GUIDE FOR

APPLICATION OF HIGHER-STRENGTH HULL STRUCTURAL THICK STEEL PLATES IN CONTAINER CARRIERS

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ABS Plaza
16855 Northchase Drive
Houston, TX 77060 USA

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Foreword

The drive for efficient sea-borne container transportation has, over the last several decades, led to some significant growth in container carrier size. Application of hull structural thick steel plates in the upper flange of large container carriers becomes a natural choice for the hull structure to meet the required hull girder strength. Steel plates well in excess of 51 mm* are commonly found in large container carriers. More recently, one technical innovation that is having a significant impact on the next generation of container carriers is the application of hull structural thick steel plates with a minimum yield stress of 460 N/mm^2 (H47).

In addition to the ABS *Rules for Building and Classing Steel Vessels (Steel Vessel Rules),* this Guide is intended to provide the supplementary requirements for the application of higher-strength hull structural thick steel plates, greater than 51 mm, in large container carriers. For thick steel plates with a minimum yield stress of 390 N/mm^2 (H40), the requirements reflect a large and successful body of experience with large container carriers in service, taking into consideration the first principles structural analysis methodologies and the experience in material, welding, and construction that is being routinely applied to large container carriers. Also in response to the request from industry for the adoption of H47 steel grade, this Guide is developed to provide guidance on the design, construction and operation, of container carriers built with such high strength steel plates.

After a certain period for trial use, the criteria contained in this Guide will be incorporated and published in the *Steel Vessel Rule*s. ABS encourages and welcomes at any time the submission of comments on this Guide. The requirements contained in this Guide became effective on 1 January 2009.

* *Note:* The maximum thickness described in 3-1-2/1.3 of the *Steel Vessel Rules*.

GUIDE FOR

APPLICATION OF HIGHER-STRENGTH HULL STRUCTURAL THICK STEEL PLATES IN CONTAINER CARRIERS

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SECTION 1 Introduction

1 General

This Guide describes the supplementary requirements for application of higher-strength hull structural steel plates, greater than 51 mm and less than or equal to 100 mm thickness, in container carriers with regards to the following: hull structural design, testing and certification of H47 steel material, welding and fabrication of H47 steel material, and prevention of fatigue and fracture failure of H47 steel material. These requirements on the thick steel plates are to be used in conjunction with the following ABS Rules:

- Part 5C, Chapter 5 "Vessels Intended to Carry Containers 130 meters (427 feet) to 450 meters (1476 feet) in Length" of the ABS *Rules for Building and Classing Steel Vessels (Steel Vessel Rules)* for the scantling and strength requirements.
- Chapter 1 "Materials for Hull Construction" of the ABS *Rules for Materials and Welding (Part 2)*
- Chapter 4 "Welding and Fabrication" of the ABS *Rules for Materials and Welding (Part 2)*
- ABS *Rules for Survey After Construction (Part 7)*

For thick steel plates in the upper flange of the hull structure, fatigue and fracture are two most pertinent failure mechanisms. When the hull girder strength is designed to the rule minimum requirements, the accompanying effects of higher-strength thick steel plates are largely associated with higher stress levels and reduced fatigue and fracture strength characteristics. In the upper flange of the hull structure, wave-induced fatigue damages in way of thick plated weld connections are the first and foremost concern. As a countermeasure, the fatigue behavior of these weld connections is to be extensively evaluated to avoid initial crack initiation. Second, the presence of planar flaws in thick plated weld connections can adversely affect the integrity of these connections in the form of accelerated crack growth and fracture. Satisfactory fatigue and fracture characteristics are to be attained from improvements in structural design measures, steel materials, welding consumables, welding procedures and post-weld enhancements. Third, survey after construction is to be enhanced through monitoring critical areas and non-destructive inspection.

3 Application

For H40 steel grade, the supplementary requirements in the Guide are applicable to steel plate thicknesses greater than 51 mm and less than 100 mm used in the upper flange of a container carrier hull structure.

For H47 steel grade, the supplementary requirements in the Guide are applicable to steel plate thicknesses less than 100 mm used in the upper flange of a container carrier hull structure.

SECTION 2 Hull Structural Design with Higher-Strength Thick Steel Plates

1 General

The material factor Q for higher strength steels used in the hull girder strength requirement is an indirect means to minimize potential risks associated with buckling, fatigue and fracture in higher strength steels. For thick plated structural members in the upper flange of a container carrier, buckling can generally be excluded as a critical structural mode. Therefore, prevention of fatigue and fracture in the upper flange should be one of the main focuses for large container carriers. Reference is to be made to Part 5C, Chapter 5 "Vessels Intended to Carry Containers 130 meters (427 feet) to 450 meters (1476 feet) in Length" of the *Steel Vessel Rules* for the scantling and strength requirements. In this Section, specific guidance is provided on the application of higher-strength thick steel plates.

3 Selection of Material Grade

Steel materials for particular locations are not to be of lower grades than those required by Section 2, Table 1 of this Guide. Material class is given in 3-1-2/Table 2 of the *Steel Vessel Rules*.

TABLE 1
Material Grade

Thickness, t *mm*	*Material Class*		
	I	*II*	*III*
$t \le 15$	A, AH	A, AH	A, AH
$15 < t \le 20$	A, AH	A, AH	B, AH
$20 < t \le 25$	A, AH	B, AH	D, DH
$25 < t \le 30$	A, AH	D, DH	D, DH
$30 < t \le 35$	B, AH	D, DH	E, EH
$35 < t \le 40$	B, AH	D, DH	E, EH
$40 < t \le 51$	D, DH	E, EH	E, EH
$51 < t \le 70$	D, DH	E, EH	E, EH
$71 < t \le 100$	E, EH	E, EH	E, EH

5 Hull Girder Strength

5.1 Hull Girder Section Modulus

The requirement on hull girder section modulus is given in 5C-5-4/3.1 of the *Steel Vessel Rules*. When either the top or bottom flange of the hull girder, or both, is constructed of higher strength material, the section modulus, as obtained from 3-2-1/3.7 the *Steel Vessel Rules* may be reduced by the material factor Q.

$$SM_{hts} = Q(SM)$$

where

SM = section modulus as obtained from 3-2-1/3.7 of the *Steel Vessel Rules*

The material factor Q for steel materials is listed in Section 2, Table 2 of this Guide. For steel plates 51 mm and under in thickness, the material factor Q is defined in 3-2-1/5.5 of the *Steel Vessel Rules* to be 0.78 for H32, 0.72 for H36 and 0.68 for H40. However for steel plates greater than 51 mm in thickness, the material factor Q for the required section modulus is defined in Section 2, Table 2 with reference to Notes 1 and 2.

5.3 Hull Girder Moment of Inertia

The requirement on hull girder moment of inertia is given in 5C-5-4/3.3 of the *Steel Vessel Rules*. The hull girder moment of inertia is to be not less than required 3-2-1/3.7.2 of the *Steel Vessel Rules*.

If the upper flange is constructed of H47 or H40 grade with the reduced material factor Q in Note 1 of Section 2, Table 2 of this Guide, the effects of springing and whipping on fatigue strength of the hull structural strength are to be evaluated in accordance with the requirements in Subsection 2/11 of this Guide.

TABLE 2
Material Factor Q for Determining Required Hull Girder Section Modulus *(2014)*

Steel Grade	*Material Factor Q* [(3)]
Ordinary Strength Steel	1.00
H32	0.78
H36	0.72
H40	0.68 [(1)]
H47 [(2)]	0.62

Notes:

1 The material factor for H40 may be taken as 0.66, provided that the hull structure is additionally verified for compliance with the requirements of:

- ABS *Guide for 'SafeHull-Dynamic Loading Approach' for Vessels*
- ABS *Guide for Spectral-Based Fatigue Analysis for Vessels*
- Appendix 1 of this Guide

2 The above requirements are to be applied to hull structures with H47.

3 Thickness greater than 100 mm is subject to special consideration.

5.5 Hull Girder Shearing Strength

The requirements of hull girder shearing strength are given in 5C-5-4/5 of the *Steel Vessel Rules*. The material factor Q and strength reduction factor S_m for steel materials to be applied are listed in Section 2, Table 3 of this Guide.

TABLE 3
Material Factor and Strength

Steel Grade	*Material Factor, Q*	*Strength Reduction Factor,* S_m
Ordinary Strength Steel	1.00	1.00
H32	0.78	0.95
H36	0.72	0.908
H40	0.68	0.875
H47	0.62	0.824

Note: The above material factor and strength reduction factor are valid for hull girder shearing strength, hull girder torsional strength, initial scantling evaluation (except for hull girder section modulus), and total strength assessment

5.7 Hull Girder Torsional Strength

The requirements of hull girder torsional strength are defined in 5C-5-4/9 of the *Steel Vessel Rules*. The material factor Q and strength reduction factor S_m for steel materials are listed in Section 2, Table 3 of this Guide.

7 Initial Scantling Evaluation

The requirements of initial scantling evaluation are defined in Section 5C-5-4 of the *Steel Vessel Rules*. The material factor Q for the hull girder section modulus requirement is listed in Section 2, Table 2 of this Guide. For all other requirements, the material factor Q and strength reduction factor S_m for steel materials to be applied are listed in Section 2, Table 3 of this Guide.

9 Total Strength Assessment

The requirements for total strength assessment are given in Section 5C-5-5 of the *Steel Vessel Rules*. The strength reduction factor S_m for steel materials to be applied is listed in Section 2, Table 3 of this Guide.

For the hull structure constructed of higher-strength thick steel plates, special attention is to be paid to the effect of bowflare slamming on vertical hull girder bending moment and shear force, see 5C-5-3/11.3.3 of the *Steel Vessel Rules*.

11 Structural Details and Fatigue Strength Assessment

For the hull structure built with higher-strength thick steel plates of H40 or H47, special attention is to be paid to the fatigue strength of the butt welds and hatch corners in the upper flange of the hull structure. Appendix 1 provides specific guidance on the fatigue strength assessment of these structural details.

For other structural details such as longitudinal connections of web frames and transverse bulkheads, Appendix 5C-5-A1 "Fatigue Strength Assessment of Container Carriers" of the *Steel Vessel Rules* provides the detailed guidance.

For the upper flange of a hull structure constructed of higher-strength thick steel plates of H40 or H47, special attention is to be paid to the effects of whipping on the fatigue strength of the upper flange of the hull structure (A1/5.7 of this Guide).

Furthermore, for the upper flange of a hull structure constructed of higher-strength thick steel plates of H40 or H47, the effects of hull girder springing on the fatigue strength are to be accounted for by direct springing analysis (see A1/5.7 of this Guide).

SECTION 3 Testing and Certification of Thick Steel Plates with Minimum Yield Stress of 460 N/mm^2

1 General Requirements

The requirements in this Section are applicable to H47 grade hull structural steel plates up to 100 mm in thickness. The general guideline and requirements defined in the ABS *Rules for Materials and Welding (Part 2)* are to be applied, unless there are specific requirements in this Guide.

1.1 Testing and Inspection

The requirements for the testing and inspection are defined in 2-1-1/1 of the ABS *Rules for Materials and Welding (Part 2)*.

1.3 Defects

The requirements for the conditions of defects are defined in 2-1-1/3 of the ABS *Rules for Materials and Welding (Part 2)*.

1.5 Identification of Materials

The requirements for identification of materials are defined in 2-1-1/5 of the ABS *Rules for Materials and Welding (Part 2)*.

1.7 Manufacturer's Certificates

The requirements for manufacturer's certificates are defined in 2-1-1/7 of the ABS *Rules for Materials and Welding (Part 2)*.

1.9 Identification of Specimens and Retests

The requirements for identification of specimens and retests are defined in 2-1-1/9 of the ABS *Rules for Materials and Welding (Part 2)*.

1.11 Standard Test Specimens

The requirements for preparations of specimens for tension test, bend test, and impact test are defined in 2-1-1/11 of the ABS *Rules for Materials and Welding (Part 2)*.

1.13 Yield Strength and Elongation

The requirements for definition and determination of yield strength and elongation are defined in 2-1-1/13 and 2-1-1/14 of the ABS *Rules for Materials and Welding (Part 2)*.

1.15 Permissible Variations in Dimensions

The requirements for permissible variations in dimensions are defined in 2-1-1/15 of the ABS *Rules for Materials and Welding (Part 2)*.

1.17 Process of Manufacture

The requirements for process of manufacture are defined in 2-1-2/3 of the ABS *Rules for Materials and Welding (Part 2)*.

1.19 Condition of Supply

The condition of supply is to be TMCP. The requirements for supply are defined in 2-1-2/7 of the ABS *Rules for Materials and Welding (Part 2).*

1.21 Marking

The requirements for marking are defined in 2-1-2/13 of the ABS *Rules for Materials and Welding (Part 2).*

1.23 Surface Finish

The requirements for surface finish are defined in 2-1-2/15 of the ABS *Rules for Materials and Welding (Part 2).*

1.25 Fine Grain Practice

The requirements for fine grain practice are defined in 2-1-3/5 of the ABS *Rules for Materials and Welding (Part 2).*

3 Chemical Composition

3.1 Chemical Composition

The chemical composition is to be determined by the steel manufacturer on samples taken from each ladle of each heat and is to conform to Section 3, Table 1.

3.3 Carbon Equivalent

The carbon equivalent C_{eq} as determined from the ladle analysis in accordance with the following equation is to meet the requirements in Section 3, Table 2.

$$C_{eq} = \mathrm{C} + \frac{\mathrm{Mn}}{6} + \frac{\mathrm{Cr} + \mathrm{Mo} + \mathrm{V}}{5} + \frac{\mathrm{Ni} + \mathrm{Cu}}{15} \quad (\%)$$

3.5 Cold Cracking Susceptibility

The cold cracking susceptibility P_{cm} as calculated from the ladle analysis in accordance with the following equation is to meet the requirements in Section 3, Table 3.

$$P_{cm} = \mathrm{C} + \frac{\mathrm{Si}}{30} + \frac{\mathrm{Mn}}{20} + \frac{\mathrm{Cu}}{20} + \frac{\mathrm{Ni}}{60} + \frac{\mathrm{Cr}}{20} + \frac{\mathrm{Mo}}{15} + \frac{\mathrm{V}}{10} + 5\mathrm{B} \quad (\%)$$

TABLE 1
Chemical Properties of H47 Steel

Grade	AH47, DH47, EH47, FH47
Deoxidation	Killed, Fine Grain Practice (1)
Chemical Composition (2)	(Ladle Analysis), % max. unless specific in range
C	0.10
Mn	2.00
Si	0.55 (3)
P	0.030
S	0.030
Al (acid Soluble) min. (4,5)	0.015
Nb (5)	0.05
V (5)	0.10
Ti	0.02
Cu	0.35
Cr	0.25
Ni	1.50
Mo	0.08
B	0.002

Notes:

1 The steel is to contain at least one of the grain refining elements in sufficient amount to meet the fine grain practice requirement specified in 2-1-3/5 of the ABS *Rules for Materials and Welding (Part 2)*.

2 The content of any other element intentionally added is to be determined and reported.

3 Where the content of soluable aluminum is not less than 0.015%, the minimum required silicon content does not apply.

4 The total aluminum content may be used in lieu of acid soluable content, in accordance with 2-1-3/5 of the ABS *Rules for Materials and Welding (Part 2)* .

5 The indicated amount of aluminum, niobium and vanadium applies when any such element is used singly. When used in combination, the minimum content in 2-1-3/5 of the ABS *Rules for Materials and Welding (Part 2)* will apply.

TABLE 2
Carbon Equivalent for H47 Steel

Grade	*Carbon Equivalent, Max. (%)*	
	t ≤ 51 mm	*51 mm < t ≤ 100 mm*
AH47, DH47, EH47, FH47	0.46	0.49

TABLE 3
Cold Cracking Susceptibility for H47 Steel

Grade	*Cold Cracking Susceptibility, Max. (%)*
	t ≤ 100 mm
AH47, DH47, EH47, FH47	0.21

5 Tensile Properties

The material is to conform to the requirements of Section 3, Table 4 of this Guide as to tensile properties. The requirements for the preparation and procedure of tensile test are defined in 2-1-2/9 of the ABS *Rules for Materials and Welding (Part 2).*

TABLE 4
Tensile Properties of H47 Steel

Grade	*Tensile Strength* *N/mm^2 (kgf/mm^2, ksi)*	*Yield Point min.* *N/mm^2 (kgf/mm^2, ksi)*	*Elongation* *Min.%*
AH47, DH47, EH47, FH47	570–720 (58-71, 83-101)	460 (47, 67)	17

7 Impact Properties

The requirements for the preparation and procedure of Charpy V-notch impact test are defined in 2-1-2/11 of the ABS *Rules for Materials and Welding (Part 2).* The results of the test are to meet the requirements specified in Section 3, Table 5 of this Guide.

TABLE 5
Impact Properties of H47 Steel

Grade	*Temp* *°C (°F)*	*Average Absorbed Energy* *Longitudinal* *J (kgf-m, ft-lbt)*	*Average Absorbed Energy* *Transverse* *J (kgf-m, ft-lbt)*
AH47	0 (32)	64 (6.5, 47)	43 (4.4, 32)
DH47	-20 (-4)	64 (6.5, 47)	43 (4.4, 32)
EH47	-40 (-40)	64 (6.5, 47)	43 (4.4, 32)
FH47	-60 (-76)	64 (6.5, 47)	43 (4.4, 32)

Note: The energy shown is minimum for full size specimen.

9 Fracture Toughness Testing

Fracture toughness of materials and weldments of H47 steel plate is to be verified by CTOD test, ESSO test, or deep notch test by steel manufacturers. CTOD test is to be carried out as per BS 7448 Parts 1 & 2 of ASTM E1820 or any other recognized standard. The requirements for CTOD test are defined in 2-1-1/23 of the ABS *Rules for Materials and Welding (Part 2).*

SECTION 4 Welding and Fabrication of Thick Steel Plates with Minimum Yield Stress of 460 N/mm^2

1 General

The requirements in this Section are applicable to H47 grade hull structural steel plates up to 100 mm in thickness. The general guideline and requirements for the preparation and practice of welding specified in the ABS *Rules for Materials and Welding (Part 2)* is to be applied, unless there are specific requirements in this Guide.

1.1 Preparation for Welding

The requirements for the preparation of welding are defined in 2-4-1/3 of the ABS *Rules for Materials and Welding (Part 2).*

1.3 Production Welding

The requirements for the production of welding are defined in 2-4-1/5 of the ABS *Rules for Materials and Welding (Part 2).*

1.5 Butt Welds

The requirements for manual and automatic butt welding are defined in 2-4-1/7 of the ABS *Rules for Materials and Welding (Part 2).*

1.7 Workmanship Test

The requirements for workmanship test are defined in 2-4-3/7 of the ABS *Rules for Materials and Welding (Part 2).*

1.9 Welders

The requirements for qualification tests for welders are defined in 2-4-3/11 of the ABS *Rules for Materials and Welding (Part 2).*

1.11 High Heat Input Welding

The requirements for approval of manufactures of H47 steel plates for welding with high heat input are defined in Appendix 5 of the ABS *Rules for Materials and Welding (Part 2).*

3 Requirements of Filler Metals

3.1 General

Filler metals are to be a type suitable to produce sound welds that have strength and toughness comparable to the materials being welded. The requirements for the approval of welding filler metals are defined in Appendix 2 of the ABS *Rules for Materials and Welding (Part 2).*

3.3 Mechanical Properties

The tensile strength range of filler metals used for H47 steel is to be 570-720 N/mm^2.

3.5 Application of Filler Metal

The application of filler metal is to meet the requirements in Section 4, Table 1.

TABLE 1
Applicable Filler Metals

Filler Metal Grade	*Plate Thickness ≤ 51 mm*	*Plate Thickness > 51 mm*
Grade 3 Y 470	AH47, DH47	AH47
Grade 4 Y 470	AH47, DH47, EH47	AH47, DH47
Grade 5 Y 470	AH47, DH47, EH47, FH47	AH47, DH47, EH47
Grade 6 Y 470	AH47, DH47, EH47, FH47	AH47, DH47, EH47, FH47

5 Approval of Welding Procedures

5.1 General

Procedures for the welding of all joints are to be established before construction for the welding processes, types of electrodes, edge preparations, welding techniques, and positions proposed.

Welding procedure qualification test is required to determine the shipyard or fabricator's capability in the application of the proposed filler metal to the base material.

5.3 Approved Filler Metals

For butt weld test assembly and fillet weld test assembly, as applicable, one of the grades of steel, or equivalent, as listed in Section 4, Table 1 for the individual grade of filler metals is to be used. The maximum hydrogen content is to be 10 cm^3/100 g.

5.5 Test Requirements

Preparation of test specimen and test process is to follow the requirements in the ABS *Rules for Materials and Welding (Part 2)*. Charpy V-notch impact test for the toughness of weldments is to meet the requirements in Section 4, Table 2 of this Guide.

TABLE 2
Toughness Requirements of Welds

Grade	*Test Location*	*Test Temperature*	*CVN Requirement*
AH47, DH47, EH47	WM, FL, FL+1 mm, +3 mm, +5 mm	-20°C	57 J
FH47		-40°C	57 J

7 Weldability Test of Base Metal

7.1 General

The general requirements for weldability test of H47 steel plates are defined in 2-A4-2/5.13 of the ABS *Rules for Materials and Welding (Part 2)*. The mechanical properties of welds are to meet the requirements specified in this Subsection.

7.3 Tensile Properties

Tensile properties are to meet the requirements of the base plate as specified in Section 3.

7.5 Notch Toughness

Charpy V-notch impact test for the toughness of weldments are to meet the requirements specified in Section 4, Table 3.

TABLE 3
Toughness Requirements of Welds

Grade	*Test Location*	*Test Temperature*	*CVN Requirement*
AH47	FL, FL+2 mm, +5 mm, +20 mm	0°C	64 J
DH47		-20°C	64 J
EH47		-40°C	64 J
FH47		-60°C	64 J

SECTION 5 Prevention of Fatigue and Fracture Failure in Thick Steel Plates with Minimum Yield Stress of 460 N/mm^2

1 General

The upper flange of the hull structure with hatch coaming constructed with H47 steel plates over 51 mm is to be verified against possible fatigue and fracture failure. Any possibility of fatigue and fracture failure of the hull structure is controlled in three steps. The first step for the prevention of possible failure is to minimize initial defects in weldments during new construction by nondestructive inspection. The second step is to remove the possibility of fatigue crack growth to a critical size through enhanced fatigue analysis and nondestructive test of vessels in service. The third step is a suitable design measure for the upper deck structure to arrest a fatigue crack or fracture failure through the block joint weld between hatch coaming side plate and upper deck.

3 Nondestructive Inspection of Welds

3.1 General

Radiographic and ultrasonic inspections are to be carried out in accordance with the ABS *Guide for Nondestructive Inspection of Hull Welds.*

Nondestructive inspection of weldments is to be conducted at a minimum interval of 72 hours after welding unless specially approved otherwise.

3.3 New Construction

All butt joints of hatch coaming and upper deck structures are to be inspected by ultrasonic test and magnetic particle test.

3.5 Vessels in Service

Butt welds of hatch coaming top and side plates are to be inspected for cracks within $0.3L \sim 0.7L$ of vessel length at every Special Periodical Survey.

All butt welds of hatch coaming top and side plates are to be visually inspected. Additional ultrasonic, magnetic particle, or eddy current test may be required depending on the inspection results.

Ultrasonic test is to be used for all butt welds of hatch coaming top plate at the location of block erection.

3.7 Requirements for Nondestructive Test

Acceptance levels for allowable sizes of discontinuities are to be determined in accordance with the ABS *Guide for Nondestructive Inspection of Hull Welds*.

5 Prevention of Fatigue Failure

5.1 Fatigue Strength Assessment

Butt weld connections of hatch coaming top plates close to hatch corners are to be analyzed to meet a minimum design fatigue life of 20 years in the North Atlantic wave environment.

The hull structure is to be verified for compliance with the requirements of:

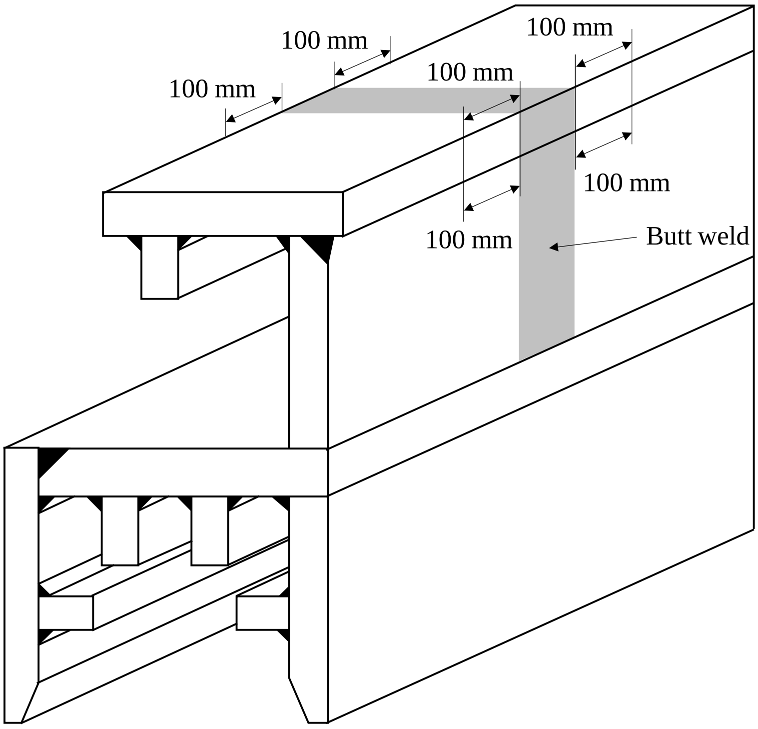
- ABS *Guide for 'SafeHull-Dynamic Loading Approach' for Vessels*
- ABS *Guide for Spectral-Based Fatigue Analysis for Vessels*
- Appendix 1 of this Guide

5.3 Fatigue Strength Improvement of Welds

The upper and lower edges of the hatch coaming top plate in way of the butt weld are to be ground smooth with a radius of 3 ~ 5 mm or 3C to reduce the possibility of a fatigue crack initiation. Butt weld edges at both side of hatch coaming top plate are to be ground smooth. The extent of the grinding is to be 100 mm forward and aft of the butt weld as shown in Section 5, Figure 1. Away from the aforementioned areas, the upper and lower edges are to be ground to 1C, as a minimum.

For the upper flange of a hull structure, outfitting members are to be connected to the hatch coaming top plate by a non-welding means. However, if any outfitting member has to be welded to the hatch coaming top plate, the front and rear end weld profile is to be ground smooth. Alternatively, improvement to the fatigue strength can be achieved through ultrasonic peening or ultrasonic impact treatment.

FIGURE 1
Grinding of Butt Weld



7 Prevention of Fracture Failure

7.1 General *(1 February 2012)*

To prevent a serious failure along the block joints of the upper flange structure, appropriate design measures are to be adopted to arrest the propagation of a crack in the hatch coaming and main deck structures. One or a combination of the design measures in this Subsection may be considered. The detailed design measure applied to avoid crack propagation is to be submitted for review.

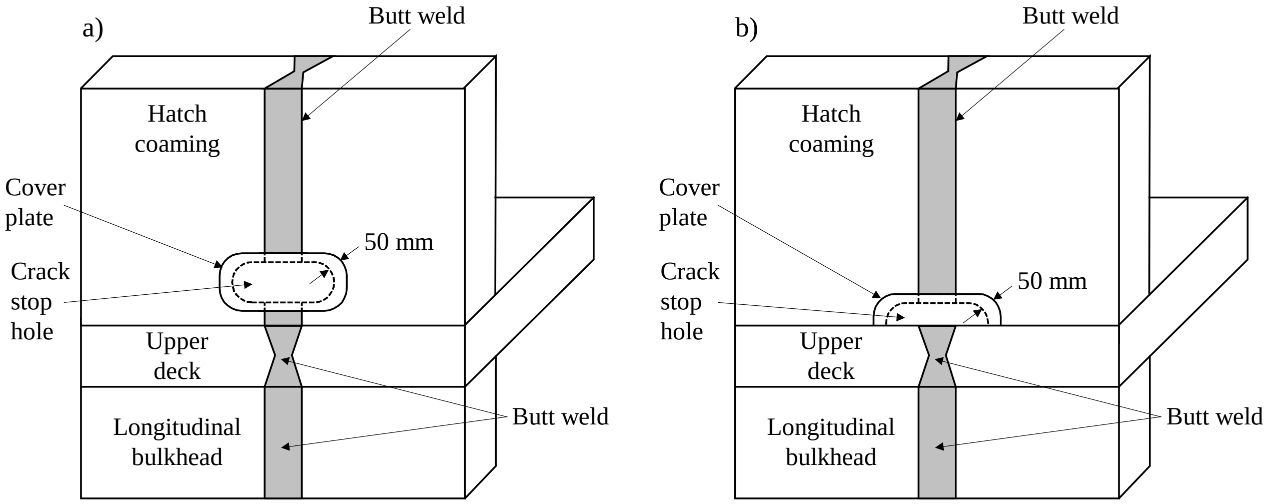
7.3 Crack Stop Hole

A crack stop hole of a sufficient size is to be provided at the bottom of the hatch coaming side plate as shown in Section 5, Figure 2. In general, the radius of the edges of the crack stop hole is to be half of the hatch side plate thickness.

The edges of a crack stop hole are to be ground smooth with a radius of 3 ~ 5 mm. Butt welds in way of the crack stop hole are to be ground flush. Outside of the hole is to be covered with a thin H36 grade steel plate of approximately 10 mm with a minimum overlap length of 50 mm. Fillet weld toes of the cover plate are to be ground smooth. Alternatively, improvement to the fatigue strength can be achieved through ultrasonic peening or ultrasonic impact treatment. Rubber or silicon sealing can be used to cover the hole instead of steel plate.

With the presence of the crack stop holes, the hull girder section modulus requirement is to be verified in accordance with 3-2-1/9.3 of the *Steel Vessel Rules*. The fatigue life in way of the crack stop hole is to have a design fatigue life of more than 20 years in the North Atlantic wave environment. A welding procedure specification involving crack stop hole is to be submitted to the attending Surveyor to demonstrate the capability to produce sound welds.

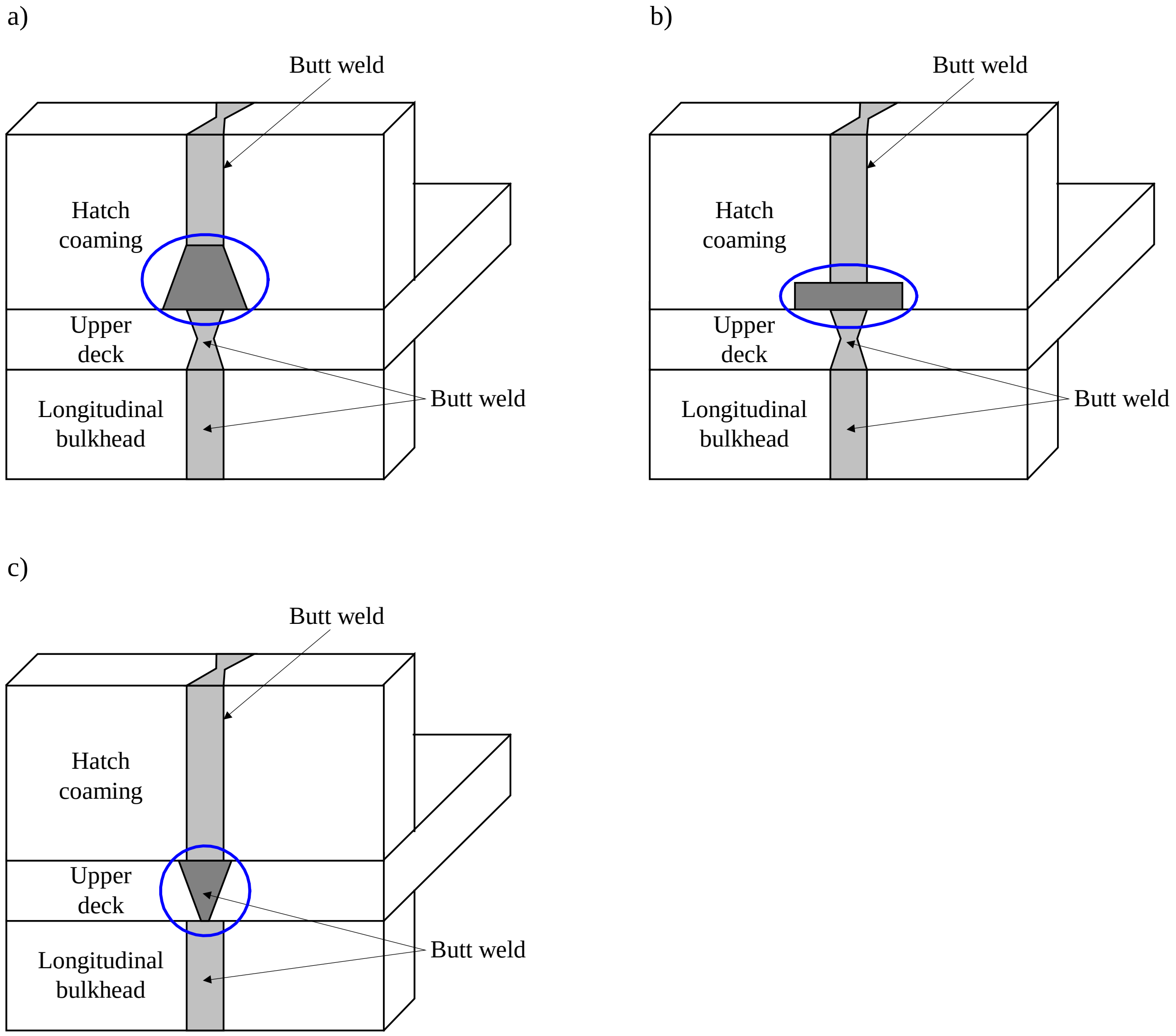
FIGURE 2
Crack Stop Holes



7.5 High Toughness Weld

In general, high toughness weld consumables with Ni content greater than 2.5% or other high toughness consumables are to be used at the bottom of hatch coaming side plate with an appropriate weld shape to stop a propagating crack as shown in Section 5, Figure 3. Test data are to be submitted to demonstrate that the high toughness weld has adequate capability to stop or alter the path of a crack. A welding procedure specification involving high toughness weld is to be submitted to the attending surveyor to demonstrate the capability to produce sound welds.

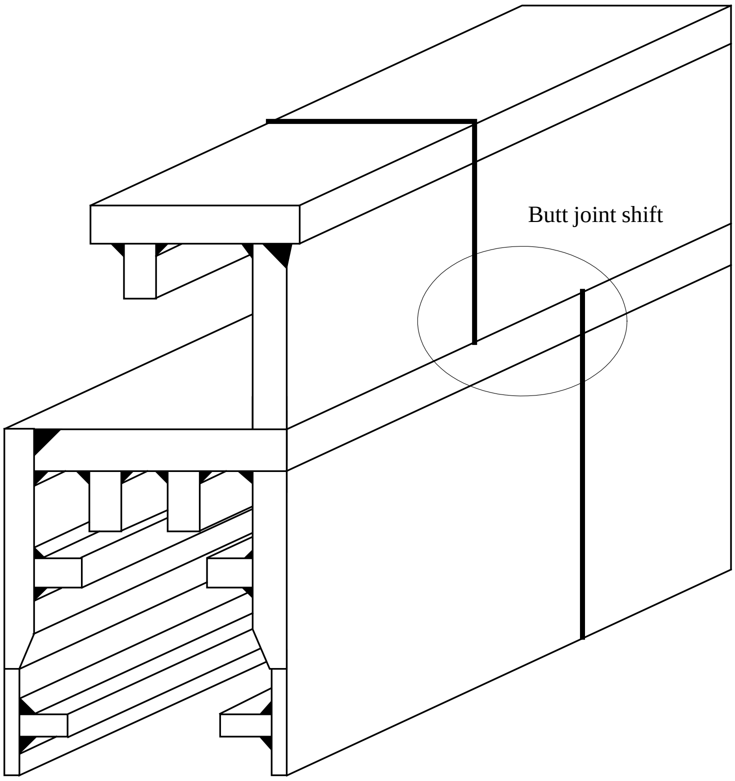
FIGURE 3
High Toughness Weld



7.7 Block Joint Shift

The butt weld lines in the hatch coaming top and side plates are to be shifted from the butt weld lines of the upper deck structure so that a fatigue crack initiated in the butt weld of the hatch coaming is prevented from propagating through the upper deck as shown in Section 5, Figure 4. Likewise, a fatigue crack in the butt weld of the upper deck structure also cannot propagate to the hatch coaming plates with this design measure.

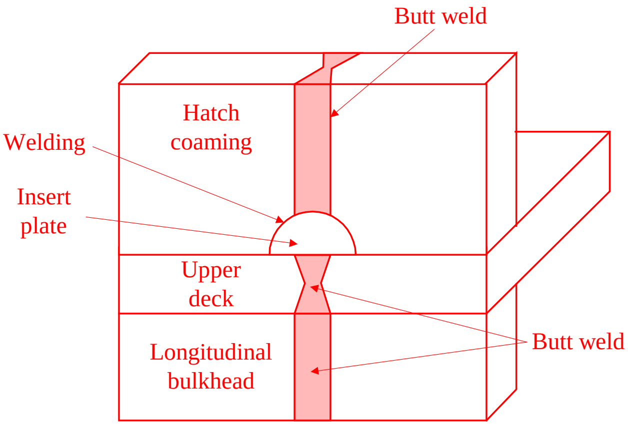
FIGURE 4
Block Joint Shift



7.9 Insert Plate *(1 February 2012)*

An insert plate is to be provided at the bottom of the hatch coaming side plate as shown in Section 5, Figure 5. The minimum size of the insert plate is to be 150 mm depth × 300 mm length. The thickness and the material of the insert plate are to be the same as the hatch coaming side plate. The insert plate is to be welded to the hatch coaming side plate and upper deck by double-V or double-bevel groove deep penetration welding. Surface of the weld is to be ground smoothly to remove any stress concentration.

FIGURE 5
Insert Plate *(1 February 2012)*



9 Hull Girder Residual Strength

With the measures to arrest cracking in the hatch coaming top and side plates, the hull girder structure is to have adequate residual strength against overloading. The residual strength limit state is to be verified in accordance with the requirements in Appendix 2.

APPENDIX 1 Full Ship Finite Element Based Fatigue Strength Assessment of Upper Flange Structure

1 General

1.1 Note

The criteria in 5C-5-A1 of the *Steel Vessel Rules* provide a designer oriented approach to fatigue strength assessment which may be used, for certain structural details, in lieu of more elaborate methods such as spectral fatigue analysis. This Appendix offers specific guidance on a full ship finite element based fatigue strength assessment of certain structural details in the upper flange of container carrier hull structure. The term assessment is used here to distinguish this approach from the more elaborate analysis.

Under the design torsional moment curves defined in 5C-5-3/5.1.5 of the *Steel Vessel Rules*, the warping stress distributions can be accurately determined from a full ship finite element model for novel container carrier configurations, for example,

- Engine room and deckhouse co-located amidships
- Engine room and deckhouse that are separately located
- Fuel oil tanks located within cargo tanks

The full ship finite element based fatigue strength assessment is considered an essential step in evaluating hull structural thick steel plates in large container carriers.

The criteria in this Appendix are developed from various sources including the Palmgren-Miner linear damage model, S-N curve methodologies, long-term environment data of the North-Atlantic Ocean, etc., and assume workmanship of commercial marine quality acceptable to the Surveyor.

1.3 Applicability

The criteria in this Appendix are specifically written for container carriers to which Part 5C, Chapter 5 of the *Steel Vessel Rules* is applicable.

1.5 Loadings

The criteria have been written for ordinary wave-induced motions and loads. Other cyclic loadings, which may result in significant levels of stress ranges over the expected lifetime of the vessel, are also to be considered by the designer.

Where it is known that a vessel will be engaged in long-term service on a route with more severe environment, the fatigue strength assessment criteria in this Guide are to be modified accordingly.

1.7 Effects of Corrosion

To account for the mean wastage throughout the service life, the total stress range calculated from a full ship finite element model using the gross scantlings is modified by a factor c_f. See A1/9.3.1.

1.9 Format of the Criteria

The criteria in this Appendix are presented as a comparison of fatigue strength of the structure (capacity) and fatigue inducing loads (demands) as represented by the calculated cumulative fatigue damage over the design service life of 20 years in the North Atlantic Ocean. In other words, the calculated cumulative fatigue damage is to be not less than 0.8.

3 Connections to be Considered for the Fatigue Strength Assessment

3.1 General

These criteria in this Appendix have been developed to allow consideration of a broad variation of structural details and arrangements in the upper flange of a container carrier hull structure so that most of the important structural details anywhere in the vessel can be subjected to an explicit (numerical) fatigue assessment using these criteria. However, where justified by comparison with details proven satisfactory under equal or more severe conditions, an explicit assessment can be exempted.

3.3 Guidance on Locations

As a general guidance for assessing fatigue strength for a container carrier, the following connections and locations are to be considered:

3.3.1 Hatch Corners

The following locations of hatch corners:

3.3.1(a) Typical hatch corners within 0.4*L* amidships

3.3.1(b) Hatch corners at the forward cargo hold

3.3.1(c) Hatch corners immediately forward and aft of the engine room

3.3.1(d) Hatch corners immediately forward and after the accommodation block, if it is not collocated with the engine room

3.3.1(e) Hatch corners subject to significant warping constraint from the adjacent structures

3.3.2 Connection of Longitudinal Hatch Girders and Cross Deck Box Beams to Other Supporting Structures

Representative locations of each hatch girder and cross deck box beam connections.

3.3.3 Representative Cut-outs

Representative cut-outs in the longitudinal bulkheads, longitudinal deck girder, hatch side coamings and cross deck box beams.

3.3.4 Other Regions and Locations

Highly stressed by fluctuating loads, as identified from the full ship finite element torsional analysis

For the structural details identified above, the stress concentration factor (SCF) may be calculated by the approximate equations given in Subsection A1/9. Alternatively, the stress concentration factor (SCF) may be determined from fine mesh F.E.M. analyses (see Subsection A1/11).

3.5 Fatigue Classification

3.5.1 Welded Connections with One Load Carrying Member

Fatigue classification for structural details is shown in Appendix 1, Table 1.

TABLE 1
Fatigue Classification for Structural Details

Class Designation — *Description*

B Parent materials, plates or shapes as-rolled or drawn, with no flame-cut edges. In case with any flame-cut edges, the flame-cut edges are subsequently ground or machined to remove all visible sign of the drag lines

C

1) Parent material with automatic flame-cut edges
2) Full penetration seam welds or longitudinal fillet welds made by an automatic submerged or open arc process, and with no stop-start positions within the length.

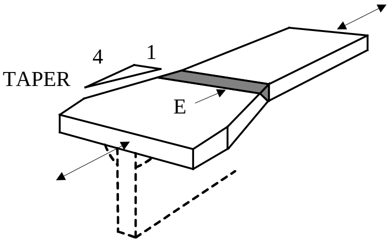
D

1) Full penetration butt welds made either manually or by an automatic process other than submerged arc, from both sides, in downhand position.
2) Weld in C-2) with stop-start positions within the length

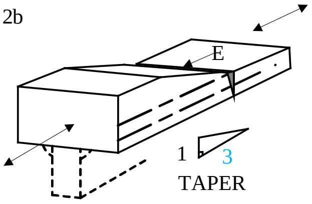
E

1) Full penetration butt welds made by other processes than those specified under D-1)
2) Full penetration butt welds made from both sides between plates of unequal widths or thicknesses

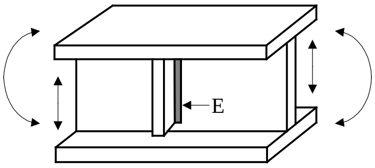
2a



2b



3) Welds of brackets and stiffeners to web plate of girders



F

1) Full penetration butt weld made on a permanent backing strip
2) Rounded fillet welds as shown below

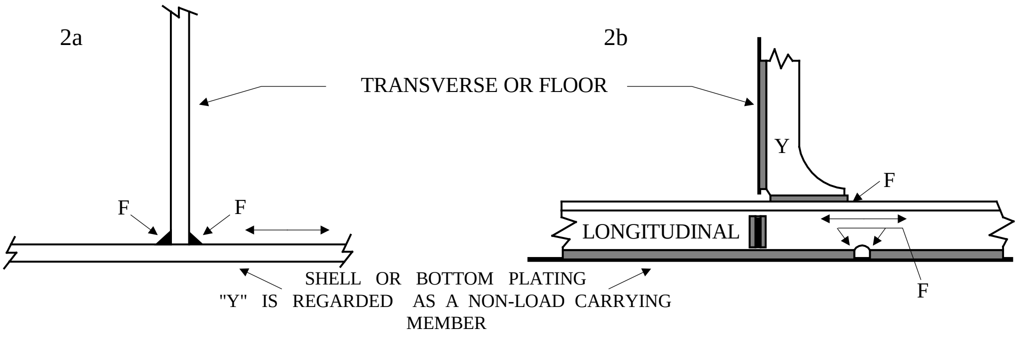
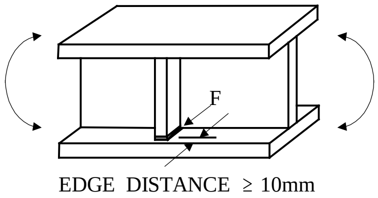
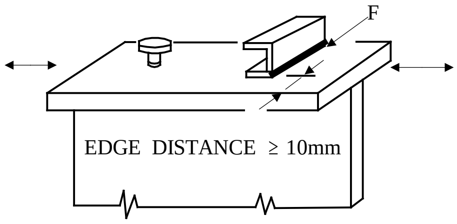


TABLE 1 (continued)
Fatigue Classification for Structural Details

Class Designation	*Description*
	3) Welds of brackets and stiffeners to flanges



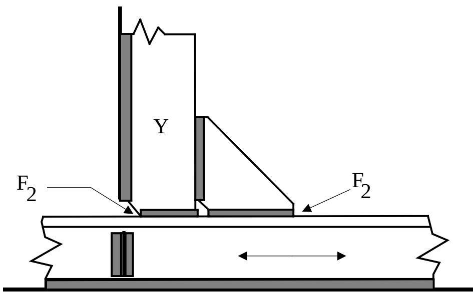
Class Designation	*Description*
	4) Attachments on plate or face plate



(Class G for edge distance < 10 mm)

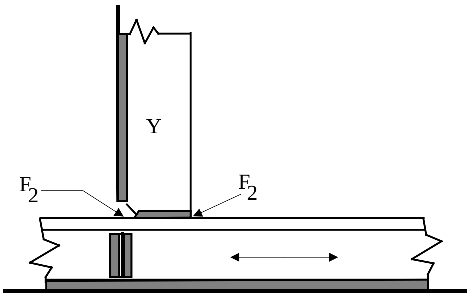
Class Designation	*Description*
F_2	1) Fillet welds as shown below with rounded welds and no undercutting

1a



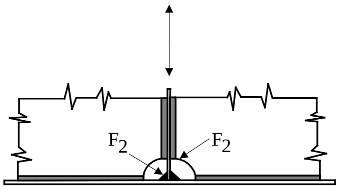
"Y" is a non-load carrying member

1b



Class Designation	*Description*
	2) Fillet welds with any undercutting at the corners dressed out by local grinding

2a)



2b)

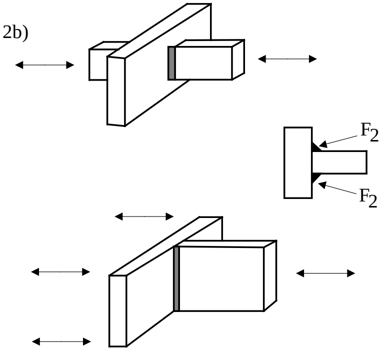
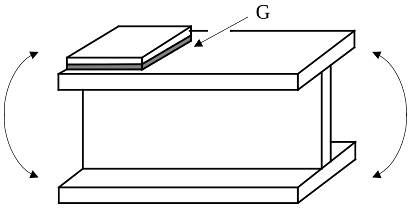


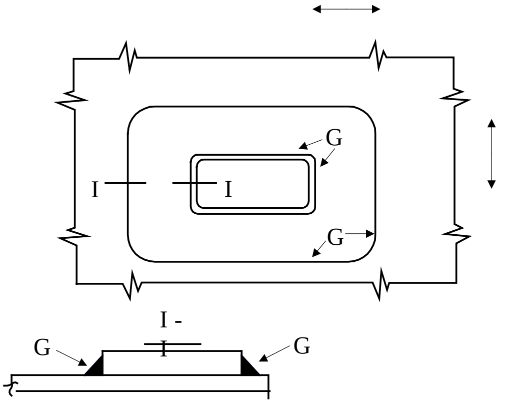
TABLE 1 (continued)
Fatigue Classification for Structural Details

Class Designation *Description*

G

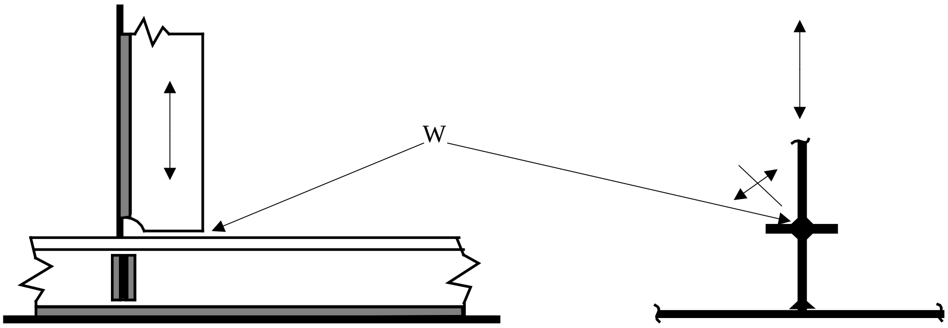
1) Fillet welds in F_2 - 1) without rounded tow welds or with limited minor undercutting at corners or bracket toes
2) Fillet welds in F_2 - 2) with minor undercutting
3) Doubler on face plate or flange, small deck openings
4) Overlapped joints as shown below





W

1) Fillet welds in G - 3) with any undercutting at the toes
2) Fillet welds – weld throat

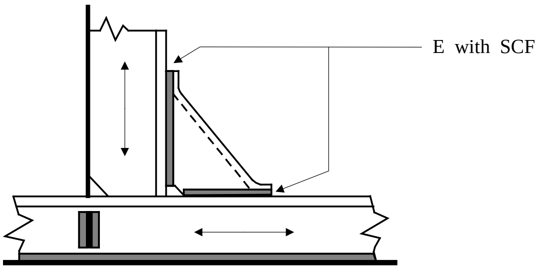


3.5.2 Welded Joint with Two or More Load Carrying Members

For brackets connecting two or more load carrying members, an appropriate stress concentration factor (SCF) determined from fine mesh finite element analysis is to be used. In this connection, the fatigue class at bracket toes may be upgraded to class E. Sample connections are illustrated below with/without SCF.

TABLE 2
Welded Joint with Two or More Load Carrying Members

a Connections of Longitudinal and Stiffener



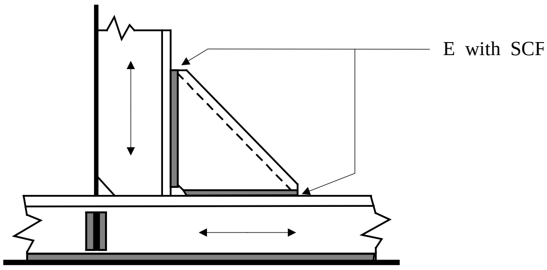
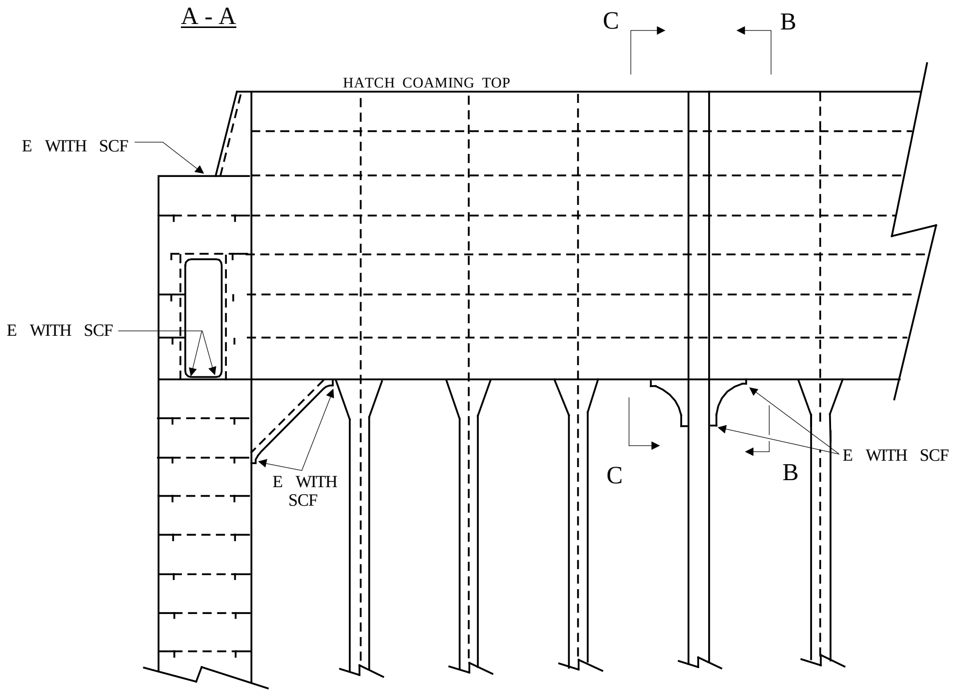


TABLE 2 (continued)
Welded Joint with Two or More Load Carrying Members

b Connections of Longitudinal Deck Girders and Cross Deck Box



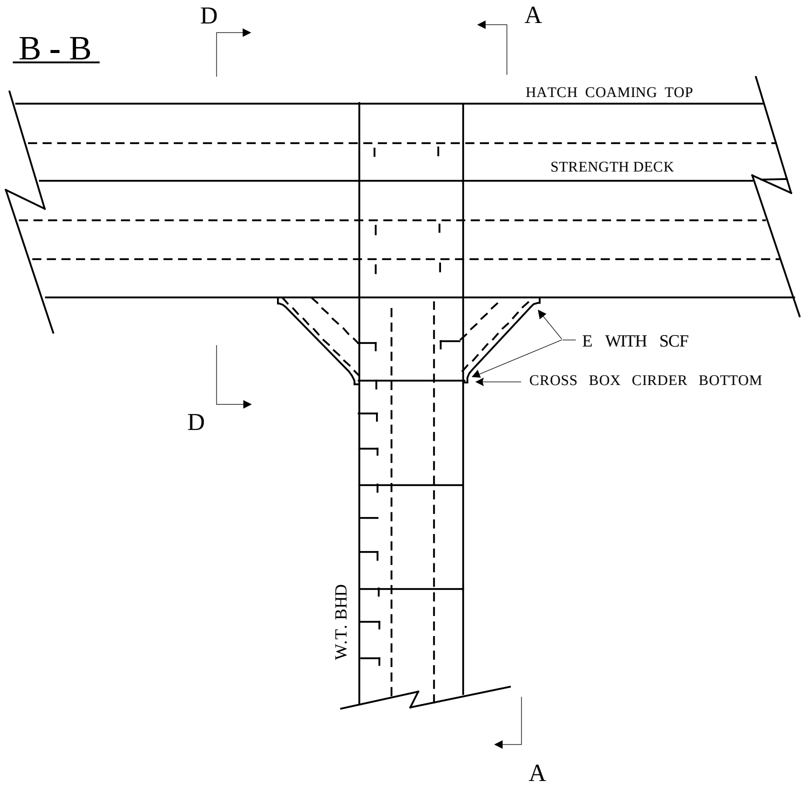
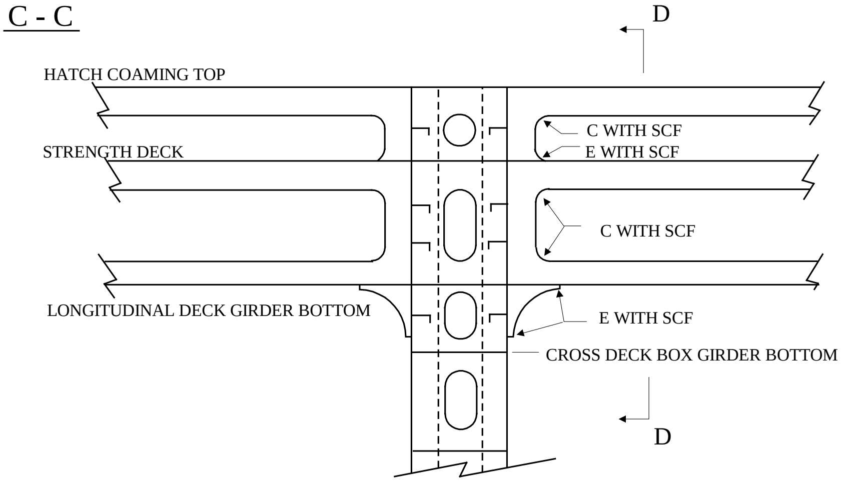


TABLE 2 (continued)
Welded Joint with Two or More Load Carrying Members



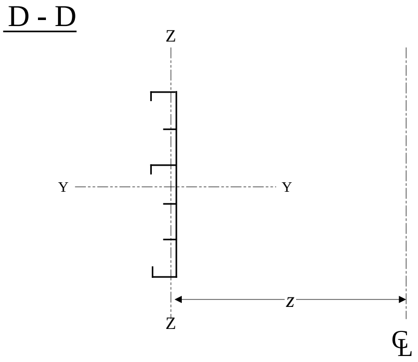
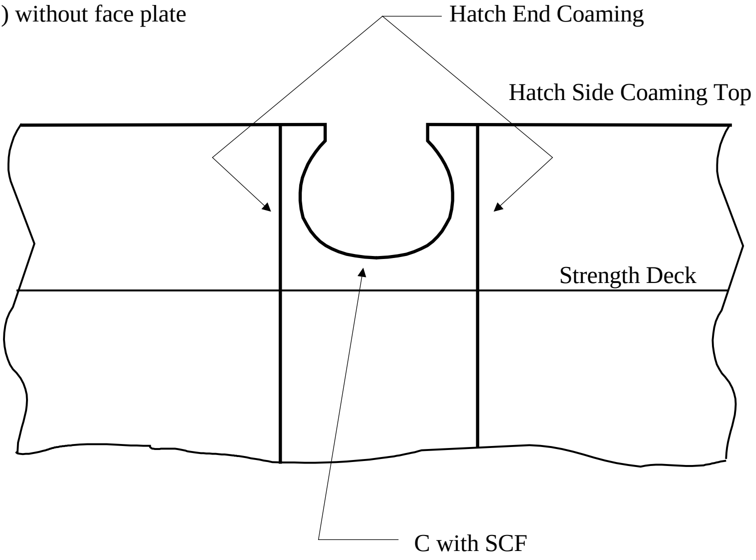


TABLE 2 (continued)
Welded Joint with Two or More Load Carrying Members

c Discontinuous Hatch Side Coaming

1) without face plate



2) with face plate

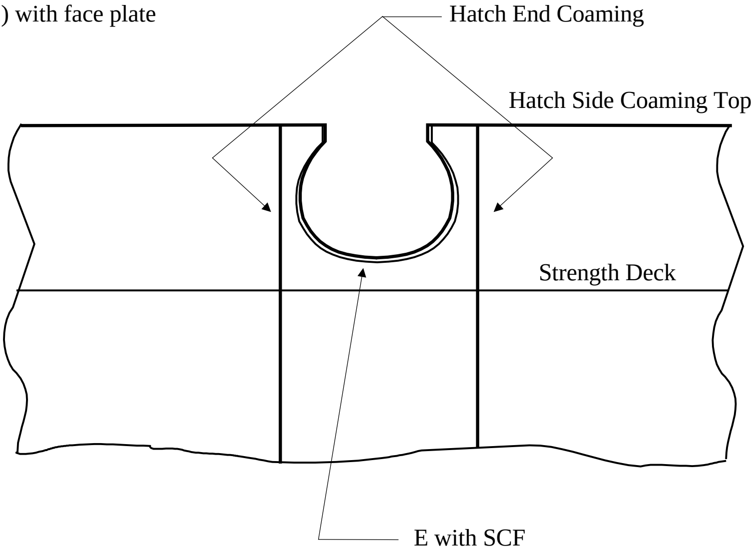
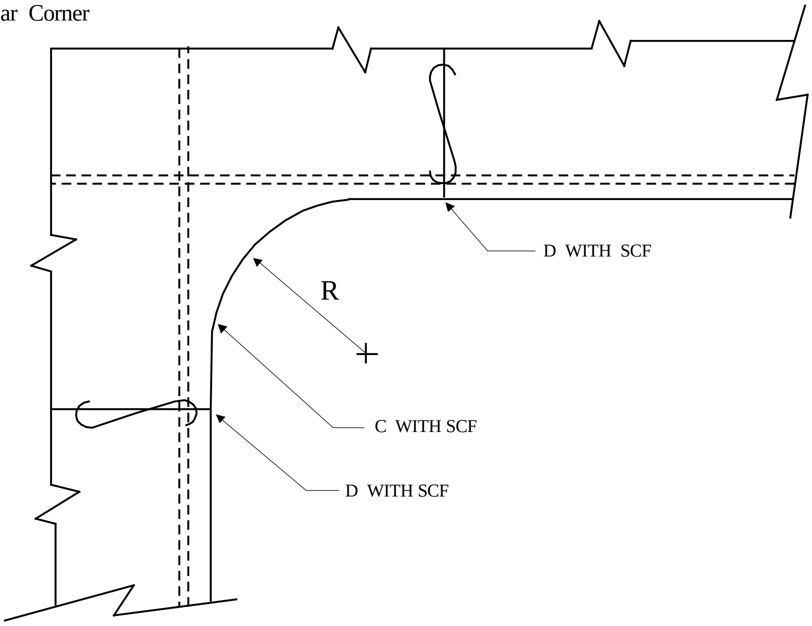


TABLE 2 (continued)
Welded Joint with Two or More Load Carrying Members

d Hatch Corners

Circular Corner



Double Curvature

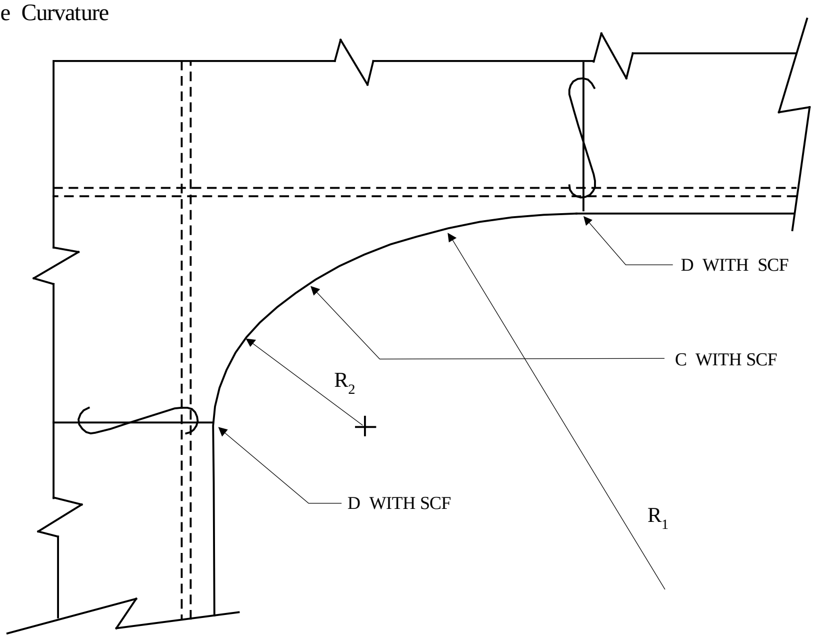


TABLE 2 (continued)
Welded Joint with Two or More Load Carrying Members

Cut-out Radius

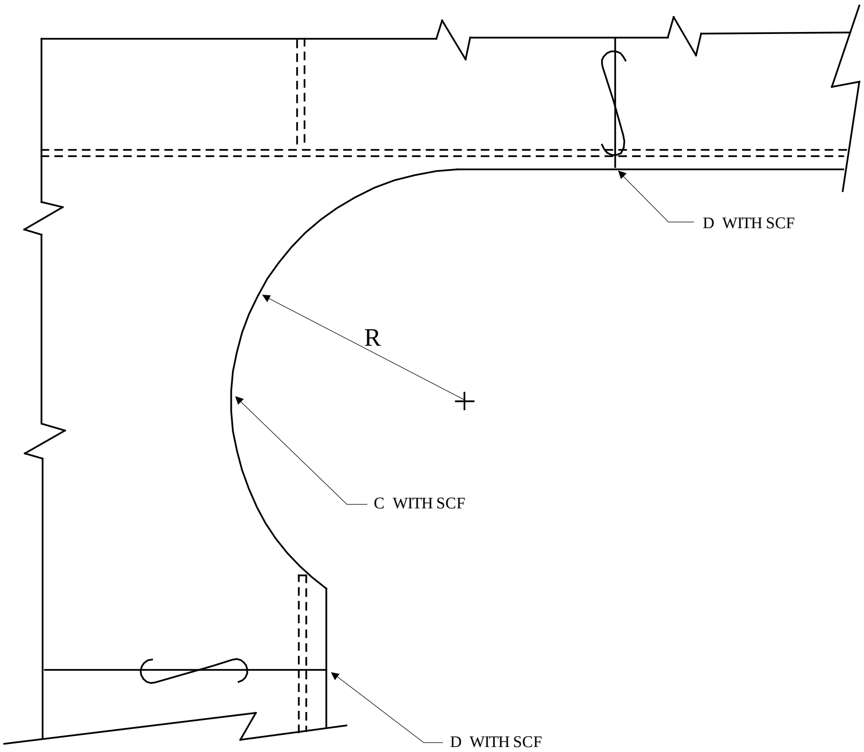
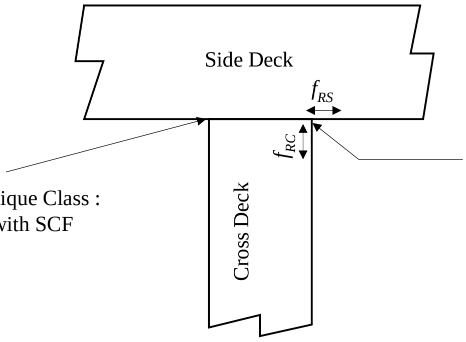


TABLE 2 (continued)
Welded Joint with Two or More Load Carrying Members

End Connections at Lower Deck



or
Fatique Class :
E with SCF

Fatique Class: F_2

$f_R = \alpha\,(f_{RS}^2 + f_{RC}^2)^{1/2}$

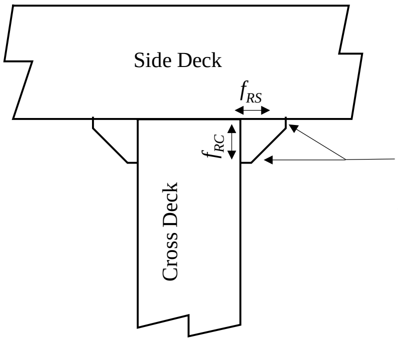
where $\alpha = 1.25$

$f_{RS} = C_f(f_{RG1} + f_{RL1})$

$f_{RC} = C_f(f_{RG2} + f_{RL2})$

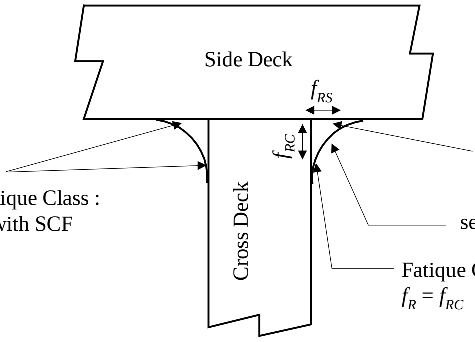
f_{RG1}, f_{RL1}, f_{RG2} and f_{RL2} are as specified in 5C-5-A1/9.5.1 of the *Steel Vessel Rules*

C_f is defined in 5C-5-A1/7.5.1 of the *Steel Vessel Rules*



Fatique Class: F_2

$f_R = (f_{RS}^2 + f_{RC}^2)^{1/2}$



or
Fatique Class :
E with SCF

Fatique Class: F
$f_R = f_{RS}$

see 5C-5-A1/9.5.1 of the *Steel Vessel Rules*

Fatique Class: F
$f_R = f_{RC}$

Note: Thickness of brackets is to be not less than that of cross deck plating in the same location (level).

For fitting of cell guide, no cut nor welding to the brackets is allowed.

5 Fatigue Damage Calculation

5.1 Assumptions

The fatigue damage of a structural detail under the loads specified here is to be evaluated using the criteria contained in this Subsection. The key assumptions employed are listed below for guidance.

- A linear cumulative damage model (i.e., Palmgren-Miner's Rule) has been used in connection with the S-N data in Appendix 1, Figure 1 (extracted from Ref. 1*).

  * Ref. 1: "Offshore Installations: Guidance on Design, Construction and Certification", Department of Energy, U.K., Fourth Edition - 1990, London: HMSO

- Cyclic stresses due to the loads in Subsection A1/9 have been used and the effects of mean stress have been ignored.
- The target design life of the vessel is taken to be 20 years.
- The long-term stress ranges on a detail can be characterized by using a modified Weibull probability distribution parameter (γ).
- Structural details are classified and described in Appendix 1, Table 1, "Fatigue Classification for Structural Details".

The structural detail classification in Appendix 1, Table 1 is based on joint geometry and direction of the dominant load. Where the loading or geometry is too complex for a simple classification, a finite element analysis of the details is to be carried out to determine the stress concentration factors. Subsection A1/11 contains guidance on finite element analysis modeling to determine stress concentration factors for weld toe locations that are typically found at longitudinal stiffener end connections.

5.3 Criteria

The fatigue damage, D_f, obtained using the criteria in A1/5.7, is to be not greater than 0.8.

5.5 Long Term Stress Distribution Parameter, γ

The long-term stress distribution parameter, γ, can be determined as below.

$$\gamma = \alpha\left(1.1 - 0.35\frac{L-100}{300}\right)$$

where

α = 1.0 for deck structures, including side shell and longitudinal bulkhead structures within 0.1D from the deck

= 1.05 for bottom structures, including inner bottom and side shell, and longitudinal bulkhead structures within 0.1D from the bottom

= 1.1 for side shell and longitudinal bulkhead structures within the region of 0.25D upward and 0.3D downward from the mid-depth

= 1.1 for transverse bulkhead structures

α may be linearly interpolated for side shell and longitudinal bulkhead structures between 0.1D and 0.25D from the deck, and between 0.1D and 0.2D from the bottom.

L and D are the vessel's length and depth, as defined in 3-1-1/3.1 and 3-1-1/7 of the *Steel Vessel Rules*.

5.7 Fatigue Damage

The cumulative fatigue damage, D_f, is to be taken as

$$D_f = \frac{1}{6}\alpha_s \alpha_w \left(D_{f\_12} + D_{f\_34}\right) + \frac{1}{3}D_{f\_56} + \frac{1}{3}D_{f\_78} \le 0.8$$

where

α_s = fatigue damage factor due to hull girder springing. α_s is the ratio of the fatigue damage of a flexible hull girder and that of a rigid body hull girder due to wave induced vertical bending moment in head or rear seas. If the effect of hull girder springing is ignored, α_s is equal to 1.0. For a flexible hull girder structure, α_s is greater than 1.0. α_s is to be determined based on well documented experimental data or analytical studies. When these direct calculations are not available, α_s may be conservatively taken as 1.3.

α_w = fatigue damage factor due to hull girder whipping. α_w is the ratio of the fatigue damage of a flexible hull girder and that of a rigid body hull girder due to wave induced vertical bending moment in head or rear seas. If the effect of hull girder whipping is ignored, α_w is equal to 1.0. For a flexible hull girder structure, α_w is greater than 1.0. α_w is to be determined based on well documented experimental data or analytical studies. When these direct calculations are not available, α_w may be conservatively taken as 1.3.

D_{f_12}, D_{f_34}, D_{f_56} and D_{f_78} are the fatigue damage accumulated due to load case pairs 1 & 2, 3 & 4, 5 & 6 and 7 & 8, respectively (see Subsection A1/7 for load case pairs).

Assuming the long term distribution of stress ranges follow the Weibull distribution, the fatigue damage accumulated due to load pair *jk* is

$$D_{f\_jk} = \frac{N_T}{K_2}\frac{\left(k_t k_h f_{R\_jk}\right)^m}{\left(\ln N_R\right)^{m/\gamma}}\mu_{jk}\Gamma\left(1 + \frac{m}{\gamma}\right)$$

where

N_T = number of cycles in the design life.

= $\dfrac{f_0 D_L}{4\log L}$

f_0 = 0.85, factor for net time at sea

D_L = design life in seconds, 6.31×10^8 for a design life of 20 years

L = ship length defined in 3-1-1/3.1 of the *Steel Vessel Rules*

m, K_2 = S-N curve parameters as defined in Appendix 1, Figure 1 of the Guide

f_{R_jk} = stress range of load case pair *jk* at the representative probability level of 10^{-4}, in kgf/cm^2

k_t = thickness correction factor

= $\left(\dfrac{t}{22}\right)^n$ for $t \ge 22$ mm, where t is the plate thickness

= 1 for $t < 22$ mm

n = 0.20 for a transverse butt weld with its upper and lower edges as built or ground to 1C

= 0.10 for a transverse butt weld with its upper and lower edges ground with a radius of 3 ~ 5 mm. The extent of the grinding is to be 100 mm forward and aft of the butt weld as shown in Section 5, Figure 1.

= 0.10 for hatch corner insert plate away from the welds. The upper and lower edges are ground with a radius of 3 ~ 5 mm

k_h = correction factor for higher-strength steel, applicable to parent material only

= 1.000 for mild steel or welded connections

= 0.926 for H32 steel

= 0.885 for H36 steel

= 0.870 for H40 steel

= 0.850 for H47 steel

N_R = 10000, number of cycles corresponding to the probability level of 10^{-4}

γ = long-term stress distribution parameter as defined in A1/5.5

Γ = Complete Gamma function

$$\mu_{jk} = 1 - \left\{ \frac{\Gamma_0\left(1 + \frac{m}{\gamma}, \nu_{jk}\right) - \nu_{jk}^{-\Delta m/\gamma}\,\Gamma_0\left(1 + \frac{m + \Delta m}{\gamma}, \nu_{jk}\right)}{\Gamma\left(1 + \frac{m}{\gamma}\right)} \right\}$$

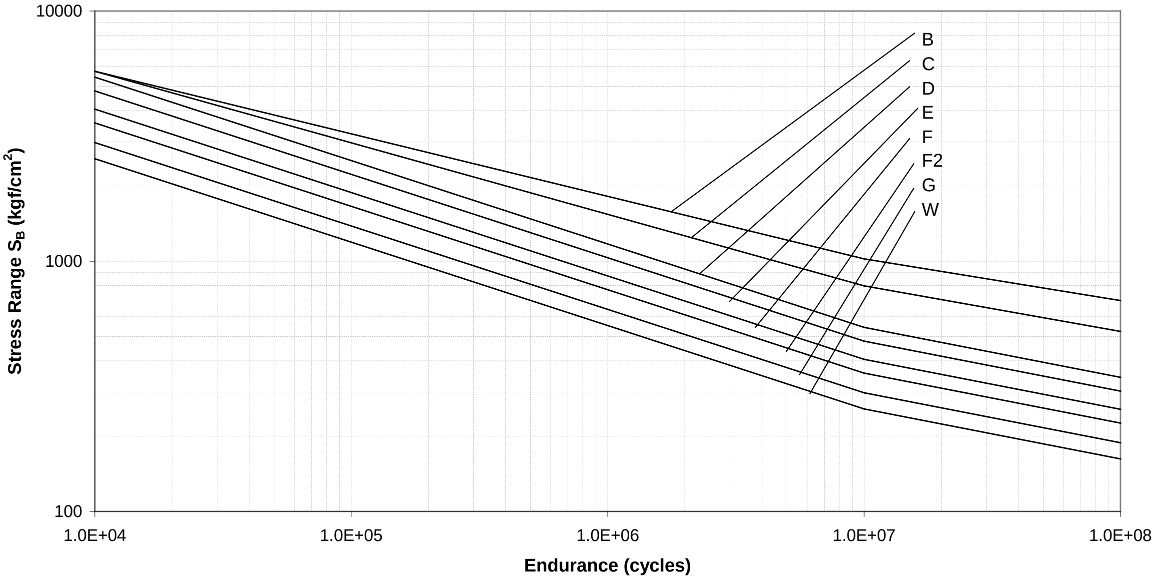
$$\nu_{jk} = \left(\frac{f_q}{f_{R\_jk}}\right)^{\gamma} \ln N_R$$

f_q = stress range at the intersection of the two segments of the S-N curve

Δm = 2, slope change of the upper-lower segment of the S-N curve

$\Gamma_0(\,)$ = incomplete Gamma function, Legendre form

FIGURE 1
Basic Design S-N Curves



Notes for Figure 1:

Basic design S-N curves

The basic design curves consist of linear relationships between $\log(S_B)$ and $\log(N)$. They are based upon a statistical analysis of appropriate experimental data and may be taken to represent two standard deviations below the mean line. Thus the basic S-N curves are of the form:

$$\log(N) = \log(K_2) - m\log(S_B)$$

where

$\log(K_2)$ = $\log(K_1) - 2\sigma$

N = predicted number of cycles to failure under stress range S_B;

K_1 = a constant relating to the mean S-N curve;

σ = standard deviation of $\log N$;

m = inverse slope of the S-N curve.

The relevant values of these terms are shown in the table below and stress range is in kgf/cm^2. The S-N curves have a change of inverse slope from m to $m + 2$ at $N = 10^7$ cycles.

Class	K_1	$\log_{10} K_1$	m	σ	K_2	$\log_{10} K_2$
B	2.521×10^{19}	19.4016	4.0	0.1821	1.09×10^{19}	19.0374
C	3.660×10^{17}	17.5635	3.5	0.2041	1.43×10^{17}	17.1553
D	4.225×10^{15}	15.6258	3.0	0.2095	1.61×10^{15}	15.2068
E	3.493×10^{15}	15.5432	3.0	0.2509	1.10×10^{15}	15.0414
F	1.825×10^{15}	15.2614	3.0	0.2183	6.68×10^{14}	14.8248
F_2	1.302×10^{15}	15.1148	3.0	0.2279	4.56×10^{14}	14.6590
G	6.051×10^{14}	14.7818	3.0	0.1793	2.65×10^{14}	14.4232
W	3.978×10^{14}	14.5996	3.0	0.1846	1.70×10^{14}	14.2304

7 Fatigue Inducing Loads and Load Combination Cases

7.1 General

This Subsection provides: 1) the criteria to define the individual load components considered to cause fatigue damage in the upper flange of a container carrier hull structure (see A1/7.3); 2) the load combination cases to be considered for the upper flange of the hull structure containing the structural detail being evaluated (see A1/7.5).

7.3 Wave-induced Loads

The fluctuating load components to be considered are those induced by the seaway. They are divided into the following three groups:

- Hull girder wave-induced vertical bending moment
- Hull girder wave-induced horizontal bending moment
- Hull girder wave-induced torsional moment

7.5 Combinations of Load Cases for Fatigue Assessment

A container loading condition is considered in the calculation of stress range. For this loading condition, eight (8) load cases, as shown in Appendix 1, Table 3, are defined to form four (4) pairs. The combinations of load cases are to be used to find the characteristic stress range corresponding to a probability of exceedance of 10^{-4}, as indicated below.

TABLE 3
Combined Load Cases for Fatigue Strength Formulation

	L.C. 1	*L.C. 2*	*L.C. 3*	*L.C. 4*	*L.C. 5*	*L.C. 6*	*L.C. 7*	*L.C. 8*
Wave Induced Vertical Bending Moment	Sag 100%	Hog 100%	Sag 70%	Hog 70%	Sag 30%	Hog 30%	Sag 40%	Hog 40%
Wave Induced Horizontal Bending Moment	0.0	0.0	0.0	0.0	Stbd Tens 30%	Port Tens 30%	Stbd Tens 50%	Port Tens 50%
Wave Induced Torsional Moment	0.0	0.0	0.0	0.0	(–) 55%	(+) 55%	(–) 100%	(+) 100%
Wave Heading Angle	Head & Follow	Head & Follow	Head & Follow	Head & Follow	Beam	Beam	Oblique	Oblique

Notes:

1 Wave induced vertical bending moment is defined in 5C-5-3/5.1.1 of the *Steel Vessel Rules.*

2 Wave induced horizontal bending moment is defined in 5C-5-3/5.1.3 of the *Steel Vessel Rules.*

3 Wave induced torsional moment and sign convention are defined in 5C-5-3/5.1.5 of the *Steel Vessel Rules.*

7.5.1 Standard Load Combination Cases

7.5.1(a) Calculate dynamic component of stresses for load cases LC1 through LC8, respectively.

7.5.1(b) Calculate four sets of stress ranges, one each for the following four pairs of combined loading cases.

LC1 and LC2,

LC3 and LC4,

LC5 and LC6, and

LC7 and LC8

7.5.2 Vessels with Either Special Loading Patterns or Special Structural Configuration

For vessels with either special loading patterns or special structural configurations/features, additional load cases may be required for determining the stress range.

9 Determination of Wave Induced Stress Range

9.1 General

This Subsection contains information on fatigue inducing stress range to be used in the fatigue assessment.

Where, for a particular example shown, no specific value of SCF is given when one is called for, it indicates that a finite element analysis is needed. When the fine mesh finite element approach is used, additional information on calculations of stress concentration factors and the selection of compatible S-N data is given in Subsection A1/11.

9.3 Hatch Corners

9.3.1 Hatch Corners at Decks and Coaming Top

The peak stress range, f_R, for hatch corners at the strength deck, the top of the continuous hatch side coaming and the lower decks which are effective for the hull girder strength may be approximated by the following equation:

$$f_R = 0.5^{1/\gamma} \times c_f\,(K_{s1}c_{L1}f_{RG1} + K_{s2}c_{L2}\,f_{RG2}) \quad \text{N/cm}^2\ (\text{kgf/cm}^2,\ \text{lbf/in}^2)$$

where

f_{RG1} = global dynamic longitudinal stress range at the inboard edge of the strength deck, top of continuous hatch side coaming and lower deck of hull girder section under consideration clear of hatch corner, in N/cm^2 (kgf/cm^2, lbf/in^2)

= $|f_{d1vi} - f_{d1vj}| + |f_{d1hi} - f_{d1hj}| + |f_{d1wi} - f_{d1wj}|$

f_{RG2} = bending stress range in connection with hull girder twist induced by torsion in cross deck structure in transverse direction, in N/cm^2 (kgf/cm^2, lbf/in^2)

= $|f_{d1ci} - f_{d1cj}|$

c_f = adjustment factor to reflect a mean wasted condition

= 1.05

f_{d1vi}, f_{d1vj} = wave-induced component of the primary stresses produced by hull girder vertical bending, in N/cm^2 (kgf/cm^2, lbf/in^2), for load case *i* and *j* of the selected pairs of combined load cases, respectively. For this purpose, k_w is to be taken as $(1.09 + 0.029V - 0.47C_b)^{1/2}$ in calculating M_w (sagging and hogging) in 5C-5-3/5.1.1 of the *Steel Vessel Rules*

f_{d1hi}, f_{d1hj} = wave-induced component of the primary stresses produced by hull girder horizontal bending, in N/cm^2 (kgf/cm^2, lbf/in^2), for load case *i* and *j* of the selected pairs of combined load cases, respectively. See 5C-5-3/5.1.3 of the *Steel Vessel Rules*

f_{d1wi}, f_{d1wj} = wave-induced component of the primary stresses produced by hull girder torsion (warping stress) moment, in N/cm^2 (kgf/cm^2, lbf/in^2), for load case *i* and *j* of the selected pairs of combined load cases, respectively. See 5C-5-3/5.1.5 of the *Steel Vessel Rules*. The warping stress values in the longitudinal and transverse directions are to be taken at 1/8th of the 40-foot container bay length from the hatch opening corner.

For calculating the wave induced stresses, sign convention is to be observed for the respective directions of wave-induced loads, as specified in Appendix 1, Table 3. These wave-induced stresses are to be determined based on the gross ship scantlings (A1/1.7).

f_{d1v} and f_{d1h} may be calculated by a simple beam approach. f_{d1w} in way of hatch corners at strength deck, top of continuous hatch side coaming and lower deck may be determined from the full ship finite element model.

γ is as defined in A1/5.5.

K_{s1} and K_{s2} are stress concentration factors for the hatch corners considered and can be obtained by a direct finite element analysis. When a direct analysis is not available, these may be obtained from the following equations, but not to be taken less than 1.0:

$$K_{s1} = c_t \alpha_{t1} \alpha_c \alpha_s k_{s1}$$

$$K_{s2} = \alpha_{ct} \alpha_{t2} k_{s2}$$

where

k_{s1} = nominal stress concentration factor in longitudinal direction, as given in the table below

k_{s2} = nominal stress concentration factor in transverse direction, as given in the table below

c_t = 0.8 for locations where coaming top terminates

= 1.0 for other locations

α_c = adjustment factor for cutout at hatch corners

= 1.0 for shapes without cutout

= $[1 - 0.04(c/R)^{3/2}]$ for circular shapes with a cutout

= $[1 - 0.04(c/r_d)^{3/2}]$ for double curvature shapes with a cutout

= $[1 - 0.04(c/R_1)^{3/2}]$ for elliptical shapes with a cutout

α_s = adjustment factor for contour curvature

= 1.0 for circular shapes

= $0.33[1 + 2(r_{s1}/r_d) + 0.1(r_d/r_{s1})^2]$ for double curvature shapes

= $0.33[1 + 2(R_2/R_1) + 0.1(R_1/R_2)^2]$ for elliptical shapes

α_{ct} = 1.0 for shapes without cutout

= 0.5 for shapes with cutout

α_{t1} = $(t_s/t_i)^{1/2}$

α_{t2} = $6.0/[5.0 + (t_i/t_c)]$, but not less than 0.85

α_{t1} or α_{t2} is to be taken as 1.0 where longitudinal or transverse extent of the reinforced plate thickness in way of the hatch corner is less than that required in A1/9.3.3, as shown in Appendix 1, Figure 2.

r_{s1} = R for circular shapes in Appendix 1, Figure 3, in mm (in.)

= $[3R_1/(R_1 - R_2) + \cos\theta]r_{e2}/[3.816 + 2.879R_2/(R_1 - R_2)]$ for double curvature shapes in Appendix 1, Figure 4, in mm (in.)

= R_2 for elliptical shapes in Appendix 1, Figure 5, in mm (in.)

r_{s2} = R for circular shapes in Appendix 1, Figure 3, in mm (in.)

= R_2 for double curvature shapes in Appendix 1, Figure 4, in mm (in.)

= R_2^2/R_1 for elliptical shapes in Appendix 1, Figure 5, in mm (in.)

r_d = $(0.753 - 0.72R_2/R_1)[R_1/(R_1 - R_2) + \cos\theta]r_{e1}$

t_s = plate thickness of the strength deck, hatch side coaming top or lower deck clear of the hatch corner under consideration, in mm (in.)

t_c = plate thickness of the cross deck, hatch end coaming top or bottom of cross box beam clear of the hatch corner under consideration, in mm (in.)

t_i = plate thickness of the strength deck, hatch coaming top or lower deck in way of the hatch corner under consideration, in mm (in.)

R, R_1 and R_2 for each shape are as shown in Appendix 1, Figures 3, 4 and 5.

θ for double curvature shapes is defined in Appendix 1, Figure 4.

r_{e1} and r_{e2} are also defined for double curvature shapes in A1/9.3.3.

r_{e1} = R for circular shapes in Appendix 1, Figure 3, in mm (in.)

= $R_2 + (R_1 - R_2)\cos\theta$ for double curvature shapes in Appendix 1, Figure 4, in mm (in.)

= $(R_1 + R_2)/2$ for elliptical shapes in Appendix 1, Figure 5, in mm (in.)

r_{e2} = R for circular shapes in Appendix 1, Figure 3, in mm (in.)

= $R_1 - (R_1 - R_2)\sin\theta$ for double curvature shapes in Appendix 1, Figure 4, in mm (in.)

= R_2 for elliptical shapes in Appendix 1, Figure 5, in mm (in.)

k_{s1}

r_{s1}/w_1	0.1	0.2	0.3	0.4	0.5
k_{s1}	1.945	1.89	1.835	1.78	1.725

k_{s2}

r_{s2}/w_2	0.1	0.2	0.3	0.4	0.5
k_{s2}	2.35	2.20	2.05	1.90	1.75

Note: k_{s1} and k_{s2} may be obtained by interpolation for intermediate values of r_{s1}/w_1 or r_{s2}/w_2.

where

w_1 = transverse width of the cross deck under consideration, in mm (in.), for hatch corners of the strength deck and lower deck

= $0.1b_1$ for width of cross deck that is not constant along hatch length

w_2 = longitudinal width of the cross deck under consideration, in mm (in.), for strength deck and lower deck

b_1 = width of the hatch opening under consideration, in mm (in.)

K_{s1} and K_{s2} for hatch corners with configurations other than that specified in this Appendix are to be determined from fine mesh finite element analysis.

The angle ϕ in degrees along the hatch corner contour is defined as shown in Appendix 1, Figures 3, 4 and 5 and c_{L1} and c_{L2} at a given ϕ may be obtained by the following equations. For determining the maximum f_R, c_{L1} and c_{L2} are to be calculated at least for 5 locations, i.e., at $\phi = \phi_1$, ϕ_2 and three intermediate angles for each pair of the combined load cases considered.

- For circular shapes, $25 \le \phi \le 55$

  c_{L1} = $1 - 0.00045(\phi - 25)^2$

  c_{L2} = $0.8 - 0.0004(\phi - 55)^2$

- For double curvature shapes, $\phi_1 \le \phi \le \phi_2$

  c_{L1} = $[1.0 - 0.02(\phi - \phi_1)]/[1 - 0.015(\phi - \phi_1) + 0.00014(\phi - \phi_1)^2]$ for $\theta < 55$

  = $[1.0 - 0.026(\phi - \phi_1)]/[1 - 0.03(\phi - \phi_1) + 0.0012(\phi - \phi_1)^2]$ for $\theta \ge 55$

  c_{L2} = $0.8/[1.1 + 0.035(\phi - \phi_2) + 0.003(\phi - \phi_2)^2]$

  where

  ϕ_1 = $\mu(95 - 70r_{s1}/r_d)$
  ϕ_2 = $95/(0.6 + r_{s1}/r_d)$
  μ = $0.165(\theta - 25)^{1/2}$ for $\theta < 55$
  = 1.0 for $\theta \ge 55$

- For elliptical shapes, $\phi_1 \le \phi \le \phi_2$

  c_{L1} = $1 - 0.00004(\phi - \phi_1)^3$

  c_{L2} = $0.8/[1 + 0.0036(\phi - \phi_2)^2]$

  where

  ϕ_1 = $95 - 70R_2/R_1$

  ϕ_2 = $88/(0.6 + R_2/R_1)$

The peak stress range, f_R, is to be obtained through calculations of c_{L1} and c_{L2} at each ϕ along a hatch corner.

The formulas for double curvature shapes and elliptical shapes may be applicable to the following range:

$0.3 \le R_2/R_1 \le 0.6$ and $45° \le \theta \le 80°$ for double curvature shapes

For hatch coaming top and longitudinal deck girders, R_2/R_1 may be reduced to 0.15.

$0.3 \le R_2/R_1 \le 0.9$ for elliptical shapes

9.3.2 Hatch Corners at the End Connections of Longitudinal Deck Girder

The total stress range, f_R, for hatch corners at the connection of longitudinal deck girder with cross deck box beam may be approximated by the following equation:

$$f_R = 0.5^{1/\gamma} \times c_f(\alpha_i K_{d1} f_{RG1} + K_{d2}\, f_{RG2}) \qquad \text{N/cm}^2 \text{ (kgf/cm}^2\text{, lbf/in}^2\text{)}$$

where

f_{RG1} = wave-induced stress range by hull girder vertical and horizontal bending moments and torsional moment at the longitudinal deck girder of hull girder section, in N/cm^2 (kgf/cm^2, lbf/in^2)

= $|f_{d1vi} - f_{d1vj}| + |f_{d1hi} - f_{d1hj}| + |f_{d1wi} - f_{d1wj}|$

f_{RG2} = wave-induced stress range by hull girder torsional moment at the connection of the longitudinal deck girder with the cross deck box beam, in N/cm^2 (kgf/cm^2, lbf/in^2)

= $|f_{d1di} - f_{d1dj}|$

α_i = 1.0 for symmetrical section of the longitudinal deck girder about its vertical neutral axis

= 1.25 for unsymmetrical section of the longitudinal deck girder about its vertical neutral axis

c_f and γ are as defined in A1/9.3.1 and A1/5.5.

f_{d1vi}, f_{d1vj}, f_{d1hi}, f_{d1hj}, f_{d1wi}, and f_{d1wj} are as defined in A1/9.3.1.

K_{d1} and K_{d2} may be obtained from the following equations, but not to be taken less than 1.0:

$K_{d1} = 1.0$

$K_{d2} = \alpha_t \alpha_s k_d$

where

k_d = nominal stress concentration factor as given in the table below

α_s = 1.0 for circular shapes

= $0.33[1 + 2(r_{s1}/r_d) + 0.1(r_d/r_{s1})^2]$ for double curvature shapes

= $0.33[1 + 2(R_2/R_1) + 0.1(R_1/R_2)^2]$ for elliptical shapes

α_t = $(t_d/t_i)^{1/2}$

α_t is to be taken as 1.0 where longitudinal or transverse extent of the reinforced plate thickness in way of the hatch corner is less than that in A1/9.3.3, as shown in Appendix 1, Figure 6.

t_d = flange plate thickness of the longitudinal deck girder clear of the hatch corner under consideration, in mm (in.)

t_i = plate thickness at the end connection of the longitudinal deck girder under consideration, in mm (in.).

R, R_1 and R_2 for each shape are as shown in Appendix 1, Figures 3, 4 and 5.

θ for double curvature shapes is defined in Appendix 1, Figure 4.

r_{s1} and r_d are as defined for double curvature shapes in A1/9.3.1, above.

r_{e1} and r_{e2} are as defined for double curvature shapes in A1/9.3.3, below.

k_d

r_{s1}/w_d	0.1	0.2	0.3	0.4	0.5
k_d	2.35	2.20	2.05	1.90	1.75

Note: k_d may be obtained by interpolation for intermediate values of r_{s1}/w_d.

where

w_d = width of the longitudinal deck girder, in mm (in.)

9.3.3 Extent of Reinforced Plate Thickness at Hatch Corners

Where plating of increased thickness is inserted at hatch corners, the extent of the inserted plate, as shown in Appendix 1, Figures 2 and 6, is to be generally not less than that obtained from the following:

$\ell_i = 1.75 r_{e1}$ mm (in.)

$b_i = 1.75 r_{e2}$ mm (in.)

$b_d = 1.1 r_{e2}$ mm (in.)

for a cut-out radius type,

$\ell_{i1} = 1.75 r_{e1}$ mm (in.)

$\ell_{i2} = 1.0 r_{e1}$ mm (in.)

$b_i = 2.5 r_{e2}$ mm (in.)

$b_d = 1.25 r_{e2}$ mm (in.)

where

r_{e1} = R for circular shapes in Appendix 1, Figure 3, in mm (in.)

= $R_2 + (R_1 - R_2)\cos\theta$ for double curvature shapes in Appendix 1, Figure 4, in mm (in.)

= $(R_1 + R_2)/2$ for elliptical shapes in Appendix 1, Figure 5, in mm (in.)

r_{e2} = R for circular shapes in Appendix 1, Figure 3, in mm (in.)

= $R_1 - (R_1 - R_2)\sin\theta$ for double curvature shapes in Appendix 1, Figure 4, in mm (in.)

= R_2 for elliptical shapes in Appendix 1, Figure 5, in mm (in.)

At welding joints of the inserted plates to the adjacent plates, a suitable transition taper is to be provided and the fatigue assessment at these joints may be approximated by the following:

$f_R = 0.5^{1/\gamma} \times c_f K_t f_s$ N/cm^2 (kgf/cm^2, lbf/in^2)

where

f_s = nominal stress range at the joint under consideration

= f_{RG1} for side longitudinal deck box, as specified in A1/9.3.1, in N/cm^2 (kgf/cm^2, lbf/in^2)

= f_{RG2} for cross deck box beam, as specified in A1/9.3.1, in N/cm^2 (kgf/cm^2, lbf/in^2)

= $f_{RG1} + f_{RG2}$ for longitudinal deck girder, as specified in A1/9.3.2, in N/cm^2 (kgf/cm^2, lbf/in^2)

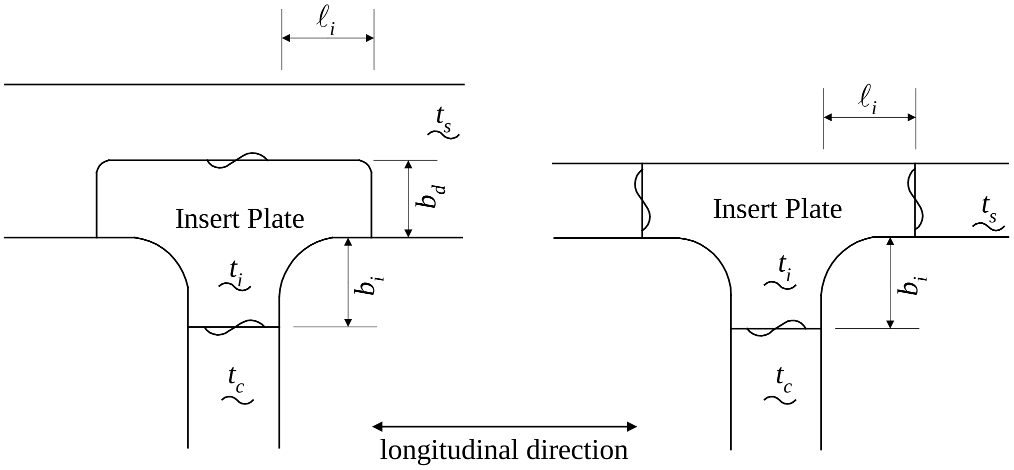
K_t = $0.25(1 + 3t_i/t_a) \le 1.25$

t_i = plate thickness of inserted plate, in mm (in.)

t_a = plate thickness of plate adjacent to the inserted plate, in mm (in.)

c_f and γ are as defined in A1/9.3.1 and A1/5.5.

FIGURE 2
Hatch Corners at Decks and Coaming Top



(Strength Deck & Lower Deck)

(Hatch Coaming Top)

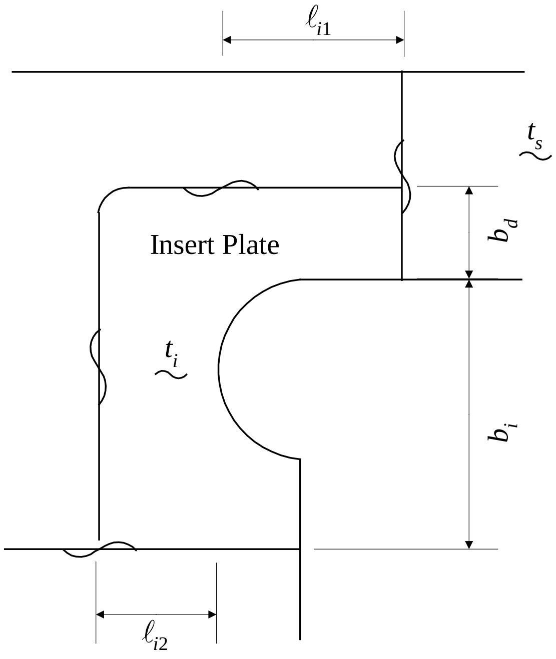
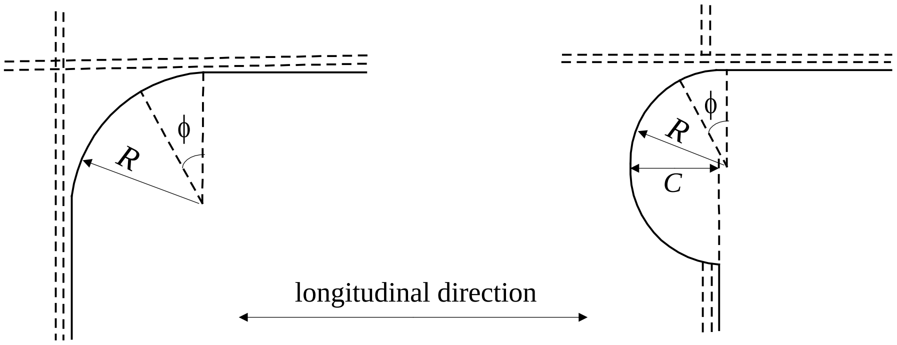


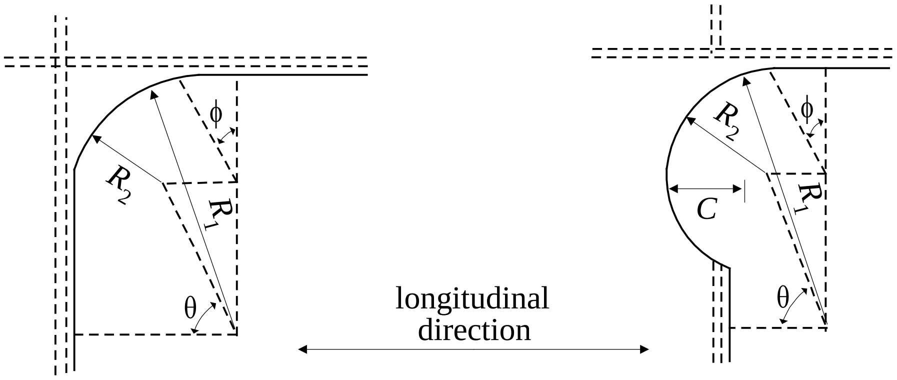
FIGURE 3
Circular Shape



without cutout

with cutout

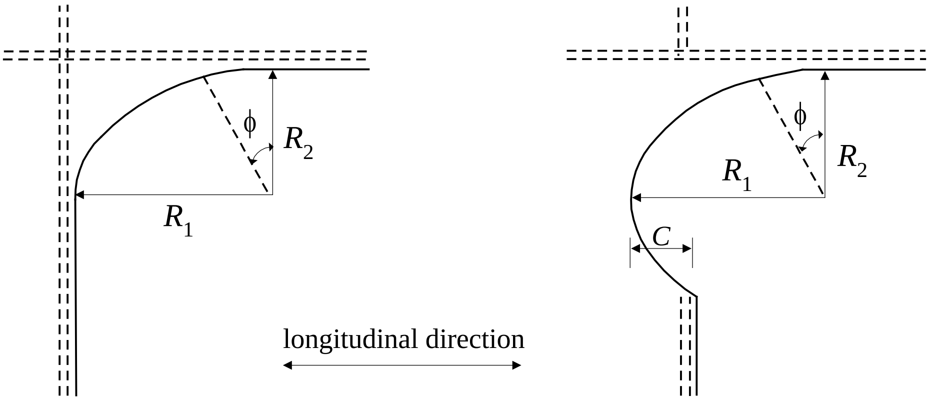
FIGURE 4
Double Curvature Shape



without cutout

with cutout

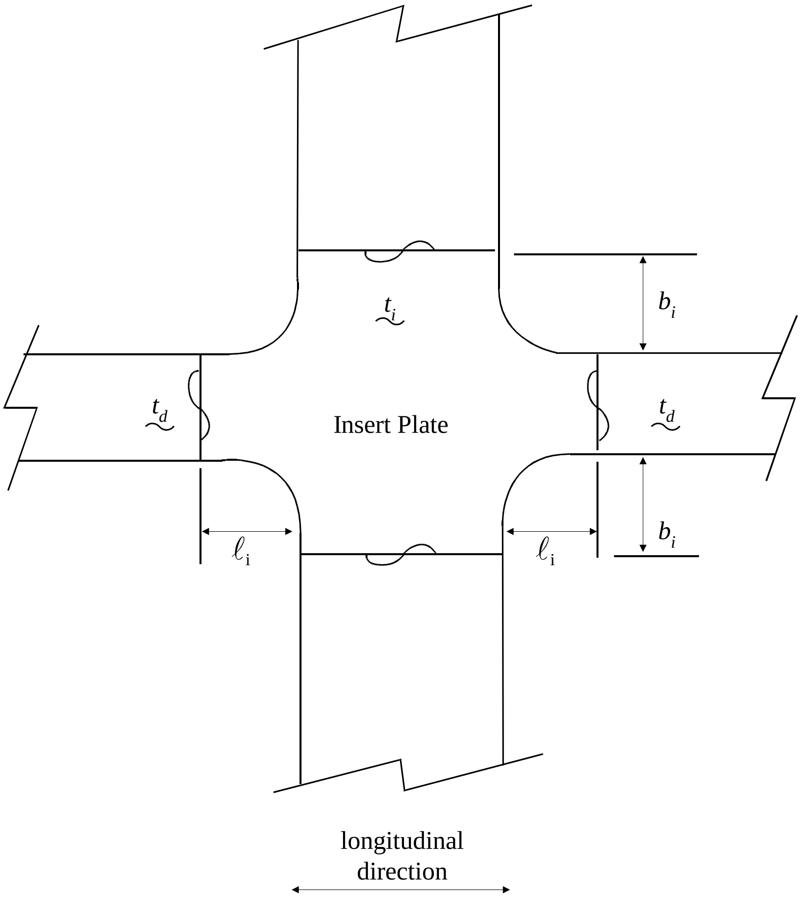
FIGURE 5
Elliptical Shape



without cutout

with cutout

FIGURE 6
Hatch Corner for Longitudinal Deck Girder



11 Hot Spot Stress Approach with Finite Element Analysis

11.1 Introduction

In principle, the fatigue strength of all connections can be assessed with the hot spot stress approach described in this Subsection. However, for some details as indicated in A1/3.3, in lieu of the hot spot stress approach, the nominal stress approach can also be employed to evaluate the fatigue strength.

Hot spot stress is defined as the surface stress at the hot spot. Note that the stress change caused by the weld profile is not included in the hot spot stress, but the overall effect of the connection geometry on the nominal stress is represented. Therefore, in hot spot stress approach, the selection of an S-N curve depends on: 1) weld profile, i.e., existence of weld and weld type (fillet, partial penetration or full penetration); 2) predominant direction of principal stress; and 3) crack locations (toe, root or weld throat).

There are various adjustments (reductions in capacity) that may be required to account for factors such as a lack of corrosion protection (coating) of structural steel and relatively large plate thickness. The imposition of these adjustments on fatigue capacity will be in accordance with ABS practice for vessels.

There are other adjustments that could be considered to increase fatigue capacity above that portrayed by the cited S-N data. These include adjustments for compressive "mean stress" effects, a high compressive portion of the acting variable stress range, and the use of "weld improvement" techniques. The use of a weld improvement technique, such as weld toe grinding or peening to relieve ambient residual stress, can be effective in increasing fatigue life. However, credit should not be taken of such a weld improvement in the design phase of the structure. Consideration for granting credit for the use of weld improvement techniques is to be reserved for situations arising during construction, operation, or future reconditioning of the structure. An exception may be made if the target design fatigue life cannot be satisfied by other preferred design measures such as refining layout, geometry, scantlings and welding profile to minimize fatigue damage due to high stress concentrations. Grinding or ultrasonic peening can be used to improve fatigue life in such cases. The calculated fatigue life is to be greater than 15 years excluding the effects of life improvement techniques. Where improvement techniques are applied, full details of the improvement technique standard including the extent, profile smoothness particulars, final weld profile, and improvement technique workmanship and quality acceptance criteria are to be clearly shown on the applicable drawings and submitted for review together with supporting calculations indicating the proposed factor on the calculated fatigue life.

Grinding is preferably to be carried out by rotary burr and to extend below the plate surface in order to remove toe defects, and the ground area is to have effective corrosion protection. The treatment is to produce a smooth concave profile at the weld toe with the depth of the depression penetrating into the plate surface to at least 0.5 mm below the bottom of any visible undercut. The depth of groove produced is to be kept to a minimum, and, in general, kept to a maximum of 1 mm. In no circumstances is the grinding depth to exceed 2 mm or 7% of the plate gross thickness, whichever is smaller. Grinding has to extend to areas well outside the highest stress region.

The finished shape of a weld surface treated by ultrasonic peening is to be smooth, and all traces of the weld toe are to be removed. Peening depths below the original surface are to be maintained to at least 0.2 mm. Maximum depth is generally not to exceed 0.5 mm.

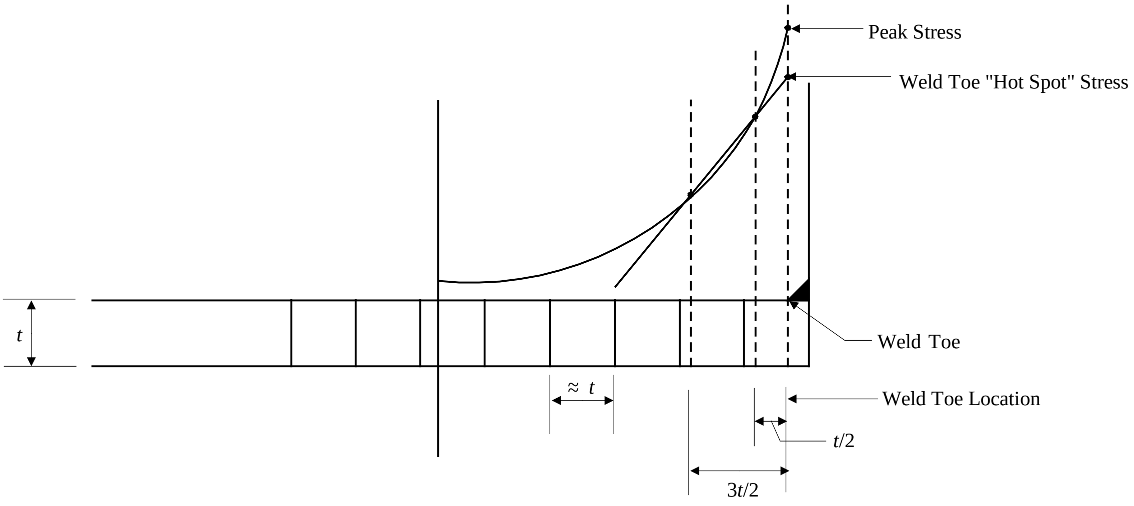
Provided these recommendations are followed, an improvement in fatigue life by grinding or ultrasonic peening up to a maximum of 2 times may be granted.

11.3 Calculation of Hot Spot Stress at a Weld Toe

Appendix 1, Figure 7 shows an acceptable method which can be used to extract and interpret the “near weld toe” element dynamic stress ranges (refer to as stresses for convenience in the following text in this Subsection) and to obtain a (linearly) extrapolated stress (dynamic stress range) at the weld toe. When plate or shell elements are used in the modeling, it is recommended that each element size is to be equal to the plate thickness.

Weld hot spot stress can be determined from linear extrapolation of surface component stresses at $t/2$ and $3t/2$ from weld toe. The principal stresses at hot spot are then calculated based on the extrapolated stresses and used for fatigue evaluation. Description of the numerical procedure is given below.

FIGURE 7



The algorithm described in the following is applicable to obtain the hot spot stress for the point at the toe of a weld. The weld typically connects either a flat bar member or a bracket to the flange of a longitudinal stiffener, as shown in Appendix 1, Figure 8.

Consider the four points, P_1 to P_4, measured by the distances X_1 to X_4 from the weld toe, designated as the origin of the coordinate system. These points are the centroids of four neighboring finite elements, the first of which is adjacent to the weld toe. Assuming that the applicable surface component stresses (or dynamic stress ranges), S_i, at P_i have been determined from FEM analysis, the corresponding stresses at "hot spot" (i.e., the stress at the weld toe) can be determined by the following procedure:

11.3.1

Select two points, *L* and *R*, such that points *L* and *R* are situated at distances $t/2$ and $3t/2$ from the weld toe; i.e.:

$$X_L = t/2, \qquad X_R = 3t/2$$

where *t* denotes the thickness of the member to which elements 1 to 4 belong (e.g., the flange of a longitudinal stiffener).

11.3.2

Let $X = X_L$ and compute the values of four coefficients, as follows:

$$C_1 = [(X - X_2)(X - X_3)(X - X_4)] / [(X_1 - X_2)(X_1 - X_3)(X_1 - X_4)]$$

$$C_2 = [(X - X_1)(X - X_3)(X - X_4)] / [(X_2 - X_1)(X_2 - X_3)(X_2 - X_4)]$$

$$C_3 = [(X - X_1)(X - X_2)(X - X_4)] / [(X_3 - X_1)(X_3 - X_2)(X_3 - X_4)]$$

$$C_4 = [(X - X_1)(X - X_2)(X - X_3)] / [(X_4 - X_1)(X_4 - X_2)(X_4 - X_3)]$$

The corresponding stress at Point *L* can be obtained by interpolation as:

$$S_L = C_1S_1 + C_2\,S_2 + C_3\,S_3 + C_4\,S_4$$

11.3.3

Let $X = X_R$ and repeat the step in A1/11.3.2 to determine four new coefficients. The stress at Point *R* can be interpolated likewise, i.e.:

$$S_R = C_1S_1 + C_2\,S_2 + C_3\,S_3 + C_4\,S_4$$

11.3.4

The corresponding stress at hot spot, S_0, is given by

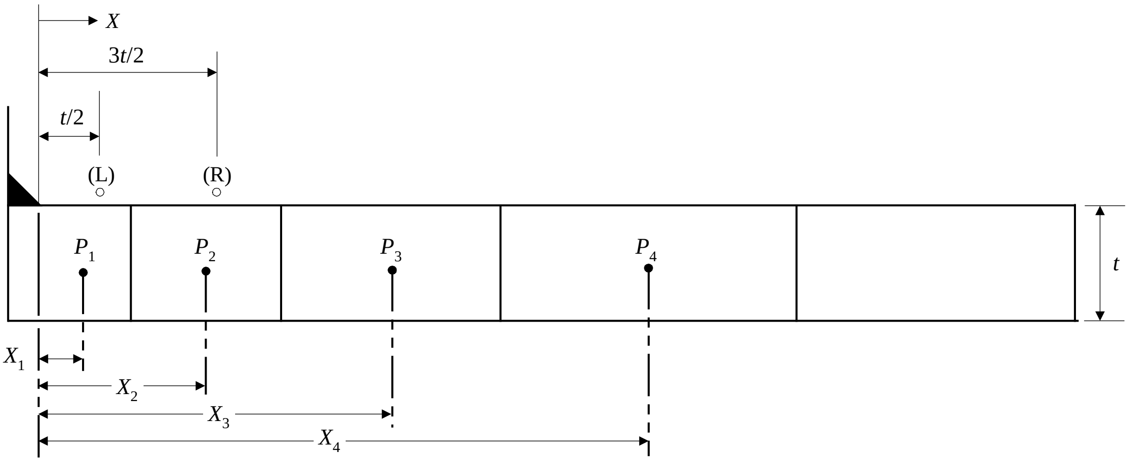
$$S_0 = (3S_L - S_R)/2$$

Notes:

The algorithm presented in the foregoing involves two types of operations. The first is to utilize the stress values at the centroid of the four elements considered to obtain estimates of stress at Points *L* and *R* by way of an interpolation algorithm known as Lagrange interpolation. The second operation is to make use of the stress estimates, S_L and S_R, to obtain the hot spot stress via linear extrapolation.

While the Lagrange interpolation is applicable to any order of polynomial, it is not advisable to go beyond the 3rd order (cubic). Also, the even order polynomials are biased, so that leaves the choice between a linear scheme and a cubic scheme. Therefore, the cubic interpolation, as described in A1/11.3.2, should be used. It can be observed that the coefficients, C_1 to C_4 are all cubic polynomials. It is also evident that, when $X = X_j$, which is not equal to X_i, all of the *C*'s vanish except C_i, and if $X = X_i$, $C_i = 1$.

FIGURE 8



11.5 Calculation of Hot Spot Stress at the Edge of Cut-out or Bracket

In order to determine the hot spot stress at the edge of cut-out or bracket, dummy rod elements can be attached to the edge. The sectional area of the dummy rod may be set at 0.01cm^2. The mesh needs to be fine enough to determine the local stress concentration due to the geometry change. The axial stress range of the dummy rod is to be used to assess the fatigue strength of the cut-out or bracket (edge crack).

APPENDIX 2 Hull Girder Residual Strength

1 General

The residual strength of the hull structure is to be verified with the fatigue cracking assumption that the coaming top and side plates are ineffective at individual cross sections.

3 Vertical Hull Girder Residual Limit State

The vertical hull girder residual bending capacity is to satisfy the following limit state equation:

$$\gamma_S M_{sw} + \gamma_W M_w \le \frac{M_R}{\gamma_R}$$

where

M_{sw} = still water bending moment, in kN-m (tf-m), in accordance with 3-2-1/3.3 of the *Steel Vessel Rules*

M_w = maximum wave-induced bending moment, in kN-m (tf-m), in accordance with 5C-5-3/5.1.1 of the *Steel Vessel Rules* for container carriers. For container carriers with $k_w = 1.0$ for wave hogging bending moment and $k_w = 1.84 – 0.56C_b$ for wave sagging bending moment

M_R = vertical hull girder residual bending capacity with hatch coaming top and side plates ineffective, in kN-m (tf-m), as defined in the following Subsection

γ_S = 1.0 partial safety factor for the still water bending moment

γ_w = 1.1 partial safety factor for the vertical wave bending moment covering environmental and wave load prediction uncertainties

γ_R = 1.0 partial safety factor for the vertical hull girder bending capacity covering material, geometric and strength prediction uncertainties

5 Vertical Hull Girder Residual Bending Moment Capacity

5.1 General

The vertical residual bending moment capacities of a hull girder section, in hogging and sagging conditions, are defined as the maximum values (positive M_{UH}, negative M_{US}) on the static non-linear bending moment-curvature relationship M-κ, see Appendix 2, Figure 1. The curve represents the progressive collapse behavior of hull girder under vertical bending. Hull girder failure is controlled by buckling, ultimate strength, and yielding of longitudinal structural elements. The curvature of the critical inter-frame section κ, is defined as:

$$\kappa = \frac{\theta}{\ell} \quad \text{m}^{-1}$$

where,

θ = relative angle rotation of the two neighboring cross-sections at transverse frame positions

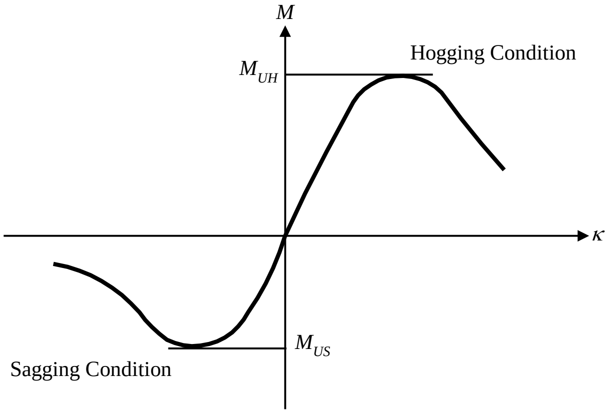
ℓ = transverse frame spacing, in m, i.e., span of longitudinals

The method for calculating the residual hull girder capacity is to identify the critical failure modes of all main longitudinal structural elements.

Assuming the hatch coaming top and side plates are ineffective, the remaining longitudinal structural members in the upper flange compressed beyond their buckling limit have reduced load carrying capacity. All relevant failure modes for individual structural elements, such as plate buckling, torsional stiffener buckling, stiffener web buckling, lateral or global stiffener buckling; and their interactions, are to be considered in order to identify the weakest inter-frame failure mode.

The effects of shear force, torsional loading, horizontal bending moment and lateral pressure are neglected.

FIGURE 1
Bending Moment – Curvature Curve M-κ



5.3 Physical Parameters

For the purpose of describing the calculation procedure in a concise manner, the physical parameters and units used in the calculation procedure are given below.

5.3.1 Hull Girder Load and Cross Section Properties

M_i = hull girder bending moment, in kN-m (tf-m)

F_i = hull girder longitudinal force, in kN (tf)

I_v = hull girder moment of inertia, in m^4

SM = hull girder section modulus assuming hatch coaming top and side plates ineffective, in m^3

SM_{dk} = elastic hull girder section modulus at deck at side, in m^3

SM_{kl} = elastic hull girder section modulus at bottom, in m^3

κ = curvature of the ship cross section, in m^{-1}

z_j = distance from baseline, in m

5.3.2 Material Properties

σ_{yd} = specified minimum yield stress of the material, in N/cm^2 (kgf/cm^2)

E = Young's modulus for steel, 2.06×10^7 N/cm^2 (2.1×10^6 kgf/cm^2)

ν = Poisson's ratio, may be taken as 0.3 for steel

Φ = edge function as defined in A2/5.9.2

ε = relative strain defined in A2/5.9.2

5.3.3 Stiffener Sectional Properties

The properties of a longitudinal's cross section are shown in Appendix 2, Figure 2.

A_s = sectional area of the longitudinal or stiffener, excluding the associated plating, in cm^2

b_1 = smaller outstanding dimension of flange with respect to centerline of web, in cm

b_f = total width of the flange/face plate, in cm

d_w = depth of the web, in cm

t_p = net thickness of the plating, in cm

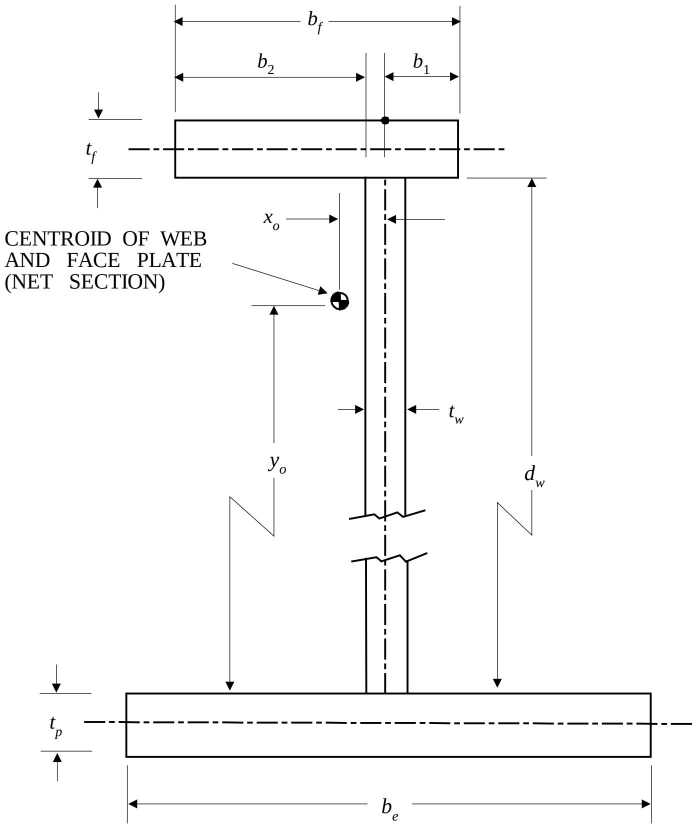
t_f = net thickness of the flange/face plate, in cm

t_w = net thickness of the web, in cm

x_o = distance between centroid of the stiffener and centerline of the web plate, in cm (see Appendix 2, Figure 2)

y_o = distance between the centroid of the stiffener and the attached plate, in cm (see Appendix 2, Figure 2)

FIGURE 2
Dimensions and Properties of Stiffeners



5.5 Calculation Procedure

The ultimate hull girder bending moment capacity M_U is defined as the peak value of the curve with vertical bending moment M versus the curvature κ of the ship cross section as shown in Appendix 2, Figure 1.

The curve M-κ is obtained by means of an incremental-iterative approach; the steps involved in the procedure are given below.

The bending moment M_i which acts on the hull girder transverse section due to the imposed curvature κ_i is calculated for each step of the incremental procedure. This imposed curvature corresponds to an angle of rotation of the hull girder transverse section about its effective horizontal neutral axis, which induces an axial strain ε in each hull structural element.

The stress σ induced in each structural element by the strain ε is obtained from the stress-strain curve σ-ε of the element, which takes into account the behavior of the structural element in the non-linear elasto-plastic domain.

The force in each structural element is obtained from its area times the stress and these forces are summated to derive the total axial force on the transverse section. Note the element area is taken as the total net area of the structural element. This total force may not be zero as the effective neutral axis may have moved due to the non-linear response. Hence it is necessary to adjust the neutral axis position, recalculate the element strains, forces and total sectional force, and iterate until the total force is zero.

Once the position of the new neutral axis is known, then the correct stress distribution in the structural elements is obtained. The bending moment M_i about the new neutral axis due to the imposed curvature κ_i is then obtained by summating the moment contribution given by the force in each structural element.

The main steps of the incremental-iterative approach are summarized as follows:

Step 1 Divide the hull girder transverse section into structural elements, i.e., longitudinal stiffened panels (one stiffener per element), hard corners and transversely stiffened panels, see A2/5.7.

Step 2 Derive the stress-strain curves (or so called load-end shortening curves) for all structural elements, see A2/5.9.

Step 3 Derive the expected maximum required curvature κ_F. The curvature step size $\Delta\kappa$ is to be taken as $\kappa_F/300$. The curvature for the first step, κ_1 is to be taken as $\Delta\kappa$.

Derive the neutral axis $z_{NA\text{-}i}$ for the first incremental step ($i = 1$) with the value of the elastic hull girder section modulus, see 3-2-1/9 of the *Steel Vessel Rules*.

Step 4 For each element (index j), calculate the strain $\varepsilon_{ij} = \kappa_i\ (z_j - z_{NA\text{-}i})$ corresponding to κ_i, the corresponding stress σ_j, and hence the force in the element $\sigma_j A_j$. The stress σ_j corresponding to the element strain ε_{ij} is to be taken as the minimum stress value from all applicable stress-strain curves σ-ε for that element.

Step 5 Determine the new neutral axis position $z_{NA\text{-}i}$ by checking the longitudinal force equilibrium over the whole transverse section. Hence adjust z_{NA_i} until

$$F_i = 10^{-3}\ \Delta A_j \sigma_j = 0$$

Note σ_j is positive for elements under compression and negative for elements under tension. Repeat from Step 4 until equilibrium is satisfied. Equilibrium is satisfied when the change in neutral axis position is less than 0.0001 m.

Step 6 Calculate the corresponding moment by summating the force contributions of all elements as follows:

$$M_i = 10^{-3} \sum \sigma_j A_j \left| \left(z_j - z_{NA-i} \right) \right|$$

Step 7 Increase the curvature by $\Delta\kappa$, use the current neutral axis position as the initial value for the next curvature increment and repeat from step 4 until the maximum required curvature is reached. The residual capacity is the peak value M_u from the M-κ curve. If the peak does not occur in the curve, then κ_F is to be increased until the peak is reached

The expected maximum required curvature κ_F is to be taken as:

$$\kappa_F = 3\frac{\max(SM_{dk}\sigma_{yd}, SM_{kl}\sigma_{yd})}{EI_v}$$

5.7 Assumptions and Modeling of the Hull Girder Cross-Section

In applying the procedure described in Appendix 2, the following assumptions are to be made:

i) The residual strength is calculated at a hull girder transverse section between two adjacent transverse webs.

ii) The hull girder transverse section remains plane during each curvature increment.

iii) The material properties of steel are assumed to be elastic, perfectly plastic.

iv) The hull girder transverse section can be divided into a set of elements which act independently of each other.

v) The elements making up the hull girder transverse section are:

- Longitudinal stiffeners with attached plating, the structural behavior is given in A2/5.9.2, A2/5.9.3, A2/5.9.4, A2/5.9.5, and A2/5.9.6
- Transversely stiffened plate panels, the structural behavior is given in A2/5.9.7
- Hard corners, as defined below, the structural behavior is given in A2/5.9.1

vi) The following structural areas are to be defined as hard corners:

- The plating area adjacent to intersecting plates
- The plating area adjacent to knuckles in the plating with an angle greater than 30 degrees.
- Plating comprising rounded gunwales

vii) An illustration of hard corner definition for girders on longitudinal bulkheads is given in Appendix 2, Figure 3.

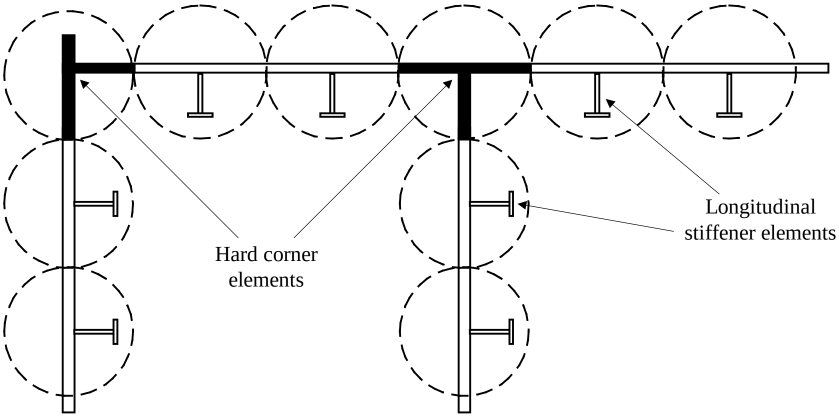
viii) The size and modeling of hard corner elements is to be as follows:

- It is to be assumed that the hard corner extends up to $s/2$ from the plate intersection for longitudinally stiffened plate, where s is the stiffener spacing
- It is to be assumed that the hard corner extends up to $20t_{grs}$ from the plate intersection for transversely stiffened plates, where t_{grs} is the gross plate thickness.

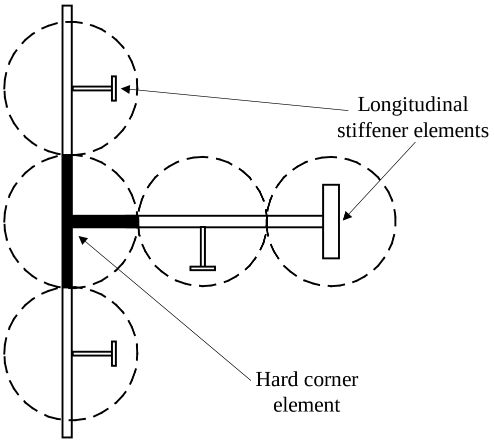
Note: For transversely stiffened plate, the effective breadth of plate for the load shortening portion of the stress-strain curve is to be taken as the full plate breadth, i.e., to the intersection of other plates – not from the end of the hard corner. The area is to be taken as the breadth between the intersecting plates.

FIGURE 3
Example of Defining Structural Elements

a) Example showing side shell, inner side and deck



b) Example showing girder on longitudinal bulkhead



5.9 Stress-strain Curves σ-ε (or Load-end Shortening Curves)

5.9.1 Hard Corners

Hard corners are sturdier elements which are assumed to buckle and fail in an elastic, perfectly plastic manner. The relevant stress strain curve σ-ε is to be obtained for lengthened and shortened hard corners according to A2/5.9.2.

5.9.2 Elasto-Plastic Failure of Structural Elements

The equation describing the stress-strain curve σ-ε or the elasto-plastic failure of structural elements is to be obtained from the following formula, valid for both positive (compression or shortening) of hard corners and negative (tension or lengthening) strains of all elements (see Appendix 2, Figure 4):

$$\sigma = \Phi\ \sigma_{yd} \quad \text{kN/cm}^2\ (\text{kgf/cm}^2)$$

where

Φ = edge function

= -1 for $\varepsilon < -1$

= ε for $-1 < \varepsilon < 1$

= 1 for $\varepsilon > 1$

ε = relative strain

= $\dfrac{\varepsilon_E}{\varepsilon_{yd}}$

ε_E = element strain

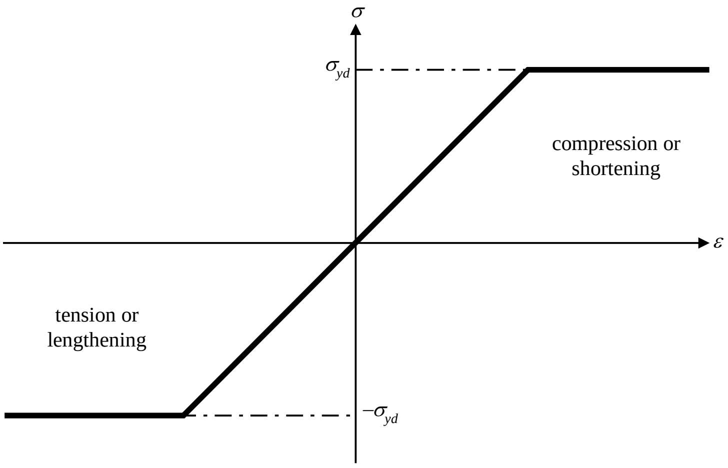
ε_{yd} = strain corresponding to yield stress in the element

= $\dfrac{\sigma_{yd}}{E}$

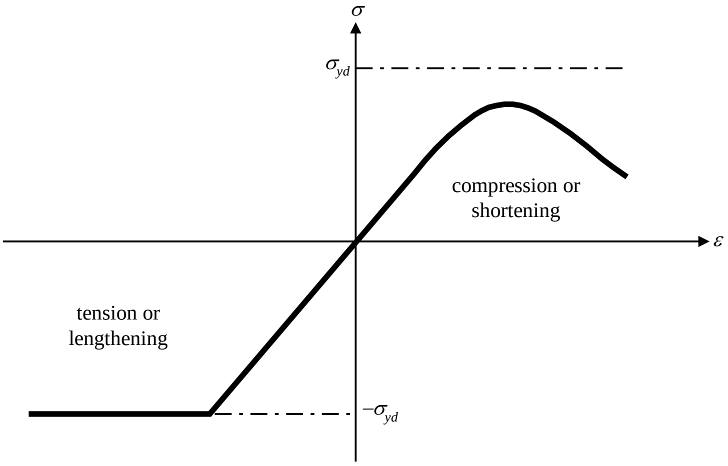
Note: The signs of the stresses and strains in this Appendix are opposite to those in the rest of the Guide.

FIGURE 4
Example of Stress Strain Curves σ-ε

a) Stress strain curve σ-ε for elastic, perfectly plastic failure of a hard corner



b) Typical stress strain curve σ-ε for elasto-plastic failure of a stiffener



5.9.3 Beam Column Buckling

The equation describing the shortening portion of the stress strain curve σ_{CR1}-ε for the beam column buckling of stiffeners is to be obtained from the following formula:

$$\sigma_{CR1} = \Phi \sigma_{C1} \left(\frac{A_s + b_{eff-p} t_p}{A_s + s t_p} \right) \quad \text{kN/cm}^2 \text{ (kgf/cm}^2\text{)}$$

where

σ_{C1} = critical stress in kN/cm^2 (kgf/cm^2)

= $\dfrac{\sigma_{E1}}{\varepsilon}$ for $\sigma_{E1} \le \dfrac{\sigma_{yd}}{2}\varepsilon$

= $\sigma_{yd}\left(1 - \dfrac{\sigma_{yd}\varepsilon}{4\sigma_{E1}}\right)$ for $\sigma_{E1} > \dfrac{\sigma_{yd}}{2}\varepsilon$

σ_{E1} = Euler column buckling stress in kN/cm^2 (kgf/cm^2)

= $\pi^2 E \dfrac{I_E}{A_E \ell^2}$

ℓ = unsupported span of the longitudinal, in cm

s = plate breadth taken as the spacing between the stiffeners, in cm

I_E = net moment of inertia of stiffeners, in cm^4, with attached plating of width b_{eff-s}

b_{eff-s} = effective width, in cm, of the attached plating for the stiffener

= $\dfrac{s}{\beta_p}$ for $\beta_p > 1.0$

= s for $\beta_p \le 1.0$

β_p = $\dfrac{s}{t_p}\sqrt{\dfrac{\varepsilon \sigma_{yd}}{E}}$

A_E = net area of stiffeners, in cm^2, with attached plating of width b_{eff-p}

b_{eff-p} = effective width, in cm, of the plating

= $\left(\dfrac{2.25}{\beta_p} - \dfrac{1.25}{\beta_p^2}\right)s$ for $\beta_p > 1.25$

= s for $\beta_p \le 1.25$

5.9.4 Torsional Buckling of Stiffeners

The equation describing the shortening portion of the stress-strain curve σ_{CR2}-ε for the lateral-flexural buckling of stiffeners is to be obtained according to the following formula:

$$\sigma_{CR2} = \Phi \left(\frac{A_s \sigma_{C2} + s t_p \sigma_{CP}}{A_s + s t_p} \right) \quad \text{kN/cm}^2 \text{ (kgf/cm}^2\text{)}$$

where

σ_{C2} = critical stress

= $\dfrac{\sigma_{E2}}{\varepsilon}$ for $\sigma_{E2} \leq \dfrac{\sigma_{yd}}{2}\varepsilon$

= $\sigma_{yd}\left(1 - \dfrac{\sigma_{yd}\varepsilon}{4\sigma_{E2}}\right)$ for $\sigma_{E2} > \dfrac{\sigma_{yd}}{2}\varepsilon$

σ_{CP} = ultimate strength of the attached plating for the stiffener

= $\left(\dfrac{2.25}{\beta_p} - \dfrac{1.25}{\beta_p^2}\right)\sigma_{yd}$ for $\beta_p > 1.25$

= σ_{yd} for $\beta_p \leq 1.25$

β_p = coefficient defined in A2/5.9.3

σ_{E2} = Euler torsional buckling stress in kN/cm^2 (kgf/cm^2), equal to reference stress for torsional buckling σ_{ET}

σ_{ET} = $E[K/2.6 + (n\pi/\ell)^2\Gamma + C_o(\ell/n\pi)^2/E]/I_o[1 + C_o(\ell/n\pi)^2/I_o f_{cL}]$

K = St. Venant torsion constant for the longitudinal's cross section, excluding the associated plating

= $\left[b_f t_f^3 + d_w t_w^3\right]/3$

I_o = polar moment of inertia of the longitudinal, excluding the associated plating, about the toe (intersection of web and plating)

= $I_x + mI_y + A_s\left(x_o^2 + y_o^2\right)$ in cm^4

I_x, I_y = moment of inertia of the longitudinal about the x- and y-axis, respectively, through the centroid of the longitudinal, excluding the plating (x-axis perpendicular to the web), in cm^4

m = $1.0 - u(0.7 - 0.1d_w/b_f)$

u = unsymmetry factor

= $1 - 2b_1/b_f$

C_o = $E t_p^3/3s$

Γ = warping constant

≅ $mI_{yf}\, d_w^2 + d_w^3\, t_w^3/36$

I_{yf} = $t_f\, b_f^3\, (1.0 + 3.0\, u^2 d_w t_w/A_s)/12$

f_{cL} = critical buckling stress for the associated plating, corresponding to n-half waves

= $\pi^2 E(n/\alpha + \alpha/n)^2(t_p/s)^2/12(1 - \nu^2)$

α = ℓ/s

ℓ = unsupported span of the longitudinal, in cm

s = plate breadth taken as the spacing between the stiffeners, in cm

n = number of half-wave which yield a smallest σ_{ET}

5.9.5 Web Local Buckling of Stiffeners with Flanged Profiles

The equation describing the shortening portion of the stress strain curve σ_{CR3}-ε for the web local buckling of flanged stiffeners is to be obtained from the following formula:

$$\sigma_{CR3} = \Phi\sigma_{yd}\left(\frac{b_{eff-p}t_p + d_{w-eff}t_w + b_f t_f}{st_p + d_w t_w + b_f t_f}\right) \quad \text{kN/cm}^2\ (\text{kgf/cm}^2)$$

where

s = plate breadth taken as the spacing between the stiffeners, in cm

$b_{eff\text{-}p}$ = effective width of the attached plating in cm, defined in A2/5.9.3

$d_{w\text{-}eff}$ = effective depth of the web in cm

$$= \left(\frac{2.25}{\beta_w} - \frac{1.25}{\beta_w^2}\right)d_w \qquad \text{for } \beta_w > 1.25$$

$$= d_w \qquad \text{for } \beta_w \le 1.25$$

$$\beta_w = \frac{d_w}{t_w}\sqrt{\frac{\varepsilon\sigma_{yd}}{E}}$$

5.9.6 Local Buckling of Flat Bar Stiffeners

The equation describing the shortening portion of the stress-strain curve σ_{CR4}-ε for the web local buckling of flat bar stiffeners is to be obtained from the following formula:

$$\sigma_{CR4} = \Phi\left(\frac{A_s\sigma_{C4} + st_p\sigma_{CP}}{A_s + st_p}\right) \quad \text{kN/cm}^2\ (\text{kgf/cm}^2)$$

where

σ_{CP} = ultimate strength of the attached plating in kN/cm^2 (kgf/cm^2)

σ_{C4} = critical stress in kN/cm^2 (kgf/cm^2)

$$= \frac{\sigma_{E4}}{\varepsilon} \qquad \text{for } \sigma_{E4} \le \frac{\sigma_{yd}}{2}\varepsilon$$

$$= \sigma_{yd}\left(1 - \frac{\sigma_{yd}\varepsilon}{4\sigma_{E4}}\right) \qquad \text{for } \sigma_{E4} > \frac{\sigma_{yd}}{2}\varepsilon$$

σ_{E4} = Euler buckling stress

$$= \frac{0.44\pi^2 E}{12(1-\nu^2)}\left(\frac{t_w}{d_w}\right)^2$$

5.9.7 Buckling of Transversely Stiffened Plate Panels

The equation describing the shortening portion of the stress-strain curve σ_{CR5}-ε for the buckling of transversely stiffened panels is to be obtained from the following formula:

$$\sigma_{CR5} = \min\begin{cases} \sigma_{yd}\Phi\left[\dfrac{s}{\ell_{stf}}\left(\dfrac{2.25}{\beta_p} - \dfrac{1.25}{\beta_p^2}\right) + 0.115\left(1 - \dfrac{s}{\ell_{stf}}\right)\left(1 + \dfrac{1}{\beta_p^2}\right)^2\right] \\ \sigma_{yd}\Phi \end{cases} \quad \text{kN/cm}^2\ (\text{kgf/cm}^2)$$

where

β_p = coefficient defined in A2/5.9.3

β_0 = $\frac{s}{t}\sqrt{\frac{\sigma_{yd}}{E}}$

s = plate breadth taken as the spacing between the stiffeners, in cm

ℓ_{stf} = span of stiffener equal to spacing between primary support members, in cm