Requirements for

Application of Higher-Strength Hull Structural Thick Steel Plates in Container Carriers

ABS

July 2024

REQUIREMENTS FOR

APPLICATION OF HIGHER-STRENGTH HULL STRUCTURAL THICK STEEL PLATES IN CONTAINER CARRIERS
JULY 2024

American Bureau of Shipping
Incorporated by Act of Legislature of
the State of New York 1862

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Foreword *(1 July 2024)*

Over the last several decades, the drive for increasingly efficient sea-borne container transportation has led to significant growth in the size of container carriers. Application of hull structural thick steel plates in the upper flange of large container carriers is a natural choice for the hull structure to meet the required hull girder strength. Steel plates well in excess of 50 mm (2 in.) in thickness are commonly found in large container carriers. More recently, one significant technical innovation 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 (47 kgf/mm^2, 67 ksi) (H47), as well as the application of brittle crack arrest steel. Higher-strength thick steel plates have been designed and applied to upper deck region* longitudinal structural members including the topmost strakes of the inner hull or bulkhead, the sheer strake, main deck, hatch coaming side plate, coaming top plate, and all attached longitudinal stiffeners.

Note: *The upper deck region is defined as the upper deck plating, hatch side coaming plating, hatch coaming top plating, and their attached longitudinals.

In addition to the ABS *Rules for Building and Classing Marine Vessels (Marine Vessel Rules)*, this document provides supplementary requirements for the application of higher-strength hull structural thick steel plates, greater than 50 mm (2 in.), in large container carriers. For thick steel plates with a minimum yield stress of 390 N/mm^2 (40 kgf/mm^2, 57 ksi) (H40), the requirements reflect a large and successful body of experience with large container carriers in service, considering the first principles structural analysis methodologies and the experience in material, welding, and construction routinely applied to large container carriers. Also, in response to requests from industry for the adoption of H47 steel grade and brittle crack arrest steel, this document provides guidance on the design, construction and operation, of container carriers built with such high strength steel.

This document provides the requirements for the optional notation, **EBCAD** (**E**nhanced **B**rittle **C**rack **A**rrest **D**esign), for the enhanced BCA application of higher-strength hull structural thick steel plates in container carriers.

The January 2021 edition also updated the requirements for H47 steel and brittle crack arrest steel and introduced a new Appendix 8 on engineering critical assessment for hatch coamings.

The February 2021 edition aligned the long-term distribution factor in A1/5.5 with the *Marine Vessel Rules*.

The March 2022 edition aligns the wave bending moment in A2/3 with 5C-5-A4a/3.5.2 of the *Marine Vessel Rules*.

This March 2023 edition introduces optional notations **WIP** and **SPR**, which denote that the strength and fatigue performance of the hull structure is evaluated considering the effects due to whipping and springing, respectively.

The July 2024 version changes the document type from "Guide" to "Requirements". "Requirements" documents contain mandatory criteria for Classification and issuance of Class Certificates, while Guides contain only requirements for optional Notations (see 1A-1-4/1.5 of the ABS *Rules for Conditions of Classification (Part 1A)*). Accordingly, editorial changes are made throughout this document.

The July 2024 version also introduces Goal Based Standards to enable the verification of alternative arrangements, new technologies, and novel concepts. It incorporates the latest updates to IACS UR W31. It also includes updates to improve clarity.

This document becomes effective on the first day of the month of publication.

Users are advised to check periodically on the ABS website www.eagle.org to verify that this version is the most current.

We welcome your feedback. Comments or suggestions can be sent electronically by email to rsd@eagle.org.

REQUIREMENTS FOR

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

CONTENTS

SECTION 1
Introduction

1 General *(1 July 2024)*

This document describes supplementary requirements for the application of higher-strength hull structural steel plates with or without specified brittle crack arrest (BCA) properties in container carriers with regards to the following:

- Hull structural design with higher-strength thick steel plates
- Requirements for H47 Non-BCA steels (H47 steels without specified BCA properties)
- Requirements for H36/H40/H47 BCA steels (H36/H40/H47 steels with specified BCA properties)
- Welding and fabrication of higher-strength thick H47 Non-BCA and BCA steel plates
- Prevention of fatigue and fracture failure of higher-strength thick steel plates

These requirements for 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 Marine Vessels (Marine 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 the two most pertinent failure mechanisms. When the hull girder strength is designed to meet 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. Three areas of focus are:

- In the upper flange of the hull structure, wave-induced fatigue damages in way of thick plated weld connections – As a countermeasure, the fatigue behavior of these weld connections is to be extensively evaluated to avoid initial crack initiation.
- The presence of planar flaws in thick plated weld connections – This 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.
- Survey after construction – It is to be enhanced through monitoring critical areas and nondestructive inspection.

3 Application *(1 July 2024)*

For H36/H40 steel grade, the supplementary requirements in the document are applicable to steel plate thicknesses greater than 50 mm (2 in.) and up to 100 mm (4 in.) used in the upper deck region* of a container carrier hull structure.

Note: *The upper deck region is defined as the upper deck plating, hatch side coaming plating, hatch coaming top plating, and their attached longitudinals.

For H47 steel grade, the supplementary requirements in the document are applicable to steel plate thicknesses up to 100 mm (4 in.) used in the upper deck region of a container carrier hull structure.

For H36/H40/H47-BCA steel grades required by Subsection 2/3, the BCA properties are to be in accordance with Subsection 3/5. BCA steels are applicable to steel plates with thicknesses greater than 50 mm (2 in.) and up to 100 mm (4 in.).

The application of steel plates with thicknesses greater than 100 mm (4 in.) is subject to special consideration and approved by Classification Society.

The supplementary requirements and BCA properties requirements in this document are applicable to the Cargo Hold Region.

4 Goal Based Standards *(1 July 2024)*

Due to the rapid adoption of new technology, Goal Based Standards have been incorporated into this document. Goal Based Standards offer a path for class approval for alternative and novel concepts in accordance with the procedure outlined in Chapter 2 of the ABS *Rules for Acceptance of Alternative Arrangements, Novel Concepts and New Technologies (Part 1D)*. Existing class requirements often prescribe a specific technological solution. Since Goal Based Standards do not dictate specific technical solutions, they are better suited to accommodate future technological developments.

The ABS incorporation of Goal Based Standards is based on IMO MSC.Circ.1394, "Generic Guidelines for Developing IMO Goal-Based Standards" and extensive experience with Novel Concepts, New Technology Qualifications, and risk-based methodologies.

5 Notations *(1 March 2023)*

5.1 Enhanced Brittle Crack Arrest Application *(1 July 2024)*

Container carriers built with enhanced BCA application of higher-strength hull structural thick steel plates in compliance with the requirements of 1/5.1 may be distinguished with the optional notation **EBCAD** (**E**nhanced **B**rittle **C**rack **A**rrest **D**esign).

The enhanced BCA application of higher-strength hull structural thick steel plates in container carriers is to be to the satisfaction of ABS with a combination of two or more of the following additional crack prevention/crack arrest measures along the cargo hold region with NDT inspection in accordance with Subsection 5/3:

i) The BCA steels are used for hatch coaming areas (including hatch coaming side plating, top plating, and all attached longitudinal stiffeners) and comply with the requirements in Subsection 2/3.

ii) The BCA design features are used and comply with the requirements in Subsection 2/13.

iii) The crack tip opening displacement (CTOD) weld, enhanced nondestructive test (NDT), and engineering critical assessment (ECA) on hatch coaming areas are used and comply with the requirements in Subsection 2/4.

In addition, the BCA steel is used for deck and hatch coaming side plating along the cargo hold region and complies with the requirements in Subsection 2/3.

Commentary:

The **EBCAD** notation may be granted for other design concepts approved in accordance with Subsection 2/13, if the equivalent enhanced BCA application is to the satisfaction of ABS.

End of Commentary

5.3 Whipping and Springing Assessment *(1 July 2024)*

Whipping and springing phenomena can be critical for large container carriers due to their design characteristics of large openings, high speed, significant bow flare.

The optional **WIP** notation may be granted if the whipping analysis procedure as indicated in the ABS *Guidance Notes on Whipping Assessment for Container Carriers* is satisfied and the following criteria are complied with:

i) Hull Girder Ultimate Strength as indicated in Appendix 5C-5-A2a of the *Marine Vessel Rules*; and

ii) Fatigue Strength in accordance with Appendix A1

The optional **SPR** notation may be granted if the springing analysis procedure as indicated in the ABS *Guidance Notes on Springing Assessment for Container Carriers and Ore Carriers* is satisfied and the following criteria are complied with:

i) Fatigue Strength in accordance with Appendix A1

For container carriers with length in excess of 350 meters (1148 feet), or with upper deck region constructed of H47 grade steel, the notations **WIP** and **SPR** are mandatory.

In this regard, all the supporting data, analysis procedures, and calculated results are to be fully documented and submitted for review.

Commentary:

The **WIP** and **SPR** notations are primarily intended for container carriers, but may also be assigned to other ship types on a case-by-case basis.

End of Commentary

SECTION 2

Hull Structural Design with Higher-Strength Thick Steel Plates

1 Introduction *(1 July 2024)*

1.1 Objective *(1 July 2024)*

1.1.1 Goals

The vessel structure is to be designed, constructed, operated and maintained to:

Goal No.	*Goal*
STRUCTURE (STRU)	
STRU 1	in the intact condition, have sufficient structural strength to withstand the environmental conditions, loading conditions, and operational loads anticipated during the design life.

Materials are to be suitable for the intended application in accordance with the following goals and support the Tier 1 goals as listed above.

Goal No.	*Goal*
MATERIALS (MAT)	
MAT 1	The selected materials' physical, mechanical, and chemical properties are to meet the design requirements appropriate for the application, operating conditions, and environment.

Goals in the cross-referenced Rules are to be met.

1.1.2 Functional Requirements

To achieve the above stated goals, the following functional requirements apply to this Section:

Functional Requirement No.	*Functional Requirements*
STRUCTURE (STRU)	
STRU-FR1	Limit crack initiation and propagation in the hatch coaming and main deck structures.
STRU-FR2	Scantlings are to have sufficient fatigue strength to resist failure when subjected to loads (including whipping and springing) anticipated throughout the service life.
MATERIALS (MAT)	
MAT-FR1	Provide materials with properties and quality appropriate for the location in the hull based on the criticality of the structure and thickness of material.

Functional requirements covered in the cross-referenced Rules are also to be met.

1.1.3 Compliance

A vessel is considered to comply with the goals and functional requirements within the scope of classification when the applicable prescriptive requirements are complied with or when an alternative arrangement has been approved by ABS. Refer to Part 1D, Chapter 2.

1.3 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. Refer to Part 5C, Chapter 5 "Vessels Intended to Carry Containers 130 meters (427 feet) to 450 meters (1476 feet) in Length" of the *Marine 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 *(1 July 2024)*

Steel materials for particular locations are not to be of lower grades than those required by 2/3 TABLE 1 of this document. Material class is given in 3-1-2/3.3 TABLE 2 of the *Marine Vessel Rules*.

The requirements for the selection of BCA steels are detailed in 2/3.7. Following the flowcharts in Subsection 2/15, the process is used to choose BCA steel and/or BCA design for hatch coaming side, top plating, or upper deck plating.

H36/H40/H47-BCA grade steel is to be EH36/EH40/EH47.

FH36/FH40/FH47-BCA grade steel is to be specially considered and agreed by ABS.

3.1 Upper Deck *(2021)*

If the hatch coaming side or top plating along the cargo hold region is grade of H40 with thickness greater than 85 mm (3.4 in.) or H47 with thickness greater than 50 mm (2 in.), BCA1 designation steel is to be used for upper deck plating where the thickness is greater than 50 mm (2 in.) and less than 100 mm (3.15 in.) and the grade of steel is H36 or H40. Use of H47 grade steel in the upper deck is to be specially considered. If the hatch coaming side or top plating is H36, BCA designation steel is not required for the upper deck.

3.3 Hatch Coaming *(2021)*

If the design requires BCA steel in the hatch coaming, and the hatch side or top plating along the cargo hold region is grade of H40 with thickness greater than 85 mm (3.4 in.) or H47 with thickness greater than 50 mm (2 in.), the steel for the hatch coaming side plating along the cargo hold region is to be:

- BCA1 designation steel of grade H40 or H47 for thickness greater than 50 mm (2 in.) and less than 80 mm (3.15 in.).
- BCA2 designation steel of grade H40 or H47 for thickness greater than 80 mm (3.15 in.) and less than 100 mm (4 in.).

Additional requirements for brittle crack arrest design are detailed in Subsection 2/13, including shifting of butt weld, crack arrest insert, crack arrest hole, etc.

For the hatch coaming side plating along the cargo hold region, the application of BCA steel and BCA design can be deferred if the measures in Subsection 2/4 are taken.

Electrogas welding (EGW) is not a high toughness welding method. Strict measures are to be taken if EGW is applied for H47-BCA steel grade, including BCA application for the upper deck, the hatch coaming side, the BCA design in Subsection 2/13, and NDT other than vision on all target block joints.

In the case where H47 steel plates are used for longitudinal structural members in the upper deck region, the steel plates are to be of EH47 grade.

3.5 Additional Arrangements *(2021)*

Additional arrangements can be applied for BCA design, if the owner and designer/shipyard agree.

TABLE 1
Material Grade *(2021)*

Thickness, t mm (in.)	*Material Class*		
	I	*II*	*III*
$t \le 15$ ($t \le 0.60$)	A, AH	A, AH	A, AH
$15 < t \le 20$ ($0.60 < t \le 0.79$)	A, AH	A, AH	B, AH
$20 < t \le 25$ ($0.79 < t \le 0.98$)	A, AH	B, AH	D, DH
$25 < t \le 30$ ($0.98 < t \le 1.18$)	A, AH	D, DH	D, DH
$30 < t \le 35$ ($1.18 < t \le 1.38$)	B, AH	D, DH	E, EH
$35 < t \le 40$ ($1.38 < t \le 1.57$)	B, AH	D, DH	E, EH
$40 < t \le 50$ ($1.57 < t \le 2.00$)	D, DH	E, EH	E, EH
$50 < t \le 70$ ($2.00 < t \le 2.80$)	D, DH	E, EH, EH-BCA	E, EH, EH-BCA
$71 < t \le 100$ ($2.80 < t \le 4.00$)	E, EH, EH-BCA	E, EH, EH-BCA	E, EH, EH-BCA

Notes:

1 Grade D of these plate thicknesses is to be normalized.

2 ASTM A36 steel, otherwise manufactured by an ABS-approved steel mill, tested and certified to the satisfaction of ABS may be used in lieu of Grade A for a thickness up to and including 12.5 mm (0.5 in.) for plate and up to and including 19 mm (0.75 in.) for sections.

3 FH or FH-BCA is to be specially considered and agreed by ABS.

3.7 Selection of Brittle Crack Arrest (BCA) Steels *(1 July 2024)*

The requirement to use BCA designation steel is dependent on the as-built thickness of the hatch coaming top and side plating. Where BCA designation steel is required, the brittle crack arrest steels for upper deck plating and hatch coaming side plating are to comply with Section 2, Table 2 where BCA1 and BCA2 are defined in 3/5.13. When the BCA steels in Section 2, Table 2 are used, the weld joints between the upper deck plating and hatch coaming side plating are required to be partial penetration weld details.

TABLE 2
BCA Steel Requirement in Function of Structural Members and Thickness *(2021)*

Structural Members Plating (1)	*Thickness t, mm (in.)*	*BCA Steel Requirement*
Upper Deck Plating	50 < t ≤ 100 (2.00 < t ≤ 4.00)	Steel grade H36 or H40 with suffix BCA1
Hatch Coaming Side Plating	50 < t ≤ 80 (2.00 < t ≤ 3.15)	Steel grade H40 or H47 with suffix BCA1
	80 < t ≤ 100 (3.15 < t ≤ 4.00)	Steel grade H40 or H47 with suffix BCA2

Note:

1 Excluding their attached longitudinals.

Commentary:

In the vicinity of block joints, alternative weld details may be used for the upper deck plating and hatch coaming side plating as approved by ABS.

End of Commentary

4 Alternative to BCA Materials *(1 July 2024)*

The BCA steel requirement in the hatch coaming side plate and BCA design may be deferred where *i)*, *ii)* and *iii)* are applied:

i) Block-to-block welds and non-staggered block sub-assembly welds are qualified crack tip opening displacement (CTOD) welds, and

ii) Enhanced nondestructive testing (NDT) of welds is applied, which increases the probability of detection by using more sensitive equipment. For example, ultrasonic testing (UT) with multiple probe angles, or phased array ultrasonic testing (PAUT), or time of flight diffraction (TOFD), or a combination of UT and TOFD.

Enhanced UT methods must also be applied for all block-to-block butt joints of all upper deck region longitudinal members in the cargo hold region, including main deck plate, hatch coaming plate, hatch coaming top plate, and all attached longitudinal stiffeners to the hatch coaming.

A suitably sensitive surface NDT method, such as magnetic particle or dye penetrant testing is also to be carried out.

iii) Unless otherwise agreed, acceptance criteria for NDT inspection are to be determined by the designer/shipyard, applying methods such as Engineering Critical Assessment (ECA) (Ref. BS 7910). The ECA procedure is to follow Appendix 7 in this document and is to be submitted for review. The minimum detectable flaw size by the applicable NDE technique is to be determined. This minimum detectable flaw size is to be smaller than the allowable flaw size determined by ECA.

Additional arrangements can be applied for BCA design, if the owner and designer/shipyard agree.

5 Hull Girder Strength

5.1 Hull Girder Section Modulus *(1 July 2024)*

The requirement on hull girder section modulus is given in 5C-1-5/3.1 of the *Marine 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 *Marine Vessel Rules* may be reduced by the material factor Q.

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

where

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

The material factor Q for steel materials is listed in Section 2, Table 3. For steel plates 50 mm (2 in.) and under in thickness, the material factor Q is defined in 3-2-1/5.3 of the *Marine Vessel Rules*. However, for steel plates greater than 50 mm (2 in.) in thickness, the material factor Q for the required section modulus is defined in Section 2, Table 3 with reference to Notes 1 and 2.

5.3 Hull Girder Moment of Inertia *(1 July 2024)*

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

If the upper deck region is constructed of H47 or H40 grade with the reduced material factor Q in Note 1 of Section 2, Table 3, 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.

TABLE 3
Material Factor Q for Determining Required Hull Girder Section Modulus
(1 July 2024)

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 can 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 document

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

3 Thickness greater than 100 mm (4 in.) is subject to special consideration.

5.5 Hull Girder Shearing Strength *(1 July 2024)*

The requirements of hull girder shearing strength are given in 5C-1-5/5 of the *Marine Vessel Rules*. The material factor Q and strength reduction factor S_m for steel materials to be applied are listed in Section 2, Table 4.

TABLE 4
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 *(1 July 2024)*

The requirements of hull girder torsional strength are defined in 5C-1-6/5 of the *Marine Vessel Rules*. The material factor Q and strength reduction factor S_m for steel materials are listed in Section 2, Table 4.

7 Initial Scantling Evaluation *(1 July 2024)*

The requirements of initial scantling evaluation are defined in Sections 5C-1-5 and 5C-1-6 of the *Marine Vessel Rules*. The material factor Q for the hull girder section modulus requirement is listed in Section 2, Table 3. 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 4.

9 Total Strength Assessment *(1 July 2024)*

The requirements for total strength assessment are given in Sections 5C-1-7, 5C-1-8, and 5C-1-9 of the *Marine Vessel Rules*. The strength reduction factor S_m for steel materials to be applied is listed in Section 2, Table 4.

11 Structural Details and Fatigue Strength Assessment *(1 July 2024)*

For the hull structure built with higher-strength thick steel plates of H40 or H47, the following analyses are mandatory. The supporting data, analysis procedures, and calculated results are to be fully documented and submitted to ABS for review.

The fatigue strength of the butt welds and hatch corners in the upper flange of the hull structure is to be assessed. Appendix 1 provides specific guidance on the fatigue strength assessment of these structural details.

The fatigue strength of other structural details such as longitudinal connections of web frames and transverse bulkheads are to be assessed according to the guidance of Section 5C-1-9 “Fatigue Strength Assessment ” of the *Marine Vessel Rules*.

The effects of whipping on the fatigue strength of the upper deck region of the hull structure constructed of higher strength thick plates of H40 or H47 are to be considered. (see A1/5.7).

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

13 Brittle Crack Arrest Design *(1 July 2024)*

Below are examples of proper brittle crack arrest design.

i) Brittle crack arrest steel for the upper deck plating along the cargo hold region is to be used in such a way as to arrest a brittle crack initiating in the coaming and propagating into the structure below.

ii) Where there is a shift between block-to-block butt welds of the hatch coaming and the upper deck (see 5/7.7), the shift is to be 300 mm (12 in.) at minimum.

iii) Where crack arrest holes are provided in way of block-to-block butt welds in the area that the hatch coaming meets the deck weld (see 5/7.3), the fatigue strength of the lower end butt weld is to be assessed. Countermeasures are also to be included for the possibility of a brittle crack initiating in the weld line and propagating into the upper deck or hatch coaming.

iv) Where arrest insert plates of brittle crack arrest steel or weld metal inserts with high crack arrest toughness properties are provided in way of block-to-block butt welds in the area that the hatch coaming meets the deck weld (see 5/7.9), additional countermeasures are to be taken to prevent a brittle crack deviating from the weld line into the hatch coaming or upper deck.

Commentary:

Other design concepts for brittle crack arrest may be approved on a case-by-case basis.

End of Commentary

15 Overall Process for BCA Steel and BCA Design *(2021)*

The overall process to choose BCA steel and BCA design is summarized in the following figures:

- Section 2, Figure 1A: “H36 Steel Grade for Hatch Coaming Side and Top Plating”
- Section 2, Figure 1B: “H40 Steel Grade for Hatch Coaming Side and Top Plating”
- Section 2, Figure 1C: “H47 Steel Grade for Hatch Coaming Side and Top Plating”

FIGURE 1A
Flowchart for BCA Steel/BCA Design – H36 Steel Grade for Hatch Coaming Side and Top Plating *(2021)*

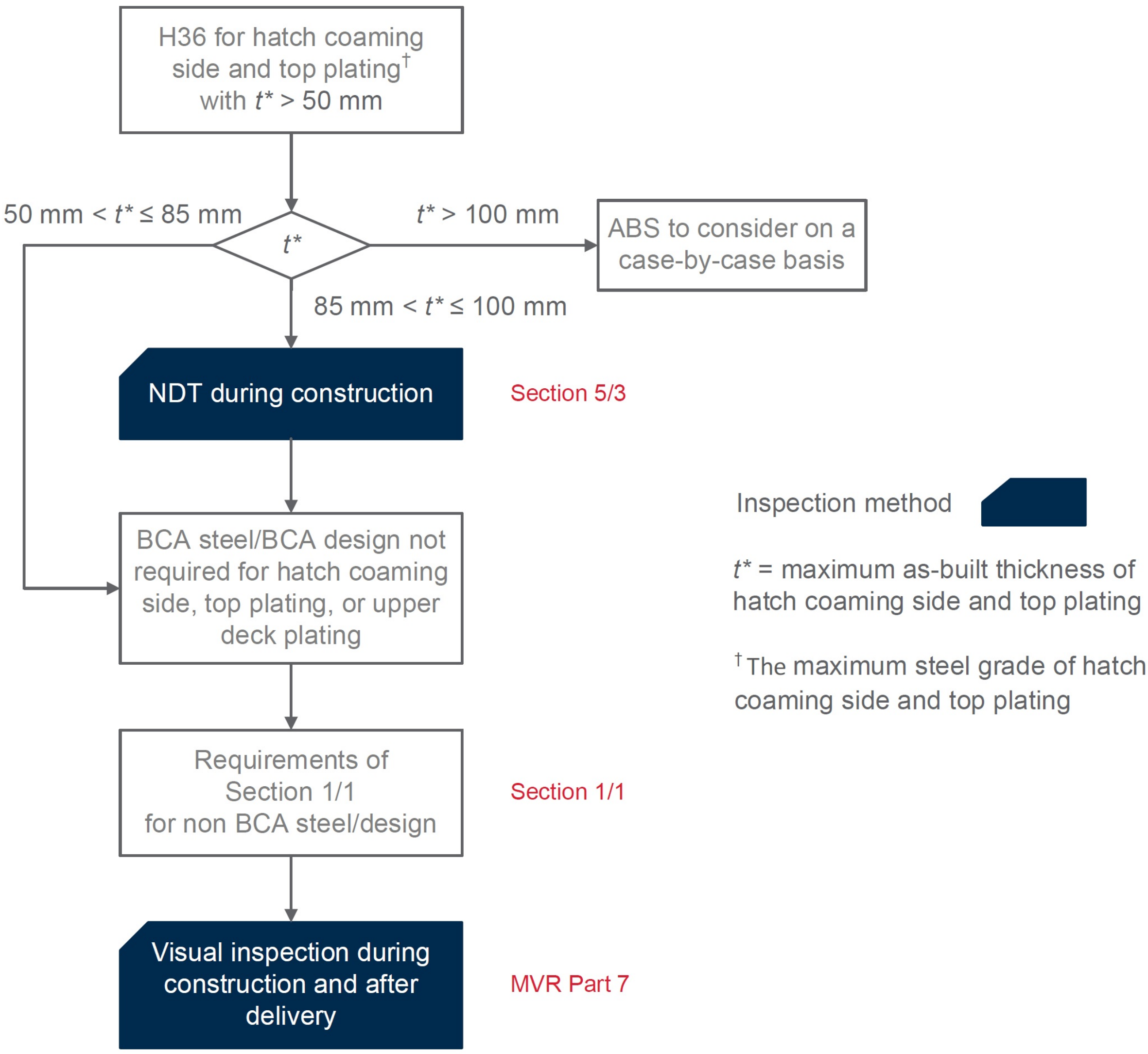


FIGURE 1B
Flowchart for BCA Steel/BCA Design – H40 Steel Grade for Hatch Coaming Side and Top Plating *(2021)*

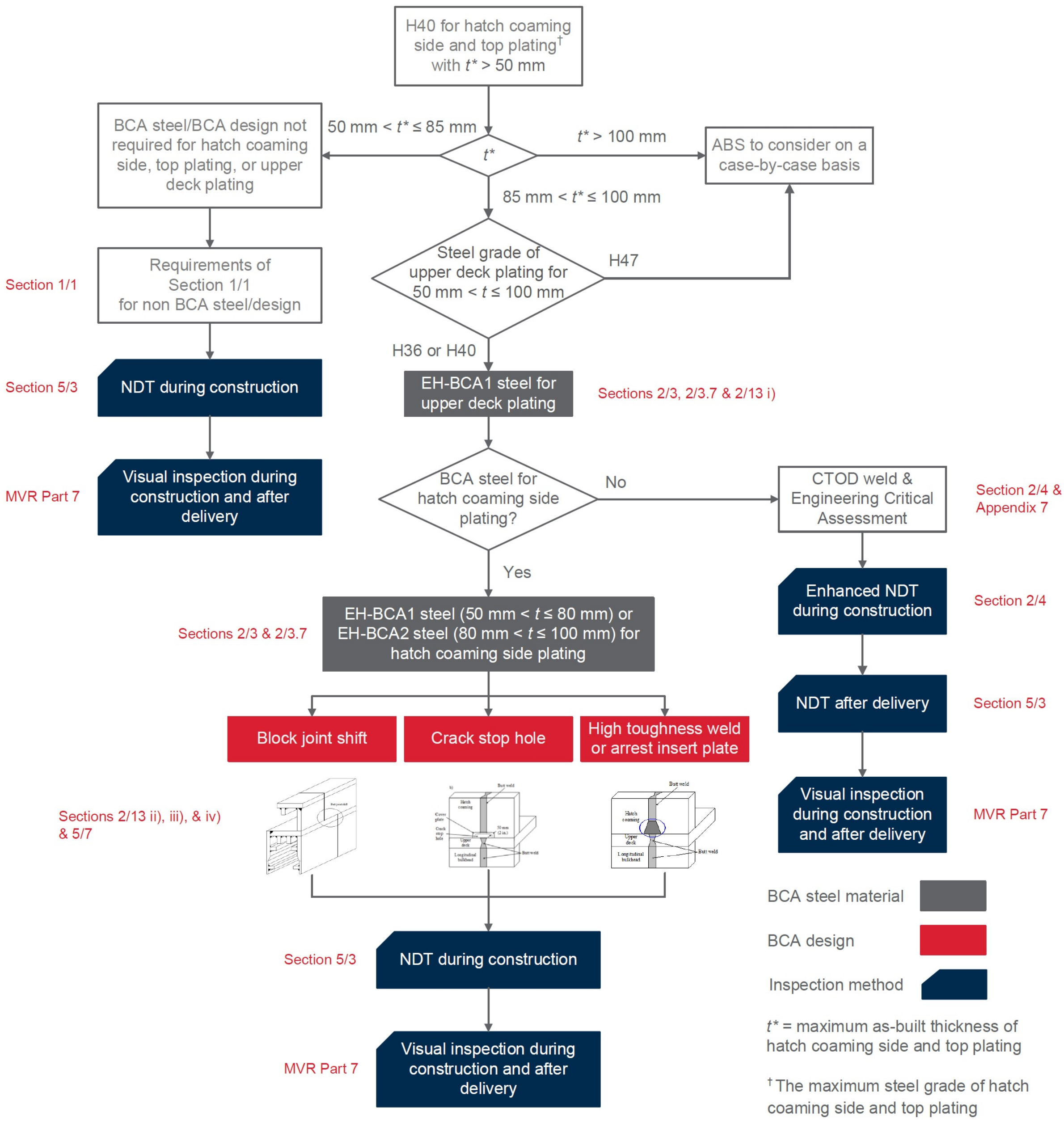
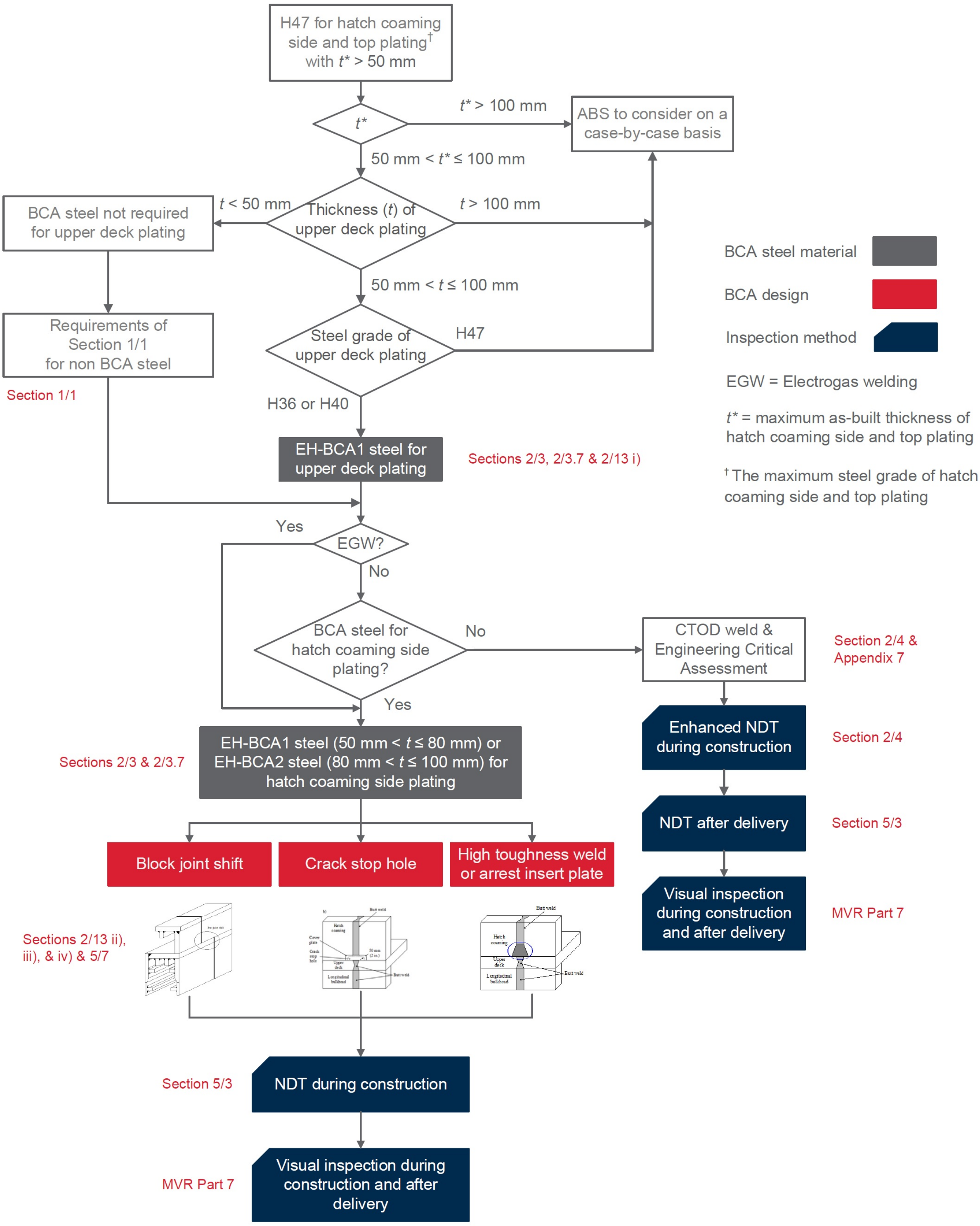


FIGURE 1C
Flowchart for BCA Steel/BCA Design – H47 Steel Grade for Hatch Coaming Side and Top Plating *(2021)*



SECTION 3

Testing and Certification of Thick Steel Plates

1 Introduction *(1 July 2024)*

1.1 Objective *(1 July 2024)*

1.1.1 Goals

Materials are to be suitable for their intended application in accordance with the following goals and support the Tier I goals listed elsewhere in the this document.

Goal No.	*Goals*
MATERIALS (MAT)	
MAT 1	The selected materials' physical, mechanical, and chemical properties are to meet the design requirements appropriate for the application, operating conditions, and environment.
MAT 2	The manufacturing process is to be capable of producing products to meet the specified quality and property requirements.

The goals in the cross-referenced Rules are to be met.

Commentary:

i In general, the Designer selects the material grade/specification suitable for the loads, operating conditions, and the environment to satisfy the MAT 1 goal . An order is issued to the manufacturer to procure the products in accordance with the material specification. In some cases, an experienced manufacturer may assist the designer in selecting the appropriate material.

ii Alternative manufacturing methods can be applied to meet the specified quality and property requirements.

iii Material specifications include requirements for manufacturing process, chemistry, heat treatment, mechanical properties, surface and internal quality requirements, and any other relevant details.

iv Refer to Appendix 2-A1-2 of the ABS *Rules for Materials and Welding (Part 2)* for physical, chemical, and mechanical properties that may be considered during material selection and design assessment.

End of Commentary

1.1.2 Functional Requirements

To achieve the above stated goals, the materials are to comply with the following functional requirements:

Functional Requirement No.	*Functional Requirements*
MATERIALS (MAT)	
MAT-FR1	Products are to be manufactured to a documented process. The manufacturing process is to be capable of attaining the specified material properties.
MAT-FR2	Steel making is to be capable of producing steel within the specified chemical limits and quality requirements.
MAT-FR3	Chemical composition is to be appropriate to achieve the specified material properties and be suitable for welding, when applicable.
MAT-FR4	Products are to undergo sufficient plastic deformation to meet specified material properties.
MAT-FR5	Heat treatment, when applicable, is to be capable of producing the specified material properties and an appropriate microstructure.

The functional requirements covered in the cross-referenced Rules are also to be met.

Commentary:

There are many failure mechanisms that could occur in materials which could be associated with improper manufacturing practices and lack of quality control.

End of Commentary

1.1.3 Compliance

A vessel is considered to comply with the goals and functional requirements within the scope of classification when the applicable prescriptive requirements are complied with or when an alternative arrangement has been approved. Refer to Part 1D, Chapter 2.

1.3 General Requirements *(1 July 2024)*

The general guidelines and requirements defined in the ABS *Rules for Materials and Welding (Part 2)* are to be applied, unless there are specific requirements in this document.

Subsections 3/1, 3/3, and 3/7 apply to H47 Non-BCA steels. The requirements of H36/H40 Non-BCA are defined in Section 2-1-3 of the ABS *Rules for Materials and Welding (Part 2)*. Subsections 3/1, 3/5, and 3/7 apply to H36/H40/H47 BCA steels.

The requirements for H47 Non-BCA steel are applicable to steel plate up to 100 mm (4 in.) in thickness. The requirements for H36/H40/H47 BCA steel are applicable to steel plate thickness greater than 50 mm (2 in.) and up to 100 mm (4 in.).

All products for hull construction are to be manufactured at steel works approved by ABS in accordance with 2-1-1/1.2 and Appendix 4 of the ABS *Rules for Materials and Welding (Part 2)*. The additional approval of the manufacturer for higher-strength BCA thick steel plate is to be in accordance with Appendix 3 of this document.

3 H47 Steels *(2021)*

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 3/3.5 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 3/3.5 TABLE 2.

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

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 3/3.5 TABLE 3

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

TABLE 1
Chemical Properties of H47 Non-BCA Steel *(2021)*

Grade	AH47, DH47, EH47, FH47
Deoxidation	Killed, Fine Grain Practice [1]
Chemical Composition [2]	(Ladle Analysis), % max. unless specific in range
C	0.18 [7]
Mn	0.90-2.00
Si	0.55 [3]
P	0.020
S	0.020
Al (acid Soluble) min. [4,5]	0.015
Nb [5,6]	0.02-0.05
V [5,6]	0.05-0.10
Ti [6]	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 amounts 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 soluble 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 soluble 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.

6 *(2021)* The total amount of niobium, vanadium, and titanium is not to exceed 0.12%.

7 *(2021)* For improved weldability, the maximum Carbon content may be reduced to 0.12%.

TABLE 2
Carbon Equivalent for H47 Non-BCA Steel *(2021)*

Grade	*Carbon Equivalent, Max. (%)*	
	t ≤ 50 mm (t ≤ 2 in.)	*50 mm < t ≤ 100 mm (2 in. < t ≤ 4 in.)*
AH47, DH47, EH47, FH47	0.46	0.49

TABLE 3
Cold Cracking Susceptibility for H47 Non-BCA Steel *(2021)*

Grade	*Cold Cracking Susceptibility, Max. (%)*
	t ≤ 100 mm (t ≤ 4 in.)
AH47, DH47, EH47, FH47	0.22

3.7 Tensile Properties *(2021)*

The material is to conform to the requirements of Section 3, Table 4 as to tensile properties. The requirements for the preparation and procedure of the 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 Non-BCA and BCA Steel *(2021)*

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

3.9 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.

TABLE 5
Impact Properties of H47 Non-BCA and BCA Steel *(2021)*

Grade	*Temp °C (°F)*	*t ≤ 70 mm (t ≤ 2.8 in.)*		*70 mm < t ≤ 85 mm (2.8 in. < t ≤ 3.4 in.)*		*85 mm ≤ t < 100 mm (3.4 in. < t ≤ 4.0 in.)*	
		Average Absorbed Energy Longitudinal, J (kgf-m, ft-lbf)	*Average Absorbed Energy Transverse, J (kgf-m, ft-lbf)*	*Average Absorbed Energy Longitudinal J (kgf-m, ft-lbt)*	*Average Absorbed Energy Transverse J (kgf-m, ft-lbt)*	*Average Absorbed Energy Longitudinal, J (kgf-m, ft-lbf)*	*Average Absorbed Energy Transverse, J (kgf-m, ft-lbf)*
AH47 Non-BCA	0 (32)	53 (5.4, 39)	37 (3.8, 27)	64 (6.5, 47)	45 (4.6, 33)	75 (7.6, 55)	53 (5.4, 39)
DH47 Non-BCA	-20 (-4)	53 (5.4, 39)	37 (3.8, 27)	64 (6.5, 47)	45 (4.6, 33)	75 (7.6, 55)	53 (5.4, 39)

Grade	*Temp °C (°F)*	*t ≤ 70 mm (t ≤ 2.8 in.)*		*70 mm < t ≤ 85 mm (2.8 in. < t ≤ 3.4 in.)*		*85 mm ≤ t < 100 mm (3.4 in. < t ≤ 4.0 in.)*	
		Average Absorbed Energy Longitudinal, J (kgf-m, ft-lbf)	*Average Absorbed Energy Transverse, J (kgf-m, ft-lbf)*	*Average Absorbed Energy Longitudinal J (kgf-m, ft-lbt)*	*Average Absorbed Energy Transverse J (kgf-m, ft-lbt)*	*Average Absorbed Energy Longitudinal, J (kgf-m, ft-lbf)*	*Average Absorbed Energy Transverse, J (kgf-m, ft-lbf)*
EH47 Non-BCA and BCA	-40 (-40)	53 (5.4, 39)	37 (3.8, 27)	64 (6.5, 47)	45 (4.6, 33)	75 (7.6, 55)	53 (5.4, 39)
FH47 Non-BCA and BCA	-60 (-76)	53 (5.4, 39)	37 (3.8, 27)	64 (6.5, 47)	45 (4.6, 33)	75 (7.6, 55)	53 (5.4, 39)

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

5 H36/H40/H47 BCA Steels *(2021)*

5.1 General *(1 July 2024)*

In addition to the requirements in Section 3 of this document for H47 and Section 2-1-3 of the ABS *Rules for Materials and Welding (Part 2)* for H36/H40, the requirements in this Subsection apply for H36/H40/H47-BCA steels.

The additional brittle crack arrest properties will require adjustments in chemistry, specialized manufacturing processes and additional testing.

Materials qualification is to be in accordance with Appendix 3. Materials during production are to comply with Subsection 3/7.

The application of H36-BCA is for special cases and should be submitted for review and approval.

5.3 Chemical Composition

The manufacturer is to provide the specified chemical composition, manufacturing process, and production control for the BCA steels, with an emphasis on production parameters that could influence the BCA properties.

The specified chemistry composition for BCA steel is to be similar to the requirements of the corresponding grade of Non-BCA steel, with some adjustment to meet the required BCA properties.

The chemical composition is to be determined by the steel manufacturer from samples taken from each ladle of each heat and is to conform to Section 3, Table 6 and the qualified specification. The steel manufacturer is to verify the compliance with the specification.

TABLE 6
Chemical Properties of H36/H40/H47 BCA Steel *(2021)*

Grade	*H36-BCA*	*H40-BCA*	*H47-BCA*
Deoxidation	*Killed, Fine Grain Practice* (1)		
Chemical Composition (2)	*(Ladle Analysis), % max. unless specific in range*		
C (7)	0.18	0.18	0.18
Mn	0.90-2.00	0.90-2.00	0.90-2.00
Si (3)	0.50	0.50	0.55
P	0.020	0.020	0.020
S	0.020	0.020	0.020
Al (acid Soluble) min. (4,5)	0.015	0.015	0.015
Nb (5,6)	0.02-0.05	0.02-0.05	0.02-0.05
V (5,6)	0.05-0.10	0.05-0.10	0.05-0.10
Ti (6)	0.02	0.02	0.02
Cu	0.50	0.50	0.50
Cr	0.25	0.25	0.50
Ni	2.00	2.00	2.00
Mo	0.08	0.08	0.08
B	0.002	0.002	0.002

Notes:

1 The steel is to contain at least one of the grain refining elements in sufficient amounts 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 soluble 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 soluble 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.

6 The total amount of niobium, vanadium, and titanium is not to exceed 0.12%.

7 For improved weldability, the maximum Carbon content may be reduced to 0.12%.

5.5 Carbon Equivalent

The carbon equivalent C_{eq} as determined from the ladle analysis is to meet the requirements in Section 3, Table 7.

TABLE 7
Carbon Equivalent for H40/H47 BCA Steels *(2021)*

*Grade **	*Carbon Equivalent, Max. (%)*
	50 mm < t ≤ 100 mm (2 in. < t ≤ 4 in.)
XH36-BCA	0.47
XH40-BCA	0.49
XH47-BCA	0.55

Note: *Where X is E or F.

5.7 Cold Cracking Susceptibility

The cold cracking susceptibility P_{cm} as calculated from the ladle analysis is to meet the requirements in Section 3, Table 8.

TABLE 8
Cold Cracking Susceptibility for H47 BCA Steels *(2021)*

*Grade **	*Cold Cracking Susceptibility, Max. (%)*
	50 mm < t ≤ 100 mm (2 in. < t ≤ 4 in.)
XH47-BCA	0.24

Note: *Where X is E or F.

5.9 Tensile Properties

Tensile properties for H47-BCA steels are to be in accordance with Section 3, Table 4.

Tensile properties for H36/H40-BCA steels are to be in accordance with 2-1-3/Table 2 of the ABS *Rules for Materials and Welding (Part 2)*.

5.11 Impact Properties

Impact properties for H47-BCA steels are to be in accordance with Section 3, Table 5.

Impact properties for H36/H40-BCA steels are to be in accordance with 2-1-3/Table 4 of the ABS *Rules for Materials and Welding (Part 2)*.

5.13 BCA Properties *(1 July 2024)*

Steels designated as BCA are to be tested to determine the BCA properties by large scale ESSO test (detailed in Appendix 4), small scale double tension test (detailed in ASTM E1221 and Appendix 6 of this document) or CAT (Crack Arrest Temperature) test (detailed in Appendix 5), or another alternative test as agreed by ABS. Brittle crack arrest requirements are detailed in Section 3, Table 9. Test specimens are to be taken from each piece (that is, the rolled product from a single slab or ingot if rolled directly into plates), unless otherwise agreed by ABS.

TABLE 9
Requirements for H36/H40/H47 BCA Properties *(2021)*

Suffix to the Steel Grade (1)	*Thickness Range mm (in.)*	*Brittle Crack Arrest Properties (3,7,8)*	
		Brittle Crack Arrest Toughness K_{ca} at –10°C (14°F) Minimum N/mm$^{3/2}$ (ksi-in$^{1/2}$) (4)	*Crack Arrest Temperature CAT Maximum °C (°F) (5)*
BCA1	50 < t ≤ 100 (2.0 < t ≤ 4.0)	6,000 (173)	–10 (14)
BCA2 (2)	80 < t ≤ 100 (3.2 < t ≤ 4.0)	8,000 (230) (6)	(9)

Notes:

1 Suffix "BCA1" or "BCA2" is to be affixed to the steel grade designation (e.g., EH40-BCA1, EH47-BCA1, EH47-BCA2, etc.).

2 In the case where the thickness of hatch side coaming exceeds 80 mm, brittle crack arrest steels with suffix of BCA2 are to be applied.

3 Brittle crack arrest properties for brittle crack arrest steels are to be verified by either the brittle crack arrest toughness, K_{ca}, or crack arrest temperature, CAT.

4 K_{ca} value is to be determined by ESSO test or double tension test.

5 CAT is to be determined by the manufacturer in accordance with Appendix 5 or an appropriate test method agreed by ABS.

6 K_{ca} = 8,000 N/mm$^{3/2}$ (230 ksi-in$^{1/2}$) has been established only on test plates of 100 mm (4 in.). Where requested, K_{ca} values less than 8,000 N/mm$^{3/2}$ (230 ksi-in$^{1/2}$) will be considered for plates of lower thickness than 100 mm (4 in.) and above 80 mm (3.2 in.) subject to the submission of supporting data and analysis, and ABS agreement.

7 Small-scale alternative testing methods can be employed for product testing, in accordance with Appendix 6, provided the correlation between small-scale tests and large-scale tests has been established and agreed upon at the time of approval.

8 In the case where H40 steels are applied to the upper deck as brittle crack arrest steels, the brittle crack arrest property of H40-BCA is to be verified against the anticipated design stress.

9 Criterion of CAT for brittle crack arrest steels corresponding to K_{ca} = 8,000 N/mm$^{3/2}$ (230 ksi-in$^{1/2}$) with thickness exceeding 80 mm (3.2 in.) is to be submitted and approved.

7 Testing and Inspection during Production *(2021)*

7.1 General

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

7.3 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)*.

7.5 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)*.

7.7 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)*.

7.9 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)*.

7.11 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)*.

7.13 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)*.

7.15 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)*.

7.17 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)*.

7.19 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)*.

7.21 Marking

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

For BCA steels the suffix "-BCA1 or -BCA2" is also to be added (e.g., AB/EH47-BCA1, AB/EH47-BCA2 etc.).

7.23 Surface Finish

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

7.25 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)*.

7.27 Additional Tests for BCA Steels

Steels are to be tested for BCA properties during production. Large-scale ESSO, double tension, or CAT tests are to be used to obtain the BCA properties. Alternatively, small-scale testing could be carried out in lieu of large-scale testing if agreed to at the time of qualification. See Appendix 3 for details.

7.29 Ultrasonic Examination of Plate Materials

The requirements for ultrasonic examination for steel plates are defined in 2-1-1/21 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/mm² (47 kgf/mm², 67 ksi) *(2021)*

1 Introduction *(1 July 2024)*

1.1 Objective

1.1.1 Goals

Welding and fabrication are to be suitable for their intended application in accordance with the following goals and support the Tier I goals listed elsewhere in this document.

Goal No.	*Goals*
MATERIALS (MAT)	
MAT 1	The selected materials' physical, mechanical, and chemical properties are to meet the design requirements appropriate for the application, operating conditions, and environment.
MAT 3	The fabrication and welding process is to be capable of producing products that meets the specified quality and property requirements.

Goals in the cross-referenced Rules are to be met.

Commentary:

i In general, the Designer selects the material grade/specification suitable for the loads, operating conditions, and the environment to satisfy the MAT 1 goal .An order is issued to the manufacturer to procure the products in accordance with the material specification. In some cases, an experienced manufacturer may assist the designer in selecting the appropriate material.

ii Alternative manufacturing methods can be applied to meet the specified quality and property requirements.

iii Material specifications include requirements for manufacturing process, chemistry, heat treatment, mechanical properties, surface and internal quality requirements and any other relevant details.

iv Refer to Appendix 2-A1-2 of the ABS *Rules for Materials and Welding (Part 2)* for physical, chemical, and mechanical properties that may be considered during material selection and design assessment.

End of Commentary

1.1.2 Functional Requirements

To achieve the above stated goals, the materials are to comply with the following functional requirements:

Functional Requirement No.	*Functional Requirements*
MATERIALS (MAT)	
MAT-FR1	Welding is to be performed to a documented procedure which includes relevant variables appropriate for the application.
MAT-FR2	The welding procedure is to be capable of producing weldments that meet the specified weldment properties and specified quality requirements appropriate for the application.
MAT-FR3	The chemical composition and storage/handling of the filler metal is to be capable of achieving the specified weldment properties.
MAT-FR4	Welding personnel are to be qualified and demonstrate they are capable of producing weldments which meet the specified weldment properties and quality requirements.
MAT-FR5	Relevant welding variables/parameters are to be controlled and monitored during production welding.

The functional requirements covered in the cross-referenced Rules are also to be met.

1.1.3 Compliance

A vessel is considered to comply with the goals and functional requirements within the scope of classification when the applicable prescriptive requirements are complied with or when an alternative arrangement has been approved. Refer to Part 1D, Chapter 2.

2 General *(1 July 2024)*

The requirements in this Section are applicable to H47 (Non-BCA and BCA) grade hull structural steel plates. 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 document.

2.1 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)*.

2.3 Production Welding *(1 July 2024)*

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

In addition, preheating is to be 50°C (122°F) or greater when the air temperature is 5°C (41°F) or below.

Repair welds are to be preheated to 50°C (122°F) or greater, regardless of air temperature.

Commentary:

In the case where P_{cm} is less than or equal to 0.19, working in an air temperature of 0°C (32°F) or below may be specially approved by ABS.

End of commentary

2.5 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)*.

2.7 Workmanship Test

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

2.9 Short Bead *(1 July 2024)*

Short bead length for tack and repairs of welds by welding is not to be less than 50 mm (2 in.).

Commentary:

In the case that P_{cm} is less than or equal to 0.19, 25 mm (1.0 in.) of short bead length may be accepted on a case-by-case basis.

End of Commentary

2.11 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 *(2021)*

The mechanical properties of welding consumables for H47 Non-BCA and BCA steel plates are to comply with Section 4, Table 1. For consumables used in butt weld applications, mechanical properties are to be in accordance with Section 4, Table 2.

TABLE 1
Mechanical Properties for Deposited Metal Tests for Welding Consumables
(2021)

Mechanical Properties			*Impact Test*	
Yield Strength, min. N/mm² (kgf/mm², ksi)	*Tensile Strength N/mm² (kgf/mm², ksi)*	*Elongation, min. %*	*Test Temp. °C (°F)*	*Minimum Average Impact Energy, min. J (kgf-m, ft-lbf)*
460 (47, 67)	570-720 (58-71, 83-101)	19	–20 (–4)	64 (6.5, 47)

TABLE 2
Mechanical Properties for Butt Weld Tests for Welding Consumables *(2021)*

Tensile Strength N/mm^2 (kgf/mm^2, ksi)	*Bend Test Ratio: D/t*	*Charpy V-notch Impact Tests*		
		Test Temperature °C (°F)	*Minimum Average Absorbed Energy, min. J (kgf-m, ft-lbf)*	
			Downhand, Horizontal, Overhead	*Vertical (Upward and Downward)*
570-720 (58-71, 83-101)	4	–20 (–4)	64 (6.5, 47)	64 (6.5, 47)

3.5 Application of Filler Metal

The application of filler metal is to meet the requirements in Section 4, Table 3.

TABLE 3
Applicable Filler Metals *(2021)*

Filler Metal Grade	*Plate Thickness ≤ 50 mm (2 in.)*	*Plate Thickness > 50 mm (2 in.)*
Grade 3 Y 460	AH47, DH47	AH47
Grade 4 Y 460	AH47, DH47, EH47	AH47, DH47
Grade 5 Y 460	AH47, DH47, EH47, FH47	AH47, DH47, EH47
Grade 6 Y 460	AH47, DH47, EH47, FH47	AH47, DH47, EH47, FH47

Note: Use of higher-grade filler metal is allowed to meet the required mechanical properties as approved by ABS. EH 47 is EH47 Non-BCA or BCA. FH 47 is FH47 Non-BCA or BCA.

5 Approval of Welding Procedures

5.1 General *(2021)*

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. The maximum P_{cm} is to be included in the Welding Procedure Specification (WPS). Refer to 3/3.5 for P_{cm} calculation. Also refer to 4/1.3 for preheat of production welding in accordance with the calculated P_{cm}.

A welding procedure qualification test is required to determine the shipyard or fabricator's ability to apply the proposed filler metal to the base material.

Where a WPS for a non-BCA steel grade (excluding those with the suffix "BCA1" or "BCA2") has been approved by the Classification Society, the said WPS is applicable to the same grade of the brittle crack arrest steels.

Special care is to be paid to the final welding so that harmful defects do not remain. Jig mountings are to be completely removed with no defects.

5.3 Approved Filler Metals *(2021)*

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 (2.8 in^3/lbf).

5.5 Test Requirements

5.5.1 General *(2021)*

Preparation of test specimens and test processes are to follow the requirements in Section 2-4-3 and 2-A4-2/5.13 of the ABS *Rules for Materials and Welding (Part 2)*. The additional requirements for approval of welding procedures of H47 Non-BCA and BCA steels are included in this section.

5.5.2 Tensile Properties *(2021)*

The butt weld tensile strength is not to be less than 570 N/mm^2 (58 kgf/mm^2, 83 ksi). The fracture location is to be depicted and reported. The weld metal, fusion line, base metal, and fracture location are to be denoted.

5.5.3 Charpy Properties *(2021)*

Charpy V-notch impact test for the toughness of weldments is to meet the requirements in Section 4, Table 4 for both high heat input and low heat input for WPQT (welding procedure qualification test).

TABLE 4
Toughness Requirements of Welds of H47 Non-BCA and BCA Steel
(2021)

Grade	*Test Location*	*Test Temperature*	*CVN Requirement, Average, Min.*
			t ≤ 100 mm (4 in.)
AH47 Non-BCA	WM, FL, FL + 2 mm, + 5 mm, + 20 mm (WM, FL, FL + 0.08 in., + 0.2 in., + 0.8 in.)	20°C (68°F)	64 J (6.5 kgf-m, 47 ft-lbf)
DH47 Non-BCA		0°C (32°F)	64 J (6.5 kgf-m, 47 ft-lbf)
EH47 Non-BCA and BCA		–20°C (–4°F)	64 J (6.5 kgf-m, 47 ft-lbf)
FH47 Non-BCA and BCA		–40°C (–40°F)	64 J (6.5 kgf-m, 47 ft-lbf)

Note: WM, FL, FL+ are defined in Appendix 2-A9-A1 of ABS *Rules for Materials and Welding (Part 2)*.

5.5.4 CTOD Test *(1 July 2024)*

A3/7.17 is applicable to the CTOD test. Depending upon the design methodologies, the CTOD test is required during the welding procedure qualification test (WPQT) for the application of BCA steel as the brittle crack arrest method.

Commentary:

The CTOD test may be deferred during WPQT if the welding design is adopted as the brittle crack arrest method shown in Section 5.

End of Commentary

5.5.5 Bend Test *(2021)*

The bending mandrel diameter is to be 5 × *t*. The bending angle is to be a minimum of 180 degrees. After bending, the test sample is to pass the nondestructive inspection.

5.5.6 Hardness *(1 July 2024)*

The maximum hardness of the weld is not to exceed 350 HV10 for H47 Non-BCA and 380 HV10 for H47-BCA, respectively, and measurement points are to include a mid-thickness position in addition to those specified in 2-A9-1/7.3.2(g) and 2-A4-2/5.13 of the ABS *Rules for Materials and Welding (Part 2)*.

7 Welding Qualification *(2021)*

7.1 Welding Equipment Operator Qualification

The welding operator is responsible for setting up and/or adjusting the fully mechanized and automatic equipment, such as submerged arc welding, gravity welding, electro-gas welding and MAG welding with auto-carriage, etc. The welding equipment operator is to be qualified in accordance with the requirements found in Appendix 11 of ABS *Rules for Materials and Welding (Part 2)*.

7.3 Welder Qualification

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

9 Nondestructive Examination *(2021)*

9.1 General

Nondestructive examination is to be carried out following 2-4-1/5.17 of the ABS *Rules for Materials and Welding (Part 2)*, in accordance with the ABS *Guide for Nondestructive Inspection (NDI Guide)*.

9.3 Enhanced Criteria

The enhanced criteria in Subsection 2/4 is applicable for all block-to-block butt joints of all upper deck region longitudinal members in the cargo hold region, , main deck, coaming plate, coaming top plate, and all attached longitudinal stiffeners.

SECTION **5**

Prevention of Fatigue and Fracture Failure in Thick Steel Plates

1 Introduction *(1 July 2024)*

1.1 Objective *(1 July 2024)*

1.1.1 Goals

The vessel structure is to be designed, constructed, operated and maintained to:

Goal No.	*Goal*
STRUCTURE (STRU)	
STRU 1	In the intact condition, have sufficient structural strength to withstand the environmental conditions, loading conditions, and operational loads anticipated during the design life.

Goals in the cross-referenced Rules are to be met.

1.1.2 Functional Requirements

To achieve the above stated goals, the following functional requirements apply to this Section:

Functional Requirement No.	*Functional Requirements*
STRUCTURE (STRU)	
STRU-FR1	Minimize initial defects in weldments during new construction and operation for the prevention of possible failure.
STRU-FR2	Prevent fatigue crack growth to a critical size in weldments of the hatch coaming and main deck structures.
STRU-FR3	Provide 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.
STRU-FR4	Provide adequate hull girder residual strength against overloading.

Functional requirements covered in the cross-referenced Rules are also to be met.

1.1.3 Compliance

A vessel is considered to comply with the goals and functional requirements within the scope of classification when the applicable prescriptive requirements are complied with or when an alternative arrangement has been approved by ABS. Refer to Part 1D, Chapter 2.

1.3 General *(2021)*

The upper deck region of the hull structure with hatch coaming constructed of steel plates over 50 mm (2 in.) 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

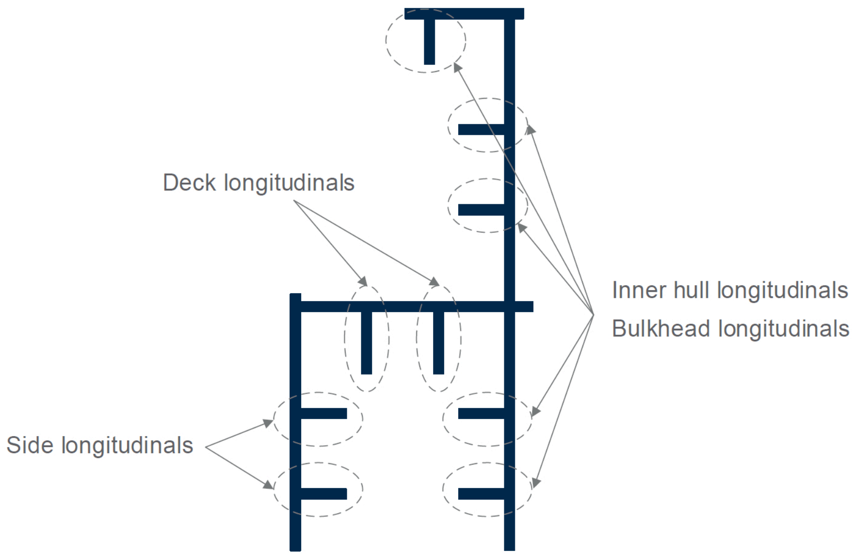
3.1 General *(2021)*

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

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

UT methods are to be applied for all block-to-block butt joints of all upper flange longitudinal members in the cargo hold region, including the topmost strakes of the inner hull/bulkhead, the sheer strake, main deck, hatch coaming plate, hatch coaming top plate, and all attached longitudinal stiffeners. These members are defined in Section 5, Figure 1.

FIGURE 1
Upper Flange Longitudinal Structural Members *(2021)*



3.3 New Construction *(2021)*

All butt joints of hatch coaming and upper deck structures are to be inspected by visual inspection, surface NDT such as magnetic particle test or eddy current test, and volumetric NDT such as ultrasonic test.

3.5 Vessels in Service *(1 July 2024)*

Within 0.3L ~ 0.7L of vessel length, butt welds of hatch coaming top and side are to be inspected for cracks at every Special Periodical Survey in accordance with the following:

- All butt welds of hatch coaming top and side plates are to be visually inspected. Surface NDT, magnetic particle, or eddy current test and volumetric NDT, UT, may be required depending on the visual inspection results.
- In addition, if the alternative to BCA material defined in Subsection 2/4 is applied during construction, surface NDT is to be applied on all butt welds of the hatch coaming top and side plates, and ultrasonic testing is to be applied for all butt welds of the hatch coaming top and side plate at the location of block erection joints.

The shipyard is to submit to ABS an NDT plan of joints to be inspected during service. This document is available to the Surveyor performing the special periodical survey.

NDT findings are to be reported and submitted to ABS Corporate Class, Engineering and Materials prior to repair.

3.7 Requirements for Nondestructive Test *(1 July 2024)*

As minimum, acceptance levels for allowable sizes of discontinuities are to be determined in accordance with the ABS *Guide for Nondestructive Inspection*.

In the case that more stringent acceptance criteria have been determined by ECA in accordance with Appendix 7 of this document, these acceptance criteria prevail over the *NDI Guide* criteria. The ECA acceptance is to be documented and made to be available to ABS.

5 Prevention of Fatigue Failure

5.1 Fatigue Strength Assessment *(1 July 2024)*

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:

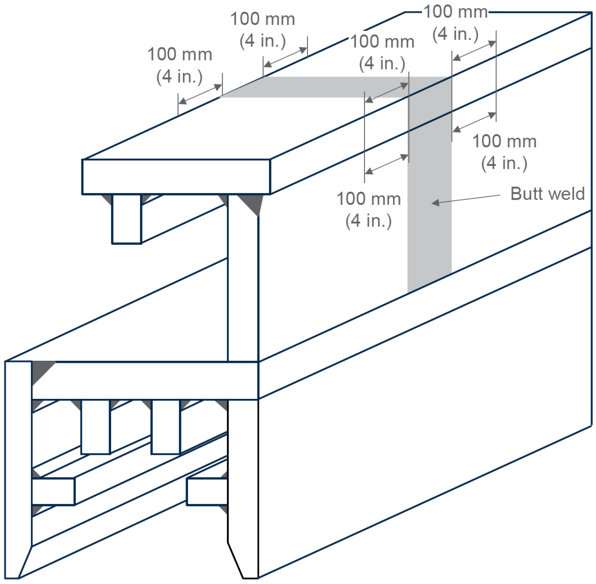
- ABS *Guide for SafeHull-Dynamic Loading Approach for Vessels*
- ABS *Guide for Spectral-Based Fatigue Analysis for Vessels*
- Appendix 1 of this document

5.3 Fatigue Strength Improvement of Welds *(2021)*

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 (0.12 in. ~ 0.2 in.) 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 (4 in.) forward and aft of the butt weld as shown in Section 5, Figure 2. Away from the aforementioned areas, the upper and lower edges are to be ground to 1C, as a minimum.

For the upper deck region 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 2
Grinding of Butt Weld



7 Prevention of Fracture Failure

7.1 General *(1 July 2024)*

To prevent a serious failure along the block joints of the upper deck region 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 is to be adopted. The detailed design measure applied to avoid crack propagation is to be submitted for review.

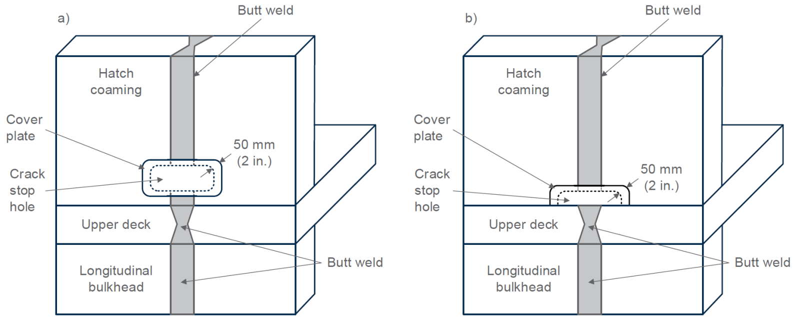
7.3 Crack Stop Hole *(2021)*

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 3. 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 (0.12 in. ~ 0.2 in.). Butt welds in way of the crack stop hole are to be ground flush. The outside of the hole is to be covered with a thin H36 grade steel plate of approximately 10 mm (0.4 in.) with a minimum overlap length of 50 mm (2 in.). 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 in lieu 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 *Marine Vessel Rules*. The fatigue life 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.

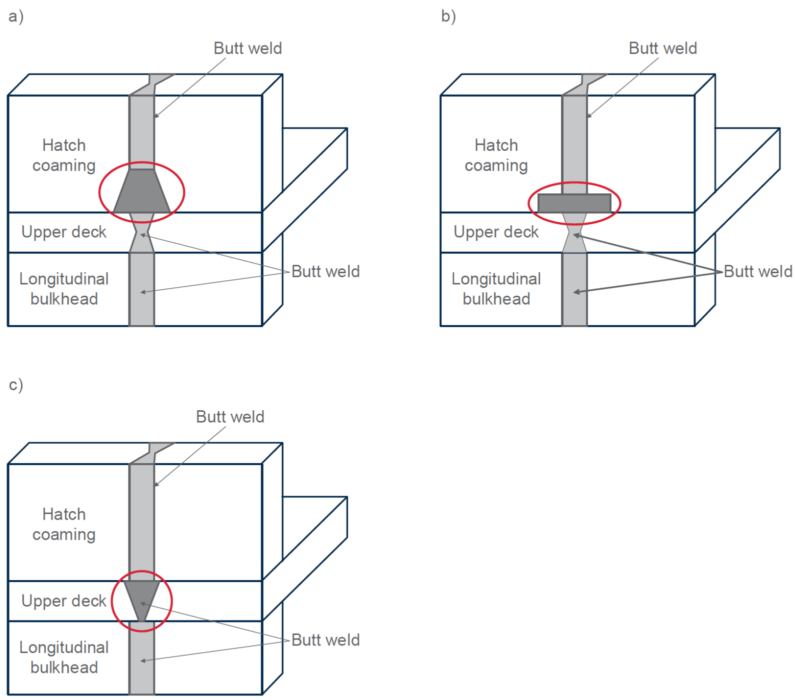
FIGURE 3
Crack Stop Holes



7.5 High Toughness Weld

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 4. 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.

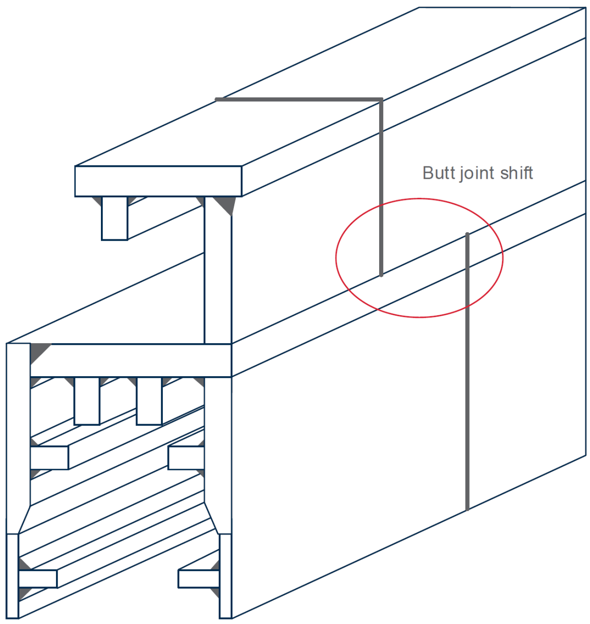
FIGURE 4
High Toughness Weld



7.7 Block Joint Shift *(2021)*

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 5. Likewise, a fatigue crack in the butt weld of the upper deck structure cannot propagate to the hatch coaming plates when using this design measure.

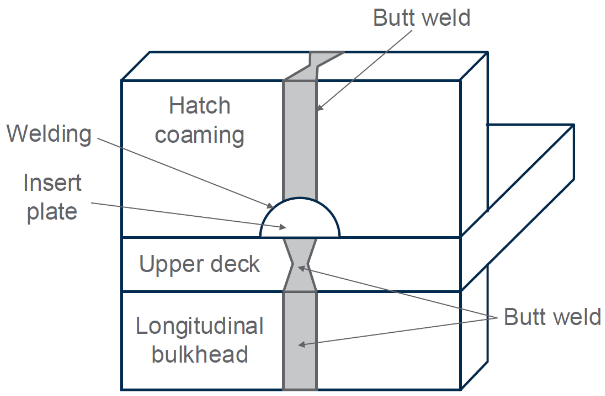
FIGURE 5
Block Joint Shift



7.9 Insert Plate *(2021)*

An insert plate is to be provided at the bottom of the hatch coaming side plate as shown in Section 5, Figure 6. The minimum size of the insert plate is to be 150 mm depth × 300 mm length (6 in. depth × 12 in. 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. The surface of the weld is to be ground smoothly to remove any stress concentration.

FIGURE 6
Insert Plate *(1 February 2012)*



9 Hull Girder Residual Strength *(2021)*

In addition to 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 *(2021)*

The criteria in Appendix 5C-5-A1 of the *Marine 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 *Marine 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, and long-term environment data of the North-Atlantic Ocean, 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 *Marine Vessel Rules* is applicable.

1.5 Loadings *(2021)*

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 a more severe environment, the fatigue strength assessment criteria in this document are to be modified accordingly.

1.7 Effects of Corrosion *(2021)*

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

The 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 0.4L 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) (2021)

Hatch corners immediately forward and aft of 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 Cutouts *(2021)*

Representative cutouts 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 A1/9. Alternatively, the stress concentration factor (SCF) may be determined from fine mesh F.E.M. analyses (see A1/11).

3.5 Fatigue Classification

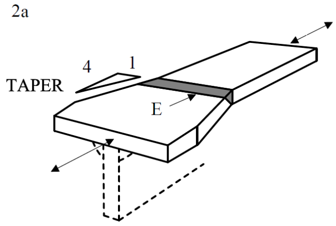
3.5.1 Welded Connections with One Load Carrying Member

Fatigue classification for structural details is shown in A1/3.5.1 TABLE 1.

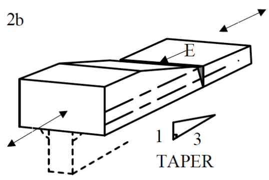
TABLE 1
Fatigue Classification for Structural Details *(2021)*

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 to be 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

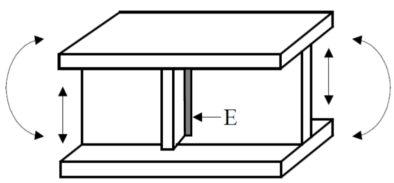
2a



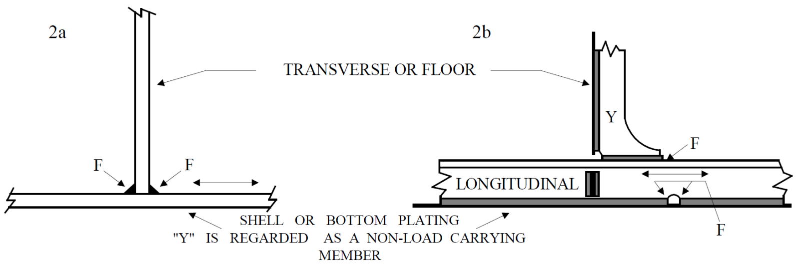
2b



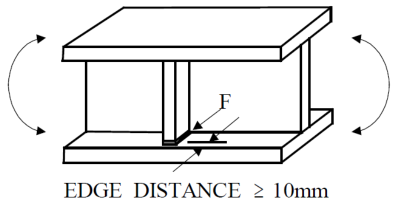
3) Welds of brackets and stiffeners to web plate of girders



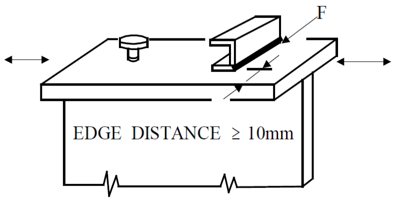
Class Designation		*Description*
F	1)	Full penetration butt weld made on a permanent backing strip
	2)	Rounded fillet welds as shown below



3) Welds of brackets and stiffeners to flanges



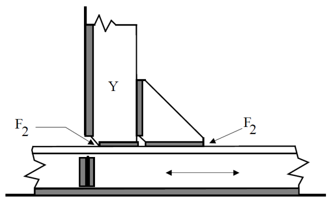
4) Attachments on plate or face plate



(Class G for edge distance < 10 mm)

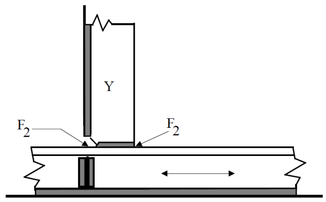
Class Designation		*Description*
F_2	1)	Fillet welds as shown below with rounded welds and no undercutting

1a



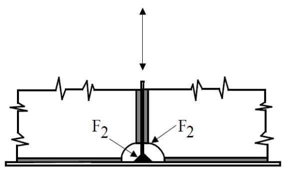
"Y" is a non-load carrying member

1b

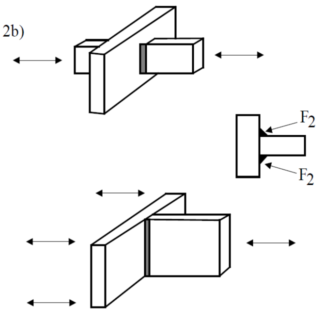


	2)	Fillet welds with any undercutting at the corners dressed out by local grinding

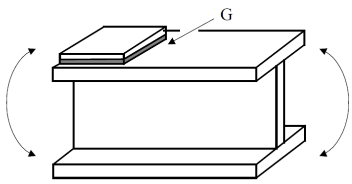
2a)

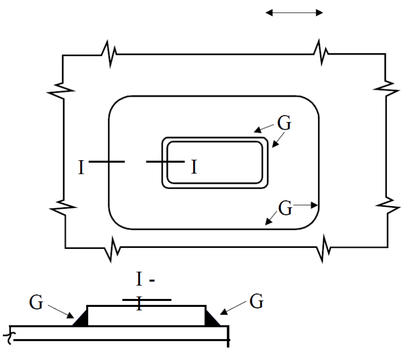


2b)

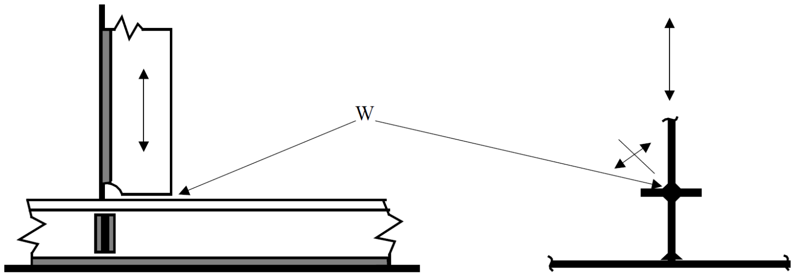


G	1)	Fillet welds in F_2 - 1) without rounded tow welds or with limited minor undercutting at corners or bracket toes
	2)	Fillet welds in F_2 - 2) with minor undercutting
	3)	Doubler on face plate or flange, small deck openings
	4)	Overlapped joints as shown below





Class Designation		*Description*
W	1)	Fillet welds in G - 3) with any undercutting at the toes
	2)	Fillet welds – weld throat

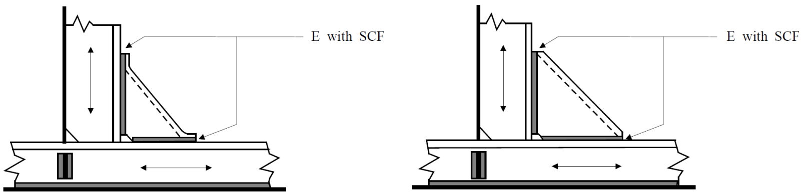


3.5.2 Welded Joint with Two or More Load Carrying Members *(2021)*

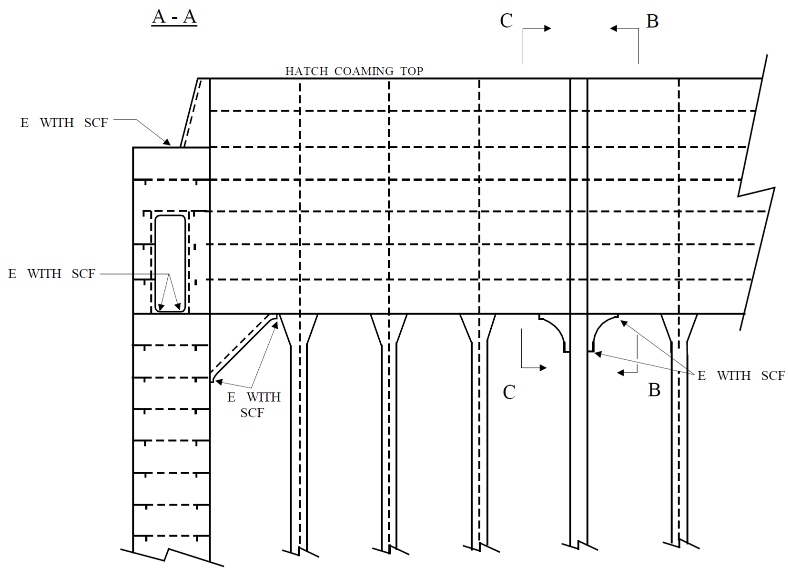
For brackets connecting two or more load carrying members, an appropriate stress concentration factor (SCF) determined from fine mesh finite element analysis is to be used. In this connection, the fatigue class at bracket toes may be upgraded to class E. Sample connections are illustrated below with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

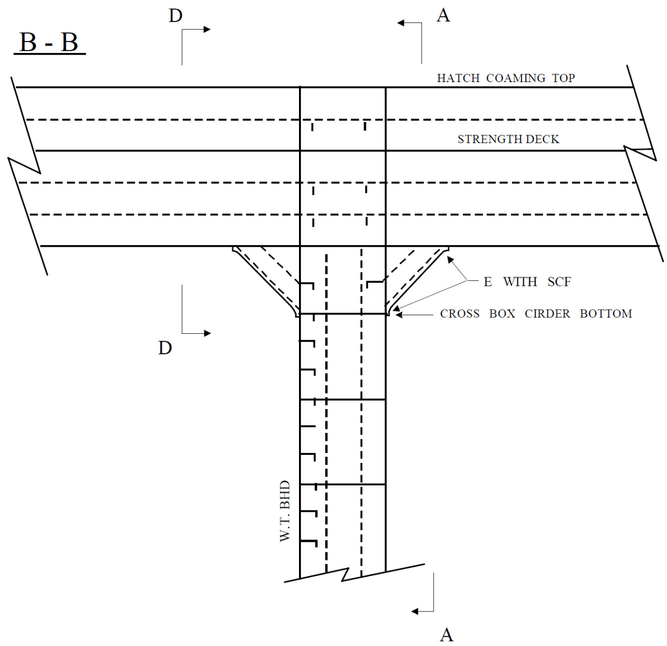
TABLE 2
Welded Joint with Two or More Load Carrying Members

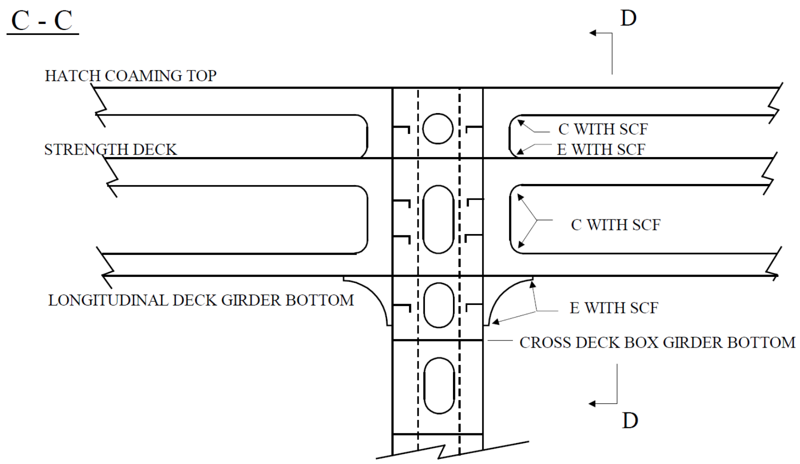
a Connections of Longitudinal and Stiffener

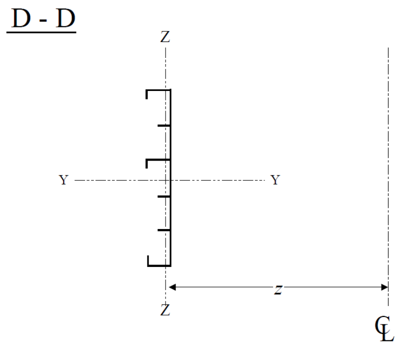


b Connections of Longitudinal Deck Girders and Cross Deck Box

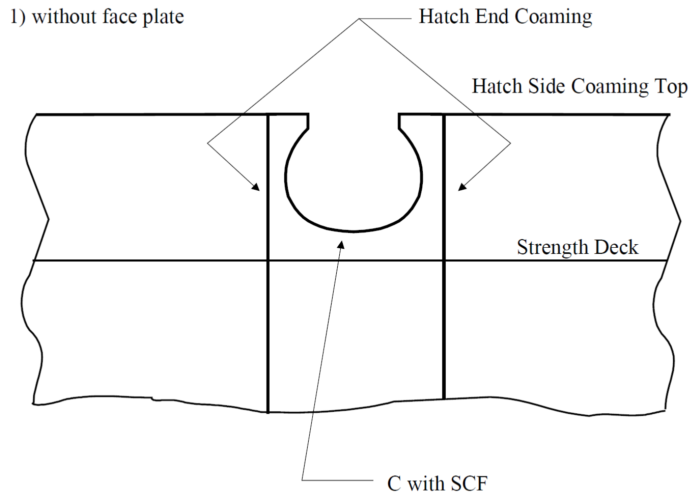


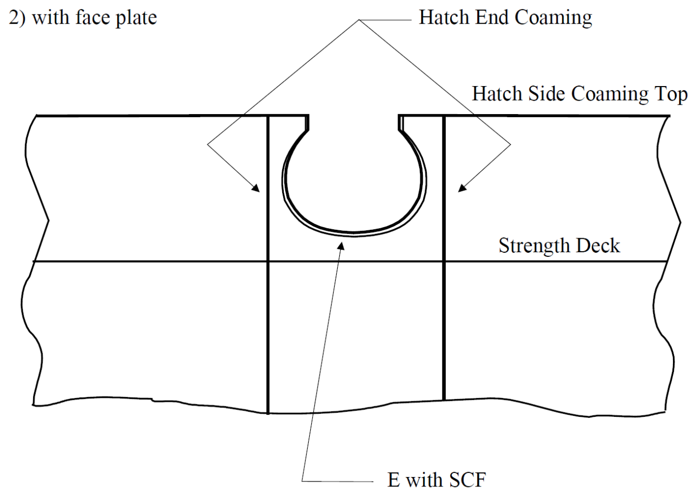



C - C
D
HATCH COAMING TOP
STRENGTH DECK
C WITH SCF
E WITH SCF
C WITH SCF
LONGITUDINAL DECK GIRDER BOTTOM
E WITH SCF
CROSS DECK BOX GIRDER BOTTOM
D


D - D
Z
Y
Y
z
Z
CL

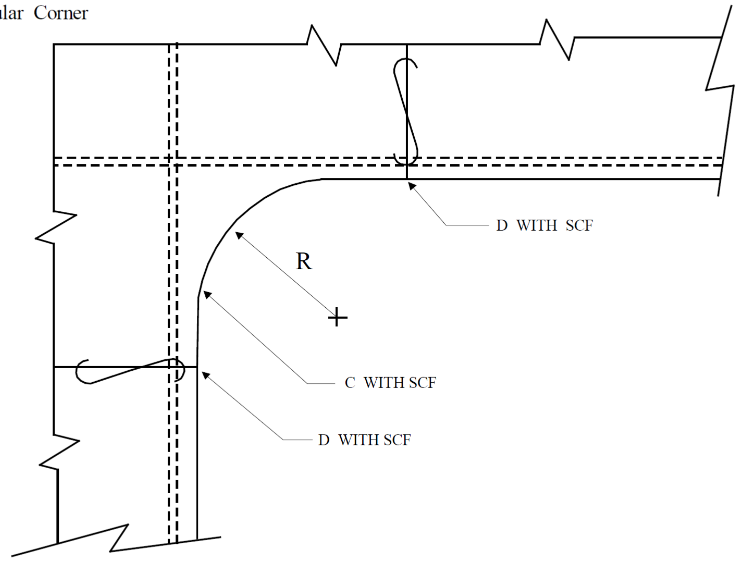
c Discontinuous Hatch Side Coaming



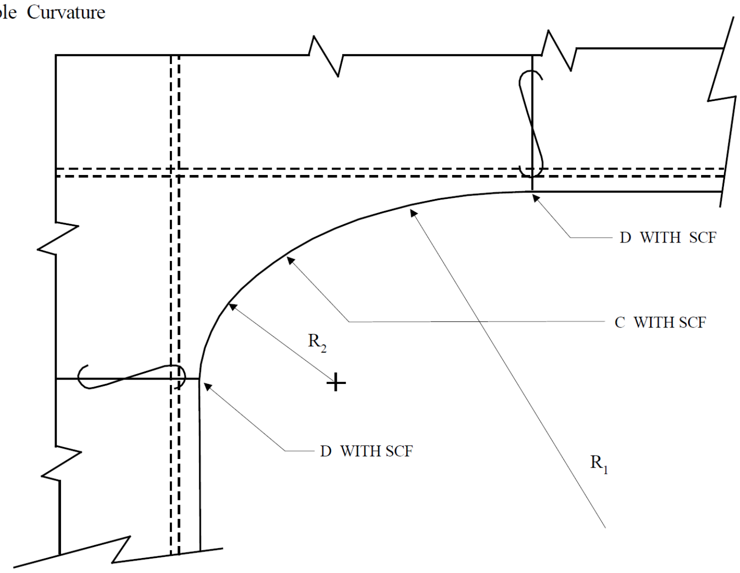


d Hatch Corners

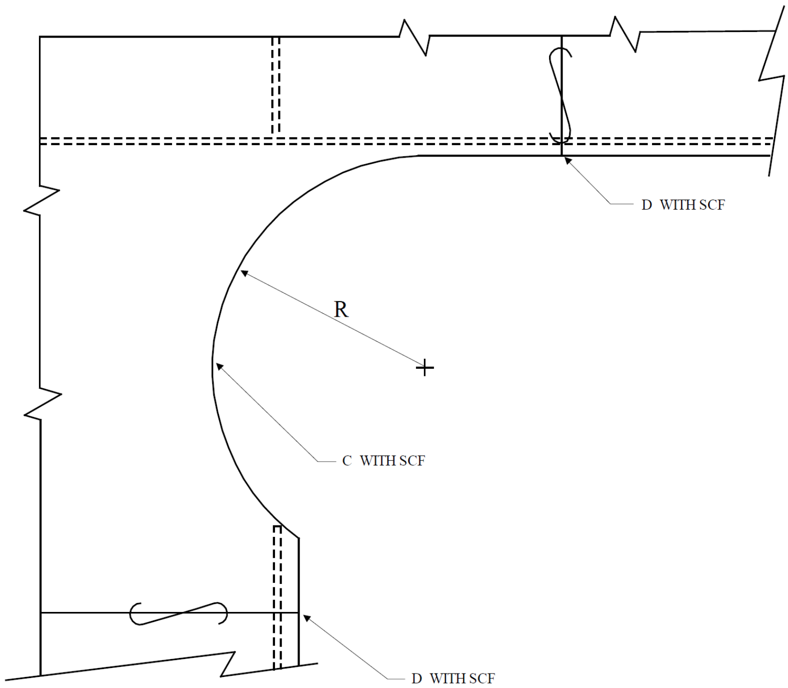
Circular Corner

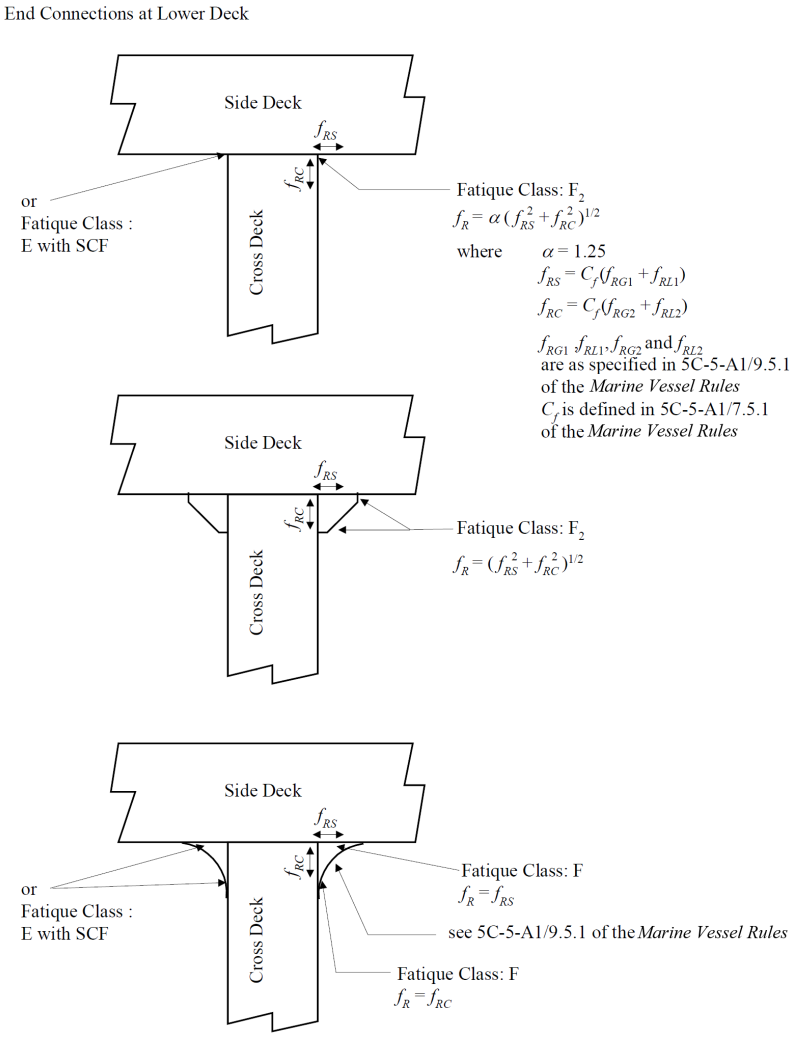


Double Curvature



Cut-out Radius





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 A1/5.7 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 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 A1/3.5.1 TABLE 1, "Fatigue Classification for Structural Details".

The structural detail classification in A1/3.5.1 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. 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 *(1 February 2021)*

The long-term stress distribution parameter, γ, is determined in accordance with 5C-5-A1/5.5 of the *Marine 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 A1/7 for load case pairs).

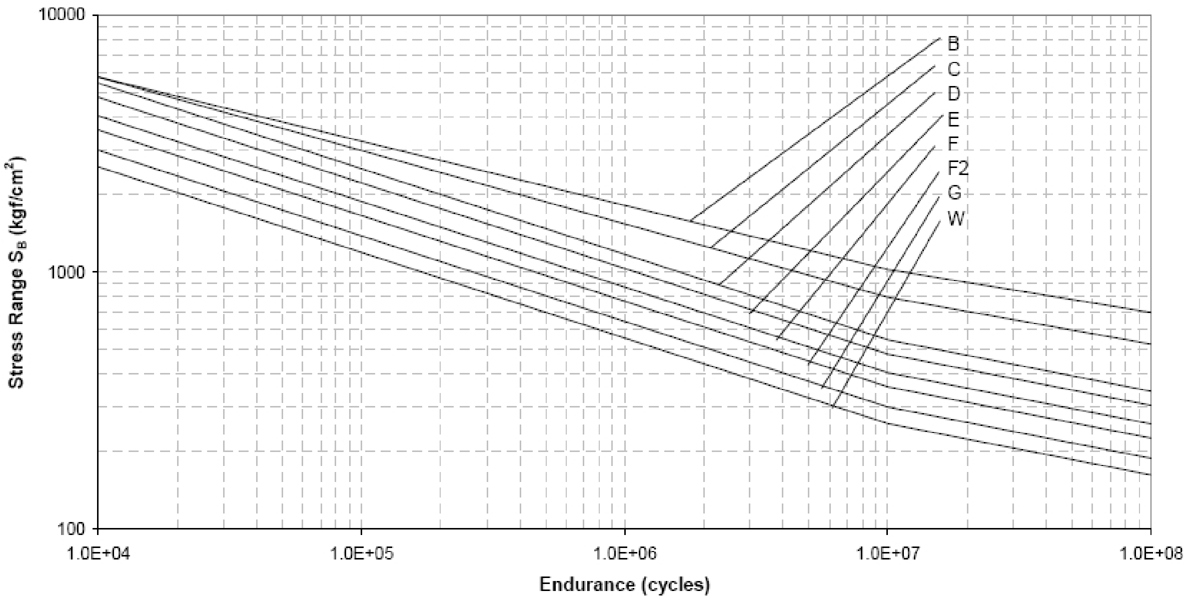
Assuming the long term distribution of stress ranges follow the Weibull distribution, the fatigue damage accumulated due to load pair jk is

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

where

N_T	=	number of cycles in the design life.	
	=	$\frac{f_0 D_L}{4\log L}$	
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 *Marine Vessel Rules*	
m, K_2	=	S-N curve parameters as defined in A1/5.7 FIGURE 1 of this document	
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	
	=	$\left(\frac{t}{22}\right)^n$	for $t \geq 22$ 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 5/5.3 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	
μ_{jk}	=	$1 - \left\{\frac{\Gamma_0\left(1+\frac{m}{\gamma}, \nu_{jk}\right) - \nu_{jk}^{-\Delta m/\gamma}\Gamma_0\left(1+\frac{m+\Delta m}{\gamma}, \nu_{jk}\right)}{\Gamma\left(1+\frac{m}{\gamma}\right)}\right\}$	
ν_{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:

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

Class	K_1	$\log_{10}K_1$	m	σ	K_2	$\log_{10}K_2$
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 *(2021)*

This Subsection provides 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), as well as 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 A1/7.5 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 *Marine Vessel Rules*.

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

3 Wave induced torsional moment and sign convention are defined in 5C-5-3/5.1.5 of the *Marine 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 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:

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

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 *Marine Vessel Rules*

f_{d1hi}, f_{d1hj}	=	wave-induced component of the primary stresses produced by hull girder horizontal bending, in N/cm² (kgf/cm², lbf/in²), for load case i and j of the selected pairs of combined load cases, respectively. See 5C-5-3/5.1.3 of the *Marine Vessel Rules*
f_{d1wi}, f_{d1wj}	=	wave-induced component of the primary stresses produced by hull girder torsion (warping stress) moment, in N/cm² (kgf/cm², lbf/in²), for load case i and j of the selected pairs of combined load cases, respectively. See 5C-5-3/5.1.5 of the *Marine 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 A1/7.5 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
	=	$\left[1 - 0.04(c/R)^{3/2}\right]$	for circular shapes with a cutout
	=	$\left[1 - 0.04(c/r_d)^{3/2}\right]$	for double curvature shapes with a cutout
	=	$\left[1 - 0.04(c/R_1)^{3/2}\right]$	for elliptical shapes with a cutout
α_s	=	adjustment factor for contour curvature	
	=	1.0	for circular shapes
	=	$0.33\left[1 + 2(r_{s1}/r_d) + 0.1(r_d/r_{s1})^2\right]$	for double curvature shapes
	=	$0.33\left[1 + 2(R_2/R_1) + 0.1(R_1/R_2)^2\right]$	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 A1/9.3.3 FIGURE 2.

r_{s1} = R for circular shapes in A1/9.3.3 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 A1/9.3.3 FIGURE 4, in mm (in.)

= R_2 for elliptical shapes in A1/9.3.3 FIGURE 5, in mm (in.)

r_{s2} = R for circular shapes in A1/9.3.3 FIGURE 3, in mm (in.)

= R_2 for double curvature shapes in A1/9.3.3 FIGURE 4, in mm (in.)

= ${R_2}^2/R_1$ for elliptical shapes in A1/9.3.3 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 A1/9.3.3 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 A1/9.3.3 FIGURE 3, in mm (in.)

= $R_2 + (R_1 - R_2)\cos\theta$ for double curvature shapes in A1/9.3.3 FIGURE 4, in mm (in.)

= $(R_1 + R_2)/2$ for elliptical shapes in A1/9.3.3 FIGURE 5, in mm (in.)

r_{e2} = R for circular shapes in A1/9.3.3 FIGURE 3, in mm (in.)

= $R_1 - (R_1 - R_2)\sin\theta$ for double curvature shapes in A1/9.3.3 FIGURE 4, in mm (in.)

= R_2 for elliptical shapes in A1/9.3.3 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} = $[1.0 - 0.02(\phi - \phi_1)]/\left[1 - 0.015(\phi - \phi_1) + 0.00014(\phi - \phi_1)^2\right]$ for $\theta < 55$

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

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

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 $\theta \geq 55$

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

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

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

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:

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

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

$0.3 \leq R_2/R_1 \leq 0.9$ 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:

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

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
	=	$0.33\left[1 + 2(r_{s1}/r_d) + 0.1(r_d/r_{s1})^2\right]$	for double curvature shapes
	=	$0.33\left[1 + 2(R_2/R_1) + 0.1(R_1/R_2)^2\right]$	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 A1/9.3.3 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 A1/9.3.3 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:

ℓ_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,

ℓ_{i1} = $1.75 r_{e1}$ mm (in.)

ℓ_{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 A1/9.3.3 FIGURE 3, in mm (in.)
	=	$R_2 + (R_1 - R_2)\cos\theta$	for double curvature shapes in A1/9.3.3 FIGURE 4, in mm (in.)
	=	$(R_1 + R_2)/2$	for elliptical shapes in A1/9.3.3 FIGURE 5, in mm (in.)
r_{e2}	=	R	for circular shapes in A1/9.3.3 FIGURE 3, in mm (in.)
	=	$R_1 - (R_1 - R_2)\sin\theta$	for double curvature shapes in A1/9.3.3 FIGURE 4, in mm (in.)
	=	R_2	for elliptical shapes in A1/9.3.3 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:

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

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)

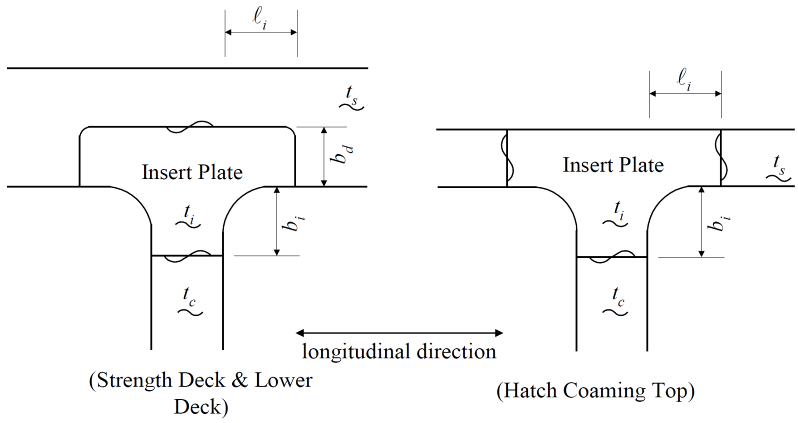
K_t = $0.25(1 + 3t_i/t_a) \le 1.25$

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



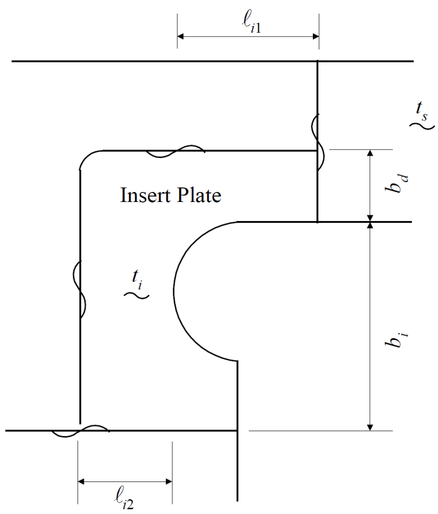


FIGURE 3
Circular Shape

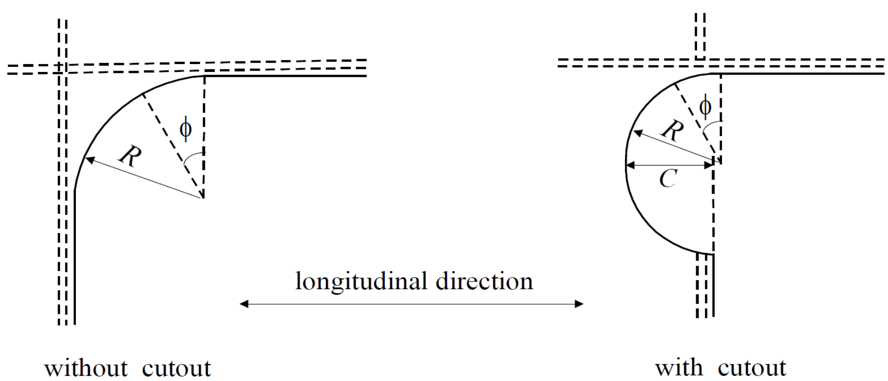


FIGURE 4
Double Curvature Shape

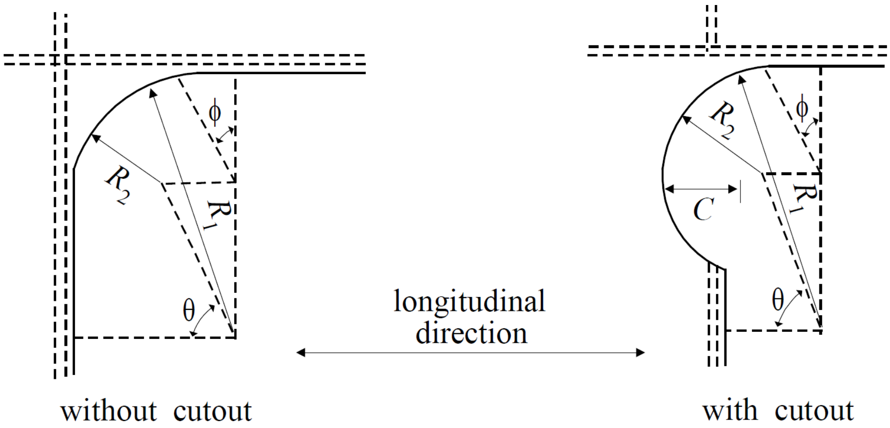


FIGURE 5
Elliptical Shape

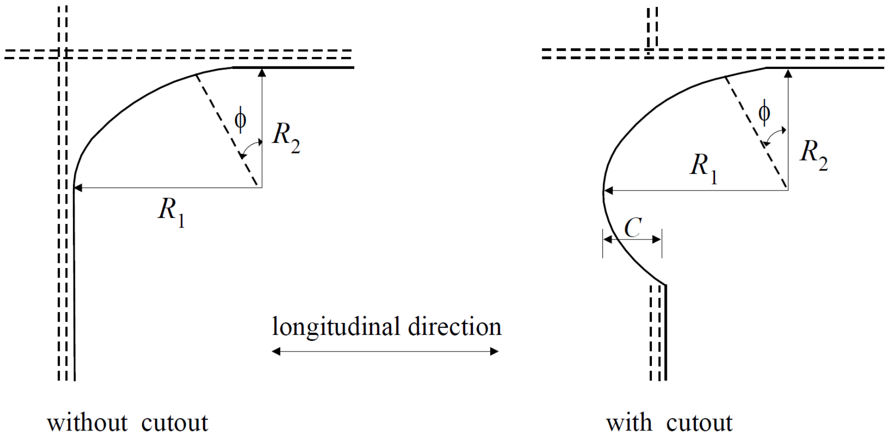
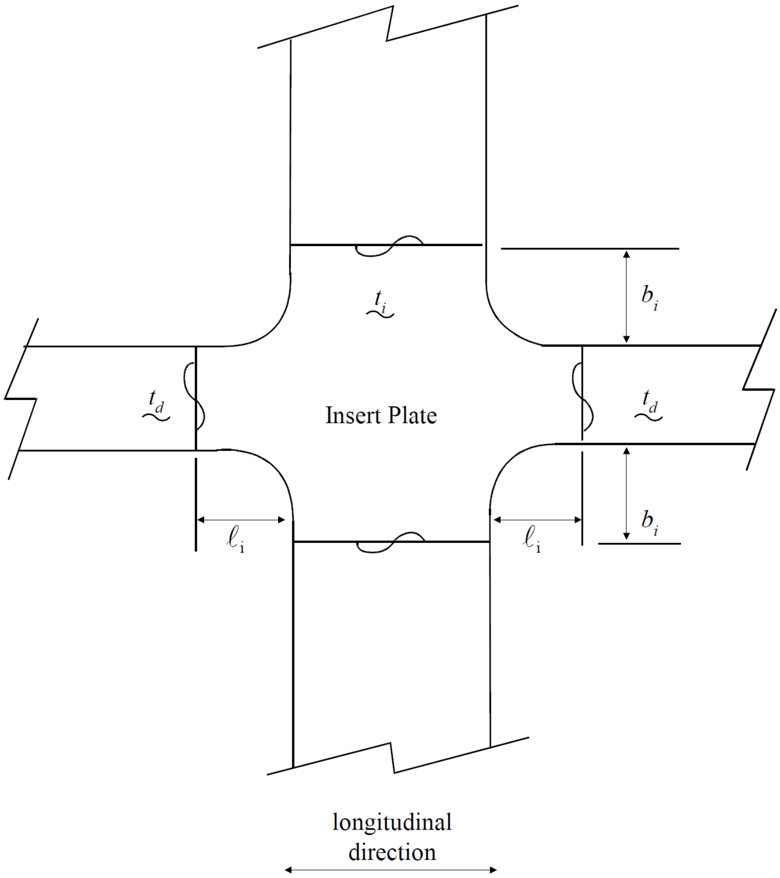


FIGURE 6
Hatch Corner for Longitudinal Deck Girder



11 Hot Spot Stress Approach with Finite Element Analysis

11.1 Introduction *(2021)*

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 the 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 for such a weld improvement during 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 extend below the plate surface in order to remove toe defects. 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 (0.02 in.) 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 (0.04 in.). In no circumstances is the grinding depth to exceed 2 mm or 7% of the plate gross thickness, whichever is smaller. Grinding is 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 (0.008 in.). Maximum depth is generally not to exceed 0.5 mm (0.02 in.).

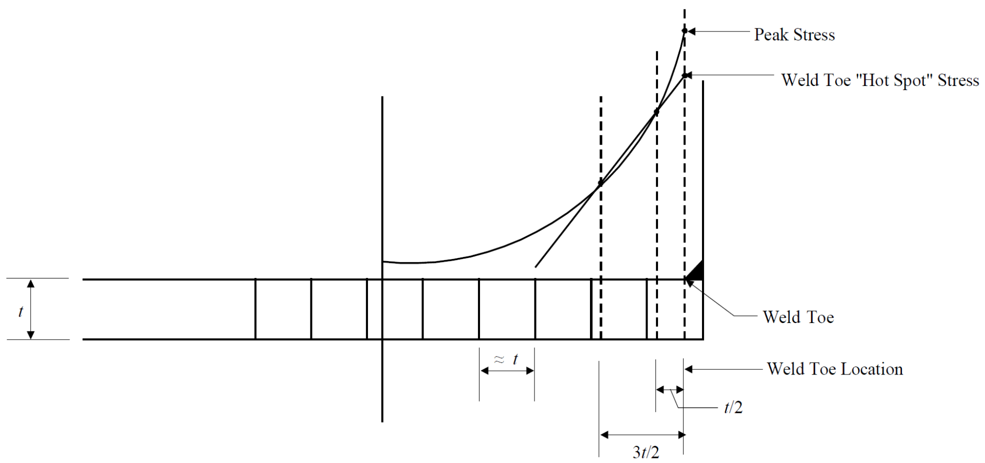
Provided these recommendations are followed, an improvement in fatigue life by grinding or ultrasonic peening up to a maximum of 2 times may be granted.

11.3 Calculation of Hot Spot Stress at a Weld Toe

A1/11.3 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 3 $t/2$ 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 A1/11.3.4 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.:

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

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:

$$S_L = C_1S_1 + C_2S_2 + C_3S_3 + C_4S_4$$

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.:

$$S_R = C_1S_1 + C_2S_2 + C_3S_3 + C_4S_4$$

11.3.4 *(2021)*

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

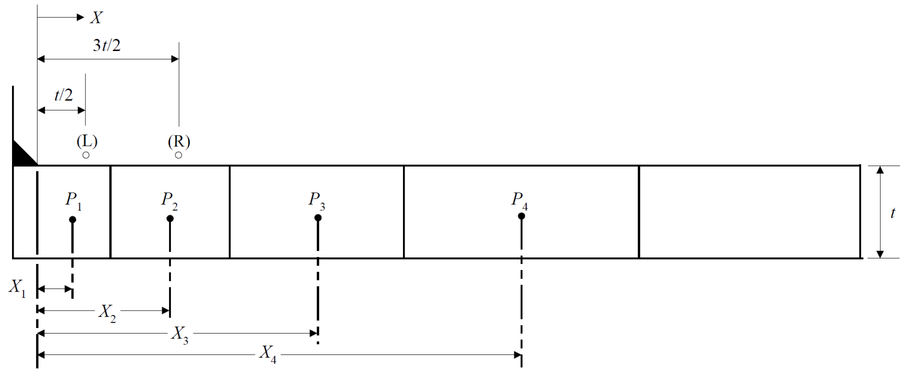
$$S_0 = (3S_L - S_R)/2$$

Note:

The algorithm presented in the foregoing involves two types of operations. The first is the use of 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 the 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 Cutout or Bracket *(2021)*

In order to determine the hot spot stress at the edge of cutout 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 (0.0015 in^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 cutout 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 *(1 July 2024)*

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 *Marine Vessel Rules*

M_w = maximum wave-induced bending moment, in kN-m (tf-m), in accordance with 5C-5-A2a/3.5.2 of the *Marine Vessel Rules* for container carriers.

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 *(1 July 2024)*

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.

The vertical hull girder residual bending moment capacity is to be calculated according to the requirements of 5C-1-8/5.5 of the *Marine Vessel Rules*, in which M_U is to be replaced with M_R.

APPENDIX 3

Procedure for the Approval of Manufacturers of Rolled Brittle Crack Arrest Hull Structural Steel *(2021)*

1 Scope

The applicable general requirements defined in the ABS *Rules for Materials and Welding (Part 2)* are to be applied.

This Appendix provides supplementary requirements for the approval of manufacturers of rolled H36/H40/H47 BCA steel plates with thickness from 50 mm (2 in.) to 100 mm (4 in.) used for large container carriers.

3 Approval Application *(1 July 2024)*

The manufacturer is to submit the following documents together with those required in Section 2-A4-2 of the ABS *Rules for Materials and Welding (Part 2)*.

The materials specification is to include the chemical composition, manufacturer process and production control, especially for the parameters to influence the BCA properties.

In addition, the following documents are to be provided:

- Approval test program for the brittle crack arrest properties.
- In-house test reports of the large scale BCA properties of the steels intended for approval.
- Production test procedure for small scale BCA properties.

Other approval tests may be required in the case of newly developed types of steel, outside the scope of Part 2, Chapter 1, or when deemed necessary by ABS.

5 Selection of the Test Products

The selected test products are to cover and qualify the full range of product types, grades, dimensions, etc., for the requested approval.

The testing products are to represent the maximum thickness for approval. If the target composition is adjusted with the thickness, the maximum thickness for each specified chemical composition is to be tested.

For each selected material grade, type and delivery condition, testing is to be carried out on plates from at least two heats representing the maximum thickness for which approval is requested.

7 Approval Tests

7.1 General *(1 July 2024)*

The qualification tests are to be performed in accordance with Section 2-A4-2 of the ABS *Rules for Materials and Welding (Part 2)*. The additional requirements are given in A3/7.1 to A3/7.17 of this document.

The number of test samples and test specimens may be increased when deemed necessary, based on brittle crack arrest properties of the steel intended for approval.

A complete requalification will be necessary for steel works applying for the additional brittle crack arrest properties for H36, H40 and H47 steels. A detailed manufacturing process is to be submitted to ABS for review to agree the extent of qualification testing.

Clauses in 2-A4-2/5.1 iii) and iv) of the ABS *Rules for Materials and Welding (Part 2)* do not apply to BCA steel, see commentary below.

Commentary:

iii) Approval for any grade of steel does not cover approval for any lower grade in the same strength level.

iv) For BCA steel, approval of one strength level does not cover the approval of the strength level immediately below.

End of Commentary

7.3 Through Thickness Tensile Test

For all steel grades, through thickness tensile test is to meet Z35 materials quality defined in 2-1-1/17 of the ABS *Rules for Materials and Welding (Part 2)*.

7.5 Charpy Impact Test

For BCA steel grades, all Charpy transition curves in the longitudinal direction are to be obtained for the as-rolled and strain-aged condition from one quarter ($t/4$) and half ($t/2$) of the thickness. The lowest testing temperature is to be below the transition temperature.

7.7 Drop Weight Test

For BCA steel grades, a Nil Ductility Transition Temperature (NDTT) is to be determined using a drop weight test per ASTM E208.

Specimens are to be taken from the surface, $t/4$ and $t/2$ unless agreed upon by ABS.

Test conditions such as specimen type, drop energy and photographs of the test specimens are to be provided.

7.9 Large-Scale Testing for BCA Properties *(1 July 2024)*

Large-scale brittle crack arrest tests are to be carried out in accordance with the following requirements.

For BCA steel grades, the test specimen is to be the maximum thickness of the steel plate requested for approval.

The thickness of the test specimens of the brittle crack arrest tests is to be the full thickness of the test plates.

The test specimens of the brittle crack arrest tests are to be taken with their longitudinal axis parallel to the final rolling direction of the test plates.

The loading direction of brittle crack arrest tests is to be parallel to the final rolling direction of the test plates.

The test specimens and repeat test specimens are to be taken from the same steel plate.

Where the brittle crack arrest properties are evaluated by K_{ca}, and the brittle crack arrest test result fails to meet the requirement, further brittle crack arrest tests may be carried out. All results are to be reported to ABS Materials department with an explanation for the non-compliance.

If brittle crack arrest properties are evaluated by K_{ca}, the brittle crack arrest test method is to be in accordance with Appendix 4. The accepted K_{ca} is greater than 6000 N/mm$^{3/2}$ (173 ksi-in$^{1/2}$) at –10°C (14°F) for BCA1 and greater than 8000 N/mm$^{3/2}$ (230 ksi-in$^{1/2}$) at –10°C (14°F) for BCA2.

If the brittle crack arrest properties are evaluated by CAT, the test method is to be in accordance with Appendix 5 or other standards approved by ABS. The accepted CAT is to be less than –10°C (14°F) for BCA1 and is to be approved by ABS for BCA2.

7.11 Small-Scale Testing for BCA Properties during Production

The alternative small-scale (Double Tension) BCA test could be proposed as a replacement of a full-scale BCA test for production. The steel works is to prepare and submit a test plan for review and approval.

Adequate testing is to be performed to correlate the full-scale tests to the alternative small-scale tests. Data supporting the correlation is to be submitted along with the extent of small-scale testing during production, for ABS review and agreement.

7.13 Weldability Testing *(1 July 2024)*

For H47 Non-BCA and BCA steel grades, a weldability test is required for plate at maximum thickness.

The weldability test is to cover high and low heat input. The high heat input is to be 5 kJ/mm (127 kJ/in.) or maximum recommended by the manufacturer. The low heat input is to be 1.5 kJ/mm (38 kJ/in.) or lower.

The Charpy V-notch impact test is to meet the requirements specified in Section 4, Table 4 of this document. Test location is to refer to the ABS *Rules for Materials and Welding (Part 2)* and depends upon the manufacturing process, thickness and welding configuration.

7.15 Y-Shape Weld Crack Test (Hydrogen Crack Test) *(1 July 2024)*

The Y Shape Weld Crack Test method is to be in accordance with recognized national standards such as ISO 17642-2. Acceptance criteria are to be in accordance with ABS practice.

7.17 Crack Tip Opening Displacement Test

Crack Tip Opening Displacement (CTOD) tests are required on the steel plate and the weldment for qualification with accordance with ISO 12135, BS7448, ASTM E1820 or equivalent.

CTOD test specimens for steel plate are to be taken from full thickness with the notch in the through thickness direction.

CTOD fracture toughness testing for the weldment is to refer to 2-A4-2/5.11.3iv) of the ABS *Rules for Materials and Welding (Part 2)*. CTOD testing of Grain Coarse Heat Affected Zone (GCHAZ) is required for both the highest and lowest heat input.

Test temperature is to be performed at –10°C (14°F) or design temperature, whichever is lower.

9 Results *(1 July 2024)*

In addition to the results required in the ABS *Rules for Materials and Welding (Part 2)* and Approval Tests in this Appendix, the brittle crack arrest properties are to be reported. In the cases where these properties are evaluated by K_{ca} or CAT, the manufacturer is to submit to ABS test reports consistent with Appendix 4 for K_{ca} and Appendix 5 for CAT of this document.

11 Approval and Certification *(1 July 2024)*

Upon receiving satisfactory results from the survey and tests, approval is granted for grades having the suffix "BCA1" or "BCA2". (e.g., EH40-BCA1, EH47-BCA1, EH47-BCA2, etc.)

13 Renewal of Approval

Renewal of approval is to be consistent with the ABS *Rules for Materials and Welding (Part 2)*. In addition to the required tests for renewal, test results for brittle crack arrest properties must also be included in the renewal application.

Chemical composition, mechanical properties, brittle crack arrest properties (e.g., brittle crack arrest test results or small-scale test results) and nominal thickness are to be described in the form of histograms or statistics.

APPENDIX 4
Testing Method for the Brittle Crack Arrest Toughness, K_{ca} *(2021)*

1 Scope *(1 July 2024)*

ISO 20064:2019 provides a test method for the determination of brittle crack arrest toughness of steel by using wide plates with a temperature gradient.

This Appendix specifies the test procedure for brittle crack arrest toughness (i.e., K_{ca}) of steel using fracture mechanics parameters and the determination method of K_{ca} at a specific temperature which are specified in ISO 20064:2019. Additionally, this Appendix specifies the evaluation method of K_{ca} of a test plate. This Appendix is applicable to hull structural steels with thicknesses of 50 mm (2 in.) to 100 mm (4 in.) specified in this document.

3 Test Procedures *(1 July 2024)*

The test procedures including testing equipment, test specimens, test methods, determination of arrest toughness, reporting of test results, etc. are to be in accordance with ISO 20064:2019. As a method for initiating a brittle crack, a secondary loading mechanism can be used in accordance with Annex D of ISO 20064:2019, except that the first sentence in Annex B.2.4 of ISO 20064:2019 is revised to "Obtain the value $\{K_{ca}/[K_0 * \exp(-c/T_{caK})]\}$ for each data point".

5 Determination of K_{ca} at a Specific Temperature and the Evaluation *(1 July 2024)*

5.1 Method *(1 July 2024)*

The method for conducting multiple tests to obtain K_{ca} value at a specific temperature is to be in accordance with annex B of ISO 20064:2019.

5.3 Evaluation *(1 July 2024)*

The straight-line approximation of an Arrhenius plot for valid K_{ca} data by the interpolation method is to comply with either *i)* or *ii)* below:

i) The evaluation temperature of K_{ca} [i.e., –10°C (14°F)] is located between the upper and lower limits of the arrest temperature, with the K_{ca} corresponding to the evaluation temperature not lower than the required K_{ca} [e.g., 6000 N/mm$^{3/2}$ (173 ksi-in$^{1/2}$) or 8,000 N/mm$^{3/2}$ (230 ksi-in$^{1/2}$)], as shown in Appendix 4, Figure 1.

ii) The temperature corresponding to the required K_{ca} [e.g., 6000 N/mm$^{3/2}$ (173 ksi-in$^{1/2}$) or 8,000 N/mm$^{3/2}$ (230 ksi-in$^{1/2}$)] is located between the upper and lower limits of the arrest temperature, with the temperature corresponding to the required K_{ca} not higher than the evaluation temperature [i.e., –10°C (14°F)], as shown in Appendix 4, Figure 2.

If both *i)* and *ii)* above are not satisfied, additional tests are to be conducted to satisfy this condition.

FIGURE 1
Example for Evaluation of K_{ca} at –10°C

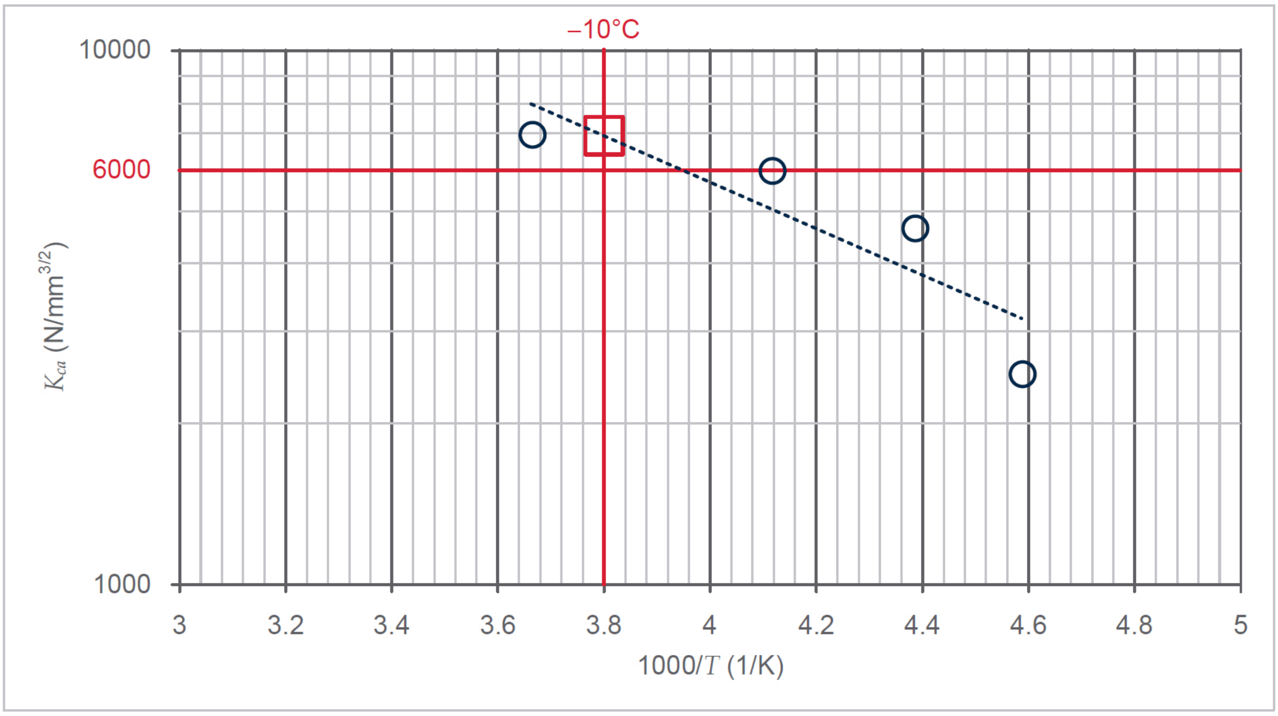
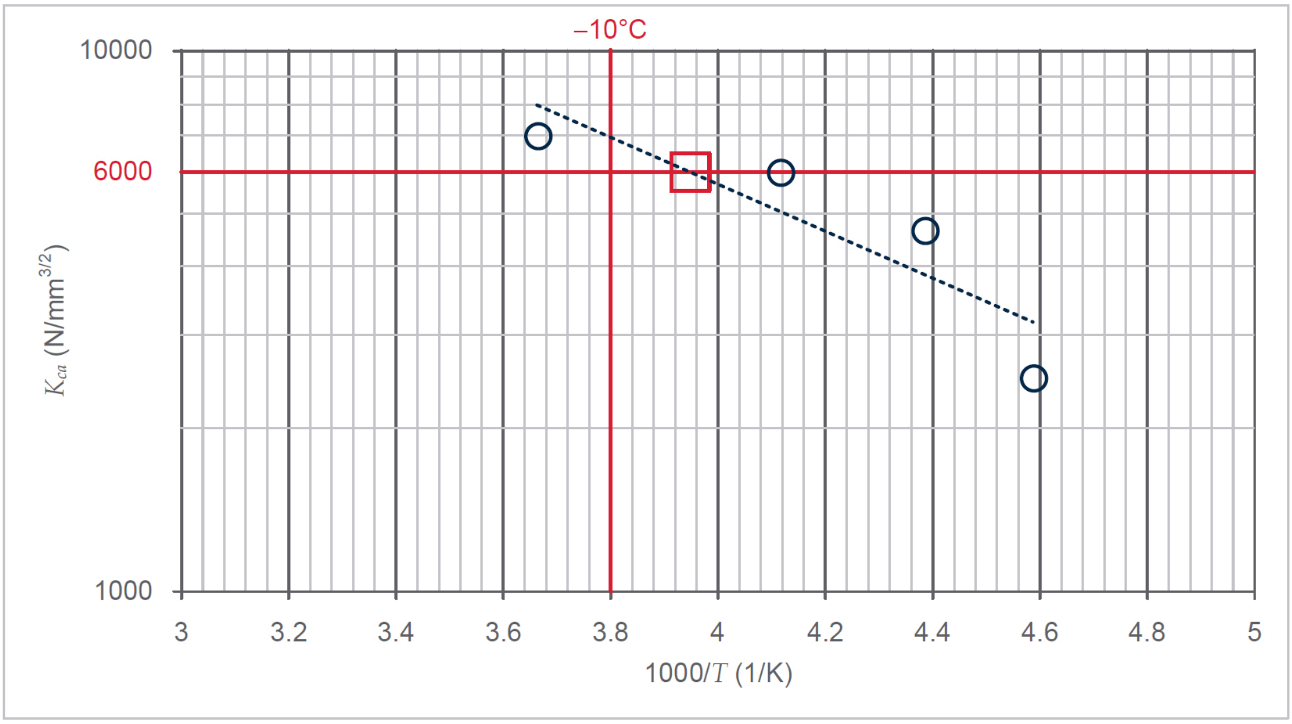


FIGURE 2
Example for Evaluation of Temperature Corresponding to the Required K_{ca}



APPENDIX 5

Outline of Requirements for Undertaking Isothermal Crack Arrest Temperature (CAT) Test *(2021)*

1 Scope of Application *(1 July 2024)*

This Appendix specifies the requirements for test procedures and test conditions using the isothermal crack arrest test to determine a valid test result. The crack arrest temperature (CAT) is to be established under isothermal conditions.

This Appendix is applicable to the plate thicknesses of 50 mm (2 in.) to 100 mm (4 in.) using CAT as a test method for BCA designation as specified in Section 3, Table 9. Unless otherwise specified in this Appendix, the other test parameters are to be in accordance with ISO 20064.

The manufacturer is to submit the test procedure to ABS for review prior to testing.

The BCA property described by CAT is to meet the requirements in Section 3, Table 9.

3 Symbols, Units, and Significance *(1 July 2024)*

The following symbols, units, and significance specific to the isothermal tests supplement ISO 20064.

Symbol	*Unit*	*Significance*
t	mm (in.)	Test specimen thickness
L	mm (in.)	Test specimen length
W	mm (in.)	Test specimen width
a_{MN}	mm (in.)	Machined notch length on specimen edge
L_{SG}	mm (in.)	Side groove length on side surface from the specimen edge. L_{SG} is defined as a groove length with constant depth except a curved section in depth at side groove end.
d_{SG}	mm (in.)	Side groove depth in section with constant depth
L_{EB-min}	mm (in.)	Minimum length between specimen edge and electron beam re-melting zone front
$L_{EB-s1,-s2}$	mm (in.)	Length between specimen edge and electron beam re-melting zone front appeared on both specimen side surfaces
L_{LTG}	mm (in.)	Local temperature gradient zone length for brittle crack runway
a_{arrest}	mm (in.)	Arrested crack length
T_{target}	°C (°F)	Target test temperature

Symbol	*Unit*	*Significance*
T_{test}	°C (°F)	Defined test temperature
T_{arrest}	°C (°F)	Target test temperature at which valid brittle crack arrest behavior is observed
σ	N/mm^2 (ksi)	Applied test stress at cross section of $W \times t$
SMYS	N/mm^2 (ksi)	Specified minimum yield strength of the tested steel grade to be approved
CAT	°C (°F)	Crack arrest temperature, the lowest temperature, T_{arrest}, at which running brittle crack is arrested

5 Testing Equipment *(1 July 2024)*

The test equipment to be used is to be of the hydraulic type of sufficient capacity to provide a tensile load equivalent to $^2/_3$ of SMYS of the steel grade to be approved. The temperature control system is to be equipped to maintain the temperature in the specified region of the specimen within ±2°C (±3.6°F) from T_{target}.

Methods for initiating the brittle crack may be of drop weight type, air gun type, or double tension tab plate type.

The detailed requirements for testing equipment are to be in accordance with ISO 20064.

7 Testing Specimens

7.1 Impact Type Crack Initiation *(1 July 2024)*

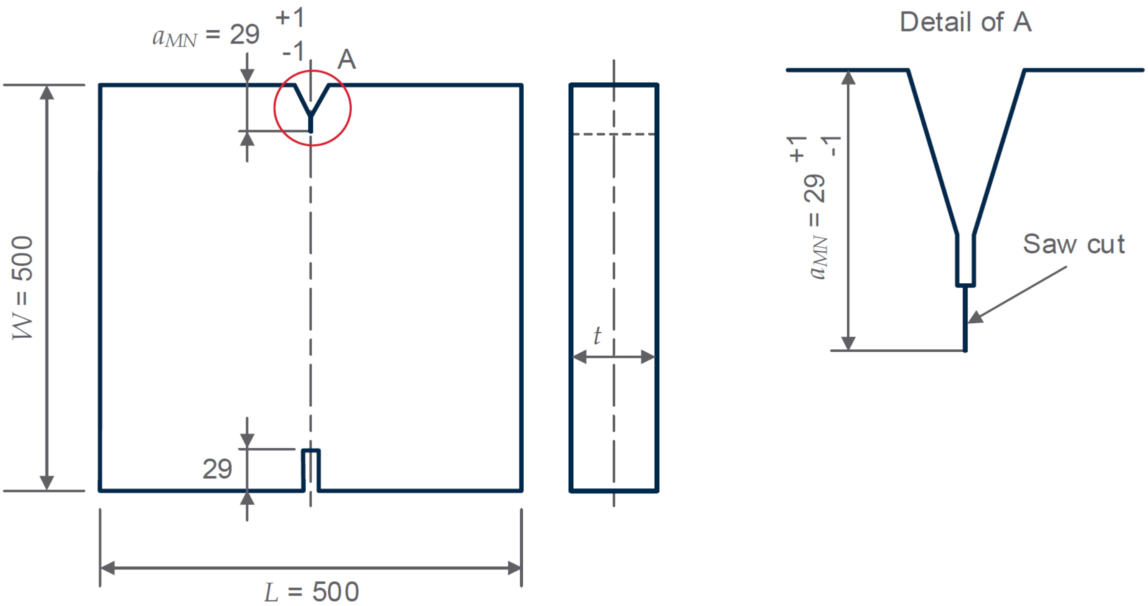
Test specimens are to be in accordance with ISO 20064, unless otherwise specified in this Appendix.

Specimen dimensions are shown in Appendix 5, Figure 1. The test specimen width, W, is to be 500 mm (20 in.). The test specimen length, L, is to be equal to or greater than 500 mm (20 in.).

V-shape notch for brittle crack initiation is machined on the specimen edge of the impact side. The whole machined notch length is to be equal to 29 mm (1.16 in.) with a tolerance range of ±1 mm (±0.04 in.).

Requirements for side grooves are described in A5/7.7.

FIGURE 1
Test Specimen Dimensions for an Impact Type Specimen *(2021)*



Note:

1 Saw cut notch radius may be machined in the range 0.1 mm *R* (0.004 in. *R*) and 1 mm *R* (0.04 in. *R*) in order to control a brittle crack initiation at test.

7.3 Double Tension Type Crack Initiation *(1 July 2024)*

Reference is to be made to annex D in ISO 20064 for the shape and sizes in secondary loading tab and secondary loading method for brittle crack initiation.

In a double tension type test, the secondary loading tab plate may be subject to further cooling to enhance an easy brittle crack initiation.

7.5 Embrittled Zone Setting

An embrittled zone is to be applied to provide the initiation of a running brittle crack. Either Electron Beam Welding (EBW) or Local Temperature Gradient (LTG) may be adopted to facilitate the embrittled zone.

In EBW embrittlement, electron beam welding is applied along the expected initial crack propagation path, which is the centerline of the specimen in front of the machined V-notch.

Complete penetration through the specimen thickness is required along the embrittled zone. One side EBW penetration is preferable, but dual side EB penetration may be also adopted when the EBW power is not enough to achieve complete penetration by one side EBW.

The EBW embrittlement is to be prepared before specimen contour machining.

In EBW embrittlement, the zone is to be of an appropriate quality.

Note: EBW occasionally behaves in an unstable manner at the start and end points. The EBW line is to start from the embrittled zone tip side to the specimen edge with an increasing power control or go/return manner at the start point to keep the EBW stable.

In the LTG system, the specified local temperature gradient between machined notch tip and isothermal test region is regulated after isothermal temperature control. LTG temperature control is to be achieved just before brittle crack initiation, nevertheless the steady temperature gradient through the thickness is to be verified.

7.7 Side Grooves *(1 July 2024)*

Side grooves on the side surface can be machined along the embrittled zone to keep brittle crack propagation straight. Side grooves are to be machined in the specified cases as follows.

In EBW embrittlement, side grooves are not necessarily mandatory. Use of EBW avoids the shear lips. However, when shear lips are evident on the fractured specimen (e.g., shear lips over 1 mm (0.04 in.) in thickness in either side), then side grooves are to be machined to suppress the shear lips.

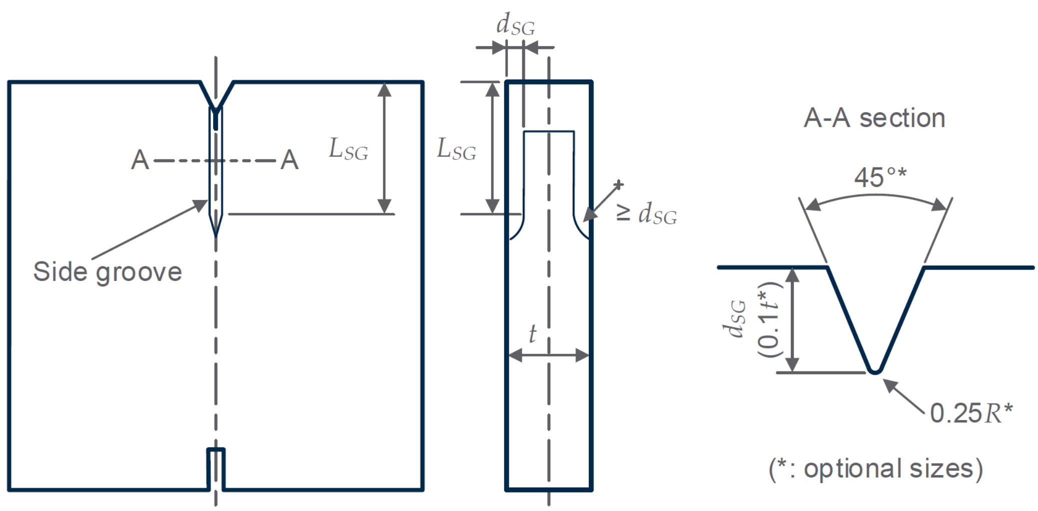
In LTG embrittlement, side grooves are mandatory. Side grooves with the same shape and size are to be machined on both side surfaces.

The length of side groove, L_{SG} is to be no shorter than the sum of the required embrittled zone length in mm (in.).

When side grooves would be introduced, the side groove depth, the tip radius, and the open angle are not specified, but should be adequately selected in order to avoid any shear lips over 1 mm (0.04 in.) thickness in either side. An example of side groove dimensions is shown in Appendix 5, Figure 2.

The side groove end is to be machined to make a groove depth gradually shallow with a curvature larger than or equal to groove depth, d_{SG}. Side groove length, L_{SG}, is defined as a groove length with constant depth except for a curved section in depth at the side groove end.

FIGURE 2
Side Groove Configuration and Dimensions *(2021)*



7.9 Nominal Length of Embrittled Zone *(1 July 2024)*

The length of the embrittled zone is to be at least 150 mm (6 in.).

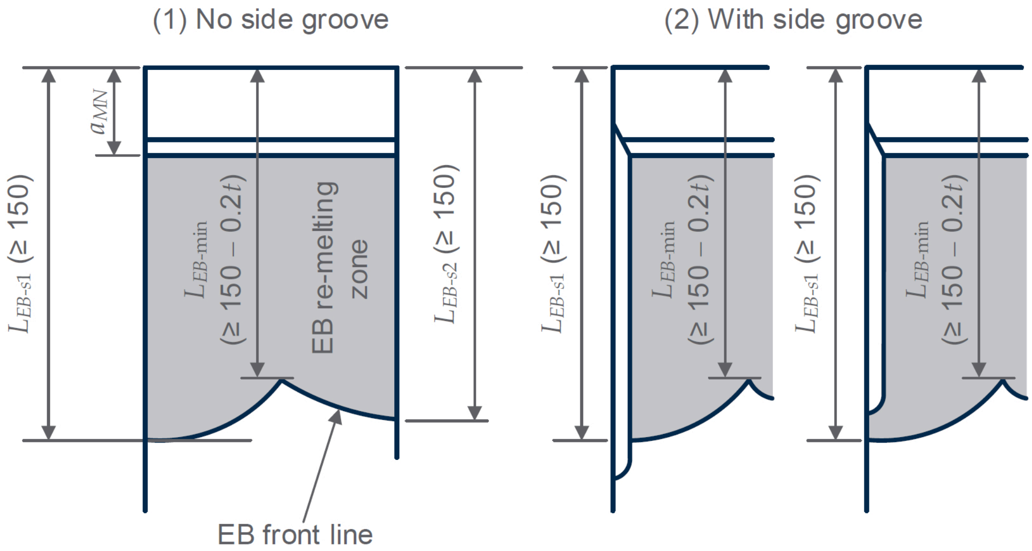
The EBW zone length is calculated by three measurements on the fracture surface after testing, as shown in Appendix 5, Figure 3: L_{EB-min} between specimen edge and EBW front line, and L_{EB-s1} and L_{EB-s2}.

The minimum length between the specimen edge and EBW front line, L_{EB-min}, is to be no smaller than 150 mm (6 in.). However, it can be acceptable even if L_{EB-min} is no smaller than 150 mm – 0.2t (6 in. – 0.2t), where t is the specimen thickness. When L_{EB-min} is smaller than 150 mm (6 in.), a temperature safety margin is to be considered into T_{test}.

Another two measurements are the lengths between the specimen edge and EBW front line on both side surfaces, as denoted with L_{EB-s1} and L_{EB-s2}. Both L_{EB-s1} and L_{EB-s2} are to be no smaller than 150 mm (6 in.).

In the LTG system, L_{LTG} is set as 150 mm (6 in.).

FIGURE 3
Definition of EBW Length *(2021)*



7.11 Tab Plate/Pin Chuck Details and Welding of Test Specimen to Tab Plates *(1 July 2024)*

The configuration and size of tab plates and pin chucks are to be as defined in ISO 20064. The welding distortion in the integrated specimen, which is welded with specimen, tab plates, and pin chucks, is also to be within the requirement in ISO 20064.

9 Test Method

9.1 Preloading

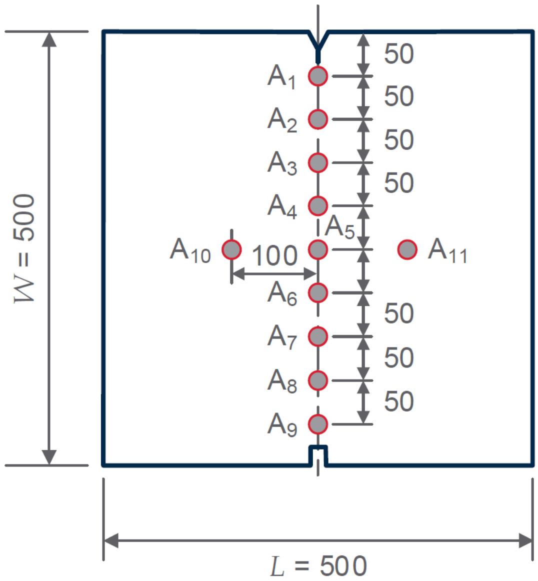
Preloading at room temperature can be applied to avoid unexpected brittle crack initiation at test. The applied load value is not to be greater than the test stress. Preloading can also be applied at higher temperature than ambient temperature when brittle crack initiation is expected in the preloading process. However, the specimen is not to be subjected to a temperature higher than 100°C (212°F).

9.3 Temperature Measurement and Control

A temperature control plan showing the number and position of thermocouples is to be as follows.

Thermocouples are to be attached to both sides of the test specimen at a maximum interval of 50 mm (2 in.) in the whole width and in the longitudinal direction at the test specimen center position (0.5W) within the range of ±100 mm (4 in.) from the centerline in the longitudinal direction (refer to Appendix 5, Figure 4).

FIGURE 4
Locations of Temperature Measurement *(2021)*



9.3.1 For EBW Embrittlement

The temperatures of the thermocouples across the range of $0.3W$~$0.7W$ in both width and longitudinal directions are to be controlled within ±2°C (±3.6°F) of the target test temperature, T_{target}.

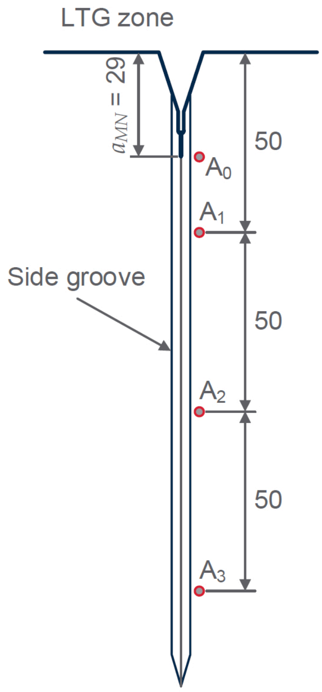
When all measured temperatures across the range of $0.3W$~$0.7W$ have reached T_{target}, steady temperature control is to be kept at least for $10 + 0.1 \times t$ mm ($0.4 + 0.004 \times t$ in.) minutes to provide a uniform temperature distribution into mid-thickness prior to applying the test load.

The machined notch tip can be locally cooled to easily initiate the brittle crack. Nevertheless, the local cooling is not to disturb the steady temperature control across the range of $0.3W$~$0.7W$.

9.3.2 For LTG Embrittlement

In the LTG system, in addition to the temperature measurements shown in Appendix 5, Figure 4, additional temperature measurement at the machine notch tip, A_0, and B_0 is required. Thermocouple positions within the LTG zone are shown in Appendix 5, Figure 5.

FIGURE 5
Detail of LTG Zone and Additional Thermocouple A_0 *(2021)*



The temperatures of the thermocouples across the range of $0.3W$~$0.7W$ in both width and longitudinal directions are to be controlled within ±2°C (±3.6°C) of the target test temperature, T_{target}. However, the temperature measurement at $0.3W$ (location of A_3 and B_3) is to be in accordance with the following requirements:

T at A_3, T at B_3 < T_{target} – 2°C

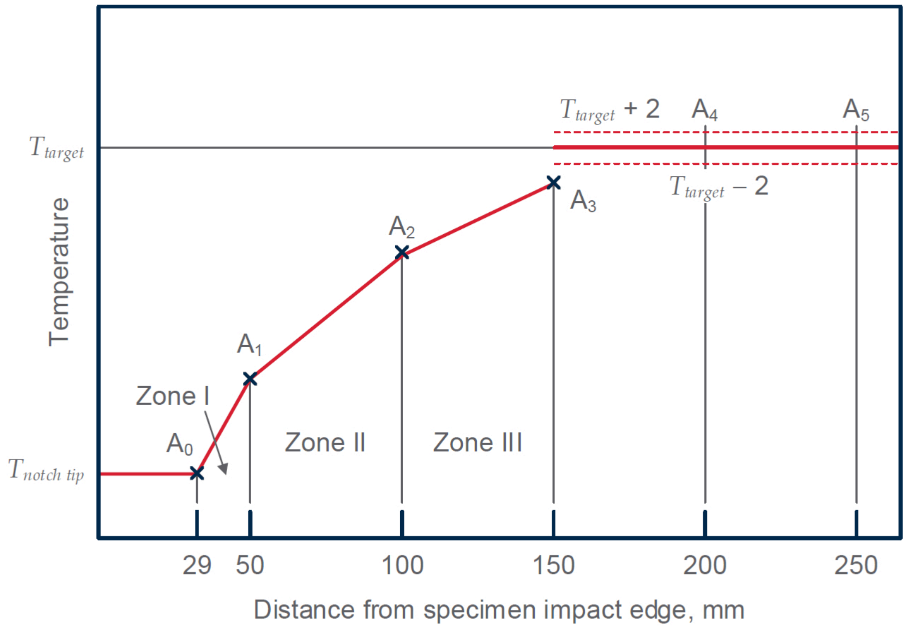
T at A_2 < T at A_3 – 5°C

T at B_2 < T at B_3 – 5°C

Once all measured temperatures across the range of $0.3W$~$0.7W$ have reached T_{target}, steady temperature control is to be kept at least for 10 + 0.1 × t mm (0.4 + 0.004 × t in.) minutes to provide a uniform temperature distribution into mid-thickness, then the test load is applied.

LTG is controlled by local cooling around the machined notch tip. The LTG profile is to be recorded by the temperature measurements from A_0 to A_3 shown in Appendix 5, Figure 6.

FIGURE 6
Schematic Temperature Gradient Profile in LTG Zone *(2021)*



The LTG zone is established by temperature gradients in three zones: Zone I, Zone II and Zone III. The acceptable range for each temperature gradient is listed in Appendix 5, Table 1.

TABLE 1
Acceptable LTG Range *(2021)*

Zone	*Location from Edge*	*Acceptable Range of Temperature Gradient*
Zone I	29 mm – 50 mm (1.16 in. – 2 in.)	2.00°C/mm – 2.30°C/mm (90°F/in. – 103.5°F/in.)
Zone II	50 mm – 100 mm (2 in. – 4 in.)	0.25°C/mm – 0.60°C/mm (0.45°F/in. – 1.08°F/in.)
Zone III *	100 mm – 150 mm (4 in. – 6 in.)	0.10°C/mm – 0.20°C/mm (0.18°F/in. – 0.36°F/in.)

Note: * The Zone III arrangement is mandatory.

The temperature profile in the LTG zone mentioned above is to be held for at least for $10 + 0.1 \times t$ mm ($0.4 + 0.004 \times t$ in.) minutes to provide a uniform temperature distribution into mid-thickness before brittle crack initiation.

The acceptance of LTG in the test is to be decided from Appendix 5, Table 1 based on the measured temperatures from A_0 to A_3.

9.3.3 For Double Tension Type Crack Initiation Specimen

Temperature control and holding time at steady state are to be the same as the case of EBW embrittlement or the case of LTG embrittlement.

9.5 Loading and Brittle Crack Initiation *(1 July 2024)*

Prior to testing, a target test temperature (T_{target}) is to be selected.

Test procedures are to be in accordance with ISO 20064 except that the applied stress is to be $^{2}/_{3}$ of SMYS of the steel grade tested.

The test load is to be held at the test target load or higher for a minimum of 30 seconds prior to crack initiation.

The brittle crack can be initiated by impact or secondary tab plate tension after all of the temperature measurements and the applied force are recorded.

11 Measurements after Test and Test Validation Judgment

11.1 Brittle Crack Initiation and Validation

If the brittle crack spontaneously initiates before the test force is achieved or the specified hold time at the test force is not achieved, the test is to be considered as invalid.

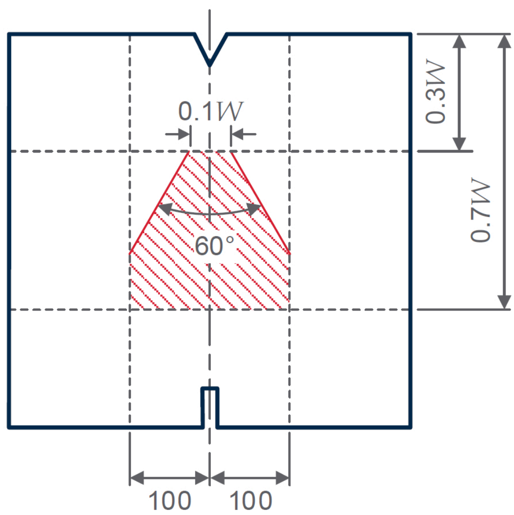
If the brittle crack spontaneously initiates without impact or secondary tab tension but after the specified time at which the test force is achieved, the test is considered as a valid initiation. The following validation judgments of crack path and fracture appearance are to be examined.

11.3 Crack Path Examination and Validation

When the brittle crack path in the embrittled zone deviates from the EBW line or side groove in the LTG system due to crack deflection and/or crack branching, the test is to be considered as invalid.

The entire crack path from the embrittled zone end is to be within the range shown in Appendix 5, Figure 7. If not, the test is to be considered as invalid.

FIGURE 7
Allowable Range of Main Crack Propagation Path *(2021)*



11.5 Fracture Surface Examination, Crack Length Measurement and Their Validation

The fracture surface is to be observed and examined. The crack "initiation" and "propagation" are to be checked for validity and judgments recorded. The crack "arrest" positions are to be measured and recorded.

When the crack initiation trigger point is clearly detected at the side groove root, other than the V-notch tip, the test is to be considered as invalid.

In the EBW embrittlement setting, EBW zone length is quantified by the three measurements of L_{EB-s1}, L_{EB-s2} and L_{EB-min}. When either or both L_{EB-s1} and L_{EB-s2} are smaller than 150 mm (6 in.), the test is to be considered as invalid. When L_{EB-min} is smaller than 150 mm – 0.2t (6 in. – 0.2t), the test is to be considered as invalid.

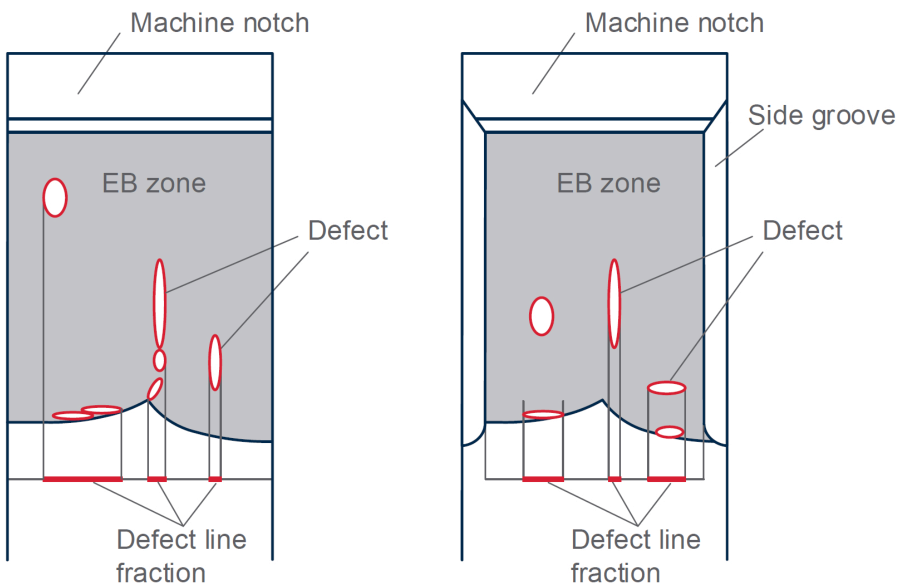
When shear lips with thickness over 1 mm (0.04 in.) in either side near side surfaces of embrittled zone are visibly observed independent of the specimens with or without side grooves, the test is to be considered as invalid.

In the EBW embrittlement setting, the penetration of the brittle crack beyond the EBW front line is to be visually examined. When any brittle fracture appearance area continued from the EB front line is not detected, the test is to be considered as invalid.

The weld defects in the EBW embrittled zone are to be visually examined. If detected, they are to be quantified. A projecting length of defect on the thickness line through the EB weld region along the brittle crack path is to be measured, and the total occupation ratio of the projected defect part to the total thickness is defined as the defect line fraction (See Appendix 5, Figure 8). When the defect line fraction is larger than 10%, the test is to be considered as invalid.

In EBW embrittlement by dual sides' penetration, if a gap on the embrittled zone fracture surface which is induced by misalignment of dual fusion lines is visibly detected at an overlapped line of dual side penetration, the test is to be considered as invalid.

FIGURE 8
Counting Procedure of Defect Line Fraction *(2021)*



13 Judgment of "Arrest" or "Propagate" *(1 July 2024)*

The final test judgment of "arrest", "propagate", or "invalid" is decided by the following requirements:

i) If the initiated brittle crack is arrested and the tested specimen is not broken into two pieces, the fracture surfaces are to be exposed with the procedures specified in ISO 20064.

ii) If the specimen was not broken into two pieces during testing, the arrested crack length, a_{arrest} is to be measured on the fractured surfaces. The length from the specimen edge of impact side to the arrested crack tip (the longest position) is defined as a_{arrest}.

iii) For LTG and EBW, a_{arrest} is to be greater than L_{LTG} and L_{EB-s1}, L_{EB-s2} or L_{EB-min}. If not, the test is to be considered as invalid.

iv) Even when the specimen was broken into two pieces during testing, it can be considered as "arrest" when brittle crack re-initiation is clearly evident. Even in the fracture surface all occupied by brittle fracture, when a part of the brittle crack surface from the embrittled zone is continuously surrounded by a thin ductile tear line, the test can be judged as re-initiation behavior. If so, the maximum crack length of the part surrounded by the tear line can be measured as a_{arrest}. If re-initiation is not visibly evident, the test is judged as "propagate".

v) The test is judged as "arrest" when the value of a_{arrest} is no greater than $0.7W$. If not, the test is judged as "propagate".

15 T_{test}, T_{arrest} and CAT Determination

15.1 T_{test} Determination

It is to be verified on the thermocouple measured record that all temperature measurements across the range of $0.3W$~$0.7W$ in both width and longitudinal direction are in the range of T_{target} ± 2°C (T_{target} ± 3.6°F) at brittle crack initiation. If not, the test is to be considered as invalid. However, the temperature measurement at $0.3W$ (location of A_3 and B_3) in the LTG system is to be exempted from this requirement.

If L_{EB-min} in EBW embrittlement is no smaller than 150 mm (6 in.), T_{test} can be defined to be equal to T_{target}. If not, T_{test} is to be equal to T_{target} + 5°C (T_{target} + 9°F).

In LTG embrittlement, T_{test} can be equal to T_{target}.

The final arrest judgment at T_{test} is concluded by at least two tests at the same test condition which are judged as "arrest".

15.3 T_{arrest} Determination

When at least two repeated "arrest" tests appear at the same T_{target}, brittle crack arrest behavior at T_{target} will be decided ($T_{arrest} = T_{target}$). When a "propagate" test result is included in the multiple test results at the same T_{target}, the T_{target} cannot to be decided as T_{arrest}.

15.5 CAT Determination

When CAT is determined, one "propagate" test is needed in addition to two "arrest" tests. The target test temperature, T_{target} for "propagate" test is to select 5°C (9°F) lower than T_{arrest}. The minimum temperature of T_{arrest} is determined as CAT.

With only the "arrest" tests, without a "propagation" test, it is decided only that CAT is lower than T_{test} in the two "arrest" tests (i.e., not deterministic CAT).

17 Reporting

The following items are to be reported:

i) *Test Material:* Grade and thickness

ii) Test machine capacity

iii) *Test Specimen Dimensions:* Thickness t, width W and length L, notch details and length a_{MN}, side groove details if machined *iv)* *Embrittled Zone Type:* EBW or LTG embrittlement

v) *Integrated Specimen Dimensions:* Tab plate thickness, tab plate width, integrated specimen unit length including the tab plates, and distance between the loading pins, angular distortion and linear misalignment

vi) *Brittle Crack Trigger Information:* Impact type or double tension. If impact type, drop weight type or air gun type, and applied impact energy

vii) *Test conditions:* Applied load; preload stress, test stress

- Judgments for preload stress limit, hold time requirement under steady test stress

viii) *Test temperature:* Complete temperature records with thermocouple positions for measured temperatures (figure and/or table) and target test temperature

- Judgments for temperature scatter limit in isothermal region
- Judgment for local temperature gradient requirements and holding time requirement after steady local temperature gradient before brittle crack trigger, if LTG system is used

ix) *Crack Path and Fracture Surface:* Tested specimen photos showing fracture surfaces on both sides and crack path side view; Mark at "embrittled zone tip" and "arrest" positions

- Judgment for crack path requirement
- Judgment for cleavage trigger location (whether side groove edge or V-notch edge)

x) *Embrittled zone information:*

a) *When EBW is Used:* L_{EB-s1}, L_{EB-s2} *and* L_{EB-min}:

- Judgment for shear lip thickness requirement
- Judgment whether brittle fracture appearance area continues from the EBW front line
- Judgment for EBW defects requirement
- Judgment for EBW lengths, L_{EB-s1}, L_{EB-s2} and L_{EB-min} requirements

b) *When LTG is used:* L_{LTG}

- Judgment for shear lip thickness requirement

xi) *Test results:*

When the specimen did not break into two pieces after brittle crack trigger, arrested crack length a_{arrest}

When the specimen broke into two pieces after brittle crack trigger:

- Judgment whether brittle crack re-initiation or not

If so, arrested crack length a_{arrest}:

- Judgment for a_{arrest} in the valid range ($0.3W < a_{arrest} \leq 0.7W$)
- Final judgment either "arrest", "propagate" or "invalid"

xii) *Dynamic Measurement Results:* History of crack propagation velocity, and strain change at pin chucks, if needed

19 Use of Test for Material Qualification Testing

Where required, the method can also be used for determining the lowest temperature at which a steel can arrest a running brittle crack (the determined CAT) as the material property characteristic in accordance with A5/15.5.

APPENDIX 6

Approval Scheme of Small-scale Test Methods for Brittle Crack Arrest Steels *(1 July 2024)*

1 Scope

1.1

This Appendix specifies the approval scheme of small-scale test methods which are used for product testing (batch release testing) of brittle crack arrest steels specified in Section 3, Table 9.

1.3

Unless otherwise specified in this Appendix, Section 3, and Appendix 3 are to be followed.

3 Approval Application

3.1

The manufacturer is to submit the following documents to ABS:

i) Application for approval of small-scale test procedure specification

ii) Small-scale test procedure specification including the following items at least:

- Applicable material grades, thickness range, deoxidation practice, heat treatment, etc.
- Types and methods of small-scale tests
- Sampling positions in plate thickness direction and final rolling direction of test specimens
- Size and dimension of test specimens
- Number of test specimens
- Test conditions, such as test temperature
- Acceptance criterion
- Example of format of test report
- Example of product inspection certificate including small-scale test results
- Handling of the products when small-scale test results do not satisfy the criterion

iii) Mechanism of achieving the brittle crack arrest properties of brittle crack arrest steels

iv) Technical background for enabling the evaluation of brittle crack arrest properties by small-scale test methods considering the mechanism specified in iii) above

v) Procedure of the evaluation for the brittle crack arrest properties of brittle crack arrest steels by small-scale test results *vi)* Data records which validate the correlation between small-scale test results and the large brittle crack arrest test results of brittle crack arrest steels whose number can satisfy the requirement for minimum data number given in A6/5.5

vii) Proposed test plan for approval

3.3

Small-scale test procedure specification is to be prepared in accordance with A6/5.5.

3.5

Where the manufacturer proposes to change any part of the approved small-scale test procedure specification, the manufacturer is to submit to ABS the documents which can cover all items specified in A6/3.1.

3.7

The documents confirming the reason for the change are to be submitted to identify the impact of those changes on the existing procedure, and the proposed actions to address any such impacts.

5 Establishment of Procedure Specification for Small-scale Testing

5.1 General

5.1.1

Small-scale test methods are to be determined based on the manufacturer's own technical philosophy with regard to achieving the brittle crack arrest properties of brittle crack arrest steels. Furthermore, description of an appropriate correlation between large scale brittle crack arrest properties and small-scale test results is required, and the acceptance criterion of the small-scale tests are to be determined, based on the following:

- Mechanism of achieving suitable brittle crack arrest properties
- Sampling position and direction
- Frequency of sampling
- Small-scale test methodology
- Demonstrated correlation between brittle crack arrest test results and small-scale test results
- Derivation of small scale testing acceptance criterion based on the statistical analysis

5.1.2

The manufacturer is to prepare the small-scale test procedure specification in accordance with the following A6/5.3 through A6/5.9.

5.3 Types and Methods of Testing

5.3.1

Types, methods, dimensions, and positions, as well as direction of test specimens, etc., of small-scale tests are to be specified by the manufacturer, and approved in accordance with this document.

5.3.2

In general, the test method is to reproduce the crack initiation, propagation, and arrest feature by such as the following test method.

- Combination of test methods (e.g., NRL drop weight test and V-notch Charpy impact test)
- One test method (e.g., press-notch Charpy impact test or side-section drop weight test)

5.3.3

In general, brittle crack arrest properties of brittle crack arrest steels are to be predicted using a regression equation on the relationship between small scale test results (e.g., transition temperature obtained by small scale tests) and large scale brittle crack arrest test results (e.g., K_{ca} or temperature corresponding to the specific brittle crack arrest properties).

Other approaches may be used subject to the approval of ABS.

Note:

Appendix 6, Table 1, Table 2, and Table 3 give the examples of small scale test methods.

5.3.4

For determination of test methods, the manufacturer is to confirm the applicability of these test methods to their brittle crack arrest steels theoretically taking into account the methodology of test methods, their own mechanism of achieving the brittle crack arrest properties, and sampling positions of test specimens (see A6/5.1.1). Then, the manufacturer is also to submit the technical background for determination of small-scale test methods to ABS as given in A6/3.1.

TABLE 1
Example of Small-scale Test Method Using NRL Drop Weight Test and V-notch Charpy Impact Test (Informative)

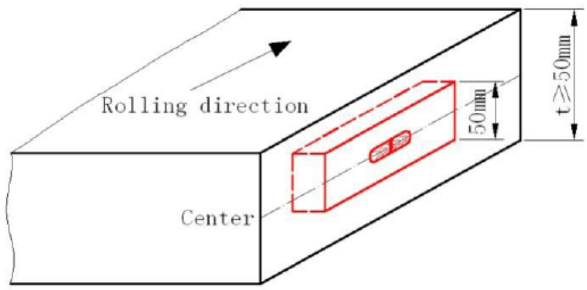
Test type:	NRL drop weight test and V-notch Charpy impact test
Standard:	ASTM E208:2020 and ISO 148-1:2016
Sampling positions of test specimens:	NRL drop weight test: at surface V-notch charpy impact test: 1/4 of thickness
Length direction of test specimen:	Parallel to the final rolling direction of test plate
Regression equation:	$T_{Kca} = \alpha \cdot (NDTT + 10) + \beta \cdot {}_{v}T_{rs} + 153(t - 5)^{1/13} - 170.5$ T_{Kca} : Temperature at K_{ca} of 6,000N/mm$^{3/2}$ or K_{ca} of 8,000N/mm$^{3/2}$, (°C) $NDTT$: Nil-ductility transition temperature (°C) ${}_{v}T_{rs}$: Transition temperature of the absorbed energy (°C) t : thickness $\alpha, \beta^{(1)}$: constant
Notes:	(1) α and β are determined by comparing small-scale test results with brittle crack arrest test results.

TABLE 2
Example of Small-scale Test Method Using Pressed-notch Charpy Impact Test (Informative)

Test type:	Pressed-notch Charpy impact test
Standard:	Dimension, shape, introducing method of notch:Manufacturer's proposal Others: ISO148-1:2016
Sampling position of test specimen:	1/2 of thickness
Length direction of test specimen:	Parallel to the final rolling direction of test plate

Regression equation:	$T_{Kca} = \alpha\ {}_pT_{E\gamma J} + \beta$ T_{Kca} : Temperature at K_{ca} of 6,000N/mm$^{3/2}$ or K_{ca} of 8,000N/mm$^{3/2}$, (°C) ${}_pT_{E\gamma J}$: Test temperature at absorbed energy of γ (J), (°C) α and β : Constant γ : Absorbed energy at brittle fracture surface ratio of δ (%),(J)
Notes:	(1) α, β,γ and δ are determined by comparing small-scale test results with brittle crack arrest test results.

TABLE 3
Example of Small-scale Test Method Using Side-section Drop Weight Test (Informative)

Test type:	Side-section drop weight test
Standard:	Dimension: P-2 type of ASTM E 208 2020
Sampling positions of test specimens:	1/2 of thickness and side-section 
Length direction of test specimen:	Parallel to the final rolling direction of test plate
Regression equation:	$T_{Kca} = \alpha + \beta \cdot T_{NDT}^{side} + \gamma \cdot t^{1.5}$ T_{Kca} : Temperature at K_{ca} of 6,000N/mm$^{3/2}$ or K_{ca} of 8,000N/mm$^{3/2}$, (°C) T_{NDT}^{side} : Nil-ductility transition temperature obtained by side-section drop weight test, (°C) t : thickness $\alpha, \beta, \gamma^{(1)}$: constant
Notes:	(1) α, β and γ are to be determined by comparing small-scale test results with brittle crack arrest test results.

5.5 Testing Data

5.5.1 Selection of Test Plates

5.5.1(a)

Brittle crack arrest tests and small-scale tests are to be conducted for each material grade (including all suffixes) of brittle crack arrest steels in accordance with A6/5.5.

5.5.1(b)

Brittle crack arrest tests and small-scale tests are to be carried out on at least 12 test plates, in accordance with A6/5.5.1(c), by which these test results can reliably estimate brittle crack arrest properties of brittle crack arrest steels.

Note:

"One test plate" means "the rolled product from a single slab or ingot if this is rolled directly into plates".

5.5.1(c)

In order to provide appropriate correlation between small-scale test results and brittle crack arrest properties with various manufacturing conditions of steel plates, the steel plates are to be representative for each combination of thickness range and heat sample to include:

- The intended maximum and minimum plate thickness
- Different heats are to be chosen for each thickness

Furthermore, the above test plates are to include a fixed number of steel plate(s) whose brittle crack arrest properties (i.e., brittle crack arrest test results) do not comply with the requirements specified in Section 3, Table 9. Such a number is to be at least one, but not exceeding one quarter of all test plates. Manufacturing process of these test plates can be different (or intentionally altered from the approved manufacturing process) from that of the brittle crack arrest steels to which the small-scale test method is applied. It is recommended that the strength grade of these test plates (non-compliant with the relevant requirements of brittle crack arrest properties) are similar to that of the brittle crack arrest steels.

Where the manufacturer has requested approval for only a single thickness, the thickness of test plates can be only a single thickness. In this case, at least four steel plates for each combination of thickness (single thickness) and heats (three different heats) are to be used, and the applicable thickness of the small scale test is only that single thickness condition.

5.5.1(d)

Brittle crack arrest steels used for the approval test of manufacturing process of these steels (and its approval test results) can also be used as the test plates specified in A6/5.5.1(c).

5.5.1(e)

Brittle crack arrest test specimens and small-scale test specimens are to be taken from the same test plate.

5.5.1(f)

A decrease of the total of the indicated number of test plates may be accepted by ABS in the following cases:

i) When the manufacturer applies a small-scale test procedure specification to multiple material grades, and the manufacturing process and mechanism to ensure the brittle crack arrest properties of these different material grades are the same.

ii) When a small-scale test procedure specification is already approved by ABS for one or some material grades, and the manufacturer applies similar small-scale test procedure specification to the other material grade(s), and the manufacturing process and mechanism to ensure the brittle crack arrest properties of these different material grades are same.

5.5.2 Brittle Crack Arrest Tests

5.5.2(a)

Brittle crack arrest tests are to be carried out for each test plate in accordance with A3/7.9.

5.5.2(b)

Where brittle crack arrest tests are carried out for evaluation of K_{ca}, K_{ca} at a specific temperature is to be obtained in accordance with A4/1.3.

5.5.2(c)

Where brittle crack arrest tests are carried out for evaluation of CAT, deterministic (actual) CAT is to be obtained in accordance with A5/15.5.

5.5.3 Small-scale Tests

5.5.3(a)

Small-scale tests are to be carried out in accordance with the small-scale test procedure specification approved for each test plate.

5.5.3(b)

In general, the test specimens of small-scale tests are to be taken with their longitudinal axis parallel to the final rolling direction of the test plates.

5.5.3(c)

The test specimens of small-scale tests are to be taken from the specified positions in plate thickness direction of the test plates, as given in A6/5.3.3.

5.7 Validation of Correlation

5.7.1

A regression equation on the relationship between the brittle crack arrest property obtained from the brittle crack arrest test and single or multiple small-scale test results is to be established. For brittle crack arrest properties, a specific temperature (e.g., TK_{ca6000} in BCA1, TK_{ca8000} in BCA2 or CAT) or the K_{ca} value at -10°C may be used.

5.7.2

The validity of the regression equation is to be examined to predict brittle crack arrest properties with enough accuracy. The correlation in brittle crack arrest properties between the calculated values from small scale tests and the brittle crack arrest test results is to be confirmed by using the value of twice the standard deviation (2σ). When using temperature for brittle crack arrest property, 2σ is not to be greater than 20°C. In other cases (e.g., K_{ca} value at -10°C), an upper limit of 2σ is to be established with the agreement of ABS.

Note:

Calculation procedure of the standard deviation (σ) is given as follows:

$$\sigma = \sqrt{\frac{1}{(n-1)}\sum_{i=1}^{n}\left(y_i - x_i\right)^2}$$

n = number of test plates

y_i = brittle crack arrest property obtained from brittle crack arrest test for one test plate

x_i = brittle crack arrest property estimated from small scale tests for one test plate

5.9 Acceptance Criterion

5.9.1

Acceptance criterion of brittle crack arrest steels by the small-scale tests is to be proposed by the manufacturer based on the regression equation which is confirmed by the correlation with brittle crack arrest properties in A6/5.7 above. The criterion is to be determined so that regression equation can predict brittle crack arrest properties on the safety side, considering the scatter of brittle crack arrest properties from the predicted value by the regression equation.

5.9.2

Unless otherwise agreed by the ABS, an acceptance criterion of small-scale tests is to be determined by following procedures:

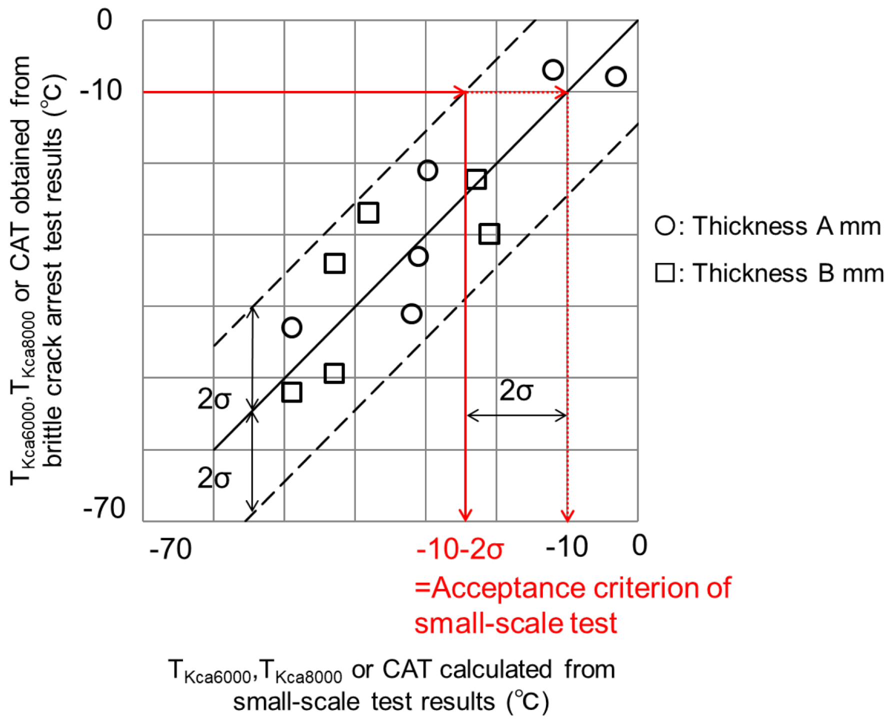
a) For correlation by means of temperature

i) The required temperature (see Appendix 6, Figure 1) is obtained by subtracting 2σ (°C) from the brittle crack arrest steel specification in Section 3, Table 9, that is -10 - 2σ (°C), where 2σ is given in A6/5.7.2.

TK_{ca6000} and TK_{ca8000} in Appendix 6, Figure 1 are the temperatures at which the K_{ca} value of steel plates equals 6000 N/mm$^{3/2}$ and 8000 N/mm$^{3/2}$, respectively.

ii) The temperature predicted from the small-scale test results through the regression equation is to be no higher than the value of -10 - 2σ (°C).

FIGURE 1
Example for Determination of Acceptance Criterion of Small-scale Test for Correlation by Means of Temperature



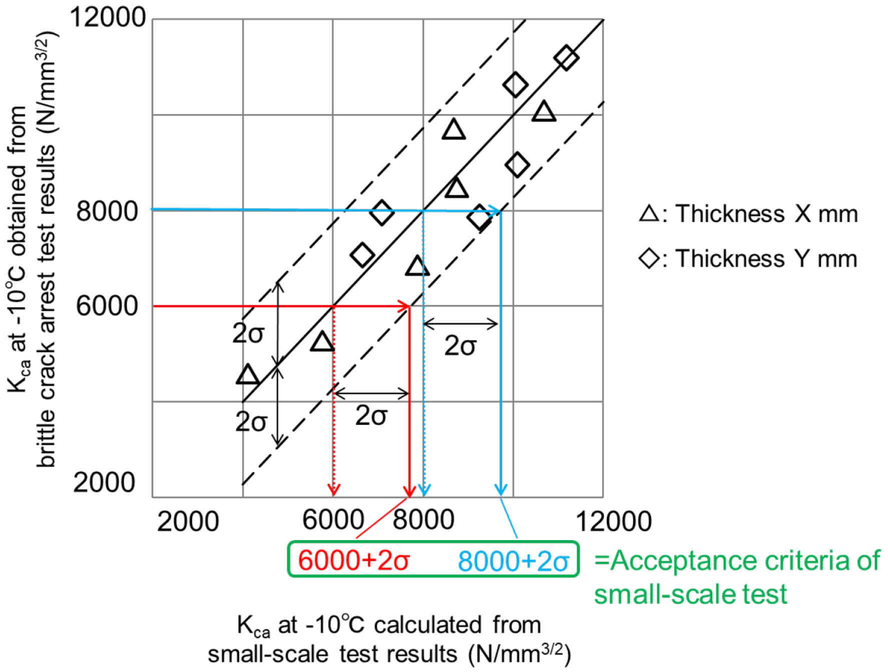
Note: This is only a schematic and may not represent the actual data obtained.

b) For correlation by means of brittle crack arrest toughness (K_{ca}):

i) The required K_{ca} (see Appendix 6, Figure 2) is obtained by adding 2σ (N/mm$^{3/2}$) to the brittle crack arrest steel specification in Section 3, Table 9, that is either 6000 + 2σ (N/mm$^{3/2}$) in BCA1 or 8000 + 2σ (N/mm$^{3/2}$) in BCA2, where 2σ is given in A6/5.7.2.

ii) The K_{ca} value predicted from the small-scale test results through the regression equation is to be no smaller than the value of 6000 + 2σ (N/mm$^{3/2}$) for BCA1, or 8000 + 2σ (N/mm$^{3/2}$) for BCA2.

FIGURE 2
Example for Determination of Acceptance Criterion of Small-scale Test for Correlation by Means of Brittle Crack Arrest Toughness (K_{ca})



Note: This is only a schematic and may not represent the actual data obtained.

7 Approval Tests

7.1 General

7.1.1

In order to confirm the validity of the submitted technical documents specified in A6/3.1, approval tests are to be carried out.

7.1.2

Approval test plan is to be approved by ABS prior to testing.

7.1.3

Considering the contents of the submitted technical documents specified in A6/3.1 above, ABS may require additional tests in the following cases:

i) When ABS determines that the number of brittle crack arrest tests or small-scale tests is too few to adequately confirm the validity of the acceptance criterion of small-scale tests (see A6/5.5.1);

ii) When the ABS determines that the testing data obtained for setting the acceptance criterion of small-scale tests varies too widely (see A6/5.7.2), or that the data is clustered producing a biased correlation curve;

iii) When ABS determines that the validity of brittle crack arrest test results or small-scale test results for setting the acceptance criterion of small-scale tests is insufficient, or has some flaws during tests and/or for test results (see A6/5.5.2 and A6/5.5.3); and

iv) Others as deemed necessary by ABS.

7.3 Extent of the Approval Tests

7.3.1

Extent of the approval tests is to be in accordance with A2/3 and A4/1.1.

7.5 Type of Tests

7.5.1 Brittle Crack Arrest Tests

7.5.1(a)

Brittle crack arrest tests are to be carried out in accordance with A2/7.9.

7.5.1(b)

Where brittle crack arrest tests are carried out for evaluation of K_{ca}, K_{ca} at a specific temperature (TK_{ca6000} or TK_{ca8000}) is to be obtained in accordance with A4/1.3.

7.5.1(c)

Where brittle crack arrest tests are carried out for evaluation of CAT, deterministic CAT is to be obtained in accordance with A5/15.5.

7.5.2 Small-scale Tests

7.5.2(a)

Small-scale tests are to be carried out in accordance with A6/5.5.3.

9 Results

9.1

Results of test items and the procedures are to comply with the test program approved by ABS.

9.3

For the brittle crack arrest test results, the manufacturer is to submit to ABS the brittle crack arrest test reports in accordance with Appendix 4 for K_{ca} and Appendix 5 for CAT.

9.5

For small-scale test results, the manufacturer is to submit to ABS the small-scale test reports in accordance with the example of format of test reports submitted as specified in A6/3.1ii).

11 Approval

The Surveyor is to attend and witness small-scale qualification tests. Acceptance of previously qualified tests witnessed by another IACS Class Society will be specifically considered subject to review by the ABS Materials Department.

Upon submittal of required technical documents and completion of the survey and tests to the satisfaction of the attending Surveyor, the approval for small-scale test procedure specification will be granted by ABS.

APPENDIX 7

Engineering Critical Assessment for Hatch Coamings *(2021)*

1 General

According to the International Association of Classification Societies (IACS) Unified Requirement S33 (December 2019), the application of enhanced nondestructive testing (NDT) (particularly time-of-flight diffraction (TOFD technique)) using a stricter flaw acceptance in lieu of standard ultrasonic testing (UT) technique can be an alternative to brittle crack arrest (BCA) steel, where the brittle crack runs straight along the butt joint.

This Appendix provides a procedure and acceptance criteria for flaws detected using enhanced NDT during the construction of block-to-block butt joints for hatch coaming. Following this procedure, an allowable zone of initial flaw size needs to be calculated during the design stage. This will then be used during associated new construction surveys.

1.1 Application

In this Appendix, fracture mechanics analysis is applicable for higher-strength hull structural steel plates on hatch coaming using non-BCA steel with thickness greater than 50 mm (2 in.) and less than or equal to 100 mm (4 in.) in container carriers. This fracture mechanics analysis also can be applied for brittle crack arrest (BCA) steel, if the owner and designer/shipyard agree. The application is to be in accordance with Subsections 1/1, 1/3, and 2/4.

1.3 Critical Areas

In this Appendix, the critical areas are located at the butt joints of hatch coaming top plates in the cargo hold region with the application specified in A7/1.1.

3 Fracture Mechanics Analysis

Fracture mechanics analysis (FMA) is to be carried out for the flaws in critical areas identified in A7/1.3. In this FMA, the fatigue crack propagation from an initial flaw size to a critical size is to be calculated to verify adequate remaining life. Based on the acceptance criteria from the Failure Assessment Diagram (FAD), the allowable initial flaw size is calculated and used to determine the acceptable detected flaws.

3.1 Fracture Mechanics Analysis Procedure

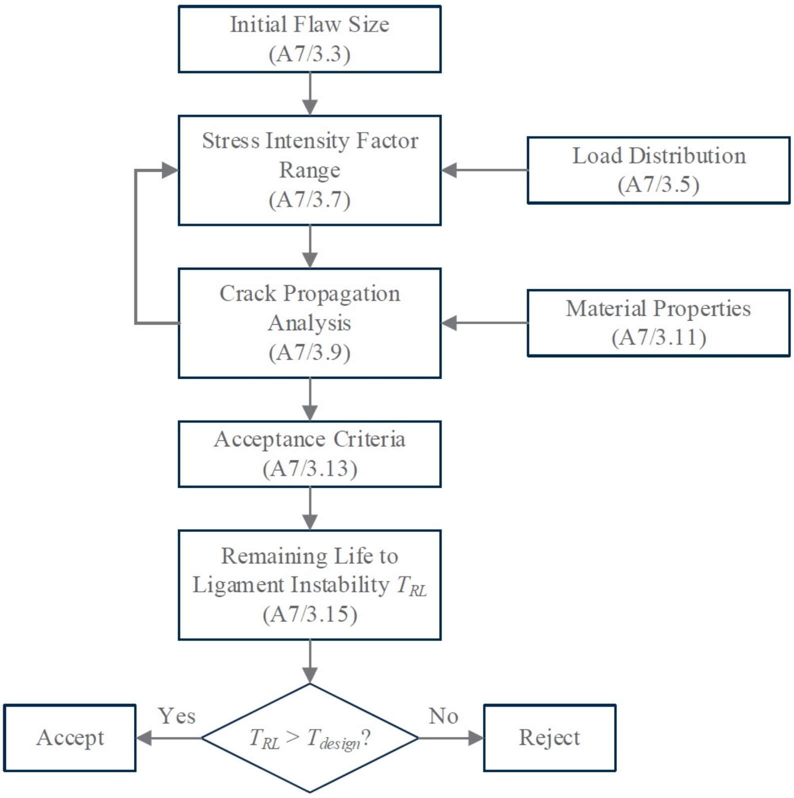
The procedure for FMA used in this Appendix include:

- Assuming initial flaw sizes and configurations
- Establishing the histogram of stress range(s)
- Calculating stress intensity factor range
- Determining material properties (e.g., fracture toughness, Paris' law parameters, etc.)
- Performing crack propagation analysis

- Determining acceptance criteria based on ligament instability
- Calculating remaining service life
- Determining allowable initial flaw sizes

A flowchart of this procedure is shown in Appendix 7, Figure 1.

FIGURE 1
FMA Procedure *(1 July 2024)*



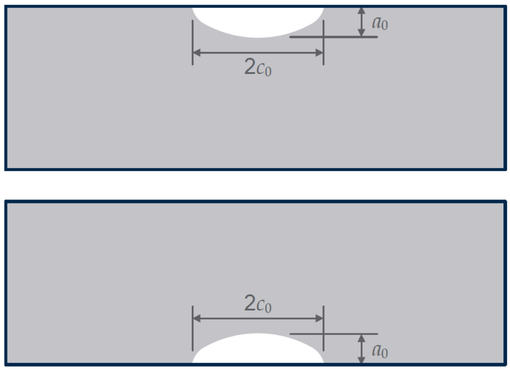
3.3 Initial Flaw Size

A single initial flaw is to be assumed in butt welded areas of coaming top plates. Two types of configurations (i.e., surface and embedded flaws) are to be considered.

3.3.1 Surface Flaw

As a starting point, the dimensions of an initial semi-elliptical surface crack are to be assumed as 0.5 mm (0.020 in.) height (a_0) and 5 mm (0.197 in.) length ($2c_0$). The surface crack could be located above or under the coaming top plate around butt welded areas, as shown in Appendix 7, Figure 2. The crack orientation is assumed to be perpendicular to the principal stress direction.

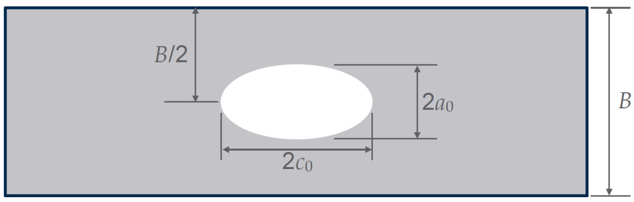
FIGURE 2
Initial Surface Crack above or under the Coaming Top Plate *(2021)*



3.3.2 Embedded Flaw

As a starting point, the dimensions of the initial elliptical embedded crack size are to be assumed as 1 mm (0.039 in.) height ($2a_0$) and 1 mm (0.039 in.) length ($2c_0$). The location of initial embedded crack is assumed to be in the middle of coaming top plate thickness (B) around butt welded areas, as shown in Appendix 7, Figure 3. The crack orientation is assumed to be perpendicular to the principal stress direction.

FIGURE 3
Initial Embedded Flaws inside Coaming Top Plate *(2021)*



3.5 Load Distribution

3.5.1 Maximum Hull Girder Stress *(1 July 2024)*

The maximum hull girder stress is to be determined by a long-term distribution corresponding to wave spectra covering the North Atlantic and a probability level of 10^{-8}. In order to acquire the maximum stress on hatch coaming top, simplified fatigue loads are applied and only the vertical hull girder loads are considered. The vertical wave induced bending moments amidships are to be calculated in accordance with 5C-1-4/7.1 of the *Marine Vessel Rules*.

The hull girder bending stress due to vertical hogging and sagging bending moments in N/mm^2 (kgf/mm^2, psi) for gross scantlings is calculated using:

$$\sigma_{w-Hog} = k_1 M_{w-Hog}(z - z_{NA})/I_Y$$

$$\sigma_{w-Sag} = k_1 M_{w-Sag}(z - z_{NA})/I_Y$$

where

k_1 = 10 (10, 2240)

M_{w-Hog} = vertical wave induced hogging bending moments, in kN-m (tf-m, Ltf-ft), in accordance with 5C-1-4/7.1 of the *Marine Vessel Rules*

M_{w-Sag} = vertical wave induced sagging bending moments, in kN-m (tf-m, Ltf-ft), in accordance with 5C-1-4/7.1 of the *Marine Vessel Rules*

I_Y = moment of inertia of cross section for gross scantlings with respect to horizontal neutral axis, z_{NA}, in cm^2-m^2 (in^2-ft^2)

z_{NA} = vertical distance of horizontal neutral axis from baseline, in m (ft)

z = vertical distance from baseline to considered location (i.e., side hatch coaming top), in m (ft)

The maximum hull girder bending stress, in N/mm^2 (kgf/mm^2, psi), for net scantlings is calculated as follows:

$$\sigma_{total} = c_f\left(\sigma_{SWBM} + \sigma_{w-Hog}\right)$$

where

σ_{SWBM} = hull girder bending stress due to maximum hogging still water bending moment, in N/mm^2 (kgf/mm^2, psi)

c_f = adjustment factor to reflect a mean wasted condition, taken as 0.95

3.5.2 Long Term Stress Range *(1 July 2024)*

The long-term stress ranges can be characterized by using a two-parameter Weibull distribution.

The probability density function of $\Delta\sigma$ is given by:

$$f(\Delta\sigma) = \frac{\gamma}{A}\left(\frac{\Delta\sigma}{A}\right)^{\gamma-1}\exp\left[-\left(\frac{\Delta\sigma}{A}\right)^{\gamma}\right]$$

where A and γ are the scale and shape parameters of the Weibull distribution, respectively.

The shape parameter of the Weibull distribution γ is determined in accordance with 5C-1-9/7.5.3 of the *Marine Vessel Rules*.

The scale parameter is determined by:

$$A = \frac{\Delta\sigma_w}{\left(\ln N_R\right)^{1/\gamma}}$$

where $\Delta\sigma_w$ is the maximum hull girder bending stress range, in N/mm^2 (kgf/mm^2, psi), and N_R is 10^8.

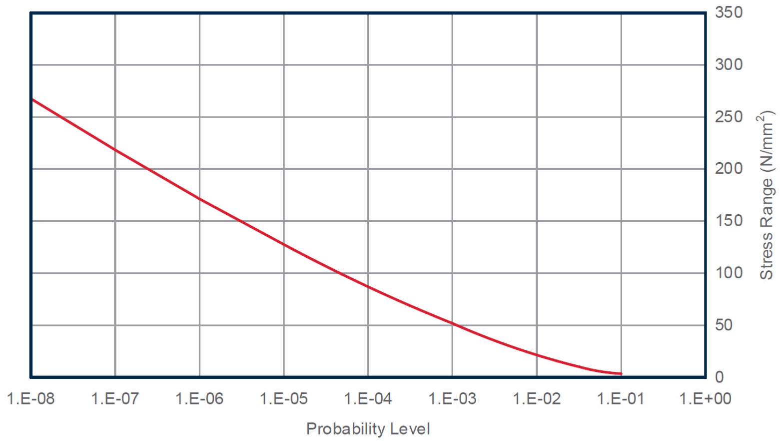
For net scantlings, $\Delta\sigma_w$ is calculated as follows:

$$\Delta\sigma_w = c_f\left|\sigma_{w-Hog} - \sigma_{w-Sag}\right|$$

where σ_{w-Hog} and σ_{w-Sag} are described in A7/3.5.1 and c_f is an adjustment factor to reflect a mean wasted condition, taken as 0.95.

A sample of the Weibull distribution stress range from the maximum hull girder stress range is shown in Appendix 7, Figure 4.

FIGURE 4
A Sample of Weibull Distribution Stress Range *(2021)*



The total load spectrum for ship design life is to be divided into more than 10 divisions in the stress range histogram. This will remove the effect of loading sequence to crack propagation life. The number of cycles in the design life is calculated as follows:

$$N_T = \frac{f_0 D_L}{4\log L}$$

where

f_0	=	factor for net time at sea
	=	0.85
L	=	scantling length of vessel, in m
D_L	=	design life in seconds

For 20 year ship design life (T_{Design}), the design life (D_L) is 6.31 × 10^8 seconds. For 25 year ship design life, the design life (D_L) is 7.88 × 10^8 seconds. The calculated number of cycles (N_T) is applied to create the histogram of stress range following the Weibull distribution.

3.7 Stress Intensity Factor Range

The stress intensity factor range is to be calculated from the stress range, crack shape parameters and size, and geometry. BS 7910:2013 for a surface or embedded crack. The stress intensity factor range, in N/mm$^{3/2}$, can be calculated by:

$$\Delta K = (Y \Delta \sigma)\sqrt{\pi a}$$

where

$Y \Delta \sigma$	=	$M f_w \{M_{km} M_m \Delta\sigma_m + M_{kb} M_b [\Delta\sigma_b + (k_m - 1)\Delta\sigma_m]\}$, in N/mm^2
M	=	bulging correction factor
	=	1 for surface and embedded cracks in plate
f_w	=	finite width correction factor
M_{km}, M_{kb}	=	weld toe notch factors

M_m, M_b	=	stress intensity magnification factors
$\Delta\,\sigma_m$	=	remote uniform tensile stress, in N/mm^2
$\Delta\,\sigma_b$	=	remote bending stress in, N/mm^2
k_m	=	misalignment factor
a	=	crack length

The expressions of these parameters herein can be found in BS 7910:2013. For a semi-elliptical surface crack and an elliptical embedded crack, the stress intensity factor ranges at the deepest point on the crack front ($\Delta\,K_a$) and at the ends ($\Delta\,K_c$) can also be calculated according to BS 7910:2013. The residual stress and welding effects at the critical location(s) needs to be considered for the calculation of stress intensity factors of surface and embedded cracks, with reference to BS 7910:2013.

3.7.1 Residual Stresses

For welds without stress relief, the residual stress is to be incorporated in the fracture mechanics analysis if a crack is small compared with the zone of influence of the residual stress. The residual stress is to be added to the applied stress and taken into account in the calculation of the stress intensity factors.

3.9 Crack Propagation Analysis

For both semi-elliptical surface and elliptical embedded cracks, the crack initiates and propagates along both thickness and length directions. There are two possibilities, one is that the crack may grow until a ligament instability occurs and another is that the crack propagates through the whole thickness without instability. As an example, the surface crack propagation calculation procedure, shown in Appendix 7, Figure 5, is described as follows:

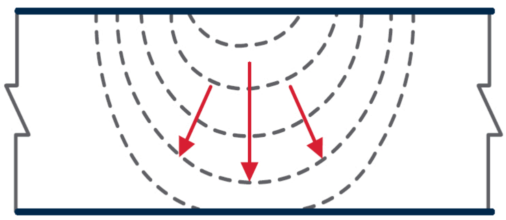
Step 1: Specify an initial surface crack with length, $2c_0$, and height, a_0, as described in A7/3.3.

Step 2: Perform crack propagation analysis on a surface crack using Paris' law with stress intensity factor range as described in A7/3.7.

Step 3: Repeat Step 2 to calculate crack propagation for each group of load spectra as described in A7/3.5 until the ligament instability occurs.

Step 4: Determine a remaining life from the specified initial surface crack size in Step 1 to ligament instability in Step 3.

FIGURE 5
Crack Propagation *(2021)*



For a semi-elliptical surface crack, a crack propagation analysis at the critical location is to be calculated using Paris' law as follows:

$\frac{da}{dN} = C(\Delta K_a)^m$ for $\Delta K_a > \Delta K_{th}$

$\frac{da}{dN} = 0$ for $\Delta K_a \leq \Delta K_{th}$

$\frac{dc}{dN} = C(K_c)^m$ for $\Delta K_c > \Delta K_{th}$

$\frac{dc}{dN} = 0$ for $\Delta K_c \leq \Delta K_{th}$

where

$dc/dN, da/dN$	=	crack propagation rate, in mm/cycle
C, m	=	Paris' law constants
ΔK_c, ΔK_a	=	stress intensity factor ranges, in N/mm$^{3/2}$, at the ends of the crack (long length) and at the deepest point on the crack front (short half-axial length), respectively
ΔK_{th}	=	threshold value of stress intensity factor range, in N/mm$^{3/2}$
c, a	=	long and short half-axial lengths for a semi-elliptical surface crack

The fatigue crack propagation path is to be assumed as perpendicular to the principal stress direction.

An embedded crack propagation calculation can follow a similar approach from the calculation of surface crack propagation. The crack propagation for both crack configurations are calculated according to BS 7910:2013.

3.11 Material Properties

The principal material properties required for FMA include modulus of elasticity, E, yield strength, σ_y, and tensile strength, σ_u, fracture toughness (K_{Ic}), and Paris' law constants C and m,. Material properties tests are to be performed for base metal, weld metal, and heat affected zone.

Modulus of elasticity, E, yield strength, σ_y, and tensile strength, σ_u are to be defined in accordance with 3/3.7 and 3/5.9.

Fracture toughness (K_{Ic}) is a property which describes the ability of a material containing a crack to resist fracture. In this Appendix, the fracture toughness (K_{Ic}), in N/mm$^{3/2}$, is calculated by the crack-tip opening displacement (CTOD) value using the following equation:

$$K_{Ic} = \sqrt{\frac{m\delta\sigma_f E}{(1-\nu^2)}}$$

where

δ	=	CTOD value, in mm
E	=	Young's modulus of the material, in N/mm^2
ν	=	Poisson's ratio of material
σ_f	=	flow stress, in N/mm^2
	=	$(\sigma_y + \sigma_u)/2$ and $\sigma_f \leq 1.2\sigma_y$
σ_y	=	yield stress of the material, in N/mm^2
σ_u	=	tensile strength of material in N/mm^2

m	=	$1.517\left(\frac{\sigma_Y}{\sigma_U}\right)^{-0.3188}$	for $0.3 < \frac{\sigma_Y}{\sigma_U} < 0.98$
σ_Y	=	yield strength of the material tested, determined at the fracture toughness test temperature, in N/mm^2	
σ_U	=	is tensile strength of the material tested, determined at the fracture toughness test temperature, in N/mm^2	

CTOD is to be established following the methods specified in 4/5.5.4.

The Paris' law constants are to be used for the crack propagation assessment. Crack propagation tests are to be performed for base metal, weld metal, and the heat affected zone. Fracture mechanics analysis is to be based on crack growth data taken as the mean plus two standard deviations of the test data. If the test data is not available, the recommended values for C and m are defined in Appendix 7, Table 1 following BS 7910:2013 for assessing the welded joints of steels in air.

TABLE 1
Details of Paris' Law Parameters *(2021)*

Threshold of Stress Intensity Factor Range ΔK_{th} *N/mm$^{3/2}$*	m *(stage A)*	C *(stage A)**	*Transition Point* ΔK *N/mm$^{3/2}$*	m *(stage B)*	C *(stage B)**
63	5.10	2.10×10^{-17}	144	2.88	1.29×10^{-12}

Note: *For da/dN in mm/cycle and ΔK in N/mm$^{3/2}$

3.13 Acceptance Criteria

The two parameters of applied stress and the stress intensity factor, together with material properties such as yield and ultimate strength and fracture toughness, are to be used for the failure assessment. Option 1 (normal assessment) in BS 7910:2013 is required for fracture assessment. The schematic of an Option 1 Failure Assessment Diagram (FAD) is shown in Appendix 7, Figure 6. The area is bounded by the axes and by the assessment line. In the FAD, there are two assessment parameters: the fracture ratio and the load ratio.

The fracture ratio, K_r, is defined as the ratio of the stress intensity factor to the fracture toughness:

$$K_r = \frac{K_I}{K_{mat}}$$

where K_I is the stress intensity factor at the current crack size due to the primary loads and secondary loads, and K_{mat} is the fracture toughness taking account of any ductile tearing following initiation.

The load ratio, L_r, is defined as the ratio of the reference stress to the flow strength:

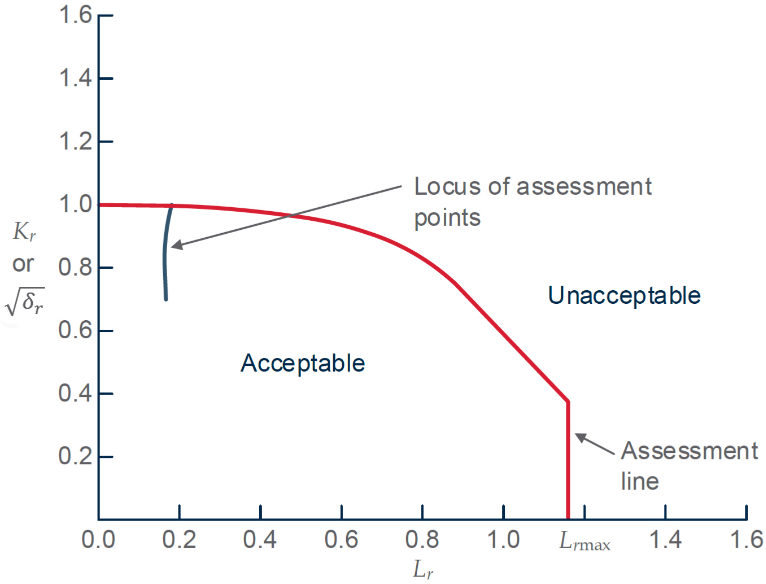
$$L_r = \frac{\sigma_{ref}}{\sigma_y}$$

where σ_{ref} is the reference stress in accordance with Annex P from BS 7910:2013 and σ_y is the yield strength.

The detailed calculation for the parameters of L_r and K_r, is from BS 7910:2013. The crack is acceptable if (K_r, L_r) falls within the enclosed region.

The crack is unacceptable if (K_r, L_r) falls out the region with any ligament instability. For a semi-elliptical surface or elliptical embedded crack, the crack will either snap to become a through thickness crack as it reaches a critical depth/height or continue increasing through the whole thickness. The time for a crack propagating to the FAD assessment line is defined as the remaining life (T_{RL}) to ligament instability or to crack propagation through the whole thickness without instability, whichever has less time.

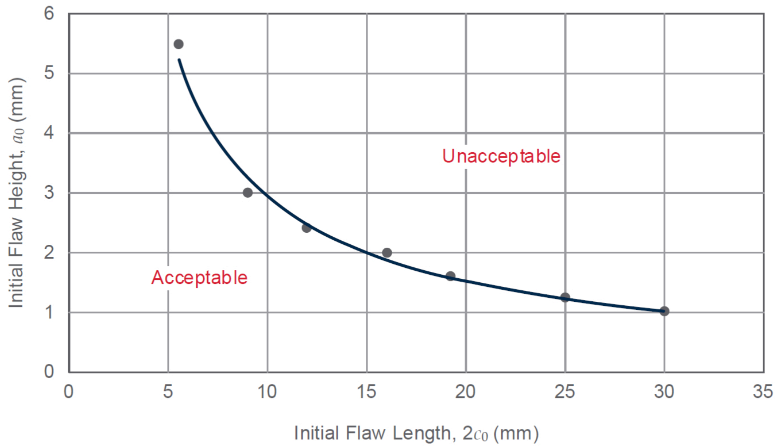
FIGURE 6
Option 1 Failure Assessment Diagram (FAD) *(2021)*



3.15 Allowable Zone of Initial Single Flaw Size

The allowable zone of initial flaw size is typically calculated during the design stage. At this stage, several initial flaw sizes and configurations are assumed, following A7/3.3. The remaining life (T_{RL}) can be calculated for each assumed initial flaw size configuration following A7/3.5 through A7/3.13. By comparing remaining life (T_{RL}) and design life (T_{Design}), the allowable zone of initial flaw sizes is created for the following typical example in Appendix 7, Figure 7. In the acceptable zone of initial flaw size, the remaining life (T_{RL}) is greater than the design life (T_{Design}). In reference to the unacceptable zone, the remaining life (T_{RL}) is less than the design life (T_{Design}). The figures for the allowable zone of initial flaw sizes are to be created for each flaw configuration (i.e., surface and embedded flaws).

FIGURE 7
Allowable Zone of Initial Flaw Size for Surface Flaw *(2021)*



If a figure for the allowable zone of initial flaws was not created at the design stage, each detected flaw should be assessed by fracture analysis during the construction period. The initial single flaw size and configuration are estimated from nondestructive testing (NDT) results for each detected flaw. Following the FMA process described in A7/3.5 through A7/3.13., the remaining life (T_{RL}) for each flaw is calculated. If the remaining life (T_{RL}) is greater than design life (T_{Design}), the detected flaw is acceptable, if not, it is unacceptable.

5 Inspection of Critical Areas on Hatch Coaming Top

5.1 Surveys during Construction

Welding during hull construction activities is to comply with the requirements of the ABS *Rules for Material and Welding (Part 2)*, unless specially approved otherwise.

Personnel engaged in NDT are to be qualified in accordance with the ABS *Guide for Nondestructive Inspection*. Their qualification is to be verified by the Surveyor.

During new construction, an attending Surveyor will monitor the NDT of these areas on the hatch coaming top. The Surveyor is to verify that the NDT personnel record the flaw size. The flaw types, configurations, and sizes are to be defined in accordance with the ABS *Guide for Nondestructive Inspection*.

During construction, any detected flaw on the hatch coaming top is to be evaluated in accordance with A7/3.15 for allowable initial single flaw size. Adjacent flaws separated by less than 2ℓ of sound metal (ℓ equals length of longest discontinuity) are to be considered as a single flaw. Multiple flaws (≥ two flaws) are evaluated in accordance with ABS *Guide for Nondestructive Inspection*.

5.3 Construction Monitoring Plan

The defined areas in A7/1.3 at the coaming top are identified as critical areas on the Construction Monitoring Plan (CMP) in accordance with Appendix 5C-A1-1 of the *Marine Vessel Rules*. This CMP is to be available onboard. When a critical area is being surveyed, the extent and scope of the survey are to be in accordance with the approved copy of the Construction Monitoring Plan. During annual, intermediate, and special surveys, attention is to be given to the critical areas which are to be visually examined.

If the allowable initial single flaw size was evaluated in accordance with A7/3.15 during construction, the allowable zone of initial flaw size for surface flaw is to be added in CMP and the identified critical areas on coaming top are to be inspected using ultrasonic testing in accordance with Subsection 5/3 .

5.5 Hull Condition Monitoring

It is recommended that a hull condition monitoring system is implemented to monitor the critical areas on the Construction Monitoring Plan (CMP). The equipment and arrangements required for the class notation **HM2**- Hull Girder Stress is to be examined in accordance with ABS *Guide for Hull Condition Monitoring*.

Acoustic Emission Testing is an alternative approach to monitor these critical areas for crack propagation activities. The equipment and arrangements should be in accordance with the ABS G*uidance Notes on Structural Monitoring using Acoustic Emissions*.