration factor K_b given for lateral loads are to be used also for stress due to relative displacements.

(b) Other connection types

When connection types other than those given in Table 3.7.2 are proposed, the fatigue strength for the proposed connection type is to be assessed either by performing a very fine mesh FE analysis as described in Section 4 to obtain directly the hot spot stress, or by calculating the stress concentration factor using FE analysis according to 3.7.3.

(c) Overlapped connection

Overlapped connection types for longitudinal stiffeners, i.e. attachments welded to the web of the longitudinals, are to be avoided in areas where fatigue might be critical e.g. in way of cargo hold region. If overlap is used an additional factor of 1.15 should be used.

(d) End stiffener without connection to web stiffener: Where the web stiffener is omitted or not connected to the longitudinal flange in way of:

- Side shell below $1.1T_{sc}$.
- Bottom.
- Inner hull longitudinal bulkhead below $1.1T_{sc}$.
- Hopper.
- Topside tank sloping plating below $1.1T_{sc}$.
- Inner bottom.

the following is required:

- A complete collar as defined in Fig. 3.7.2(a) (i.e. connection type ID 31 of Table 3.7.2.) or,
- A detail design for cut-outs as described in **Appendix A**.

Equivalence to cut-outs given in **Appendix A**, A.2.1 may be accepted provided it is assessed for fatigue by using comparative FE analysis which is based on hot spot stress around the cut-out in the web plate of the primary supporting member inclusive of the collar, as given in **Appendix A**, A.2.2.

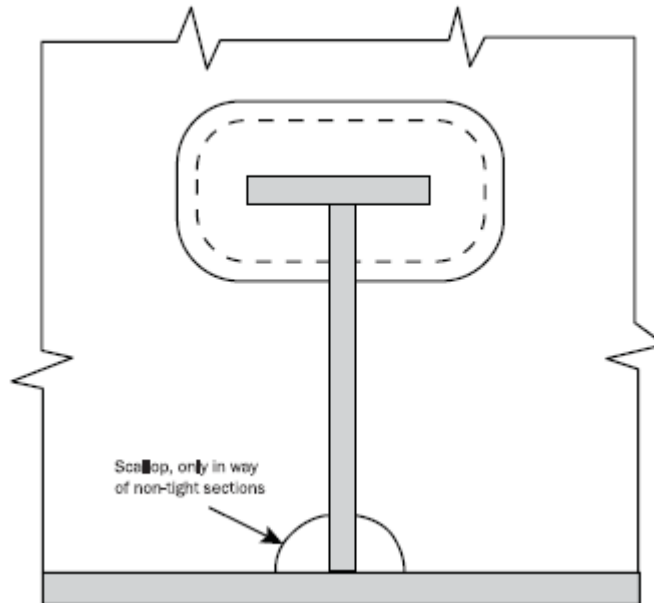


Fig. 3.7.2(a): Complete collar fitted before the stiffener is pulled through the web frame

(e) Soft toe of web stiffener and backing bracket

The toe geometry end connection of web stiffener and backing bracket is to comply with the following:

$$\theta \leq 20$$
$$h_{\text{toe}} \leq \max(t_{\text{bkt-gr}}, 15)$$

where:

- θ = Angle of the toe [deg], as shown in Fig. 3.7.2(b).
- h_{toe} = Height of the toe [mm], as shown in Fig. 3.7.2(b).
- $t_{\text{bkt-gr}}$ = Gross thickness of the bracket [mm].

Recommended detail designs for longitudinal end connections with soft toes and backing brackets are given in Fig. 3.7.2(b).

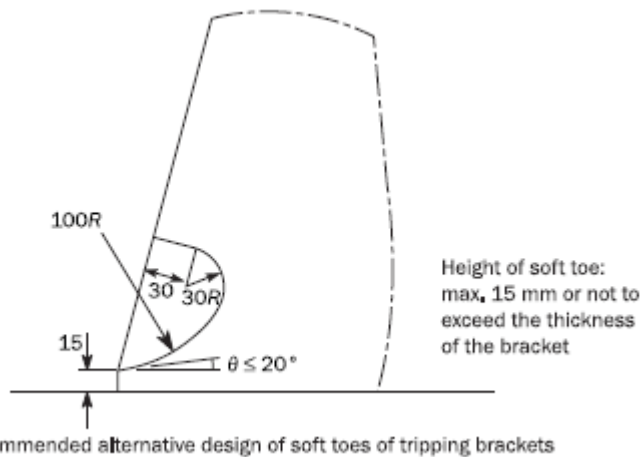
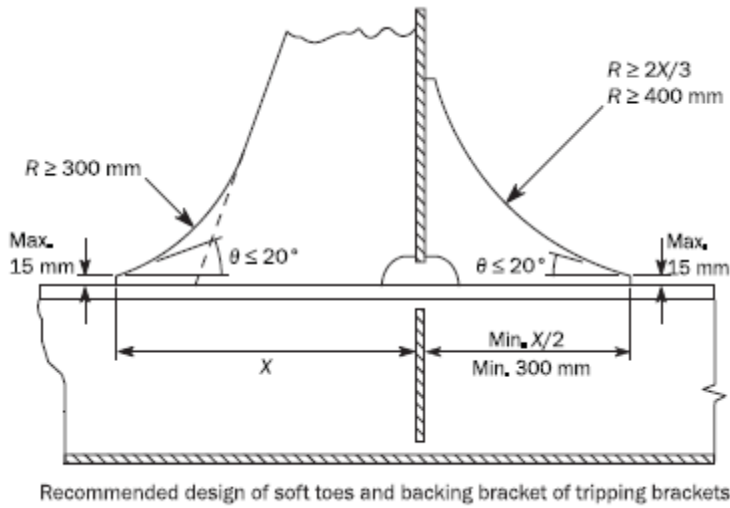
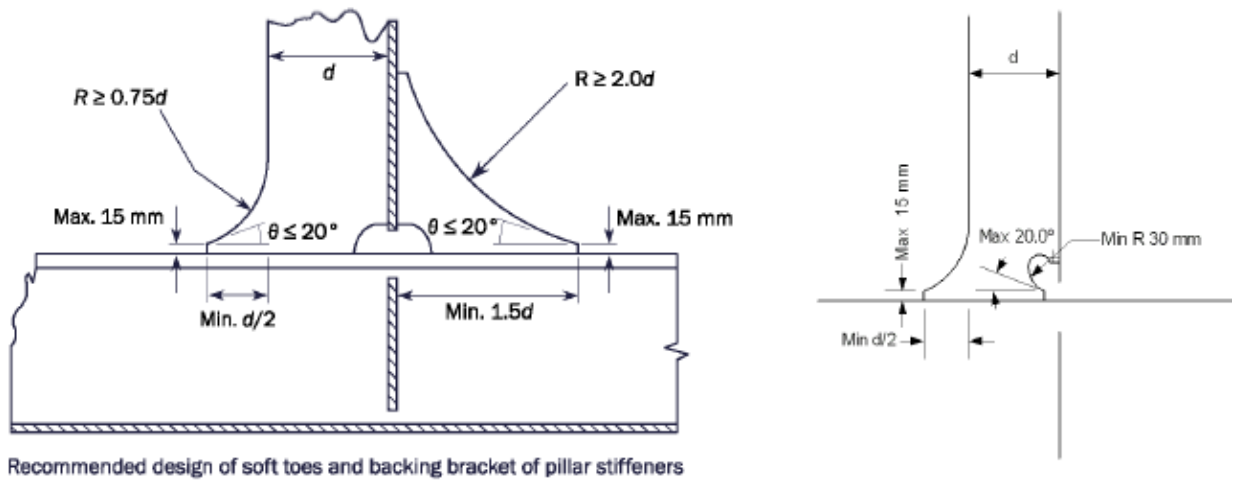
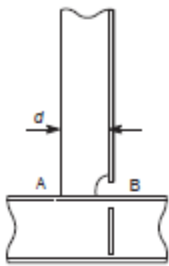
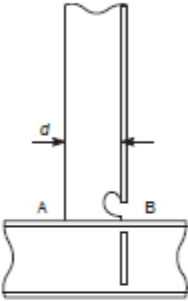
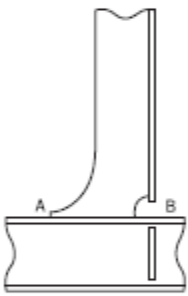
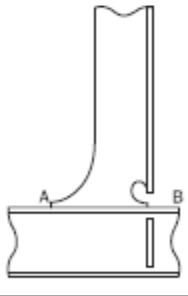
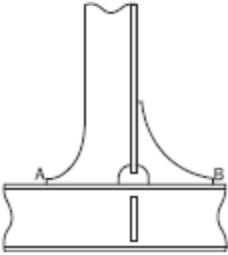
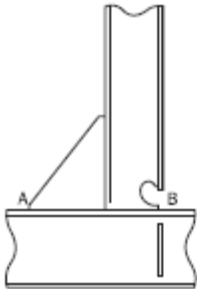
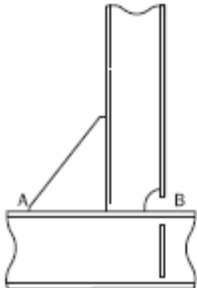
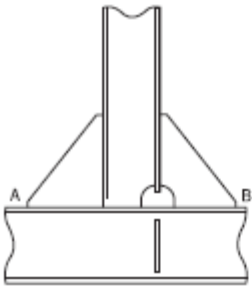
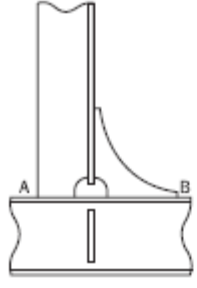
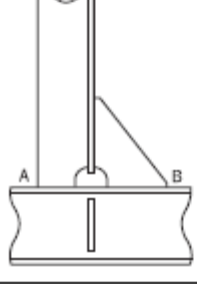
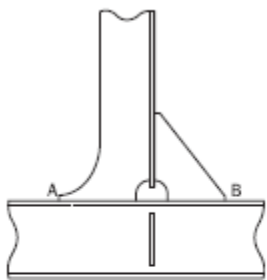
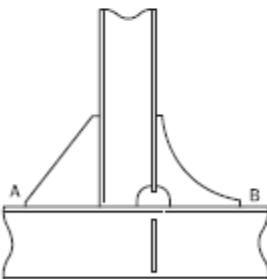
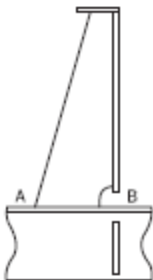
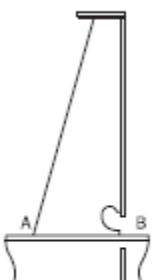
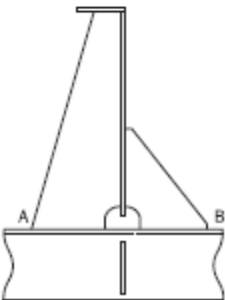


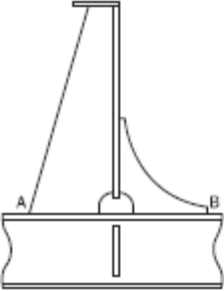
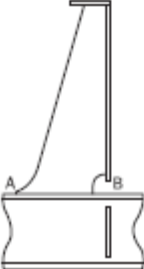
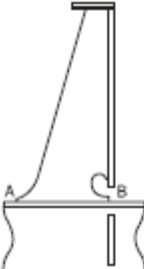
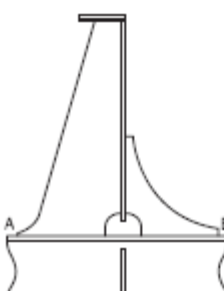
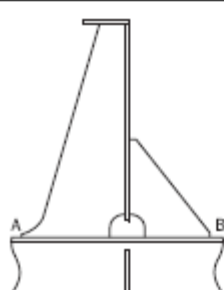
Fig. 3.7.2(b): Detail design for soft toes and backing brackets

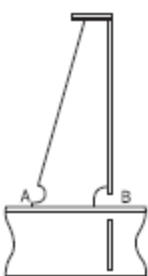
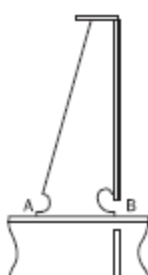
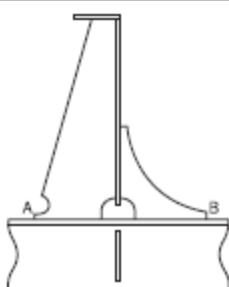
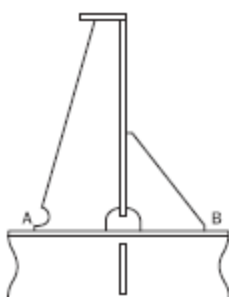
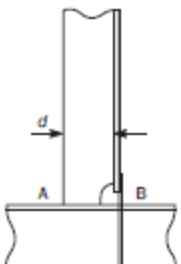
Table 3.7.2: Stress concentration factors

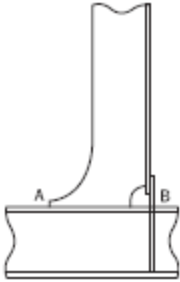
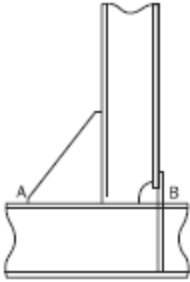
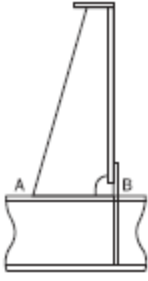
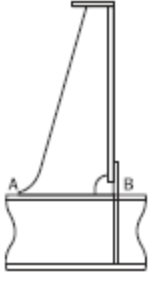
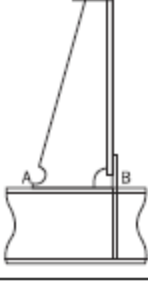
ID	Connection type ⁽²⁾⁽³⁾	Point 'A'		Point 'B'	
		K_a	K_b	K_a	K_b
1 ⁽⁴⁾		1.28 for $d \leq 150$ 1.36 for $150 < d \leq 250$ 1.45 for $d > 250$	1.40 for $d \leq 150$ 1.50 for $150 < d \leq 250$ 1.60 for $d > 250$	1.28 for $d \leq 150$ 1.36 for $150 < d \leq 250$ 1.45 for $d > 250$	1.60
2 ⁽⁴⁾		1.28 for $d \leq 150$ 1.36 for $150 < d \leq 250$ 1.45 for $d > 250$	1.40 for $d \leq 150$ 1.50 for $150 < d \leq 250$ 1.60 for $d > 250$	1.14 for $d \leq 150$ 1.24 for $150 < d \leq 250$ 1.34 for $d > 250$	1.27
3		1.28	1.34	1.52	1.67
4		1.28	1.34	1.34	1.34
5		1.28	1.34	1.28	1.34

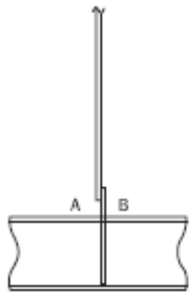
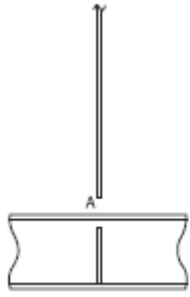
ID	Connection type ⁽²⁾ ⁽³⁾	Point 'A'		Point 'B'	
		K_a	K_b	K_a	K_b
6		1.52	1.67	1.34	1.34
7		1.52	1.67	1.52	1.67
8		1.52	1.67	1.52	1.67
9		1.52	1.67	1.28	1.34
10		1.52	1.67	1.52	1.67

ID	Connection type ⁽²⁾⁽³⁾	Point 'A'		Point 'B'	
		K_a	K_b	K_a	K_b
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

ID	Connection type ⁽²⁾ ⁽³⁾	Point 'A'		Point 'B'	
		K_a	K_b	K_a	K_b
16		1.52	1.67	1.28	1.34
17		1.28	1.34	1.52	1.67
18		1.28	1.34	1.34	1.34
19		1.28	1.34	1.28	1.34
20		1.28	1.34	1.52	1.67

ID	Connection type ⁽²⁾⁽³⁾	Point 'A'		Point 'B'	
		K_a	K_b	K_a	K_b
21		1.28	1.34	1.52	1.67
22		1.28	1.34	1.34	1.34
23		1.28	1.34	1.28	1.34
24		1.28	1.34	1.52	1.67
25 ⁽⁴⁾		1.28 for $d \leq 150$ 1.36 for $150 < d \leq 250$ 1.45 for $d > 250$	1.40 for $d \leq 150$ 1.50 for $150 < d \leq 250$ 1.60 for $d > 250$	1.14 for $d \leq 150$ 1.24 for $150 < d \leq 250$ 1.34 for $d > 250$	1.25 for $d \leq 150$ 1.36 for $150 < d \leq 250$ 1.47 for $d > 250$

ID	Connection type ⁽²⁾ ⁽³⁾	Point 'A'		Point 'B'	
		K_a	K_b	K_a	K_b
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		1.28	1.34	1.34	1.47
30		1.28	1.34	1.34	1.47

ID	Connection type ⁽²⁾⁽³⁾	Point 'A'		Point 'B'	
		K_a	K_b	K_a	K_b
31 ⁽⁴⁾		1.13	1.20	1.13	1.20
32 ⁽⁴⁾⁽⁵⁾⁽⁶⁾		1.13	1.14	N/A	N/A

(1) The attachment length d [mm], is defined as the length of the welded attachment on the longitudinal stiffener flange without deduction of scallop.

(2) Where the longitudinal stiffener is a flat bar and there is a web stiffener/bracket welded to the flat bar stiffener, the stress concentration factor listed in the table (excluding detail 31 and 32) is to be multiplied by a factor of 1.12 when the thickness of attachment is thicker than the 0.7 times thickness of flat bar stiffener. This also applies to unsymmetrical profiles where there is less than 8[mm] clearance between the edge of the stiffener flange and the attachment, e.g. bulb or angle profiles where the clearance of 8[mm] cannot be achieved.

(3) Designs with overlapped connection / attachments, see 3.7.2(c).

(4) ID. 31 and 32 refer to details where web stiffeners are omitted or not connected to the longitudinal stiffener flange. See 3.7.2(d) For detail 31, however, the collar is assumed welded to the stiffener flange.

(5) For connection type ID. 32 with no collar and/or web plate welded to the flange, the stress concentration factors provided in this table are to be used irrespective of slot configuration.

(6) The fatigue assessment point 'A' is located at the connection between the stiffener web and the transverse web frame or lug plate. The stress concentration factor represents the hot spot related to the longitudinal stress.

3.7.3 Alternative design

(a) Derivation of alternative stress concentration factors

The stress concentration factors for alternative designs are to be calculated by a very fine mesh FE analysis according to the requirements given in Section 4. Additional requirements for derivation of geometrical stress concentration factors for stiffener end connections using very fine mesh FE analysis are given below:

(b) FE model extent: the FE model, as shown in Fig. 3.7.3, is to cover at least four web frame spacings in the longitudinal stiffener direction with the detail to be considered located at the middle frame. The same type of end connection is to be modelled at all the web frames. In the transverse direction, the model may be limited to one stiffener spacing.

(c) Load application: in general, two loading cases are to be considered:

- Axial loading by enforced displacement applied to the model ends and
- Lateral loading by unit pressure load applied to the shell plating.

(d) Boundary conditions applied in the FE model considered:

- Symmetry conditions are applied along the longitudinal cut of the plate flange, along transverse and vertical cuts on web frames and on top of the web stiffener.
- For lateral pressure loading: the model is to be fixed in all degrees of freedom at both forward and aft ends.
- For axial loading: the model is to be fixed for displacement in the longitudinal direction at the aft end of the model while enforced axial displacement is applied at the forward end, or vice versa.

(e) FE mesh density: At the location of the hot spots under consideration, the element size is to be in the order of the thickness of the stiffener flange or 10[mm] depending on the type of stiffener. In the remaining part of the model, the element size is to be in the order of $s/10$, where s is the stiffener spacing.

(f) The geometric stress concentration factor is defined as the ratio of the hot spot stress derived from FE analysis up on nominal stress calculated according to analytical stress analysis for longitudinal stiffener connections.

(g) Two geometric stress concentration factors K_a and K_b are to be determined, for 2 loading cases specified above, and are determined as follows:

- For the axial loading case:

$$K_a = \frac{\sigma_{HSAx}}{\sigma_{NomAx}}$$

- For the bending loading case:

$$K_b = \frac{\sigma_{HSBd}}{\sigma_{NomBd}}$$

σ_{HSAx}	=	Hot spot stress, [N/mm ²], determined at the stiffener flange for the axial load.
σ_{NomAx}	=	Nominal axial stress, [N/mm ²], calculated at the stiffener flange according to 3.4.1 for the axial load applied for the FE calculation.
σ_{HSBd}	=	Hot spot stress, [N/mm ²], determined at the stiffener flange for the unit pressure load.
σ_{NomBd}	=	Nominal bending stress, [N/mm ²], calculated at the stiffener

flange according to [3.5.1] in way of the hot spot for the unit pressure load applied for the FE calculation.

The derivation of geometrical stress concentration factors for alternative designs is to be documented and provided to IRS.

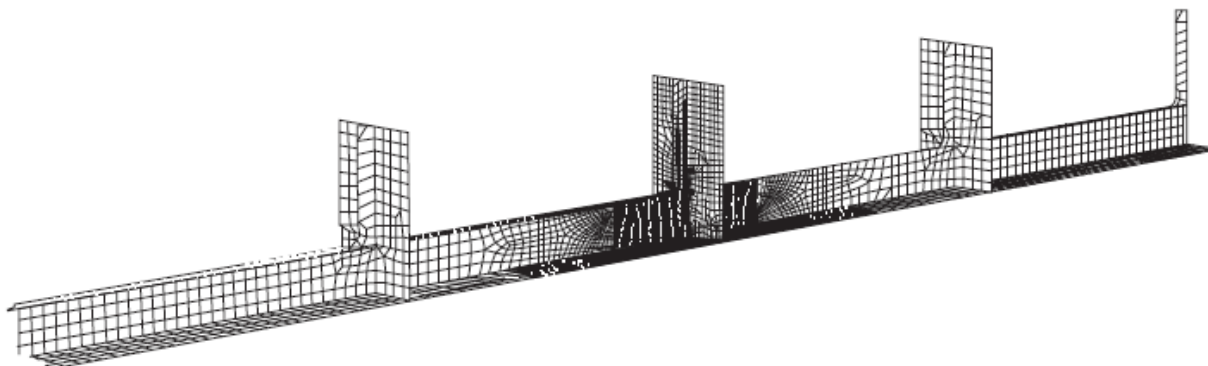


Fig. 3.7.3: Fine mesh finite element model for derivation of geometrical stress concentration factor (example of stiffener with flange)

Section 4

Finite Element Stress Analysis

4.1 General

4.1.1 Application

4.1.1.1 This section applies to fatigue assessment by finite element stress analysis. The methods are based on the hot spot stress approach and requirements are given for both plated welded joints and for non-welded hot spots. The hot spot stress takes 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.

4.1.1.2 The local nominal stress for non-welded area at cut plate edge requires a specific finite element model and a well specified method for the calculation, refer 4.2.4.

4.1.1.3 The stress at hot spot for welded joints is generally highly dependent on the finite element model used for the representation of the structure. Where other methods than those described in this Section are adopted for calculation of FEA based hot spot stress, these methods are to be submitted to IRS for review.

4.1.1.4 Limitations of the hot spot stress methodology for simple connections is given in 4.8.

4.1.1.5 Some typical structural details to be assessed for fatigue by very fine mesh analysis according to 4.2 to 4.6 are given below, irrespective of their compliance with the design standard given in **Appendix A**.

- Welded/radiused hopper knuckle (lower/upper) connection (intersection of hopper sloping plate, knuckled inner bottom plate, longitudinal girder, floor and transverse web, inner hull longitudinal bulkhead, transverse web and side stringer) at the most critical frame location.
- Connections of bulkhead (transverse/ corrugated) to the adjoining structures.
- Bracket at the heel of horizontal stringer.
- Large openings
- Upper side frame bracket toe in case of flat bottom of top wing
- Deck plating and longitudinal hatch coaming end bracket toe.
- Side frame end brackets and lower hopper knuckle for single side bulk carrier

The selection of critical locations on the structural members and the fine mesh structural models is to be in accordance with the requirements given in IRS *Guidelines IRS-G-DES-05*. Additional specific details may be requested to be checked on a case-by-case basis by IRS.

4.2 Type of details

4.2.1 General

4.2.1.1 The method for calculation of hot spot stress at weld toe for any welded details is given in 4.5 and for web stiffened cruciform joints given in 4.6. The method for calculation of local stress for non-welded area is given in 4.5.4.

4.2.1.2 Two types of hot spots denoted 'a' and 'b' are described in Table 4.2.1 at weld toe of ordinary welded joints. These are defined depending location on the plate and their orientation to the weld toe as illustrated in Figure 4.2.1.

Table 4.2.1: Types of hot spots	
Type	Description
a	Hot spot at the weld toe on plate surface
b	Hot spot at the weld toe around the plate edge

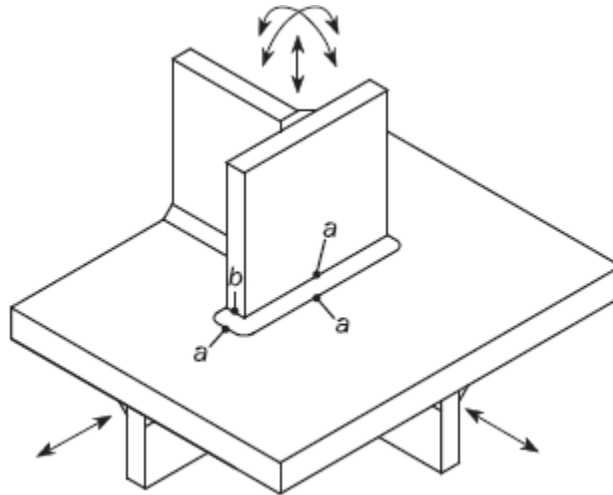


Fig. 4.2.1: Types of hot spots

4.2.2 Web-stiffened cruciform joints

A standard cruciform joint corresponds to the intersection of two plates (Fig. 4.2.2). A web-stiffened cruciform joint corresponds to a cruciform joint where the two plates are stiffened by another plate perpendicular to the first ones and acting as a web. The method for calculation of the hot spot stress at the weld toes of web-stiffened cruciform joints is given in 4.6.

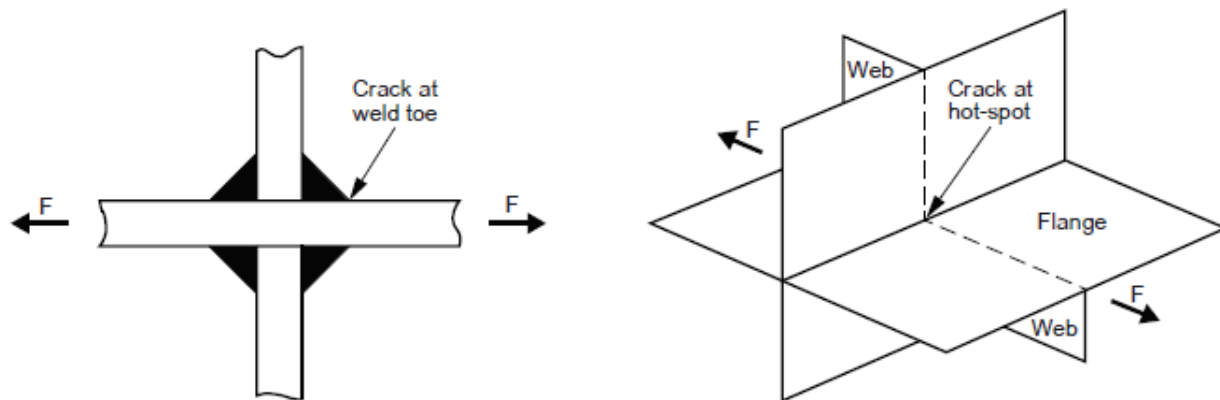


Figure 4.2.2: Standard cruciform joint (left hand side) and web-stiffened cruciform joint (right hand side)

4.2.3 Bent hopper knuckle details

Methods for the calculation of the hot spot stresses for bent hopper knuckles are given in 4.5.5.

4.2.4 Non welded details

Methods for the calculation of the local nominal stress for non-welded area such as cut plate edges, cut-outs for stiffeners connections at web frames, hatch corners, etc. are given in 4.5.4.

4.3 FE model

4.3.1 Three types of FE models are generally used:

- Full ship model
- Partial ship model, like cargo hold model for ships with cargo holds
- Local models, like hot spot models for welded details and local stress models for free plate edges

Evaluation of hot spot stresses for fatigue assessment requires FE models with very fine finite element meshes in way of areas of high stress concentration. These very fine mesh zones are either incorporated into the global FE model (Fig. 4.3.1) or by use of sub-modelling technique. The coarse mesh model of cargo holds is to be made according to IRS *Guidelines IRS-G-DES-05*. In sub-modelling technique, a separate local finite element model with very fine mesh zones in conjunction with the boundary conditions obtained from a coarse mesh global model is used. Typical examples of local finite element models with very fine mesh are shown in Figs.4.3.2, 4.3.3 and 4.3.4.

4.3.2 Corrosion model

The thickness to be used in FE analysis can be either t_{n50} or t_{gr} with the corresponding stress correction factor, f_c , as given in Section 1. The net or gross thickness are thereby referred to as the thickness t in relation to FE analysis.

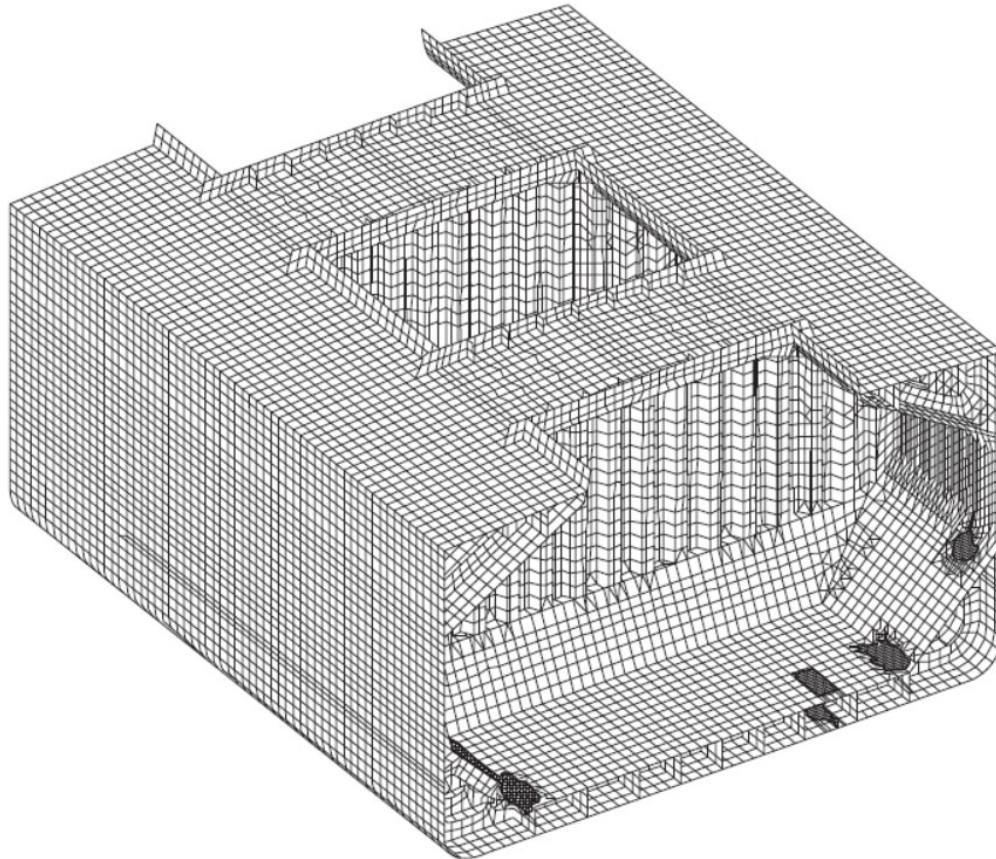


Fig. 4.3.1: Very fine mesh areas incorporated directly into the FE model

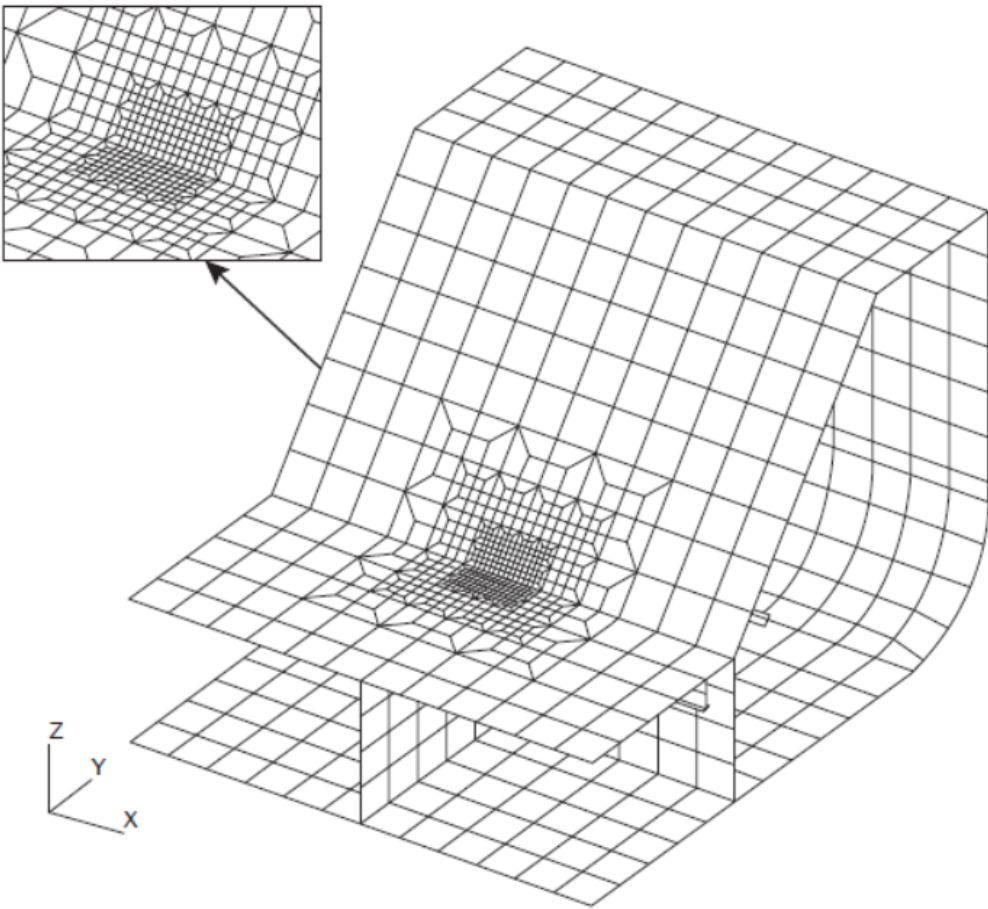


Fig. 4.3.2: Local very fine mesh model of hopper knuckle connection between inner bottom and hopper plate

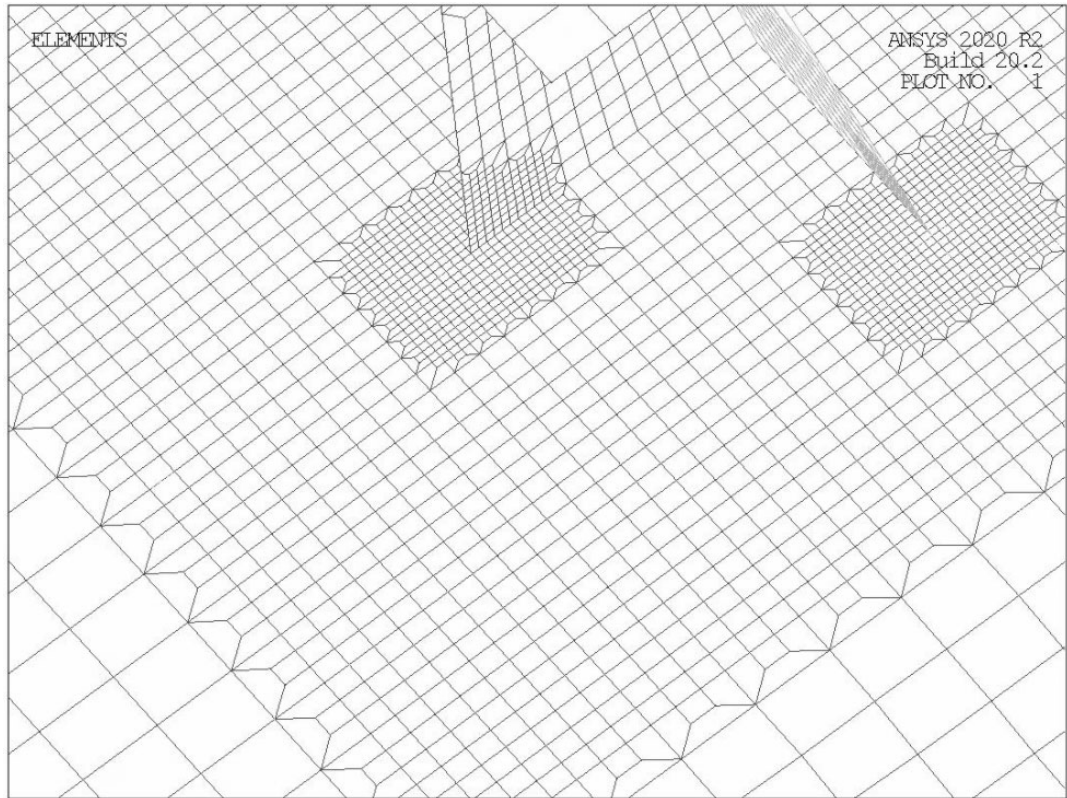


Fig. 4.3.3: Local very fine mesh model in LPG carriers

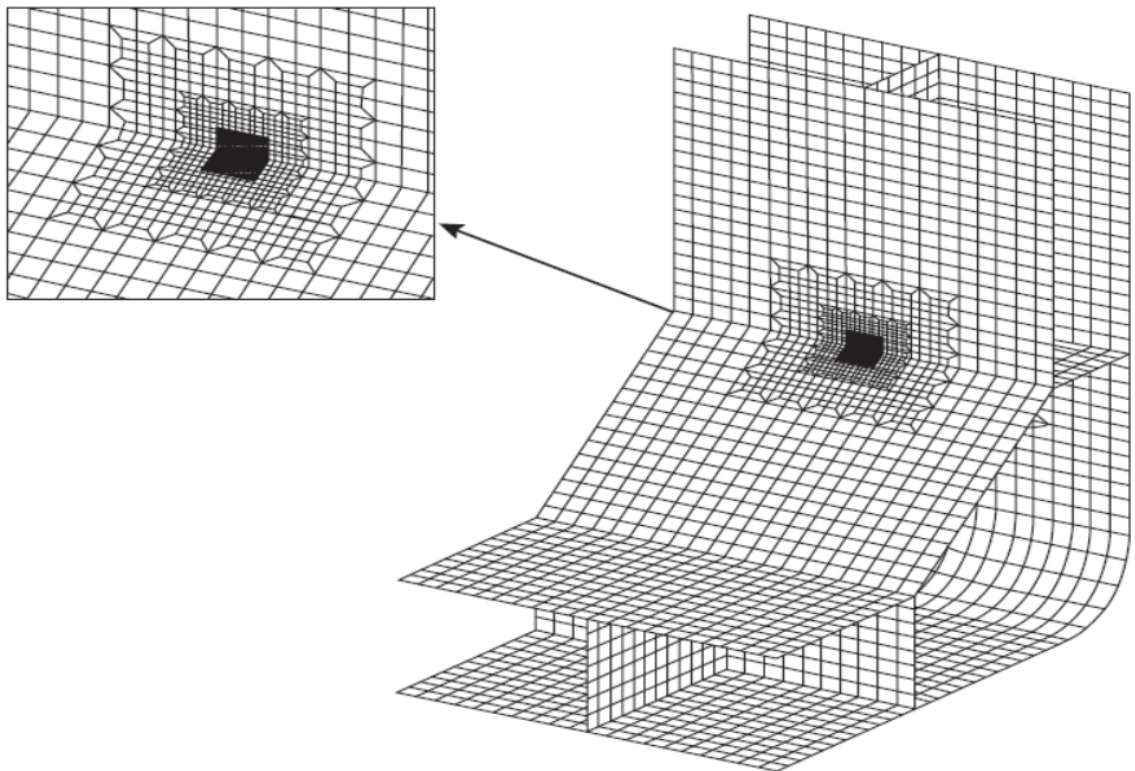


Fig. 4.3.4: Local very fine mesh model of upper hopper knuckle connection between inner side shell and hopper plate in Bulk carriers

4.4 FE modelling for hot spot stress calculation

4.4.1 Separate local FE model (Sub-modelling technique)

4.4.1.1 Where a separate local finite element model is used for evaluating the hot spot stress range, the extent of the local model is to be such that the calculated stresses are not significantly affected by the imposed boundary conditions and the applied loads are far enough from the very fine mesh zones.

4.4.1.2 Where a separate local finite element model is used for evaluating the hot spot stress range, the boundary conditions and application of loads are to be in accordance with IRS *Guidelines IRS-G-DES-05*.

4.4.1.3 The boundary of the fine mesh model is to be taken at adjacent primary supporting members such as girders, stringers and floors in the cargo hold model as far as practicable. Transverse web frames, stringer plates and girders at the boundaries of the local model need not be represented in the local model.

4.4.2 Mesh size

The evaluation of hot spot stress for 'a' type hot spot is to be based on shell element of mesh size $t \times t$, where t is the thickness of the plate in way of the considered hot spot. The evaluation of hot spot stress for a 'b' type hot spot is to be based on shell element of mesh size 10×10 [mm]. The aforementioned mesh size is to be maintained within the very fine mesh zone, extending over at least 10 elements in all directions from the fatigue 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. This transition mesh is to be such that a uniform mesh with regular shape gradually transitions from smaller elements to larger ones. An example of the mesh transition in way of the side frame bracket toe is shown in Fig. 4.4.1. Mesh transitions should not be arranged close to the hot spot location.

For efficient read out of element stresses a mesh density in the order of size $t \times t$ is generally preferred at the hot spot region.

4.4.3 Four node shell elements with adequate bending and membrane properties are to be used inside the very fine mesh zone. The four node element is to have a complete linear field of in-plane stresses and hence pure in-plane bending of the element can be exactly represented. In case of steep stress gradients, 8 node thin shell elements may be used, if deemed practical. The shell elements are to represent the mid plane of the plating. For practical purposes, adjoining plates of different thickness may be assumed to be median line aligned, i.e. no staggering in way of thickness change is required. The geometry of the weld and construction misalignment is not required to be modelled. The shell elements are to represent the mid plane of the plating as represented in Fig. 4.5.1.

4.4.4 All structure in close proximity to the very fine mesh zones is to be modelled explicitly with shell elements. Quadrilateral elements are to have 90 degrees angles as much as possible or angles between 60 degrees and 120 degrees. The aspect ratio is to be close to 1. Triangular elements are to be avoided where possible. Use of extreme aspect ratio (e.g. aspect ratio greater than 3) and distorted elements (e.g. element's corner angle less than 60 [deg] or greater than 120 [deg]) are to be avoided.

4.4.5 Where stresses are to be evaluated 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.

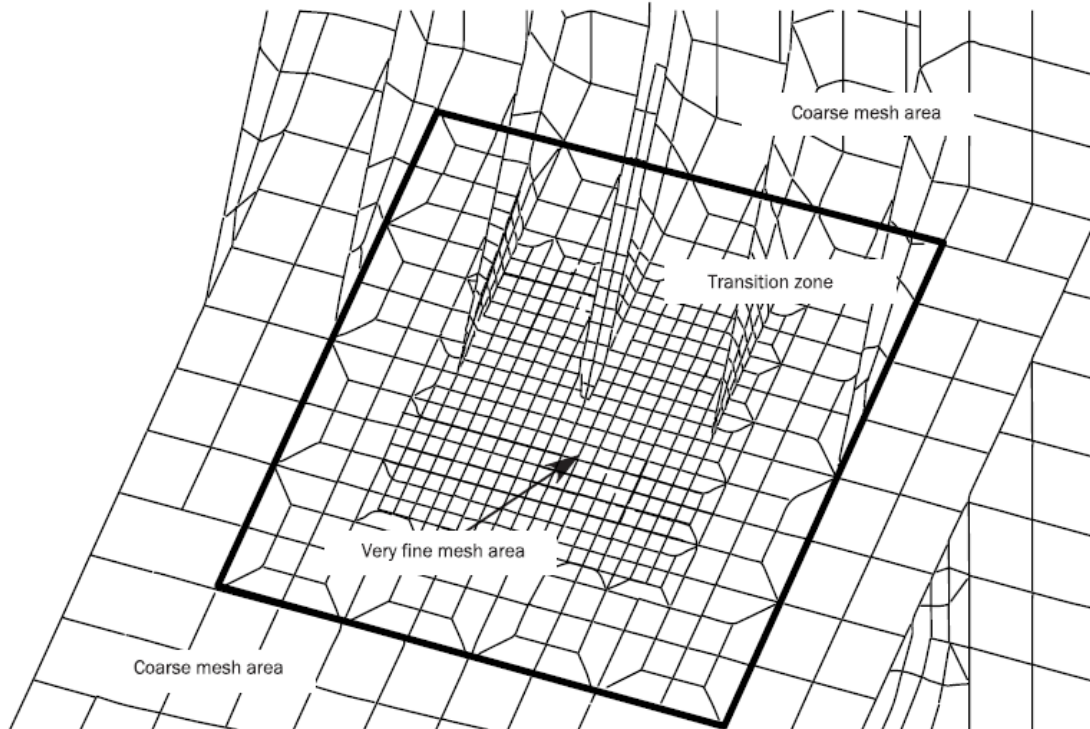


Fig. 4.4.1: Transition area between coarse and very fine mesh

4.4.6 Hatch corners and hatch coaming end bracket

4.4.6.1 In addition to the general requirements in 4.4.1 to 4.4.4, the modelling requirements in this subsection are applicable to the modelling of hatch corners/ hatch coaming end bracket. The selection of hatch corners/ hatch coaming end bracket for fatigue analysis is to be determined based on the level of stresses obtained from the cargo hold FE analysis.

4.4.6.2 Where separate local finite element models are used, the model extents are to be according to the following:

- Transversely, over the half-breadth of the ship,
- Longitudinally, from the midpoint of the cargo hold in which the concerned hatch corners/hatch coaming end bracket is located to the adjacent cargo hold up to and including the full width of the cross deck nearest to the concerned hatch corners/hatch coaming end bracket.
- Vertically, from the top plate of coaming to the intersection of the topside tank sloping plate with the side or inner side shell.

4.4.6.3 The primary supporting members and coaming stays are to be represented by shell finite elements having both membrane and bending properties. Fig. 4.4.6.1 shows a typical FE model of the toe connection of a longitudinal hatch coaming end bracket to the deck plating with the very fine mesh zone having $t \times t$ mesh size.

4.4.6.4 The hatch corner area is to be meshed using elements with a sufficiently small size to capture the local stress on the edge. In general, a minimum of 15 elements in 90° arc are to be used to describe the curvature of the hatchway radius plating for a rounded corner (Fig. 4.4.6.2). For an elliptical or parabolic

corner, a minimum of 15 elements are to be used from the inboard radius end to a point on the edge located at half the longitudinal distance of the semi-major axis. A total of 20 elements are to be used at the elliptical edge of the hatch corner (Fig. 4.4.6.3). However, the element edge dimensions along the free edge of the radius need not be less than the thickness of the plating being represented and also not to be greater than 5 times the thickness of the plating being represented. Mesh transitions should not be arranged close to bracket toes.

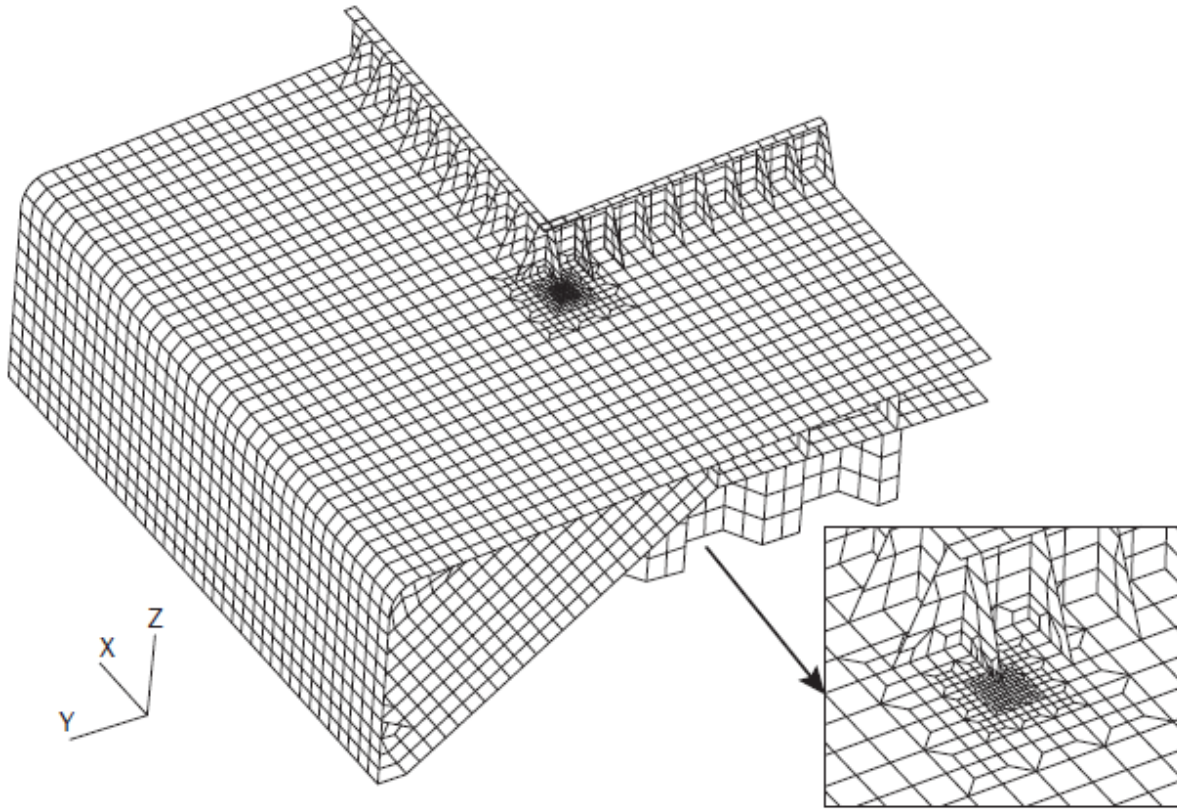


Fig. 4.4.6.1: Local FE model of longitudinal hatch coaming end bracket to the deck plating with very fine mesh zone, $t \times t$ mesh

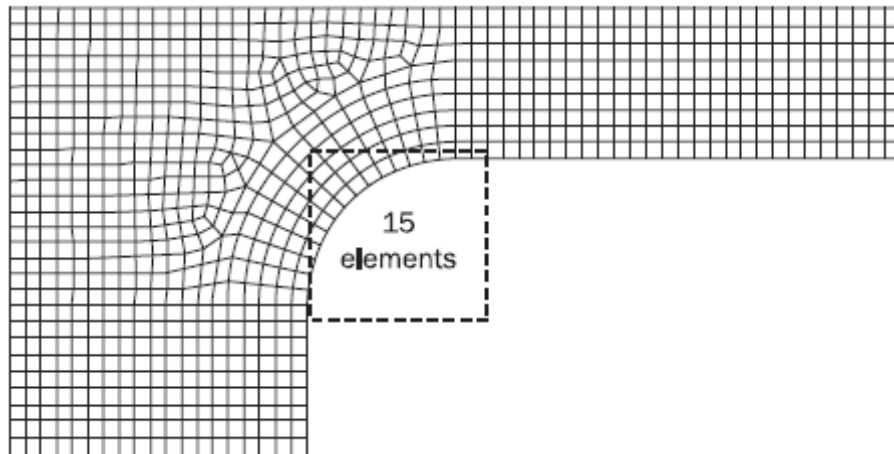


Fig. 4.4.6.2: Mesh density for rounded hatch corner

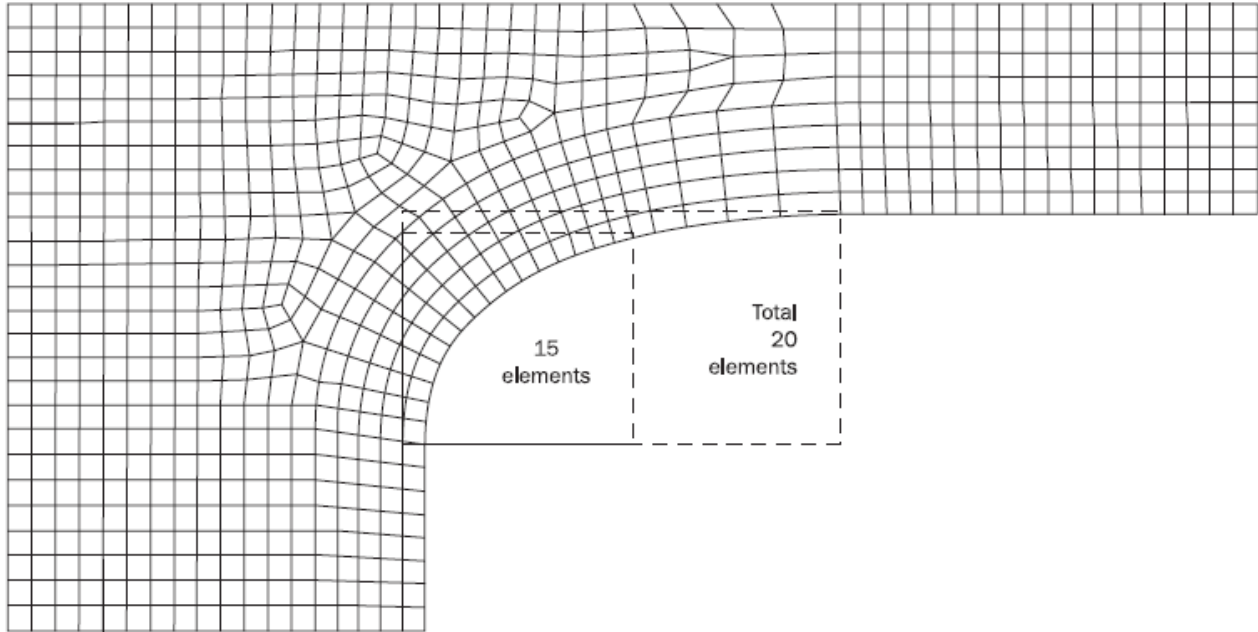


Fig. 4.4.6.3: Mesh density for elliptical hatch corner

4.5 Hot spot stress for ordinary details different from web-stiffened cruciform joints

4.5.1 Types of welded details

This section applies to ordinary welded details: butt welds, fillet welds of T joints and ordinary cruciform joints. They do not apply to web-stiffened cruciform joints and bent hopper knuckles.

4.5.2 Welded details

For hot spot type 'a', the structural hot spot stress, σ_{HS} , is calculated from a finite element analysis with $t \times t$ mesh density and is obtained by the following formula:

$$\sigma_{HS} = 1.12\sigma$$

where:

- σ = Surface principal stress, [N/mm²], read out at a distance $t/2$ away from the intersection line.
- t = Plate thickness, in [mm], in way of the weld toe.

At structural details where the hot spot type 'a' is classified as a web-stiffened cruciform joint, the stress read out procedure of 4.6 is to be applied.

For hot spot type 'b', the stress distribution is not dependent on the plate thickness; the structural hot spot stress, σ_{HS} is derived from a finite element analysis with mesh density 10×10 [mm] and is obtained by the following formula:

$$\sigma_{HS} = 1.12\sigma$$

where:

- σ = Surface principal stress, [N/mm²], read out at a distance from the intersection line of 5[mm]. The maximum of the surface principal stress from the two surfaces (edges) should be used.

4.5.3 Stress read out methods

4.5.3.1 The stress evaluation points are located at distances $t/2$ from the hot spot, where t is the plate thickness at the weld toe. This location is denoted as the stress read out point. For hot spot 'b' it would be 5 [mm] from the hot spot. For modelling with shell elements without any weld the hot spot stress is taken as the principal stress within an angle $\pm 45^\circ$ to the normal to the weld and at the read out point $t/2$ away from the intersection line.

4.5.3.2 Depending on the element type, one of the following stress read out methods are to be used:

- With 4-node shell element:
Element surface stress (surface where the weld is located) components at the centre points are linearly extrapolated to the line A-A as shown in Fig. 4.5.1 to determine the stress components at the stress read out point located at a distance $t/2$ from the intersection line for type 'a' hot spot. The principal hot spot stresses are determined at the stress read out point from each side (side L, side R) of line A-A. The average from both sides of line A-A is taken. The angle θ between the direction x of the element co-ordinate system and the principal direction pX of the principal hot spot stress range coordinate system has to be determined.

- With 8-node shell element:
With a $t \times t$ element mesh using 8-node element type, the element mid-side node is located on the line A-A at a distance $t/2$ for type 'a' hot spots. This node coincides with the stress read out point. The element surface stress components can be used directly without extrapolation within each adjacent element located on each side (side L, side R) of the line A-A as illustrated in Fig. 4.5.2. The principal hot spot stresses are determined at the stress read out point from each side (side L, side R) of line A-A. The average from both sides of line A-A is taken. The angle θ between the direction x of the element coordinate system and the principal direction pX of the principal hot spot stress range coordinate system has to be determined.

4.5.3.3 For fatigue assessment of type 'b' hot spots, a beam element is to be used to obtain the fatigue stress range at the read out point 5 [mm] from the hot spot. 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, i.e. it should not contribute to the strength and it should be compatible with the shell elements and read out the bending stress correctly.

4.5.3.4 The above read out procedure is based on element surface stresses. Generally, in FE software the element stresses are calculated at the Gaussian integration points located inside the element. Depending on the element type implemented in the FE software, it may be necessary to perform several interpolations in order to determine the actual stress at the considered stress read out point at the surface of the element mid-point or element edge.

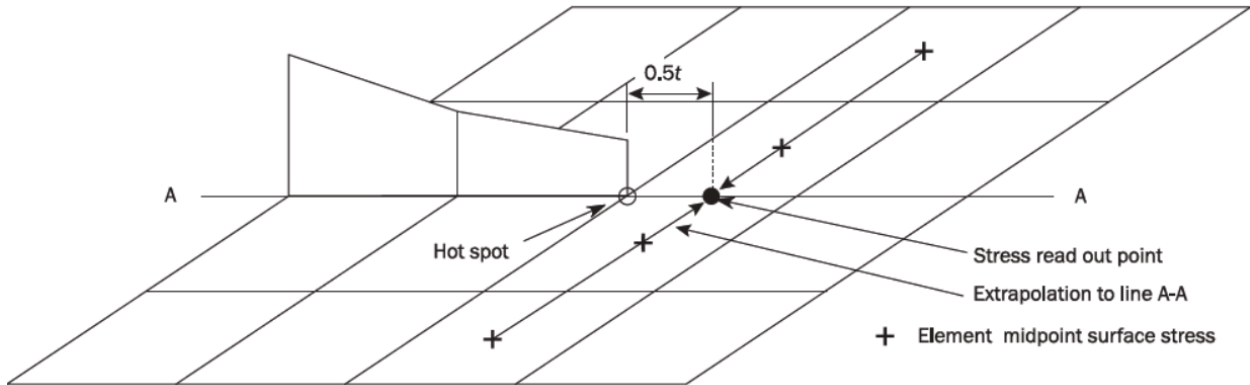


Fig. 4.5.1: Determination of stress read out points and hot spot stress for 4-node element

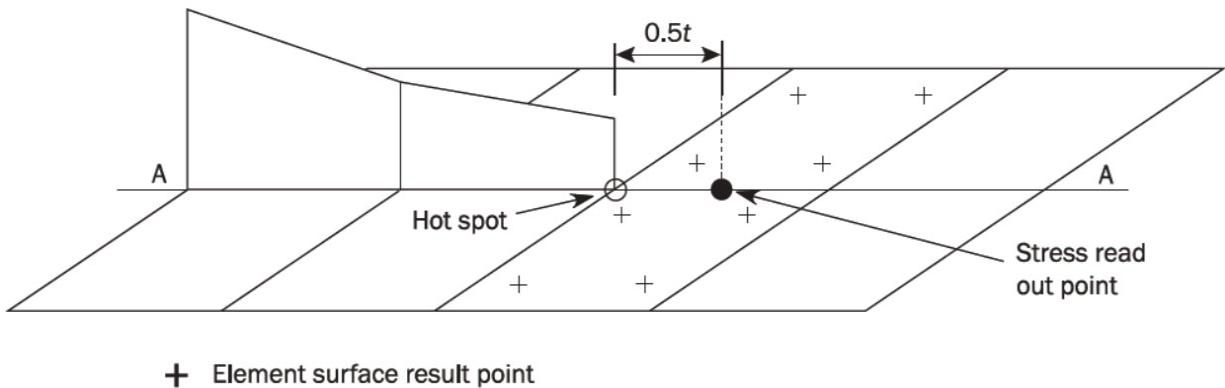


Fig. 4.5.2: Determination of stress read out points and hot spot stress for 8-node element

4.5.4 Base material free plate edges

For fatigue assessment at a free plate edge, a beam element is to be used to obtain the fatigue stress range. The beam element is to have the same depth as the connecting plate thickness while the in-plane width should be negligible.

4.5.5 Hot spot stress for bent hopper knuckle details

4.5.5.1 The hot spot stress at the inner bottom/hopper sloping plate in transverse and longitudinal directions of a bent hopper knuckle is to be taken as the surface principal stress read out from a point shifted away from the intersection line between the considered member and abutting member by the weld leg length. The hot spot stress, in [N/mm²], is to be obtained as:

$$\sigma_{HS} = \sigma_{shift}$$

where:

σ_{shift} = Surface principal stress, [N/mm²], at the shifted read out position as defined in 4.6.2(b) and taken as:

$$\sigma_{shift} = \sigma_{membrane}(x_{shift}) + \sigma_{bending}(x_{shift})$$

$\sigma_{membrane}(x_{shift})$ = Membrane stress, in [N/mm²], at position x_{shift}

$\sigma_{bending}(x_{shift})$ = Bending stress, in [N/mm²], at position x_{shift} .

The procedure for calculation of hot spot stress at flange such as inner bottom /hopper sloping plate is the same that for web-stiffened cruciform joints as described in 4.6.2(b). The procedure that applies for hot spots on the ballast tank side of the inner bottom/hopper plate in way of a bent hopper knuckle is in principle the same as that applied on the cargo tank side of the inner bottom plate for welded knuckle in Fig. 4.6.2(a) and Fig. 4.6.2(b). The intersection line is taken at the mid-thickness of the joint assuming median alignment. The plate angle correction factor and the reduction of bending stress as applied for a web-stiffened cruciform joint in 4.6.2(c) are not to be applied for the bent hopper knuckle type.

4.5.5.2 The stress at hot spots located in way of the web (such as transverse web and side girder) of a bent hopper knuckle type is to be derived as described for web-stiffened cruciform joints in 4.6.3.

4.6 Hot spot stress for web-stiffened cruciform joint

4.6.1 Application

(a) Concerning the web-stiffened cruciform joint, at the intersection of plates corresponding to the hot spot, there is a high local stress concentration with large gradients. The following structural details are typically considered as a web-stiffened cruciform joint:

- Welded hopper knuckle connection
- Heel of horizontal stringer
- Lower stool – inner bottom connection.

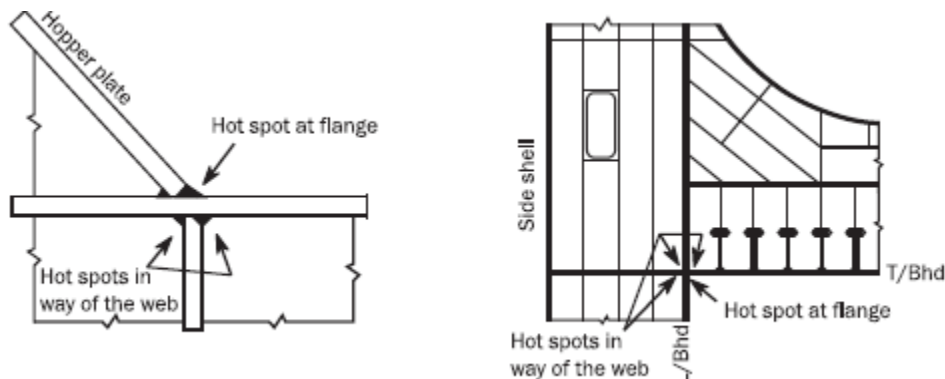
Two kinds of hot spots relative to the web-stiffened cruciform joints are to be assessed:

- Hot spots at the flange of web-stiffened cruciform joint,
- Hot spots in way of the web of web-stiffened cruciform joint.

(b) The procedure for calculating hot spot stress at flange of web-stiffened cruciform joint is given in 4.6.2.

(c) The procedure for calculating hot spot stress in way of the web of the web-stiffened cruciform joint is given in 4.6.3.

(d) Different examples of web stiffened cruciform joints are illustrated in Fig. 4.6.1.



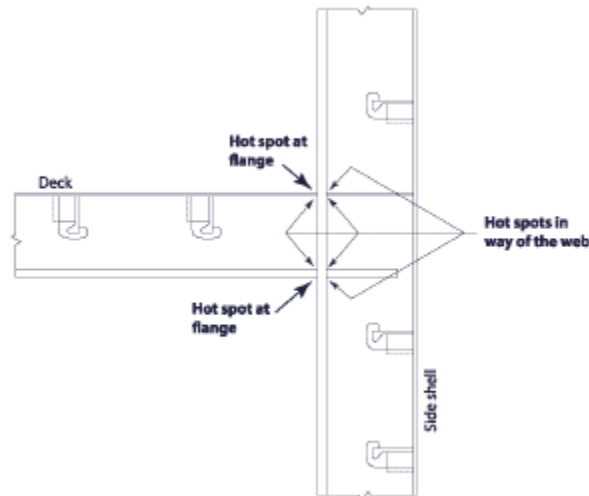


Fig. 4.6.1: Web-stiffened cruciform joints

4.6.2 Calculation of hot spot stress at the flange

(a) For hot spot at the flange of web-stiffened cruciform joints, the surface principal stress is to be read out from a point shifted away from the intersection line between the considered member and abutting member to the position of the actual weld toe and multiplied by 1.12. The intersection line is taken at the mid-thickness of the cruciform joint assuming a median alignment.

(b) The hot spot stress, in [N/mm²], is to be obtained as:

$$\sigma_{HS} = 1.12\sigma_{shift}$$

where:

σ_{shift} = Surface principal stress, [N/mm²], at shifted stress read out position.

The stress read out point shifted away from the intersection line is obtained as:

$$x_{shift} = \frac{t_1}{2} + x_{wt}$$

where:

t_1 = Plate thickness of the plate number 1, in [mm], as shown in Fig. 4.6.2(a) associated with hot spot on plate number 1. For hot spot and read out position on plate number 2, t_1 should be replaced with t_2 in estimating x_{shift} .

x_{wt} = Extended fillet weld leg length, in [mm], as defined in Fig. 4.6.2(a), not taken larger than t_1 for plate number 1, or t_2 for plate number 2.

(c) The stress at the shifted position is derived according to the following formula and illustrated in Fig. 4.6.2(b):

$$\sigma_{shift} = (\sigma_{membrane}(x_{shift}) + 0.6 \sigma_{bending}(x_{shift})) \cdot \beta$$

where:

$\sigma_{bending}(x_{shift})$ = Bending stress, [N/mm²], at the shifted position taken as:

$$\sigma_{bending}(x_{shift}) = \sigma_{surface}x_{shift} - \sigma_{membrane}x_{shift}$$

$\sigma_{surface}x_{shift}$ = Total surface stress at x_{shift} position (including membrane stress and bending stress), [N/mm²].

$\sigma_{membrane}x_{shift}$ = Membrane stress at x_{shift} position, [N/mm²].

β = Plate angle hot spot stress correction factor, taken as:

For $\alpha = 135^\circ$

$$\beta = 0.96 - 0.13 \frac{x_{wt}}{t_1} + 0.20 \left(\frac{x_{wt}}{t_1} \right)^2$$

For $\alpha = 120^\circ$

$$\beta = 0.97 - 0.14 \frac{x_{wt}}{t_1} + 0.32 \left(\frac{x_{wt}}{t_1} \right)^2$$

For $\alpha = 90^\circ$

$$\beta = 0.96 - 0.031 \frac{x_{wt}}{t_1} + 0.24 \left(\frac{x_{wt}}{t_1} \right)^2$$

α = Angle, in [deg], between the plates forming a web-stiffened cruciform joint as shown in Fig. 4.6.2(b)

The procedure is valid for $0 \leq x_{wt}/t_1 \leq 1.0$ and correction factors for connections with plate angles intermediate to those given should be derived based on a linear interpolation of the above values. The calculated hot spot stress is to be used in conjunction with the hot spot S-N curve for weld toe connections according to Section 2.

- (d) Surface principal stresses at the centre point of the two first elements (independent of 4- or 8-node elements) on left and right side of the line A-A are averaged and taken as the surface principal stresses in way of the web position (line A-A). The surface principal stresses are linearly interpolated along the line A-A in order to determine hot spot principal stresses at the stress read out point located at the x_{shift} position as shown in Fig. 4.6.2(c).

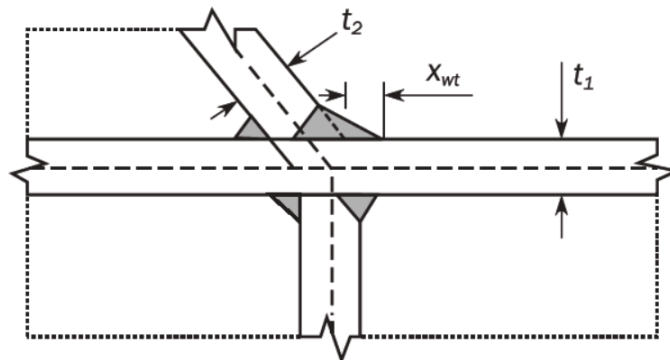


Fig. 4.6.2(a): Geometrical parameters of web-stiffened cruciform connections

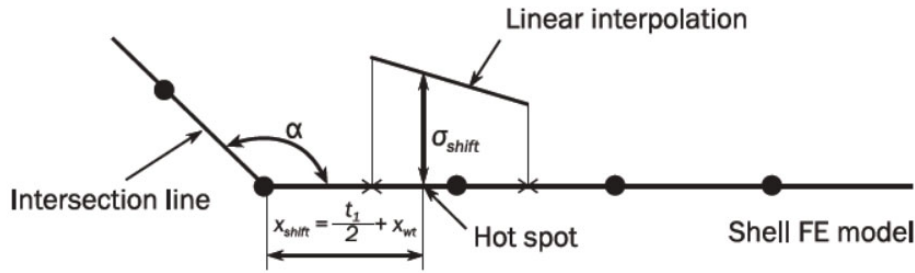


Fig. 4.6.2(b): Procedure for calculation of hot spot stress at web-stiffened cruciform connections

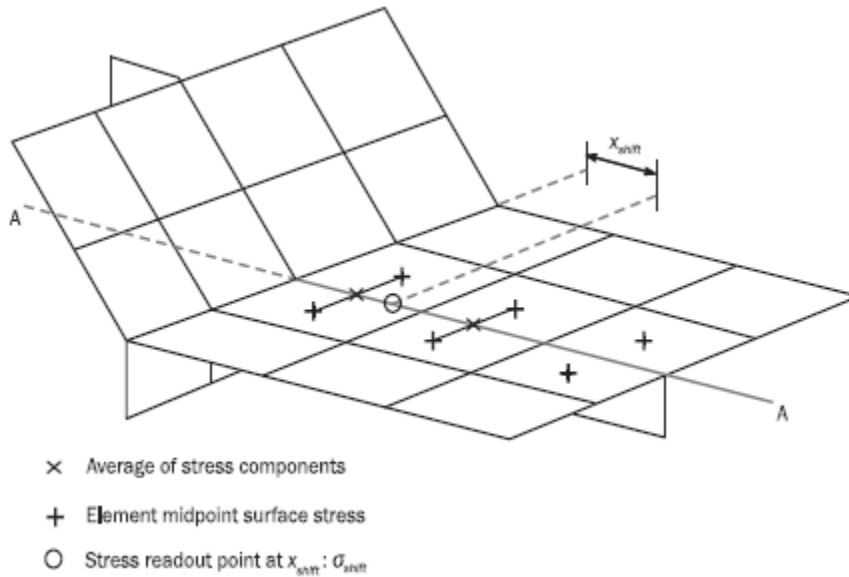


Fig. 4.6.2(c): Determination of stress read out points for the flange of web-stiffened cruciform connections

4.6.3 Calculation of hot spot stress in the web

(a) Hot spots located in way of the web as indicated in Fig. 4.6.3 are to be checked with the hot spot stress defined from the maximum principal surface stress at the intersection offset by the distance x_{shift} from the vertical and horizontal element intersection lines as illustrated in Fig. 4.6.3. The intersection line is taken at the mid thickness of the cruciform joint assuming a median alignment.

(b) The hot spot stress, $[N/mm^2]$, is to be obtained as:

$$\sigma_{HS} = \sigma_{shift}$$

where:

σ_{shift} = Maximum surface principal stress, $[N/mm^2]$, at the intersection offset by the distance x_{shift} .

The stress read out point at the intersection offset is obtained as:

$$x_{shift} = \frac{t_3}{2} + x_{wt}$$

where:

t_3 = Plate thickness of the web, $[mm]$, as shown in Fig. 4.6.3.

x_{wt} = Extended fillet weld leg length, $[mm]$, taken as

$$x_{wt} = \min(\ell_{leg1}, \ell_{leg2})$$

l_{leg1}, l_{leg2} = Leg length, [mm], of the vertical and horizontal weld lines as shown in Fig. 4.6.3.

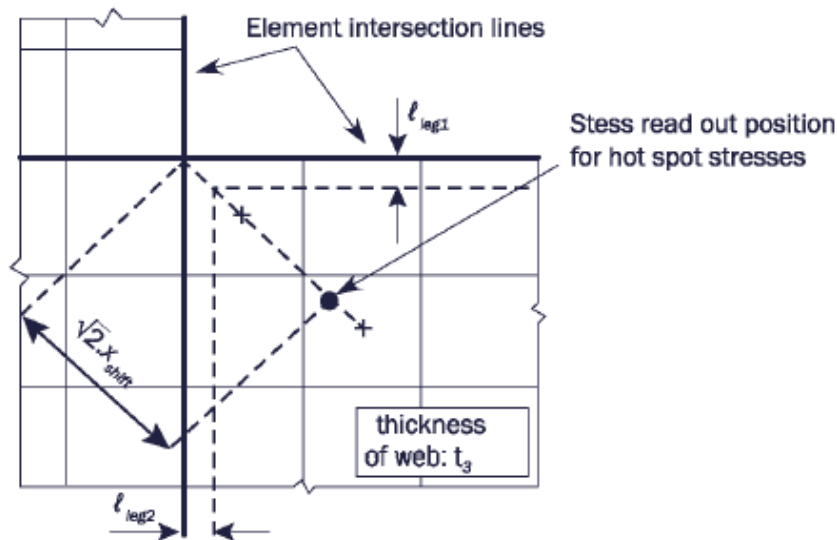


Fig. 4.6.3: Hot spots in way of web

4.7 Limitations of hot spot stress approach

4.7.1 Scope of application of hot spot stress approach

The hot spot stress approach given in Section 1, Cl. 1.2.5 is not applicable for simple cruciform joints and simple T-joints or simple butt joints when the stress flow in direction I as shown in Fig. 4.7.1 is considered. Analysing such connections with shell elements will result in a hot spot stress equal to the nominal stress. The hot spot stress approach is therefore not directly applicable when the stress flow in direction I, is considered. For stresses in the direction normal to the weld at hot spot location “c” (direction I) there is no stress flow into the transverse plating as it is represented only by one plane in the shell model. However, it attracts stresses for in-plane direction (direction II) at hot spot location “a”.

In situations where a bracket (or web) is fitted behind the transverse plate as shown in Fig. 4.7.1, acting with stiffness in the direction normal to the transverse plate, stresses flow also into the transverse plate and the hot spot methodology is considered applicable.

4.7.2 Correction of hot spot stress approach for simple cruciform joints

The hot spot stress at position ‘c’ for simple cruciform joints and simple T-joints is to be determined by the stress read out procedure given in 4.5 multiplied by a geometrical stress concentration factor of 1.3 and is taken as:

$$\sigma_{HS} = 1.3 \times 1.12\sigma$$

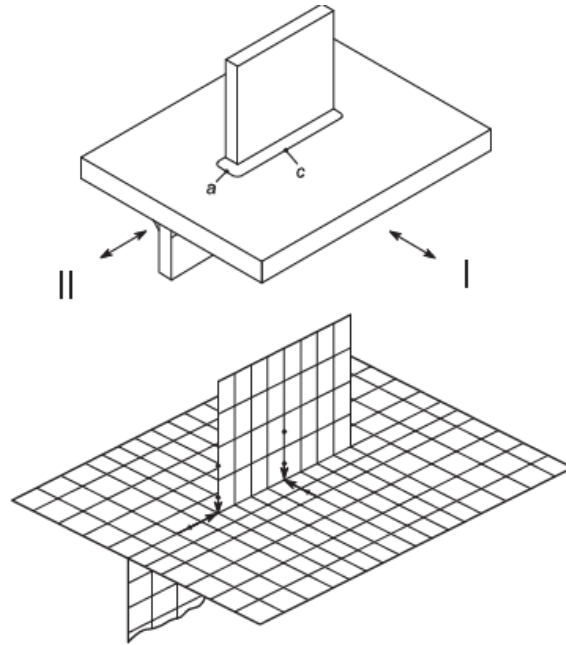


Fig. 4.7.1: Illustration of check points in way of a welded attachment under orthogonal applied in plane loads

4.8 Method for hot spot stress extraction

4.8.1 Hot spot extraction method used to obtain hot spot stress from the stress readout points is by linearly extrapolating from two or three readout points to the structural intersection line. (IIW-1823-07) recommendations for fatigue design of welded joints is utilized for this method of hot spot stress extraction.

4.8.2 In case of biaxial stress state at the plate surface, the principal stress which acts approximately in line with the perpendicular to weld toe (within $\pm 60^\circ$) are to be used. The other principal stress may need to be analyzed, if necessary, using the fatigue class in the nominal stress approach for welds parallel to the stress (IIW-1823-07).

4.8.3 While using this method of stress extraction, meshing size and the limitation to weld configurations are to be referred from the IIW recommendation.

Appendix A – Detail Design Standard

A.1 General

A.1.1 Purpose

A.1.1.1 This detail design standard is provided to ensure improved fatigue performance of structural details. Design standard provides fatigue resistant detail design at an early stage in the structural design process by giving considering the following :

- Application of fatigue design principles.
- Construction tolerances and other practical considerations.
- In-service experience and fatigue performance.

A.1.1.2 The design standard is to be applied to the design of ship structural details in following steps:

- Highlighting potential critical areas within the ship structure.
- Identification of the fatigue hot spot locations for each of the critical structural details.
- Provision of a set of alternative improved configurations from which a suitable solution can be selected.
- Requirements on geometrical configurations, scantlings, welding requirements and construction tolerances.
- Post fabrication method of improving fatigue life, such as weld toe grinding.

A.1.1.3 The detail design standard may provide requirements in order to prevent the following types of fatigue cracks initiating from the:

- Weld toe and propagating into the base material.
- Weld root and propagating into the plate section under the weld.
- Weld root and propagating through the weld throat.
- Surface irregularity or notch at the free plate edge and propagating into the base material

A.1.2 Application

The structural details described in this Appendix are to be designed according to the given design standard. Alternative detail design configurations may be accepted by IRS, subject to demonstration of satisfactory fatigue performance.

A.2 Stiffener-frame connections

A.2.1 Design standard A

A.2.1.1 Designs for cut outs in cases where web stiffeners are omitted or not connected to the longitudinals are required to adopt tight collar or the improved design standard “A” as shown in Table A.2.1 or equivalent, for the following members:

- Side shell below $1.1T_{sc}$.
- Bottom.
- Inner hull longitudinal bulkhead below $1.1T_{sc}$.
- Topside tank sloping plating below $1.1T_{sc}$.
- Hopper.
- Inner bottom.

A.2.1.2 Designs that are different from those shown in Table A.2.1 are acceptable subject to demonstration of satisfactory fatigue performance, e.g. by using comparative finite element analysis. The comparative FE analysis is to be performed following the modelling guidance given in Fig. A.2.1.

Table A.2.1: Design standard A – stiffener-frame connection

Cut outs for longitudinals in transverse webs where web stiffeners are omitted or not connected to the longitudinal flange	
Design standard A	
1	2
3	4
<p>Note 1: Soft toes marked “*” are to be dimensioned to suit the weld leg length such that smooth transition from the weld to the curved part can be achieved. Maximum 15[mm] or thickness of transverse web/collar plates/lug plates whichever is the greater.</p> <p>Note 2: Configurations 1 and 4 indicate acceptable lapped lug plate connections.</p>	

Critical location	Locations around cut-out with high stress concentration and locations in way of weld terminations.
Detail design standard	Improved slot shape to avoid high stress concentrations in transverse webs due to shear loads and local pressure loads transmitted via welded joints.
Building tolerances	Ensure alignment of all connecting members and accurate dimensional control of cut-outs according to IACS Recommendation No. 47.
Welding requirements	A wraparound weld, free of undercut or notches, around the transverse web connection to longitudinal stiffener web.

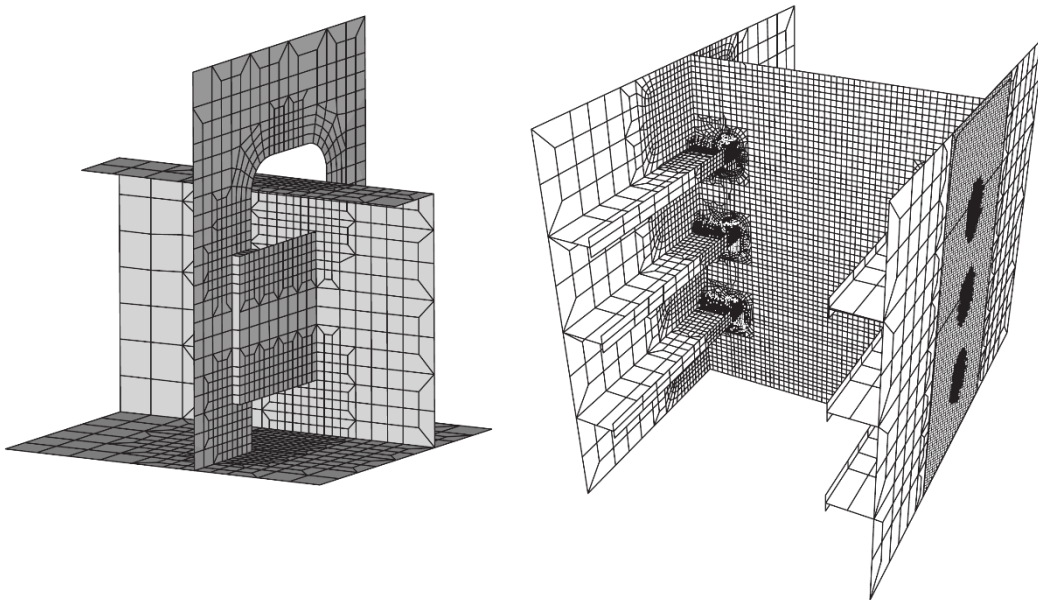


Fig. A.2.1: Finite element model for verification of equivalent design

A.2.2 Equivalent design of stiffener-frame connections

- (a) If the required designs for stiffener-frame connections A.2.1 are not followed, the alternative design is to be verified to have equivalent fatigue strength to the design standard “A” or to be verified to have satisfactory fatigue performance. The alternative design is to be verified according to the procedure given in A.2.2(b) to A.2.2(e) and documentation of results is to be submitted to IRS.
- (b) The procedure in A.2.2(c) and A.2.2(d) is provided to verify the alternative design to have equivalent fatigue strength with respect to any position in the transverse ring, i.e. double bottom and double side. The hot spot stress as well as the stress at the free plate edge of the alternative design and that of the required design is to be compared to the critical hot spots in way of the cut-out. The critical hot spots depend on the detail design and are to be selected in agreement with *IRS*. The hot spot stress is to be derived according to Section 4, Cl. 4.5.2 and 4.5.3. It is to be noted that welded hot spots at the free edge are classified as hot spot type “b”.
- (c) The very fine mesh finite element models are made to analyze the behavior in way of double side or double bottom. The models should have an extent of 3 stiffeners in cross section, i.e. 4 stiffener spacings, and the longitudinal extent is to be one half frame spacing in both forward and aft

direction. A typical model is shown in Fig. A.2.1. No cut-outs for access openings are to be included in the models. Connection between the lug or the web-frame to the longitudinal stiffener web, connections of the lug to the web-frame and free edges on lugs and cut-outs in web-frame are to be modelled with elements of net plate thickness size ($t_{n50} \times t_{n50}$). The mesh with net plate thickness size should extend at least five elements in all directions. Outside this area, the mesh size may gradually be increased in accordance with the requirements in Section 4, Cl. 4.3 and 4.4. The eccentricity of the lapped lug plates is to be included in the model. Transverse web and lug plates are to be connected by eccentricity elements (transverse plate elements). The height of eccentricity element is to be the distance between mid-layers of transverse web and lug plates having a thickness equal to 2 times the net thickness of web-frame plate t_{w-n50} . Eccentricity elements representing fillet welds are shown in Fig. A.2.2(a).

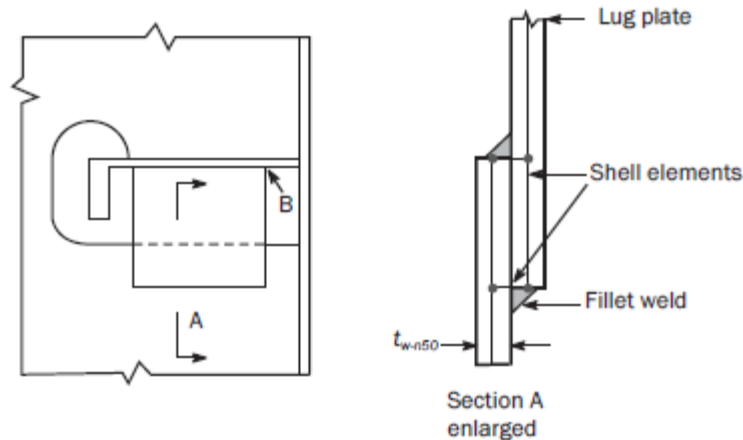


Figure A.2.2(a): Modelling of eccentric lug plate by shell elements

- (d) Three load cases are to be applied to the models of the design standard and alternative designs:
- External pressure of unit value, fixed boundary conditions at top and bottom of model.
 - Shear stress by prescribed unit displacement at the model top and fixed boundary conditions at the model bottom.
 - Axial load by prescribed unit displacement at the model top and fixed boundary conditions at the model bottom.

The forward and aft part of the model is to have symmetry condition describing the behavior in a double hull structure. Load application and boundary conditions are provided in Fig. A.2.2(b).

- (e) The alternative design may also be verified to have satisfactory fatigue performance using sub-modelling technique where a very fine mesh model of the alternative design located at the actual position of the stiffener-frame connection is analyzed. The alternative design is considered acceptable if the fatigue acceptance criterion given in Section 2.2 is achieved. The fatigue acceptance criterion is checked by applying the methodology described in Sections 1, 2 and 4. The alternative design is considered acceptable only for the particular position where it is analyzed.

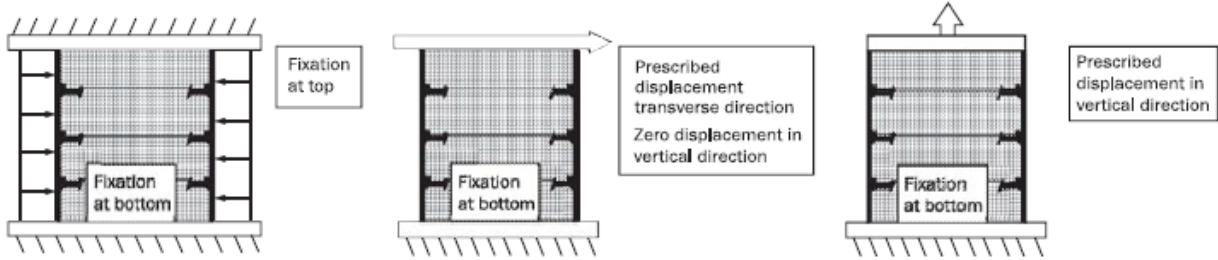


Fig. A.2.2(b): Load application and boundary conditions – FE model for verification of alternative design

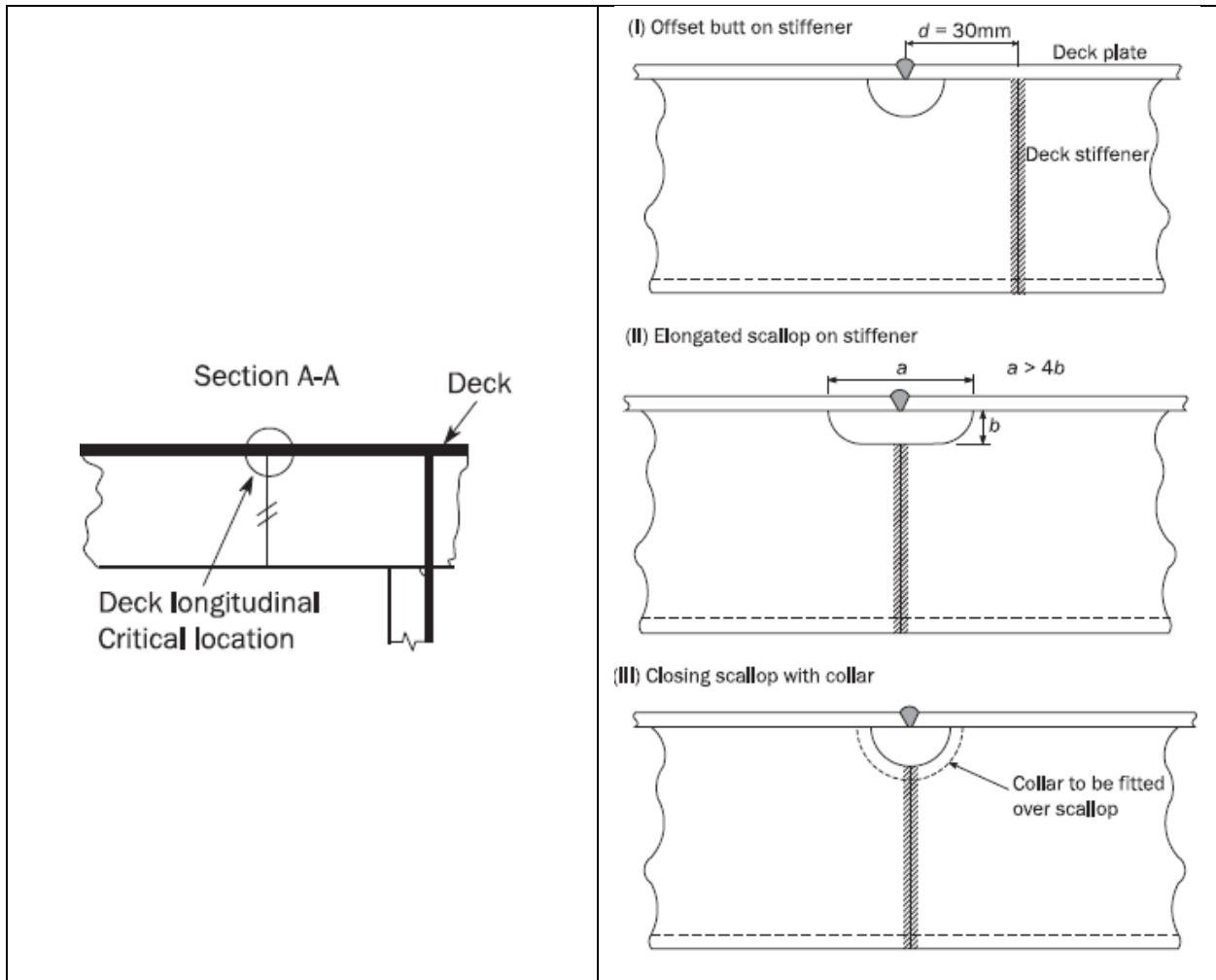
A.3 Scallops in way of block joints

A.3.1 Design standard B

Scallops in way of block joints in the cargo tank/hold region, located on the stiffeners fitted on strength deck, and side above 0.9D from the baseline, are required to be designed according to the design standard B as shown in Table A.3.1.

Table A.3.1: Design standard B – scallops in way of block joints

Welding of deck stiffeners in way of block joints	
Critical areas	Design standard B
<p>Double-Hull Oil Tanker</p>	
<p>Bulk Carrier</p>	
Critical locations	
<p>Transverse section</p>	



Note 1: Alternative scallop geometry to that shown in option II may be accepted subject to demonstration of satisfactory fatigue life based on hull girder loads taking into account additional stress concentration factor in way of weld

Critical location	Welding of deck stiffeners in way of block joints in cargo tank region, the strength deck and side above 0.9D from the baseline.
Detail design standard	All scallops are to be fitted according to detail design standard B.
Building tolerances	Ensure alignment of all structural members according to IACS Recommendation No. 47.
Welding requirements	Full penetration butt weld, free of undercut or notches, around the web and flange of the longitudinal stiffener at block joints, particularly in way of the weld termination at the scallop for option II.

A.4 HOPPER KNUCKLE CONNECTION

A.4.1 Design standard C to H

A.4.1.1 The welded knuckle between hopper plating and inner bottom plating for double-hull oil tankers is to be designed according to the design standard C in Table A.4.1. The design standard D in Table A.4.2 may be used as an alternative to increase fatigue strength at the hopper connection.

A.4.1.2 The welded knuckle between hopper plating and inner bottom plating for bulk carriers is to be designed according to the design standard E in Table A.4.3.

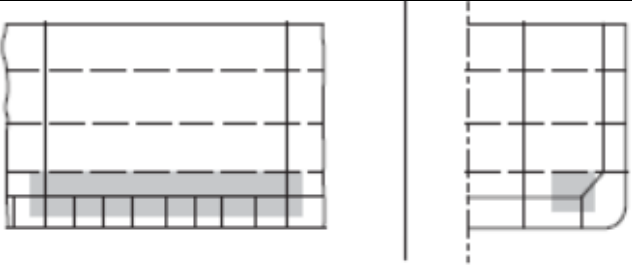
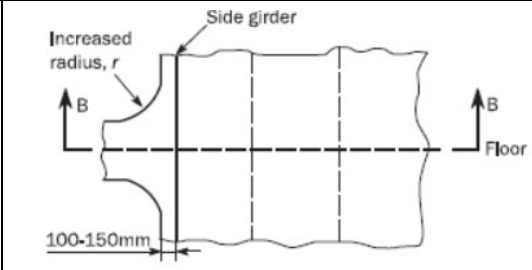
A.4.1.3 The radiused knuckle between hopper plating and inner bottom plating is to be designed according to the design standard F in Table A.4.4 for double hull oil tankers. Alternative structural arrangements may be accepted based on verification in accordance with Section 4[4.5.5].

A.4.1.4 The radiused knuckle between hopper plating and inner bottom plating for bulk carriers is to be designed according to the design standard G in Table A.4.5.

A.4.1.5 The radiused knuckle between hopper plating and inner side plating for oil tankers and double side bulk carriers is to be designed according to the design standard H in Table A.4.6.

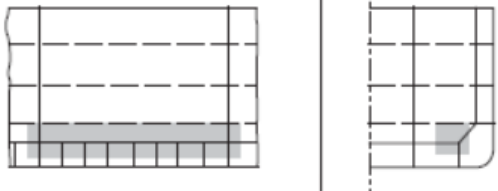
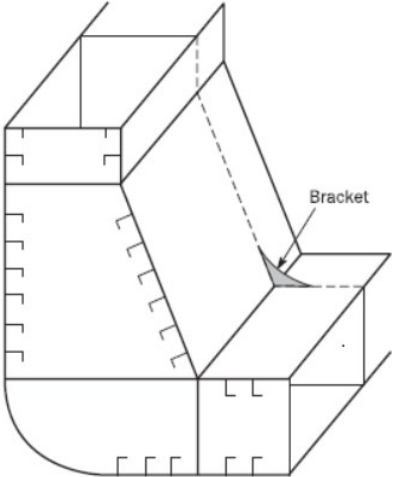
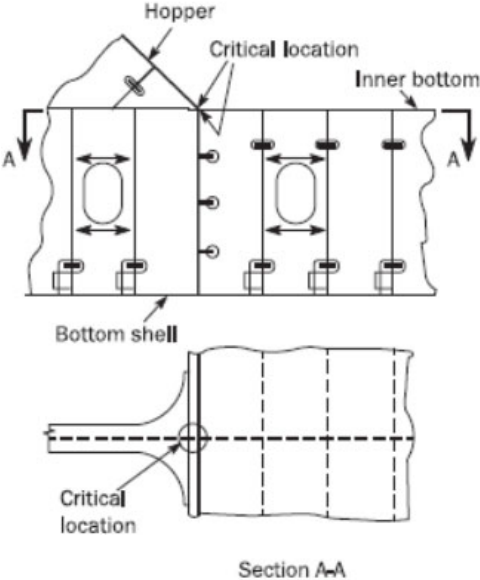
A.4.1.6 In general, the prescribed minimum requirements for welding, weld dressing and building tolerances as given in Table A.4.1 to Table A.4.6 are to be followed. Alternative positioning and/or dispensation of some support structure, such as transverse and longitudinal brackets may be accepted subject to demonstration of acceptable fatigue lives. Inserts and/or weld dressing additional to those prescribed may be required as a consequence of hot spot fatigue analysis.

Table A.4.1: Design standard C – hopper knuckle connection detail, welded, without bracket, double hull oil tanker

Connections of floors in double bottom tanks to hopper tanks Hopper corner connections employing welded inner bottom and hopper sloping plating	
Critical areas	Design standard C
	
Critical locations	

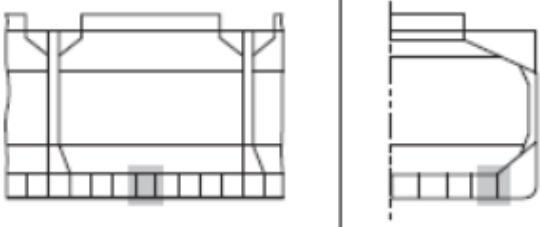
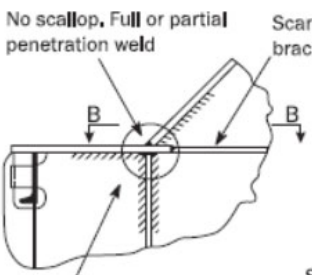
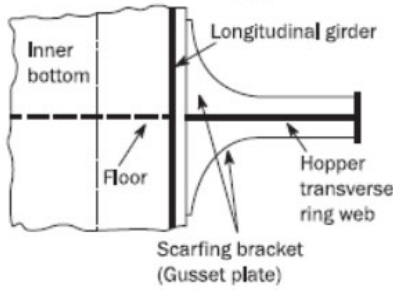
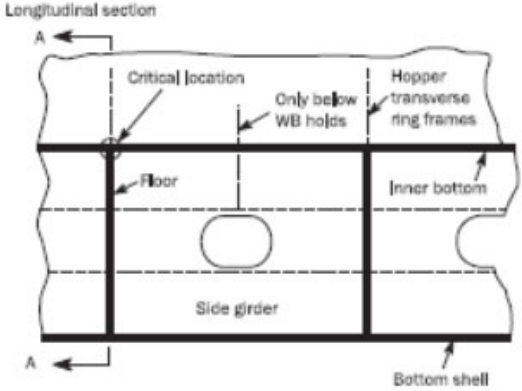
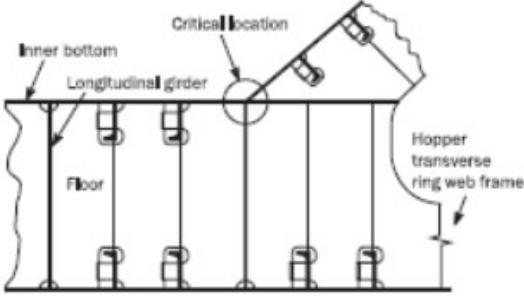
<p>Minimum requirement</p>	<p>As a minimum, detail design standard C or D is to be fitted. The ground surface is to be protected by a stripe coat of suitable paint composition, where the lower hopper knuckle region of cargo tanks is not coated.</p>
<p>Critical location</p>	<p>Hopper sloping plating connections to inner bottom plating in way of floors. Floor connections to inner bottom plating and side girder in way of hopper corners.</p>
<p>Detail design standard</p>	<p>Elimination of scallops in way of hopper corners, extension of inner bottom plating to reduce level of resultant stresses arising from cyclic external hydrodynamic pressure, cargo inertia pressure and hull girder loads. Scarfing bracket thickness is to be close to that of the inner bottom in way of the knuckle.</p>
<p>Building tolerances</p>	<p>Median line of hopper sloping plate is to be in line with the median line of the girder with an allowable tolerance of $t_{as-built}/3$ or 5 [mm], whichever is less, where $t_{as-built}$ is the as-built side girder thickness. The allowable tolerance is to be measured parallel to the inner bottom.</p>
<p>Welding requirements</p>	<p>Full or partial penetration welding is to be applied to hopper sloping plating and inner bottom plating connection. Partial penetration welding is to be applied to connections of side girder to inner bottom plating, to connections of floors to inner bottom plating and to side girder, to connections of hopper transverse webs to sloping plating, to inner bottom and to side girder in way of the hopper knuckle. Weld between hopper plating and inner bottom plating to be enlarged and ground smooth. Visible undercuts are to be removed, see Section 2[2.6]. Weld enlargement and grinding are applicable to minimum 200[mm] on each side of the floor.</p>

Table A.4.2: Design standard D – hopper knuckle connection detail, welded, with bracket, double hull oil tanker

Connections of floors in double bottom tanks to hopper tanks Hopper corner connections employing welded inner bottom and hopper sloping plating	
Critical areas	Design standard D
	 <p style="text-align: right;">Bracket</p> <p>Note 1: Bracket to be fitted inside cargo tank. Note 2: Bracket to extend approximately to the first longitudinal. Note 3: The bracket toes are to have a soft nose design. Note 4: Bracket material to be same as that of inner bottom. Note 5: Slenderness of bracket to be checked.</p>
Critical locations	
 <p style="text-align: center;">Section A-A</p>	
Minimum requirement	As a minimum, detail design standard C or D is to be applied.
Critical location	Hopper sloping plating connections to inner bottom plating in way of floors. Floor connections to inner bottom plating and side girder in way of hopper corners. The bracket connection to inner bottom and hopper sloping plate.
Detail design standard	Elimination of scallops in way of hopper corners, extension of inner bottom plating to reduce level of resultant stresses arising from cyclic external hydrodynamic pressure, cargo inertia pressure and hull girder loads. Scarfing bracket thickness similar to that of the inner bottom in way of the knuckle.
Building tolerances	Median line of hopper sloping plate is to be in line with the median line of girder with an allowable tolerance of $t_{as-built} / 3$ or 5[mm], whichever is less, where $t_{as-built}$ is the as-built side girder thickness.

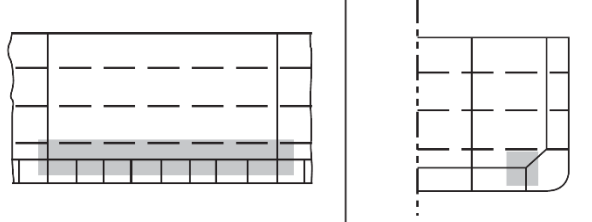
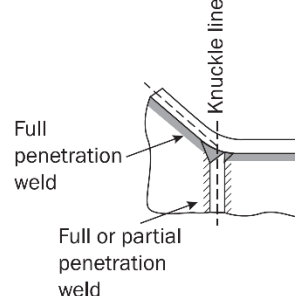
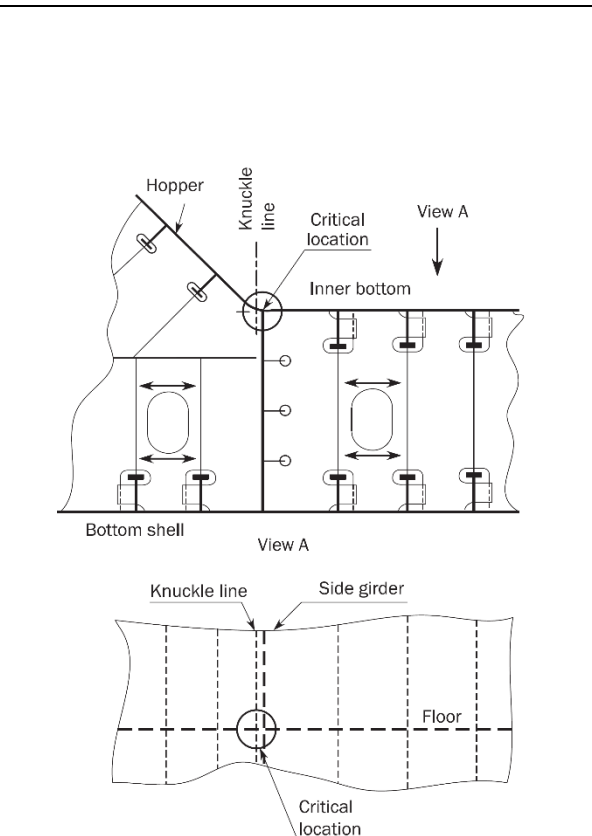
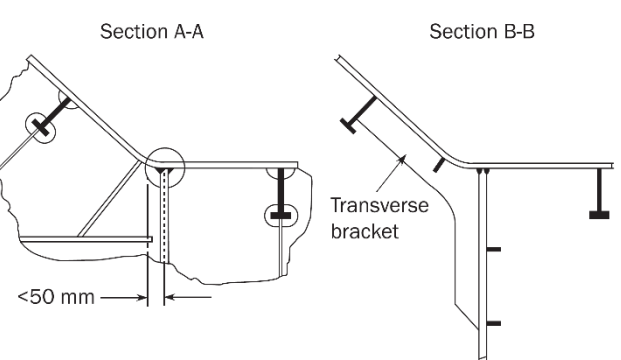
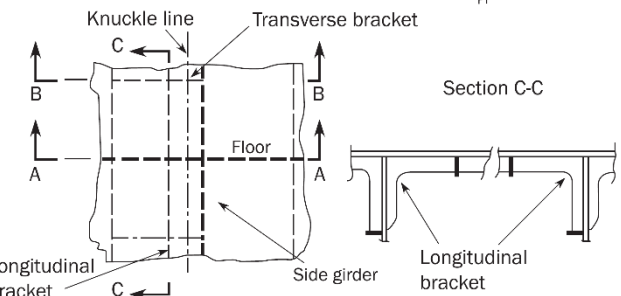
Welding requirements	<p>Partial penetration welding is to be applied to hopper sloping plating and inner bottom plating connection, to connections of side girder to inner bottom plating, to connections of floors to inner bottom plating and to side girder, to connections of hopper transverse webs to sloping plating, to inner bottom and to side girder in way of the hopper knuckle.</p> <p>Partial penetration welding is to be applied to the bracket connections to inner bottom and hopper sloping plate, full penetration welding is to be applied at bracket toes.</p>
----------------------	--

Table A.4.3: Design standard E – hopper knuckle connection detail, welded, bulk carrier

Connections of floors in double bottom tanks to hopper tanks Welded knuckle connection of hopper tank sloping plating to inner bottom plating	
Critical areas	Design standard E
	<p>a) Improvement at the knuckles</p> <p>No scallop, Full or partial penetration weld</p> <p>Scarfig bracket</p>  <p>Partial penetration weld</p> <p>Scarfig bracket arrangement (Section B-B)</p> 
Critical locations	
<p>Longitudinal section</p>  <p>Transverse section A-A</p> 	

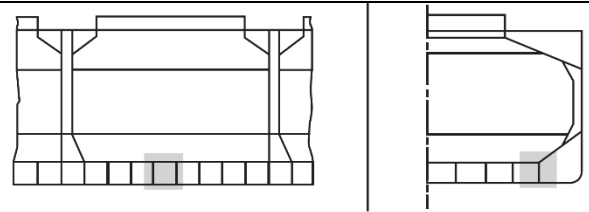
Minimum requirement	As a minimum, detail design standard E is to be fitted. Ballast holds: No scallops or close scallops with collars; scarfing bracket; intermediate bracket if floor spacing greater than 2.5[m]. Dry holds: No scallop or close scallops with collars and scarfing bracket.
Critical location	Hopper sloping plating connections to inner bottom plating in way of the floors. Floor connections to inner bottom plating and side girder in way of the hopper knuckle.
Detail design standard	Elimination of scallops in way of hopper knuckle, extension of inner bottom plating to reduce level of resultant stresses arising from cyclic external hydrodynamic pressure, cargo inertia pressure and hull girder loads. Scarfing bracket net thickness is to be minimum 80% of that of the inner bottom in way of knuckle and steel material to be of the same yield strength.
Building tolerances	Median line of hopper sloping plate is to be in line with the median line of girder with an allowable tolerance of $t_{as-built} / 3$ or 5[mm], whichever is less, where $t_{as-built}$ is the as-built side girder thickness.
Welding requirements	Full or partial penetration welding is to be applied to hopper sloping plating and inner bottom plating connection for the length of the cargo hold. Partial penetration welding is to be applied to connections of side girder to inner bottom plating, to connections of floors to inner bottom plating and to side girder, to connections of hopper transverse webs to sloping plating, to inner bottom and to side girder in way of the hopper knuckle. Weld between hopper plating and inner bottom plating is to be enlarged and ground smooth. Visible undercuts are to be removed. Weld enlargement and grinding are applicable to minimum 200[mm] on each side of the floor.

Table A.4.4: Design standard F – hopper knuckle connection detail, radiused type, for double hull oil tanker

Connections of floors in double bottom tanks to hopper tanks Hopper corner connections employing radiused knuckle between inner bottom and hopper sloping plating	
Critical areas	Design standard F
	 <p style="text-align: right;">Elimination of scallops, minimize knuckle distance from side girder and add longitudinal/transverse brackets</p>
Critical locations	
	 <p style="text-align: center;">Section A-A Section B-B</p> <p style="text-align: center;"><50 mm</p> <p style="text-align: center;">Transverse bracket</p>  <p style="text-align: center;">Section C-C</p> <p style="text-align: center;">Longitudinal bracket Side girder Longitudinal bracket</p>
	<p>Note 1: Distance from side girder to centre of knuckle is to be as small as practicable, but is not to exceed 50 mm.</p> <p>Note 2: The knuckle radius is not to be less than $4.5 \times t_{as-built}$ or 100 mm, whichever is the greater, where $t_{as-built}$ is the as-built thickness of the knuckle part.</p> <p>Note 3: Additional transverse brackets offset at a suitable distance on either side of transverse floor/hopper connection.</p> <p>Note 4: Additional longitudinal bracket on the side of sloping plate.</p> <p>Note 5: Longitudinal and/or transverse brackets may be omitted if it can be demonstrated that the girder provides sufficient support at the knuckle line, i.e. that fatigue requirements according to Sec 4 and local strength analysis requirements according to IRS Guideline IRS-G-DES-05 Sec 4 are fulfilled.</p>

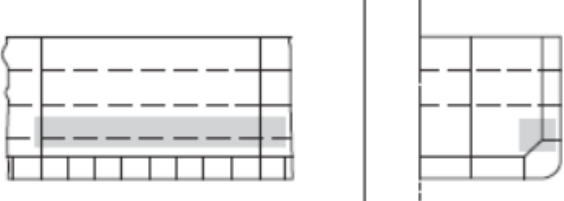
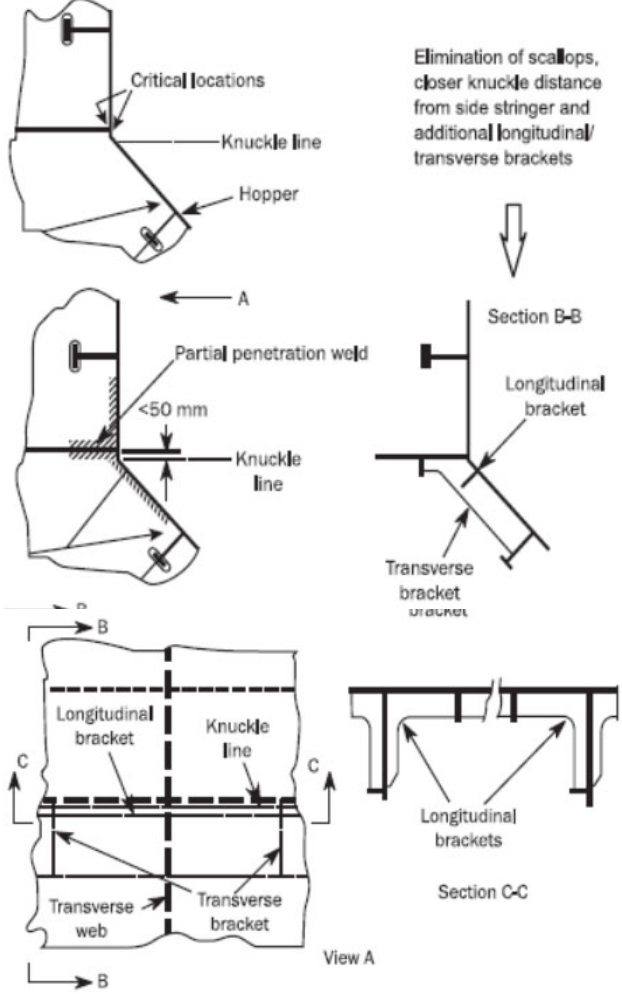
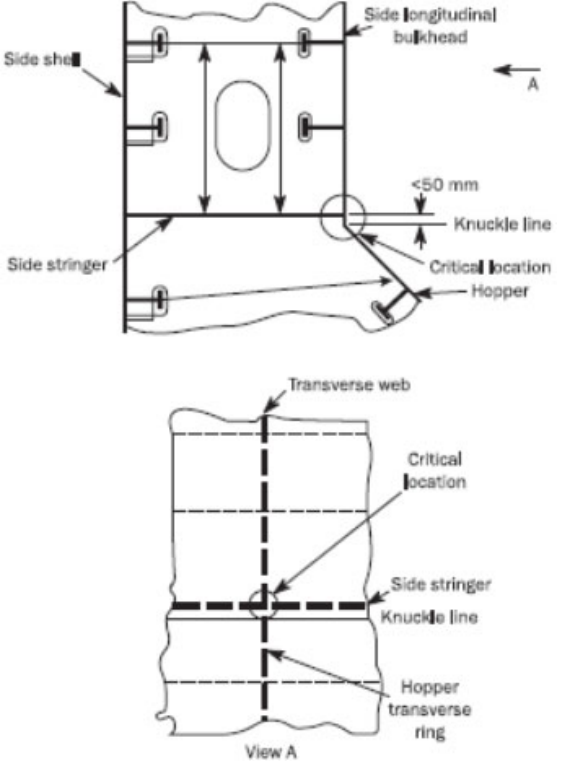
Critical location	Floor and hopper transverse web connections to inner bottom plating and hopper sloping plate, respectively and to side girder in way of hopper knuckle. Side girder connections to inner bottom plating in way of floors.
Detail design standard	Elimination of scallops in way of hopper/girder connection and additional transverse and longitudinal brackets to reduce peak and range of resultant stresses arising from cyclic external hydrodynamic pressure, cargo inertia pressure, and hull girder global loading, and provide additional support to sloping plate.
Building tolerances	The nominal distance between the centres of thickness of the two abutting members (e.g. floor and hopper web plate) is not to exceed 1/3 of the as-built thickness of the side girder.
Welding requirements	Full penetration welding is to be applied to connections of floors to hopper/inner bottom plating in way of radiused hopper knuckle. Partial penetration welding is to be applied to connections of floors/hopper transverse webs to the side girder in way of hopper corner, and to connections of side girder to hopper/inner bottom plating. In order to improve the fatigue strength, weld enlargement and grinding are applicable to full and partial penetration welds with a minimum distance of 300[mm] from the intersection point between the radiused knuckle, the floor and the side girder.

Table A.4.5: Design standard G – hopper knuckle connection detail, radiused type, bulk carrier

Connections of floors in double bottom tanks to hopper tanks Hopper corner connections employing radiused knuckle between inner bottom and hopper sloping plating	
Critical areas	Design standard G
	
Critical locations	

	<p style="font-size: small;">Note 1: Distance from side girder to centre of knuckle is to be as small as practicable, but is not to exceed 50 mm. Note 2: The knuckle radius is not to be less than 4.5 tas-built or 100 mm, whichever is the greater, in cases where tas-built is the as-built thickness of the knuckle part. Note 3: Additional transverse brackets on both side of transverse floor/hopper connection. Note 4: Transverse brackets may be omitted if it can be demonstrated that the girder provides sufficient support at the knuckle line i.e. that fatigue requirements according to Sec 4 and local strength analysis requirements according to IRS Guideline IRS-G-DES-05 Sec 4 are fulfilled.</p>
Critical location	Side girder connections to inner bottom connections in way of floors. Floor and hopper transverse web connections to inner bottom plating and hopper sloping plate, respectively, and to side girder in way of hopper corners.
Detail design standard	Elimination of scallops in way of hopper/girder connection. Ballast holds: Intermediate brackets fitted at approximately 0.5 floor space from floor/hopper web. Dry holds: Intermediate brackets fitted at 0.5 floor space from floor/hopper web if floor spacing is equal to or greater than 2.5[m].
Building tolerances	The nominal distance between the centres of thickness of the two abutting members (e.g. floor and hopper web plate and additional supporting brackets) is not to exceed 1/3 of the as-built thickness of the side girder.
Welding requirements	Full penetration welding is to be applied to connections of floors to hopper/inner bottom plating in way of radiused hopper knuckle. Partial penetration welding is to be applied to connections of floors/hopper transverse webs to the side girder in way of hopper corner, and to connections of side girder to hopper/inner bottom plating.

Table A.4.6: Design standard H – upper hopper knuckle connection detail, radiused type, oil tankers and double side bulk carrier

Connections of transverse webs in double side tanks to hopper tanks Hopper corner connections employing radiused knuckle between side longitudinal bulkhead and hopper sloping plating	
Critical areas	Design standard H
	 <p style="text-align: right;">Elimination of scallops, closer knuckle distance from side stringer and additional longitudinal/transverse brackets</p>
Critical locations	
	<p>Note 1: Distance from side stringer to centre of knuckle is to be as small as practicable, but is not to exceed 50 mm. Note 2: The knuckle radius is not to be less than $4.5t_{as-built}$ or 100 mm, whichever is the greater, where $t_{as-built}$ is the as-built thickness of the knuckle part. Note 3: Additional transverse brackets offset at a suitable distance on either side of transverse floor/hopper connection. Note 4: Additional longitudinal bracket on the side of sloping plate. Note 5: Longitudinal and/or transverse brackets may be omitted if it can be demonstrated that the girder provides sufficient support at the knuckle line i.e. that fatigue requirements according to Sec 4 and local strength analysis requirements according to IRS Guideline IRS-G-DES-05 Sec 4 are fulfilled.</p>

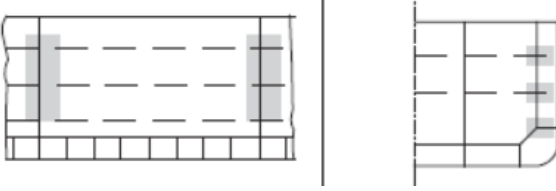
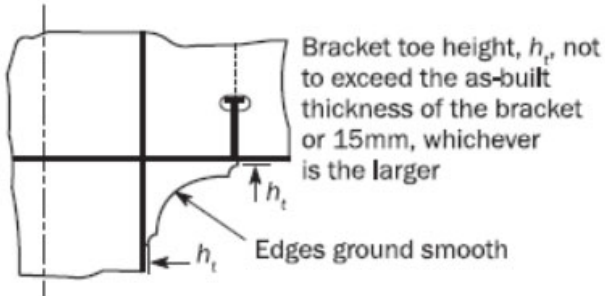
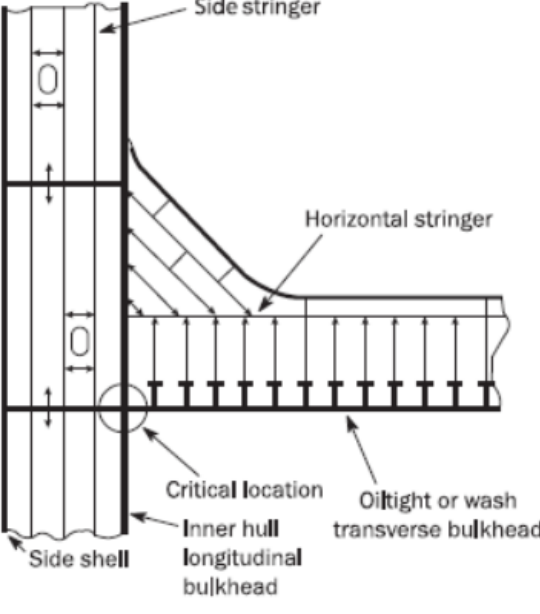
Critical location	Side stringer connections to side longitudinal bulkhead in way of transverse webs. Double side tank transverse web and hopper transverse web connections to side longitudinal bulkhead and to side stringers in way of hopper corners.
Detail design standard	Elimination of scallops in way of hopper corners, closer knuckle distance from side stringers. Additional longitudinal/transverse brackets to reduce peak and range of resultant stresses arising from cyclic external hydrodynamic pressure and cargo inertia pressure.
Building tolerances	The nominal distance between the centres of thickness of the two abutting members should not exceed 1/3 of the as-built thickness of the side stringer.
Welding requirements	Partial penetration welding is applied to connection of side stringers to side longitudinal bulkhead, connection of double side tank transverse webs to side longitudinal bulkhead and to side stringers, connection of hopper transverse webs to sloped side longitudinal bulkhead and to side stringers in way of hopper corners. Small scallops of suitable shape, which are to be closed by welding after completion of the continuous welding of side stringers to longitudinal bulkhead, are to be provided where scallops are eliminated.

A.5 HORIZONTAL STRINGER HEEL

A.5.1 Design standard I

A.5.1.1 The horizontal stringer heel location between transverse oil-tight/swash bulkhead plating and inner hull longitudinal bulkhead plating for double hull oil tankers are required to be designed according to design standard I, as shown in Table A.5.1.

Table A.5.1: Design standard I – transverse bulkhead horizontal stringer heel

Connections of horizontal stringer on plane oil-tight transverse bulkheads or wash bulkheads to inner hull longitudinal bulkheads	
Critical areas	Design standard H
	 <p>Bracket toe height, h_t, not to exceed the as-built thickness of the bracket or 15mm, whichever is the larger</p> <p>Edges ground smooth</p>
Critical locations	
 <p>Side stringer</p> <p>Horizontal stringer</p> <p>Critical location</p> <p>Oiltight or wash transverse bulkhead</p> <p>Inner hull longitudinal bulkhead</p> <p>Side shell</p>	<p>Note 1: Where a face plate is considered necessary, it is recommended that design features be adopted to reduce the stress concentration at the face plate termination (e.g. taper and soft nose). Adequate fatigue life of the weld on the bracket edge in way of such terminations is to be confirmed.</p> <p>Note 2: 'Slit type cut-outs are to be adopted in way of the bracket toe as shown. Alternatively, cut-outs with insert type collars will be accepted. Scallops are to be avoided.'</p>

Critical location	Intersections of webs of transverse bulkhead horizontal stringer and double side tank side stringer forming square corners.
Detail design standard	A soft toe backing bracket is to be fitted. The following bracket sizes are recommended: <ul style="list-style-type: none"> • VLCC: 800×800×30, R600 with soft toe as shown in figure above, • Other tankers: 800×600×25, R550 with soft toe as shown in figure above, where the longer arm length is in way of the inner skin. The specified minimum yield stress for the bracket is not to be less than 315N/mm ² . The free edge is to be ground smooth with corners rounded.
Building tolerances	The nominal distance between the centres of thickness of the two abutting members should not exceed 1/3 of the as-built plate thickness of the inner hull longitudinal bulkhead..
Welding requirements	Vertical weld between the inner hull plating and transverse bulkhead plating, fillet welding having minimum weld factor 0.44. Welding between the backing bracket and the adjoining plates is to be double sided fillet welding having minimum weld factor 0.44 except in way of the bracket toes. Full penetration welding is to be used for the connection of bracket toes to the inner hull and transverse bulkhead plating for a distance of 200 mm from the toes and the weld toes are to be ground smooth in way.

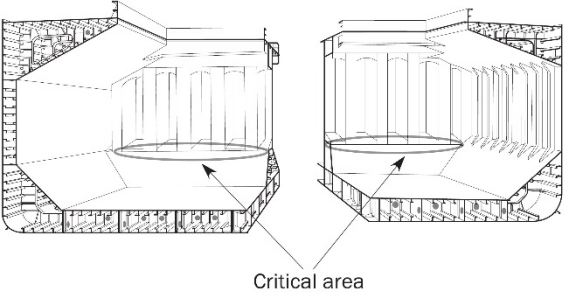
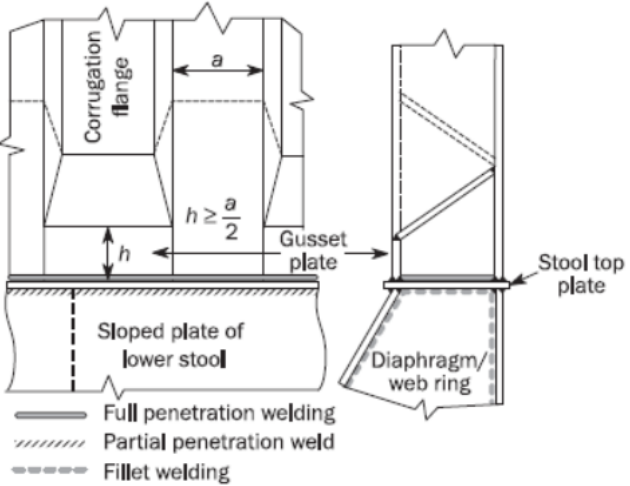
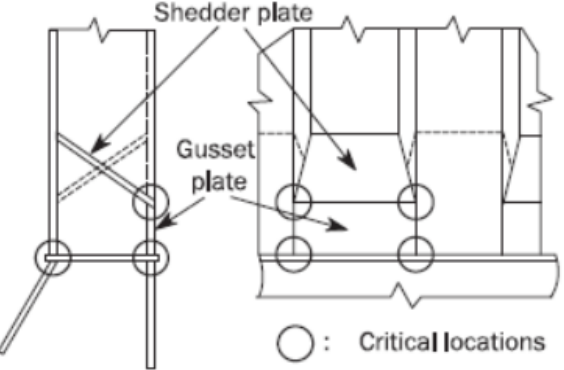
A.6 BULKHEAD CONNECTION TO LOWER AND UPPER STOOL

A.6.1 Design standard J, K and L

A.6.1.1 The welded connection of bulkhead to lower stool of bulk carriers and oil tankers are to be designed according to the design standard J and K respectively, as shown in Table A.6.1 and Table A.6.2.

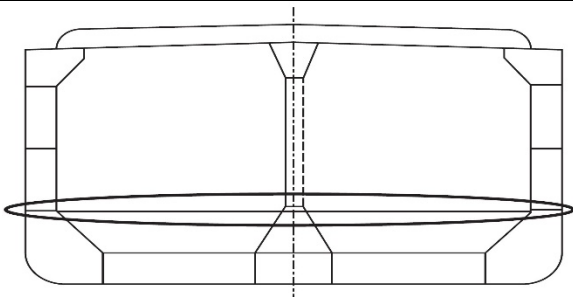
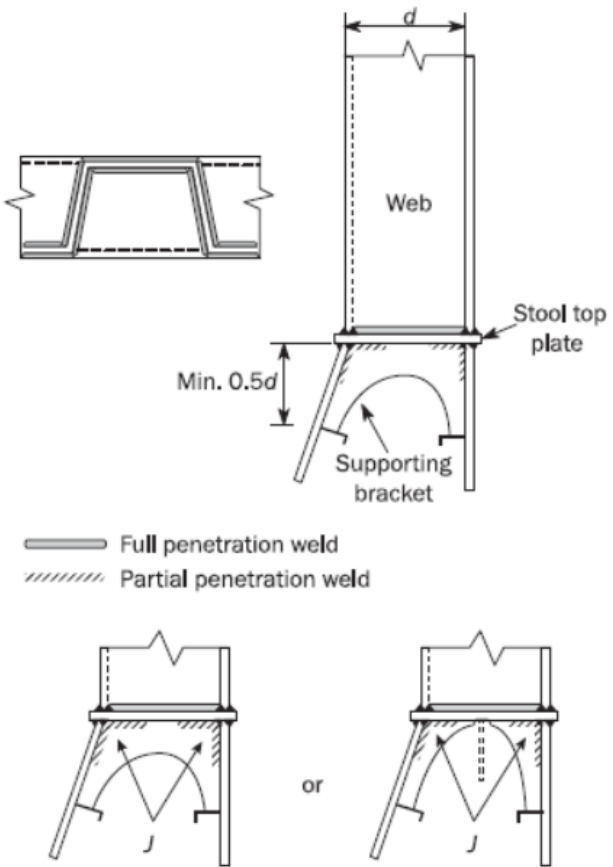
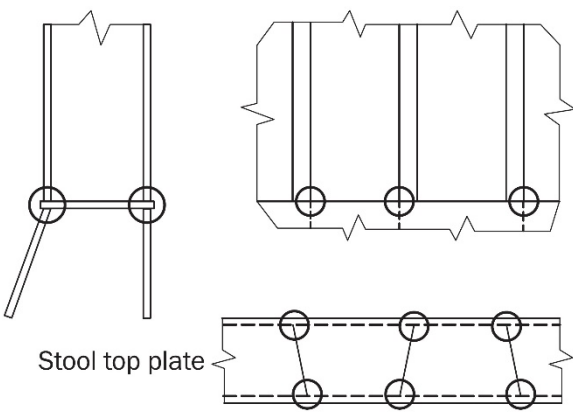
A.6.1.2 The welded connection of bulkhead to upper stool of bulk carriers are to be designed according to the design standard L, as shown in Table A.6.3.

Table A.6.1: Design standard J – transverse bulkhead connection detail, bulk carrier (ballast hold)

Connections of transverse bulkhead with lower stool	
Critical areas	Design standard J
 <p style="text-align: center;">Critical area</p>	 <p style="text-align: center;"> Full penetration welding Partial penetration weld Fillet welding </p>
Critical locations	
 <p style="text-align: center;">○ : Critical locations</p>	
Critical location	<p>Connections of lower stool shelf plate to lower stool and corrugated transverse bulkheads. Connections of shedder plates to corrugated transverse bulkhead.</p>
Detail design standard	<p>The use of scallops is to be avoided on diaphragms/web at lower stool top plates. Gusset plates are to be fitted to corrugated bulkheads. Gusset plates are to be made out of the same material and have the same asbuilt thickness as corrugated bulkheads; and, the height of gusset plates is to be greater than half of breadth of the corrugation. To reduce stress concentrations at the crossing of the shedder plates one plate is to be moved higher than the other (as shown in Figure). Alternatively, bracketed stiffener can be fitted at the crossing points underneath the shedder plating facing the ballast hold.</p>
Building tolerances	<p>Ensure alignment between lower stool sloping plates and corrugation faces according to IACS Recommendation No. 47.</p>

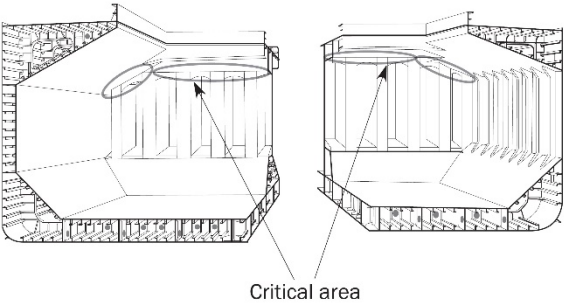
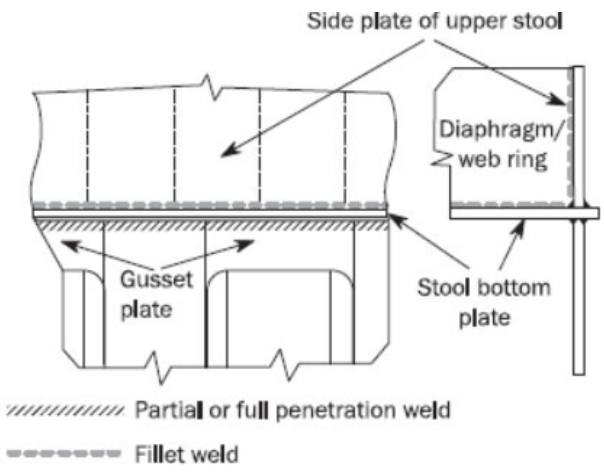
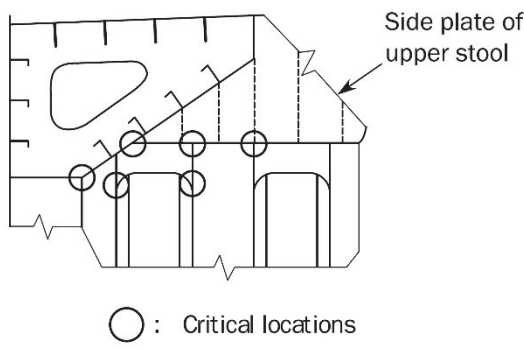
Welding requirements	<p>Full penetration welding is to be applied between lower stool top plates and the side plating of lower stools and corrugated bulkheads.</p> <p>Partial or full penetration welding is to be applied around gusset plates. However, full penetration welding is to be applied between lower stool top plates and gusset plates.</p> <p>Ensure start and stop of welding is as far away as practicable from the critical corners.</p>
----------------------	--

Table A.6.2: Design standard K – transverse or longitudinal corrugated bulkhead connection detail, oil tanker

Connections of transverse or longitudinal bulkhead with lower stool - oil tanker	
Critical areas	Design standard K
	
Critical locations	
	

Critical location	Connections of lower stool top plate to corrugated transverse or longitudinal bulkheads.
Detail design standard	The use of scallops is to be avoided on diaphragms/web at lower stool top plates. Supporting brackets are to be fitted in line with corrugation web. Scallop is not permitted in the supporting bracket.
Building tolerances	Ensure alignment between lower stool sloping plates and corrugation faces according to IACS Recommendation No. 47.
Welding requirements	Full or partial penetration welding is to be applied between lower stool top plates and the side plating of lower stools. Full penetration welding is to be applied between lower stool top plates and vertical corrugated bulkheads. Full or partial penetration welding is to be applied between lower stool top plates and supporting brackets. Ensure start and stop of welding is as far away as practicable from the critical corners. Connection 'J', as shown in the figure, of in line supporting bracket to stool top plate and side plate of lower stool is to be full or partial penetration welding, on minimum 300[mm] from the corner.

Table A.6.3: Design standard L – transverse bulkhead connection detail, bulk carrier (ballast hold)

Connections of transverse bulkhead with sloped plate of upper stool	
Critical areas	Design standard L
 <p style="text-align: center;">Critical area</p>	 <p style="text-align: center;">Side plate of upper stool Diaphragm/ web ring Gusset plate Stool bottom plate</p> <p style="text-align: center;">Partial or full penetration weld Fillet weld</p>
Critical locations	
 <p style="text-align: center;">Side plate of upper stool</p> <p style="text-align: center;">○ : Critical locations</p>	
Critical location	Connections of corrugated transverse bulkhead to the topside tank sloping plating and upper stool.
Detail design standard	<p>The use of scallops is to be avoided on diaphragms/web at upper stool bottom plates.</p> <p>Gusset plates are to be fitted between the face plates of corrugated bulkheads in way of heavy ballast hold.</p> <p>In way of heavy ballast hold, a deep transverse web or well-stiffened backing stiffener is to be provided in the topside tank in line with the face plate of the bulkhead corrugations to ensure that the loads are effectively dissipated.</p> <p>Gusset plates are to have a thickness and material properties not less than those required for corrugation flanges.</p>
Building tolerances	Ensure alignment between the face plates of corrugated bulkheads with the stool side plates as well as the watertight bulkheads and deep transverse web (or well stiffened backing stiffener) in the topside tanks according to IACS Recommendation No. 47.

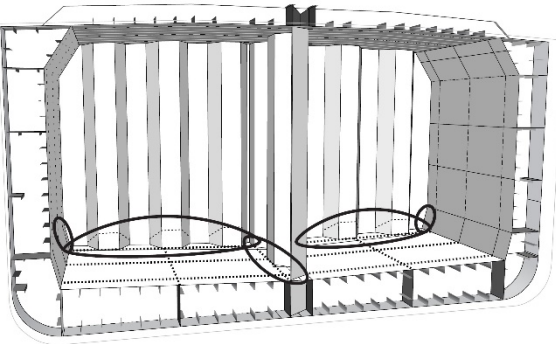
Welding requirements	<ul style="list-style-type: none"> • Partial or full penetration welding is to be applied between upper stool bottom plates and corrugation. • Fillet welding having minimum weld factor of 0.44 is to be applied between upper stool bottom plates and upper stool side plating. • Fillet welding having minimum weld factor of 0.44 is to be applied between upper stool bottom plates and diaphragms/web rings. <p>Ensure start and stop of welding is as far away as practicable from the critical corners in all holds.</p>
----------------------	---

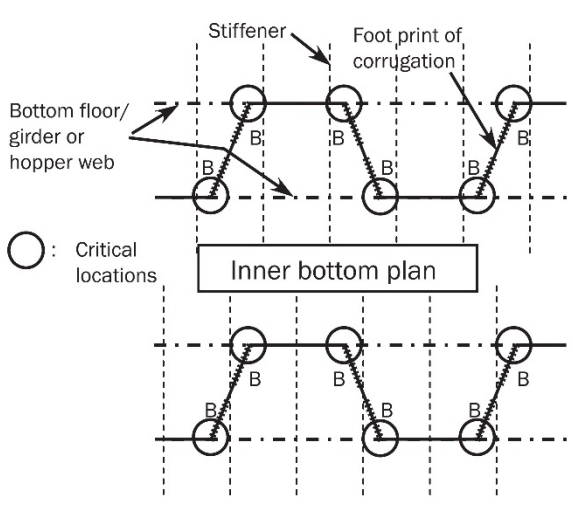
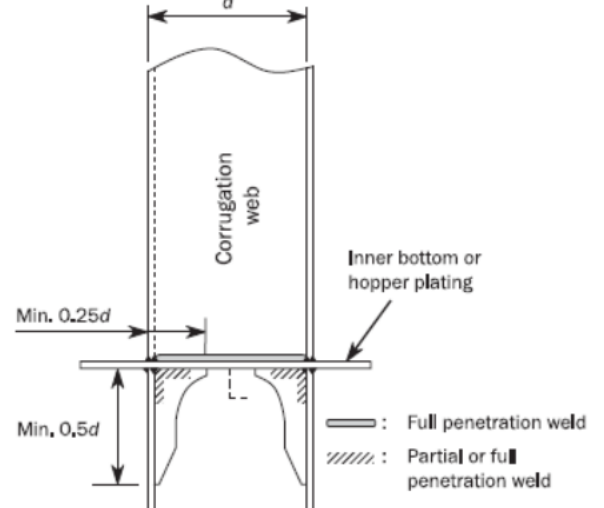
A.7 BULKHEAD CONNECTION TO INNER BOTTOM

A.7.1 Design standard M

A.7.1.1 The connection of vertically corrugated bulkhead to inner bottom/hopper plating of cargo tanks and heavy ballast hold are to be designed according to the design standard M, as shown in Table A.7.1.

Table A.7.1: Design standard M – connection details for vertically corrugated bulkheads in cargo tanks and heavy ballast hold

Connections of vertically corrugated bulkhead to inner bottom/hopper plating without stool	
Critical areas	Design standard M
	
Critical locations	

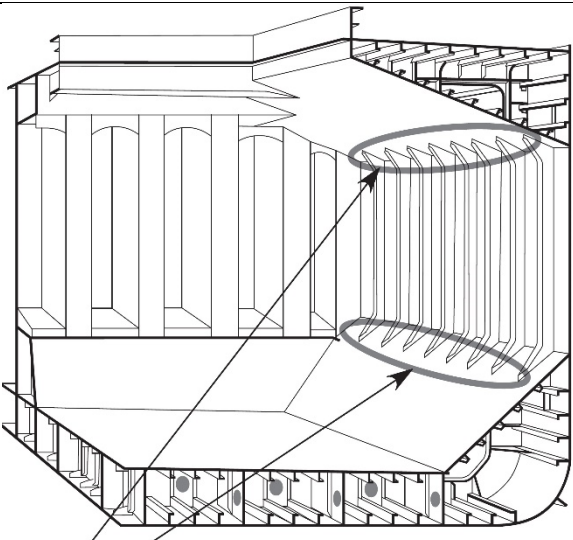
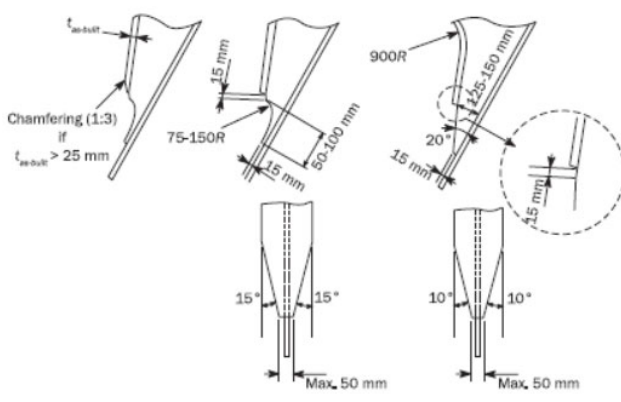
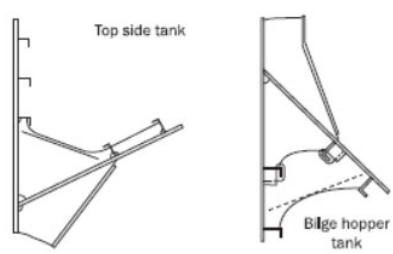
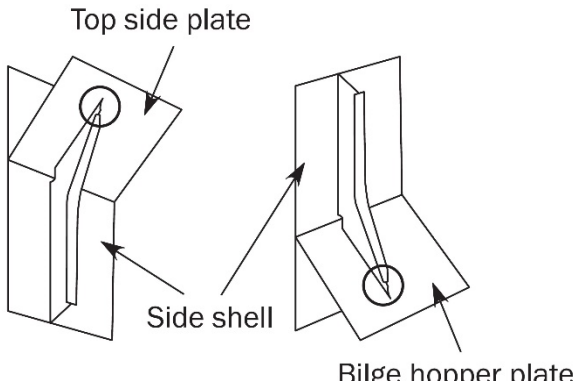
 <p style="text-align: center;">Inner bottom plan</p> <p>○ : Critical locations</p>	<p style="text-align: center;">Detail of in line bracket:</p>  <p style="text-align: center;">Note 1: Brackets are to be arranged below inner bottom and hopper tank plating in line with corrugation webs.</p>
Critical location	-
Detail design standard	Supporting brackets are to be fitted in line with corrugation web. Scallop is not permitted in the supporting bracket.
Building tolerances	Median line of corrugation is to be in line with the median line of the supporting members with an allowable tolerance of $t_{as-built}/3$ or 5[mm], whichever is less, where $t_{as-built}$ is the inner bottom thickness.
Welding requirements	For the connection of vertically corrugated bulkheads to the inner bottom/hopper plating, full penetration welding is to be provided in accordance to IRS Rules Chapter 17. For the connection of supporting structures to inner bottom/hopper plating, partial or full penetration welding is to be provided in accordance with IRS Rules Chapter 17. Partial or full penetration welding is also to be applied for the connection of in line brackets below corrugation web in accordance with IRS Rules Chapter 17 on minimum 300[mm] from the corner.

A.8 LOWER AND UPPER TOE OF HOLD FRAME

A.8.1 Design standard N

A.8.1.1 The welded connections of lower and upper bracket toes of hold frame of bulk carriers are to be designed according to design standard N, as shown in Table A.8.1.

Table A.8.1: Design standard N – lower and upper toe detail of hold frame - bulk carrier

Lower and upper hold frame connections	
Critical areas	Design standard N
 <p style="text-align: center;">Critical area</p>	 <p style="text-align: center;">Examples of the soft and extended toes at the end of hold frames.</p>  <p style="text-align: center;">Connection of lower and upper end bracket of hold frame.</p>
Critical locations	
 <p style="text-align: center;">○ : Critical location</p>	

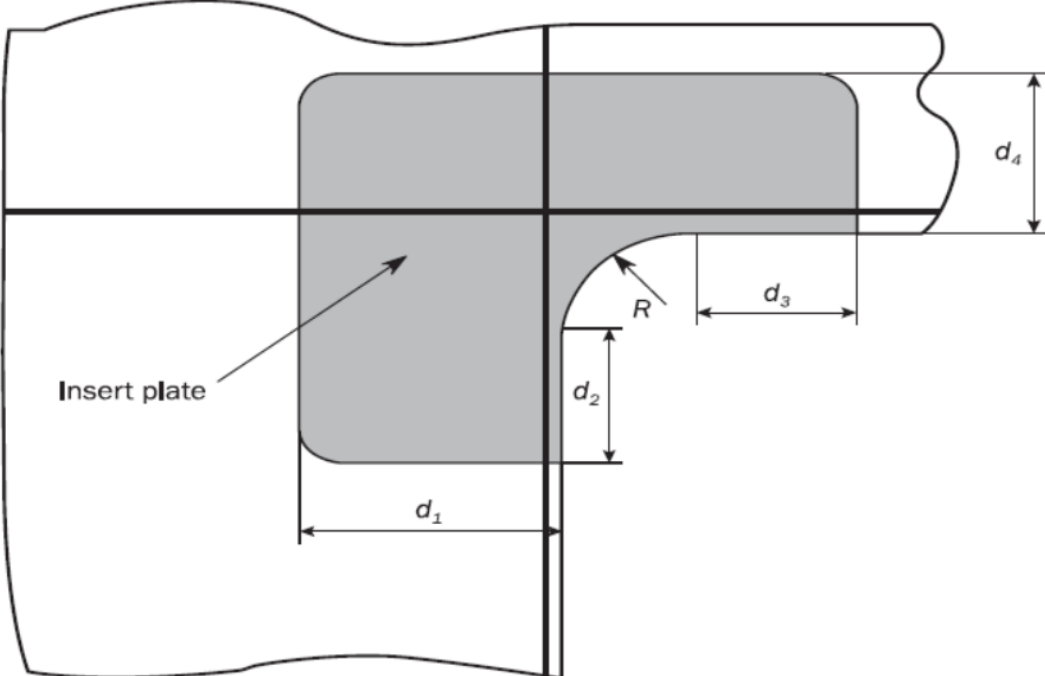
Critical location	Toe connection of side shell frame lower and upper brackets to the hopper and topside sloping plates, including face plate terminations.
Minimum requirement	As a minimum the detail design standard N is to be applied. Tapered extended toes are more effective and are to be considered for high tensile steel side shell frame.
Detail design standard	<p>Alternative geometries than stipulated above are permissible subject to demonstration of satisfactory fatigue performance. However, the maximum angles shown on the figures for thickness chamfering and face width tapering are not to be exceeded. Bracket toe height and the distance between the face plate termination and start of the toe radius (or toe taper) are to be kept to a minimum.</p> <p>The face plates of hold frames at lower or upper brackets are to be tapered and chamfered as shown. While chamfering may be dispensed with if the thickness of the face plates is less than 25[mm], it is nevertheless a recommended practice, with a larger gradient if necessary. Frames are to be built-up symmetrical sections with integral upper and lower brackets and are to be arranged with soft or elongated toes as shown. The side frame flange is to be curved (not knuckled) at the connection with the end brackets. Where the frame upper brackets are not positioned directly below a ring web, supporting brackets are to be provided. In the design ensure that if a topside tank stiffener is positioned above the end of frame upper bracket, the stiffener cut-out is avoided or closed with a full collar. Increasing the size of supporting brackets will reduce stress concentrations in the critical area.</p> <p>Where the frame lower brackets are not positioned directly above a ring web, supporting brackets are to be provided. In the design ensure that if a hopper tank stiffener is positioned below the end of the frame lower bracket, the stiffener cut-out is avoided or closed with a full collar. Increasing the size of supporting brackets will reduce stress concentrations in the critical area.</p>
Building tolerances	Ensure alignment between side shell frame lower and upper bracket and transverse ring webs or supporting brackets according to IACS Recommendation No. 47. Maximum misalignment is to be not greater than $t_{as-built} / 3$ where $t_{as-built}$ is the thinner as-built thickness of the webs to be aligned and misalignment is the overhang of the as-built thinner thickness.
Welding requirements	Welding is to comply with IRS Rules Chapter 17. In way of the wrap around weld at the face plate termination, care should be taken to ensure no over- run onto the radius part and the toe is free from notches and undercut.

A.9 HATCH CORNER

A.9.1 Design standard O

A.9.1.1 Hatch corners in the cargo hold region, located on the strength deck of bulk carriers are required to be designed according to design standard O, as shown in Table A.9.1.

Table A.9.1: Design standard O – hatch corner of bulk carriers

Hatch corner (bulk carriers)		
Design standard O		
 <p>The diagram illustrates a cross-section of a hatch corner. A vertical line represents the hatch edge. A horizontal line represents the deck plating. A shaded area represents the insert plate. The insert plate has a width d_1 and a height d_2. The corner of the insert plate is rounded with a radius R. The distance from the vertical hatch edge to the start of the rounded corner is d_3. The total height of the insert plate assembly is d_4. An arrow points to the shaded area with the label 'Insert plate'.</p>		
	without insert plate	with insert plate
Critical location	Hatch corner curve	Curved Radius Transition insert plate to deck plating
Detail design standard	Shape of hatch corner as required by IRS Rules for Bulk carriers and Oil Tankers Part 2, Ch 1, Sec 2.	Radius and insert plate dimensions and thickness as required by IRS Rules for Bulk carriers and Oil Tankers Part 2, Ch 1, Sec 2. Insert plate has to be tapered for smooth thickness transition to deck plating, the transition taper length has to be not less than 3 times the offset.
Post-treatment	Grinding of cut edge within the radius	Grinding of cut edge within the radius

-----END OF APPENDIX A-----

References:

- IIW (2008) Recommendation of fatigue design for welded joints and components - IIW-1823-07. Paris, France.
- UK Department of Energy (DEn) (1990) Offshore installations: guidance on design and construction. London.
- IACS Rec.56, "Fatigue Assessment of Ship Structures", July 1999.
- HCSR Technical Background, Part 1, Chap 9, Fatigue, June 2011

-----End of the Guidelines-----