GUIDE FOR

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

JANUARY 2021
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/mm² (47 kgf/mm², 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 Guide 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/mm² (40 kgf/mm², 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 Guide provides guidance on the design, construction and operation, of container carriers built with such high strength steel.

This Guide provides the requirements for the optional notation, EBCAD (Enhanced Brittle Crack Arrest Design), for the enhanced BCA application of higher-strength hull structural thick steel plates in container carriers.

This edition also updates the requirements for H47 steel and brittle crack arrest steel and introduces a new Appendix 8 on engineering critical assessment for hatch coamings.

This Guide becomes effective on 1 January 2021.

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

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

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SECTION 1 Introduction (2021)

1 General

This Guide 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 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. In the upper flange of the hull structure, wave-induced fatigue damages in way of thick plated weld connections are the first and foremost concern. As a countermeasure, the fatigue behavior of these weld connections is to be extensively evaluated to avoid initial crack initiation. Second, the presence of planar flaws in thick plated weld connections can adversely affect the integrity of these connections in the form of accelerated crack growth and fracture. Satisfactory fatigue and fracture characteristics are to be attained from improvements in structural design measures, steel materials, welding consumables, welding procedures and post-weld enhancements. Third, survey after construction is to be enhanced through monitoring critical areas and nondestructive inspection.

3 Application

For H36/H40 steel grade, the supplementary requirements in the Guide 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.

For H47 steel grade, the supplementary requirements in the Guide 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.).

* Note: The upper deck region is defined as the upper deck plating, hatch side coaming plating, hatch coaming top plating, and their attached longitudinals.
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 Guide are applicable to the Cargo Hold Region.

5 Notation

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** (Enhanced Brittle Crack Arrest Design).

5.1 Enhanced Brittle Crack Arrest Application

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:

1) 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.

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

3) 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.

*Note: 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.*
SECTION 2 Hull Structural Design with Higher-Strength Thick Steel Plates

1 General

The material factor $Q$ for higher strength steels used in the hull girder strength requirement is an indirect means to minimize potential risks associated with buckling, fatigue and fracture in higher strength steels. For thick plated structural members in the upper flange of a container carrier, buckling can generally be excluded as a critical structural mode. Therefore, prevention of fatigue and fracture in the upper flange should be one of the main focuses for large container carriers. 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 (2021)

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

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

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

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

#### TABLE 1

**Material Grade** *(2021)*

<table>
<thead>
<tr>
<th>Thickness, t mm (in.)</th>
<th>Material Class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>II</td>
</tr>
<tr>
<td></td>
<td>III</td>
</tr>
<tr>
<td>$t \leq 15$ ($t \leq 0.60$)</td>
<td>A, AH</td>
</tr>
<tr>
<td>$15 &lt; t \leq 20$ ($0.60 &lt; t \leq 0.79$)</td>
<td>A, AH</td>
</tr>
<tr>
<td>$20 &lt; t \leq 25$ ($0.79 &lt; t \leq 0.98$)</td>
<td>A, AH</td>
</tr>
<tr>
<td>$25 &lt; t \leq 30$ ($0.98 &lt; t \leq 1.18$)</td>
<td>A, AH</td>
</tr>
<tr>
<td>$30 &lt; t \leq 35$ ($1.18 &lt; t \leq 1.38$)</td>
<td>B, AH</td>
</tr>
<tr>
<td>$35 &lt; t \leq 40$ ($1.38 &lt; t \leq 1.57$)</td>
<td>B, AH</td>
</tr>
<tr>
<td>$40 &lt; t \leq 50$ ($1.57 &lt; t \leq 2.00$)</td>
<td>D, DH</td>
</tr>
<tr>
<td>$50 &lt; t \leq 70$ ($2.00 &lt; t \leq 2.80$)</td>
<td>D, DH</td>
</tr>
<tr>
<td>$70 &lt; t \leq 100$ ($2.80 &lt; t \leq 4.00$)</td>
<td>E, EH, EH-BCA</td>
</tr>
</tbody>
</table>

**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

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 of this Guide where BCA1 and BCA2 are defined in 3/5.13. When the BCA steels in Section 2, Table 2 of this Guide are used, the weld joints between the upper deck plating and hatch coaming side plating are required to be partial penetration weld details. In the vicinity of block joints, alternative weld details may be used for the upper deck plating and hatch coaming side plating as agreed by ABS.

#### TABLE 2

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

<table>
<thead>
<tr>
<th>Structural Members Plating</th>
<th>Thickness, t mm (in.)</th>
<th>BCA Steel Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Deck Plating</td>
<td>50 $&lt; t \leq 100$ (2.00 $&lt; t \leq 4.00$)</td>
<td>Steel grade H36 or H40 with suffix BCA1</td>
</tr>
<tr>
<td>Hatch Coaming Side Plating</td>
<td>50 $&lt; t \leq 80$ (2.00 $&lt; t \leq 3.15$)</td>
<td>Steel grade H40 or H47 with suffix BCA1</td>
</tr>
<tr>
<td></td>
<td>80 $&lt; t \leq 100$ (3.15 $&lt; t \leq 4.00$)</td>
<td>Steel grade H40 or H47 with suffix BCA2</td>
</tr>
</tbody>
</table>

**Note:**

1. Excluding their attached longitudinals.
4 Alternative to BCA Materials (2021)

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 8 in this Guide 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

The requirement on hull girder section modulus is given in 5C-5-4/3.1 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 of the Marine Vessel Rules may be reduced by the material factor $Q$.

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

where

$SM = \text{section modulus as obtained from } 3-2-1/3.7 \text{ of the Marine Vessel Rules}$

The material factor $Q$ for steel materials is listed in Section 2, Table 3 of this Guide. 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 to be 0.78 for H32, 0.72 for H36 and 0.68 for H40. 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 (2021)

The requirement on hull girder moment of inertia is given in 5C-5-4/3.3 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 of this Guide, the effects of springing and whipping on fatigue strength of the hull structural strength are to be evaluated in accordance with the requirements in Subsection 2/11 of this Guide.
TABLE 3
Material Factor $Q$ for Determining Required Hull Girder Section Modulus (2014)

<table>
<thead>
<tr>
<th>Steel Grade</th>
<th>Material Factor $Q$ ($^{(1)}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ordinary Strength Steel</td>
<td>1.00</td>
</tr>
<tr>
<td>H32</td>
<td>0.78</td>
</tr>
<tr>
<td>H36</td>
<td>0.72</td>
</tr>
<tr>
<td>H40</td>
<td>0.68 ($^{(1)}$)</td>
</tr>
<tr>
<td>H47 ($^{(2)}$)</td>
<td>0.62</td>
</tr>
</tbody>
</table>

Notes:
1. The material factor for H40 may be taken as 0.66, provided that the hull structure is additionally verified for compliance with the requirements of:
   - ABS Guide for ‘SafeHull-Dynamic Loading Approach’ for Vessels
   - ABS Guide for Spectral-Based Fatigue Analysis for Vessels
   - Appendix 1 of this Guide
2. The above requirements are to be applied to hull structures with H47.
3. Thickness greater than 100 mm (4 in.) is subject to special consideration.

5.5 Hull Girder Shearing Strength
The requirements of hull girder shearing strength are given in 5C-5-4/5 of the 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 of this Guide.

TABLE 4
Material Factor and Strength

<table>
<thead>
<tr>
<th>Steel Grade</th>
<th>Material Factor, $Q$</th>
<th>Strength Reduction Factor, $S_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ordinary Strength Steel</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>H32</td>
<td>0.78</td>
<td>0.95</td>
</tr>
<tr>
<td>H36</td>
<td>0.72</td>
<td>0.908</td>
</tr>
<tr>
<td>H40</td>
<td>0.68</td>
<td>0.875</td>
</tr>
<tr>
<td>H47 ($^{(2)}$)</td>
<td>0.62</td>
<td>0.824</td>
</tr>
</tbody>
</table>

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

5.7 Hull Girder Torsional Strength
The requirements of hull girder torsional strength are defined in 5C-5-4/9 of the Marine Vessel Rules. The material factor $Q$ and strength reduction factor $S_m$ for steel materials are listed in Section 2, Table 4 of this Guide.

7 Initial Scantling Evaluation
The requirements of initial scantling evaluation are defined in Section 5C-5-4 of the Marine Vessel Rules. The material factor $Q$ for the hull girder section modulus requirement is listed in Section 2, Table 3 of this Guide. For all other requirements, the material factor $Q$ and strength reduction factor $S_m$ for steel materials to be applied are listed in Section 2, Table 4 of this Guide.
Section 2 Hull Structural Design with Higher-Strength Thick Steel Plates

9 Total Strength Assessment

The requirements for total strength assessment are given in Section 5C-5-5 of the Marine Vessel Rules. The strength reduction factor $S_m$ for steel materials to be applied is listed in Section 2, Table 4 of this Guide.

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

11 Structural Details and Fatigue Strength Assessment (2021)

For the hull structure built with higher-strength thick steel plates of H40 or H47, the following analyses are mandatory.

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

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

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

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

13 Brittle Crack Arrest Design (2021)

Below are examples of proper brittle crack arrest design. Other design concepts may be approved on a case-by-case basis.

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.

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)

H36 for hatch coaming side and top plating with $t^* > 50$ mm

50 mm $< t^* \leq 85$ mm

NDT during construction

BCA steel/BCA design not required for hatch coaming side, top plating, or upper deck plating

Requirements of Section 1/1 in this Guide for non BCA steel/design

Visual inspection during construction and after delivery

85 mm $< t^* \leq 100$ mm

ABS to consider on a case-by-case basis

50 mm $< t^* \leq 85$ mm

$\max t^* = \text{maximum as-built thickness of hatch coaming side and top plating}$

Section 5/3

Section 1/1

MVR Part 7

†The maximum steel grade of hatch coaming side and top plating
FIGURE 1B
Flowchart for BCA Steel/BCA Design – H40 Steel Grade for Hatch Coaming Side and Top Plating (2021)

- BCA steel/BCA design not required for hatch coaming side, top plating, or upper deck plating.
- Requirements of Section 1/1 in this Guide for non BCA steel/design.
- NDT during construction.
- Visual inspection during construction and after delivery.
- MVR Part 7.

Section 2/4 & Appendix 8.

Section 5/3.

Enhanced NDT during construction.

NDT after delivery.

Visual inspection during construction and after delivery.

MVR Part 7.

BCA steel material.

BCA design.

Inspection method.

$t^*$ = maximum as-built thickness of hatch coaming side and top plating.

1 The maximum steel grade of hatch coaming side and top plating.
FIGURE 1C
Flowchart for BCA Steel/BCA Design – H47 Steel Grade for Hatch Coaming Side and Top Plating (2021)

ABS to consider on a case-by-case basis

BCA steel material
BCA design
Inspection method

EGW = Electrogas welding

‡ The maximum steel grade of hatch coaming side and top plating

Thickness (t) of upper deck plating

Steel grade of upper deck plating

H47

H36 or H40

EH-BCA1 steel for upper deck plating

Sections 2/3, 2/3.7 & 2/13 i)

H47 for hatch coaming side and top plating† with t* > 50 mm

t* > 100 mm

50 mm < t* ≤ 100 mm

50 mm < t ≤ 100 mm

BCA steel not required for upper deck plating

Requirements of Section 1/1 in this Guide for non BCA steel

Section 1/1

EGW?

No

Yes

No

Yes

BCA steel for hatch coaming side plating?

EH-BCA1 steel (50 mm < t ≤ 80 mm) or EH-BCA2 steel (80 mm < t ≤ 100 mm) for hatch coaming side plating

Sections 2/3 & 2/3.7

Sections 2/13 ii), iii) & iv) & 5/7

Block joint shift
Crack stop hole
High toughness weld or arrest insert plate

MVR Part 7

Enhanced NDT during construction

NDT after delivery

Visual inspection during construction and after delivery

Visual inspection during construction and after delivery

NDT during construction

MVR Part 7

Section 5/3

Section 2/4 & Appendix 8

Section 2/4

Section 5/3

Visual inspection during construction and after delivery

t* = maximum as-built thickness of hatch coaming side and top plating

† The maximum steel grade of hatch coaming side and top plating
SECTION 3  Testing and Certification of Thick Steel Plates  
*(2021)*

1 General

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 Guide.

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

3  H47 Steels

3.1 Chemical Composition

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

3.3 Carbon Equivalent

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

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

3.5 Cold Cracking Susceptibility

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

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5B \text{ (\%)}$$
### TABLE 1

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

<table>
<thead>
<tr>
<th>Grade</th>
<th>AH47, DH47, EH47, FH47</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deoxidation</td>
<td>Killed, Fine Grain Practice (1)</td>
</tr>
<tr>
<td>Chemical Composition (2)</td>
<td>(Ladle Analysis), % max. unless specific in range</td>
</tr>
<tr>
<td>C</td>
<td>0.18&lt;sup&gt;(7)&lt;/sup&gt;</td>
</tr>
<tr>
<td>Mn</td>
<td>0.90-2.00</td>
</tr>
<tr>
<td>Si</td>
<td>0.55&lt;sup&gt;(3)&lt;/sup&gt;</td>
</tr>
<tr>
<td>P</td>
<td>0.020</td>
</tr>
<tr>
<td>S</td>
<td>0.020</td>
</tr>
<tr>
<td>Al (acid Soluble) min. &lt;sup&gt;(4,5)&lt;/sup&gt;</td>
<td>0.015</td>
</tr>
<tr>
<td>Nb &lt;sup&gt;(5,6)&lt;/sup&gt;</td>
<td>0.02-0.05</td>
</tr>
<tr>
<td>V &lt;sup&gt;(5,6)&lt;/sup&gt;</td>
<td>0.05-0.10</td>
</tr>
<tr>
<td>Ti &lt;sup&gt;(6)&lt;/sup&gt;</td>
<td>0.02</td>
</tr>
<tr>
<td>Cu</td>
<td>0.35</td>
</tr>
<tr>
<td>Cr</td>
<td>0.25</td>
</tr>
<tr>
<td>Ni</td>
<td>1.50</td>
</tr>
<tr>
<td>Mo</td>
<td>0.08</td>
</tr>
<tr>
<td>B</td>
<td>0.002</td>
</tr>
</tbody>
</table>

**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. <sup>(2021)</sup> The total amount of niobium, vanadium, and titanium is not to exceed 0.12%.
7. <sup>(2021)</sup> For improved weldability, the maximum Carbon content may be reduced to 0.12%.

### TABLE 2

**Carbon Equivalent for H47 Non-BCA Steel**

<table>
<thead>
<tr>
<th>Grade</th>
<th>Carbon Equivalent, Max. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t ≤ 50 mm (t ≤ 2 in.)</td>
</tr>
<tr>
<td>AH47, DH47, EH47, FH47</td>
<td>0.46</td>
</tr>
</tbody>
</table>

### TABLE 3

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

<table>
<thead>
<tr>
<th>Grade</th>
<th>Cold Cracking Susceptibility, Max. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t ≤ 100 mm (t ≤ 4 in.)</td>
</tr>
<tr>
<td>AH47, DH47, EH47, FH47</td>
<td>0.22</td>
</tr>
</tbody>
</table>
### 3.7 Tensile Properties

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

#### TABLE 4

<table>
<thead>
<tr>
<th>Grade</th>
<th>Tensile Strength N/mm² (kgf/mm², ksi)</th>
<th>Yield Point min. N/mm² (kgf/mm², ksi)</th>
<th>Elongation Min.%</th>
</tr>
</thead>
<tbody>
<tr>
<td>AH47, DH47, EH47, FH47</td>
<td>570–720 (58-71, 83-101)</td>
<td>460 (47, 67)</td>
<td>17</td>
</tr>
</tbody>
</table>

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 of this Guide.

#### TABLE 5

<table>
<thead>
<tr>
<th>Grade</th>
<th>Temp °C (°F)</th>
<th>t ≤ 70 mm (t ≤ 2.8 in.)</th>
<th>70 mm &lt; t ≤ 85 mm (2.8 in. &lt; t ≤ 3.4 in.)</th>
<th>85 mm ≤ t &lt; 100 mm (3.4 in. &lt; t ≤ 4.0 in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average Absorbed Energy</td>
<td>Average Absorbed Energy</td>
<td>Average Absorbed Energy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Longitudinal, J (kgf-m, ft-lbf)</td>
<td>Transverse, J (kgf-m, ft-lbf)</td>
<td>Longitudinal, J (kgf-m, ft-lbf)</td>
</tr>
<tr>
<td>AH47 Non-BCA</td>
<td>0 (32)</td>
<td>53 (5.4, 39)</td>
<td>37 (3.8, 27)</td>
<td>64 (6.5, 47)</td>
</tr>
<tr>
<td>DH47 Non-BCA</td>
<td>−20 (−4)</td>
<td>53 (5.4, 39)</td>
<td>37 (3.8, 27)</td>
<td>64 (6.5, 47)</td>
</tr>
<tr>
<td>EH47 Non-BCA and BCA</td>
<td>−40 (−40)</td>
<td>53 (5.4, 39)</td>
<td>37 (3.8, 27)</td>
<td>64 (6.5, 47)</td>
</tr>
<tr>
<td>FH47 Non-BCA and BCA</td>
<td>−60 (−76)</td>
<td>53 (5.4, 39)</td>
<td>37 (3.8, 27)</td>
<td>64 (6.5, 47)</td>
</tr>
</tbody>
</table>

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

5 H36/H40/H47 BCA Steels

5.1 General

In addition to the requirements in Section 3 of this Guide 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 of this Guide. 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.

In general, 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)

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

**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)**

<table>
<thead>
<tr>
<th>Grade *</th>
<th>Carbon Equivalent, Max. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50 mm &lt; $t$ ≤ 100 mm (2 in. &lt; $t$ ≤ 4 in.)</td>
</tr>
<tr>
<td>XH36-BCA</td>
<td>0.47</td>
</tr>
<tr>
<td>XH40-BCA</td>
<td>0.49</td>
</tr>
<tr>
<td>XH47-BCA</td>
<td>0.55</td>
</tr>
</tbody>
</table>

* 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)**

<table>
<thead>
<tr>
<th>Grade *</th>
<th>Cold Cracking Susceptibility, Max. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50 mm &lt; $t$ ≤ 100 mm (2 in. &lt; $t$ ≤ 4 in.)</td>
</tr>
<tr>
<td>XH47-BCA</td>
<td>0.24</td>
</tr>
</tbody>
</table>

* 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 of this Guide.

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 of this Guide.

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

Steels designated as BCA are to be tested to determine the BCA properties by large scale ESSO test (detailed in Appendix 4 and Appendix 5 of this Guide), small scale double tension test (detailed in ASTM E1221 and Appendix 6 of this Guide) or CAT (Crack Arrest Temperature) test (detailed in Appendix 7 of this Guide), 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)

<table>
<thead>
<tr>
<th>Suffix to the Steel Grade (1)</th>
<th>Thickness Range mm (in.)</th>
<th>Brittle Crack Arrest Properties (3,7,8)</th>
<th>Crack Arrest Temperature CAT Maximum °C (°F) (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCA1</td>
<td>50 &lt; ( t \leq 100 ) (2.0 &lt; ( t \leq 4.0 ))</td>
<td>6,000 ( K_{ca} ) at (-10°C (14°F) ) Minimum N/mm(^{3/2}) (ksi-in(^{1/2})) (6)</td>
<td>–10 (14)</td>
</tr>
<tr>
<td>BCA2 (2)</td>
<td>80 &lt; ( t \leq 100 ) (3.2 &lt; ( t \leq 4.0 ))</td>
<td>8,000 ( K_{ca} ) (230) (9)</td>
<td></td>
</tr>
</tbody>
</table>

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 7 of this Guide 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, 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

#### 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 can 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/mm\(^2\) (47 kgf/mm\(^2\), 67 ksi)

1 General

(2021) 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 Guide.

1.1 Preparation for Welding

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

1.3 Production Welding (2021)

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. 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.

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

1.5 Butt Welds

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

1.7 Workmanship Test

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

1.9 Short Bead (2021)

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

1.11 High Heat Input Welding

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

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

3.3 Mechanical Properties (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)

<table>
<thead>
<tr>
<th>Mechanical Properties</th>
<th>Impact Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Strength, min. N/mm² (kgf/mm², ksi)</td>
<td>Tensile Strength N/mm² (kgf/mm², ksi)</td>
</tr>
<tr>
<td>460 (47, 67)</td>
<td>570-720 (58-71, 83-101)</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Tensile Strength N/mm² (kgf/mm², ksi)</th>
<th>Bend Test Ratio: D/t</th>
<th>Charpy V-notch Impact Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charpy V-notch Impact Tests</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test Temperature °C (°F)</td>
<td>Minimum Average Absorbed Energy, min. J (kgf-m, ft-lbf)</td>
<td>Downhand, Horizontal, Overhead</td>
</tr>
<tr>
<td>570-720 (58-71, 83-101)</td>
<td>4</td>
<td>−20 (−4)</td>
</tr>
</tbody>
</table>

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)

<table>
<thead>
<tr>
<th>Filler Metal Grade</th>
<th>Plate Thickness ≤ 50 mm (2 in.)</th>
<th>Plate Thickness &gt; 50 mm (2 in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade 3 Y 460</td>
<td>AH47, DH47</td>
<td></td>
</tr>
<tr>
<td>Grade 4 Y 460</td>
<td>AH47, DH47, EH47</td>
<td>DH47</td>
</tr>
<tr>
<td>Grade 5 Y 460</td>
<td>AH47, DH47, EH47, FH47</td>
<td>DH47, EH47</td>
</tr>
<tr>
<td>Grade 6 Y 460</td>
<td>AH47, DH47, EH47, FH47</td>
<td>DH47, EH47, FH47</td>
</tr>
</tbody>
</table>

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.
Section 4  Welding and Fabrication of Thick Steel Plates with Minimum Yield Stress of 460 N/mm²
(47 kgf/mm², 67 ksi)

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

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 cm³/100 g (2.8 in³/lbf).

5.5 Test Requirements (2021)

5.5.1 General

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

The butt weld tensile strength is not to be less than 570 N/mm² (58 kgf/mm², 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

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)

<table>
<thead>
<tr>
<th>Grade</th>
<th>Test Location</th>
<th>Test Temperature</th>
<th>CVN Requirement, Average, Min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>AH47 Non-BCA</td>
<td>WM, FL, FL + 2 mm, + 5 mm, + 20 mm</td>
<td>20°C (68°F)</td>
<td>64 J (6.5 kgf-m, 47 ft-lbf)</td>
</tr>
<tr>
<td>DH47 Non-BCA</td>
<td></td>
<td>0°C (32°F)</td>
<td>64 J (6.5 kgf-m, 47 ft-lbf)</td>
</tr>
<tr>
<td>EH47 Non-BCA and BCA</td>
<td>(WM, FL, FL + 0.08 in., + 0.2 in., + 0.8 in.)</td>
<td>-20°C (-4°F)</td>
<td>64 J (6.5 kgf-m, 47 ft-lbf)</td>
</tr>
<tr>
<td>FH47 Non-BCA and BCA</td>
<td></td>
<td>-40°C (–40°F)</td>
<td>64 J (6.5 kgf-m, 47 ft-lbf)</td>
</tr>
</tbody>
</table>

Notes: WM, FL, FL+ are defined in Appendix 2-A9-A1 of ABS Rules for Materials and Welding (Part 2).
5.5.4 CTOD Test
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. At the discretion of ABS, the CTOD may be deferred during WPQT if the welding design is adopted as the brittle crack arrest method shown in Section 5.

5.5.5 Bend Test
The bending mandrel diameter is to be $5 \times t$. 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
The maximum hardness of the weld is not to exceed 350 HV10 for H47 Non-BCA and 380 HV10 for H47-BCA, respectively. Measurement points are to include a mid-thickness position in addition to those specified in 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 of Hull Welds (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 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 (2021)

3.1 General

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

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

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.
3.3 **New Construction**
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**
Within $0.3L \sim 0.7L$ 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 inspection results.

- In addition, if the alternative to BCA material defined in Subsection 2/4 of this Guide 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**
As minimum, acceptance levels for allowable sizes of discontinuities are to be determined in accordance with the ABS *Guide for Nondestructive Inspection of Hull Welds*.

In the case that more stringent acceptance criteria have been determined by ECA in accordance with Appendix 8 of this Guide, these acceptance criteria prevail over the NDI *Guide* criteria. The ECA acceptance are to be documented and made to be available to ABS.

5 **Prevention of Fatigue Failure**

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

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

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

5.3 **Fatigue Strength Improvement of Welds (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.
7 Prevention of Fracture Failure

7.1 General (2021)
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 may be considered. The detailed design measure applied to avoid crack propagation is to be submitted for review.

7.3 Crack Stop Hole
A crack stop hole of a sufficient size is to be provided at the bottom of the hatch coaming side plate as shown in Section 5, Figure 3. In general, the radius of the edges of the crack stop hole is to be half of the hatch side plate thickness.

The edges of a crack stop hole are to be ground smooth with a radius of 3 ~ 5 mm (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.
Section 5  Prevention of Fatigue and Fracture Failure in Thick Steel Plates

7.5  High Toughness Weld

In general, high toughness weld consumables with Ni content greater than 2.5% or other high toughness consumables are to be used at the bottom of hatch coaming side plate with an appropriate weld shape to stop a propagating crack as shown in Section 5, Figure 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.
7.7 Block Joint Shift
The butt weld lines in the hatch coaming top and side plates are to be shifted from the butt weld lines of the upper deck structure so that a fatigue crack initiated in the butt weld of the hatch coaming is prevented from propagating through the upper deck as shown in Section 5, Figure 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.

7.9 Insert Plate (1 February 2012)
An insert plate is to be provided at the bottom of the hatch coaming side plate as shown in Section 5, Figure 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.
9 Hull Girder Residual Strength

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

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

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 Guide are to be modified accordingly.

1.7 Effects of Corrosion

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

1.9 Format of the Criteria

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

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

3.5 Fatigue Classification

3.5.1 Welded Connections with One Load Carrying Member
Fatigue classification for structural details is shown in Appendix 1, Table 1.
## TABLE 1
### Fatigue Classification for Structural Details

<table>
<thead>
<tr>
<th>Class</th>
<th>Designation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>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</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>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</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>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</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>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 3) Welds of brackets and stiffeners to web plate of girders</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>1) Full penetration butt weld made on a permanent backing strip 2) Rounded fillet welds as shown below</td>
<td></td>
</tr>
</tbody>
</table>

![Diagram](image.png)
### TABLE 1 (continued)
**Fatigue Classification for Structural Details**

<table>
<thead>
<tr>
<th>Class</th>
<th>Designation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3)</td>
<td>焊接支架和加筋板到翼缘</td>
<td>EDGE DISTANCE ≥ 10mm</td>
</tr>
<tr>
<td>4)</td>
<td>板或面板上的连接件</td>
<td>EDGE DISTANCE ≥ 10mm (Class G for edge distance &lt; 10 mm)</td>
</tr>
</tbody>
</table>

**F₂**  
1) 焊缝如图所示，并且焊缝圆角且无 undercutting  
1a)  
1b)  
“Y”是一个非承载成员  
2) 焊缝有 undercutting 并且在角落处由局部研磨清理出来  
2a)  
2b)  
Y is a non-load carrying member

**Y** is a non-load carrying member
### TABLE 1 (continued)
**Fatigue Classification for Structural Details**

<table>
<thead>
<tr>
<th>Class</th>
<th>Designation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>1)</td>
<td>Fillet welds in F2 - 1) without rounded tow welds or with limited minor undercutting at corners or bracket toes</td>
</tr>
<tr>
<td></td>
<td>2)</td>
<td>Fillet welds in F2 - 2) with minor undercutting</td>
</tr>
<tr>
<td></td>
<td>3)</td>
<td>Doubler on face plate or flange, small deck openings</td>
</tr>
<tr>
<td></td>
<td>4)</td>
<td>Overlapped joints as shown below</td>
</tr>
<tr>
<td>W</td>
<td>1)</td>
<td>Fillet welds in G - 3) with any undercutting at the toes</td>
</tr>
<tr>
<td></td>
<td>2)</td>
<td>Fillet welds – weld throat</td>
</tr>
</tbody>
</table>
3.5.2  Welded Joint with Two or More Load Carrying Members

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

**TABLE 2**

Welded Joint with Two or More Load Carrying Members

<table>
<thead>
<tr>
<th>a Connections of Longitudinal and Stiffener</th>
</tr>
</thead>
</table>

![Diagram showing connections with and without SCF]
### TABLE 2 (continued)
**Welded Joint with Two or More Load Carrying Members**

<table>
<thead>
<tr>
<th>Connections of Longitudinal Deck Girders and Cross Deck Box</th>
</tr>
</thead>
<tbody>
<tr>
<td>A - A</td>
</tr>
<tr>
<td>E WITH SCF</td>
</tr>
<tr>
<td>D</td>
</tr>
<tr>
<td>D</td>
</tr>
<tr>
<td>C</td>
</tr>
<tr>
<td>B</td>
</tr>
<tr>
<td>B - B</td>
</tr>
<tr>
<td>D</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>HATCH COAMING TOP</td>
</tr>
<tr>
<td>STRENGTH DECK</td>
</tr>
<tr>
<td>W.T. BHD</td>
</tr>
<tr>
<td>CROSS BOX CIRDER BOTTOM</td>
</tr>
<tr>
<td>E WITH SCF</td>
</tr>
</tbody>
</table>
### TABLE 2 (continued)
Welded Joint with Two or More Load Carrying Members

<table>
<thead>
<tr>
<th>C - C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>HATCH COAMING TOP</td>
<td>D</td>
</tr>
<tr>
<td>STRENGTH DECK</td>
<td>C WITH SCF</td>
</tr>
<tr>
<td>LONGITUDINAL DECK GIRDER BOTTOM</td>
<td>E WITH SCF</td>
</tr>
<tr>
<td></td>
<td>C WITH SCF</td>
</tr>
<tr>
<td></td>
<td>E WITH SCF</td>
</tr>
<tr>
<td>CROSS DECK BOX GIRDER BOTTOM</td>
<td>D</td>
</tr>
</tbody>
</table>

### D - D

<table>
<thead>
<tr>
<th>Y</th>
<th>Z</th>
</tr>
</thead>
</table>
| | }
TABLE 2 (continued)
Welded Joint with Two or More Load Carrying Members

c Discontinuous Hatch Side Coaming

1) without face plate

Hatch End Coaming
Hatch Side Coaming Top

Strength Deck

C with SCF

2) with face plate

Hatch End Coaming
Hatch Side Coaming Top

Strength Deck

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

<table>
<thead>
<tr>
<th>d</th>
<th>Hatch Corners</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular Corner</td>
<td></td>
</tr>
<tr>
<td>Double Curvature</td>
<td></td>
</tr>
</tbody>
</table>

```
<table>
<thead>
<tr>
<th></th>
<th>D WITH SCF</th>
<th>C WITH SCF</th>
<th>D WITH SCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R₂</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R₁</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```

---

**Notes:**
- SCF: Stress Concentration Factor
- D: Designated area
- C: Centerline
- R: Radius of curvature
- R₁, R₂: Secondary radii

---

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

**ABS** GUIDE FOR APPLICATION OF HIGHER-STRENGTH HULL STRUCTURAL THICK STEEL PLATES IN CONTAINER CARRIERS • 2021

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

<table>
<thead>
<tr>
<th>Cut-out Radius</th>
</tr>
</thead>
</table>

![Diagram of welded joint with cut-out radius labeled R, C, and D with SCF](image)
### TABLE 2 (continued)

**Welded Joint with Two or More Load Carrying Members**

#### End Connections at Lower Deck

<table>
<thead>
<tr>
<th>Fatigue Class</th>
<th>Side Deck</th>
<th>Cross Deck</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>F</strong></td>
<td>$f_R = (f_{RS} + f_{RC})^{1/2}$</td>
<td>$f_R = (f_{RS} + f_{RC})^{1/2}$</td>
</tr>
</tbody>
</table>

where

$$
\alpha = 1.25
$$

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

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

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

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

#### Note:

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

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

5.1 Assumptions

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

- A linear cumulative damage model (i.e., Palmgren-Miner’s Rule) has been used in connection with the S-N data in Appendix 1, Figure 1 (extracted from Ref. 1*).
- Cyclic stresses due to the loads in Subsection A1/9 have been used and the effects of mean stress have been ignored.
- The target design life of the vessel is taken to be 20 years.
- The long-term stress ranges on a detail can be characterized by using a modified Weibull probability distribution parameter ($\gamma$).
- Structural details are classified and described in Appendix 1, Table 1, “Fatigue Classification for Structural Details”.

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

5.3 Criteria

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

5.5 Long Term Stress Distribution Parameter, $\gamma$

The long-term stress distribution parameter, $\gamma$, can be determined as below.

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

where

$$\alpha = \begin{cases} 1.0 & \text{for deck structures, including side shell and longitudinal bulkhead structures within 0.1D from the deck} \\ 1.05 & \text{for bottom structures, including inner bottom and side shell, and longitudinal bulkhead structures within 0.1D from the bottom} \\ 1.1 & \text{for side shell and longitudinal bulkhead structures within the region of 0.25D upward and 0.3D downward from the mid-depth} \\ 1.1 & \text{for transverse bulkhead structures} \end{cases}$$

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

$L$ and $D$ are the vessel’s length and depth, as defined in 3-1-1/3.1 and 3-1-1/7 of the Marine Vessel Rules.
Appendix 1  Full Ship Finite Element Based Fatigue Strength Assessment of Upper Flange Structure

5.7  Fatigue Damage

The cumulative fatigue damage, \( D_f \), is to be taken as

\[
D_f = \frac{1}{6} \alpha_s \alpha_w \left( D_{f_{12}} + D_{f_{34}} \right) + \frac{1}{3} D_{f_{56}} + \frac{1}{3} D_{f_{78}} \leq 0.8
\]

where

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

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

\( D_{f_{12}}, D_{f_{34}}, D_{f_{56}} \) and \( D_{f_{78}} \) are the fatigue damage accumulated due to load case pairs 1 & 2, 3 & 4, 5 & 6 and 7 & 8, respectively (see Subsection A1/7 for load case pairs).

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

\[
D_{f_{jk}} = \frac{N_T}{K_2} \left( \frac{k_k f_{R_{jk}}}{(\ln N_R)^{m/\gamma}} \right) \mu_{jk} \left( 1 + \frac{m}{\gamma} \right)
\]

where

\[
N_T = \text{number of cycles in the design life.}
\]

\[
f_0 = 0.85, \text{ factor for net time at sea}
\]

\[
D_L = \text{design life in seconds, } 6.31 \times 10^8 \text{ for a design life of 20 years}
\]

\[
L = \text{ship length defined in 3-1-1/3.1 of the Marine Vessel Rules}
\]

\[
m, K_2 = \text{S-N curve parameters as defined in Appendix 1, Figure 1 of the Guide}
\]

\[
f_{R_{jk}} = \text{stress range of load case pair } jk \text{ at the representative probability level of } 10^{-4}, \text{ in kgf/cm}^2
\]

\[
k_t = \text{thickness correction factor}
\]

\[
= \left( \frac{t}{22} \right)^n \quad \text{for } t \geq 22 \text{ mm, where } t \text{ is the plate thickness}
\]

\[
= 1 \quad \text{for } t < 22 \text{ mm}
\]
Appendix 1  Full Ship Finite Element Based Fatigue Strength Assessment of Upper Flange Structure

\[ n = 0.20 \text{ for a transverse butt weld with its upper and lower edges as built or ground to 1C} \]
\[ = 0.10 \text{ for a transverse butt weld with its upper and lower edges ground with a radius of } 3 \sim 5 \text{ mm. The extent of the grinding is to be 100 mm forward and aft of the butt weld as shown in Section 5, Figure 1.} \]
\[ = 0.10 \text{ for hatch corner insert plate away from the welds. The upper and lower edges are ground with a radius of } 3 \sim 5 \text{ mm} \]

\[ k_p = \text{correction factor for higher-strength steel, applicable to parent material only} \]
\[ = 1.000 \text{ for mild steel or welded connections} \]
\[ = 0.926 \text{ for H32 steel} \]
\[ = 0.885 \text{ for H36 steel} \]
\[ = 0.870 \text{ for H40 steel} \]
\[ = 0.850 \text{ for H47 steel} \]

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

\[ \gamma = \text{long-term stress distribution parameter as defined in A1/5.5} \]

\[ \Gamma = \text{Complete Gamma function} \]

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

\[ \nu_{jk} = \left( \frac{f_q}{f_{R_{jk}}} \right)^\gamma \ln N_R \]

\[ f_q = \text{stress range at the intersection of the two segments of the S-N curve} \]

\[ \Delta m = 2, \text{slope change of the upper-lower segment of the S-N curve} \]

\[ \Gamma_0(\cdot) = \text{incomplete Gamma function, Legendre form} \]
### 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;
- \( \sigma \) = 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/cm². The S-N curves have a change of inverse slope from \( m \) to \( m + 2 \) at \( N = 10^7 \) cycles.

<table>
<thead>
<tr>
<th>Class</th>
<th>( K_1 )</th>
<th>( \log_{10} K_1 )</th>
<th>( m )</th>
<th>( \sigma )</th>
<th>( K_2 )</th>
<th>( \log_{10} K_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>( 2.521 \times 10^{19} )</td>
<td>19.4016</td>
<td>4.0</td>
<td>0.1821</td>
<td>( 1.09 \times 10^{19} )</td>
<td>19.0374</td>
</tr>
<tr>
<td>C</td>
<td>( 3.660 \times 10^{17} )</td>
<td>17.5635</td>
<td>3.5</td>
<td>0.2041</td>
<td>( 1.43 \times 10^{17} )</td>
<td>17.1553</td>
</tr>
<tr>
<td>D</td>
<td>( 4.225 \times 10^{15} )</td>
<td>15.6258</td>
<td>3.0</td>
<td>0.2095</td>
<td>( 1.61 \times 10^{15} )</td>
<td>15.2068</td>
</tr>
<tr>
<td>E</td>
<td>( 3.493 \times 10^{15} )</td>
<td>15.5432</td>
<td>3.0</td>
<td>0.2509</td>
<td>( 1.10 \times 10^{15} )</td>
<td>15.0414</td>
</tr>
<tr>
<td>F</td>
<td>( 1.825 \times 10^{15} )</td>
<td>15.2614</td>
<td>3.0</td>
<td>0.2183</td>
<td>( 6.68 \times 10^{14} )</td>
<td>14.8248</td>
</tr>
<tr>
<td>F₂</td>
<td>( 1.302 \times 10^{15} )</td>
<td>15.1148</td>
<td>3.0</td>
<td>0.2279</td>
<td>( 4.56 \times 10^{14} )</td>
<td>14.6590</td>
</tr>
<tr>
<td>G</td>
<td>( 6.051 \times 10^{14} )</td>
<td>14.7818</td>
<td>3.0</td>
<td>0.1793</td>
<td>( 2.65 \times 10^{14} )</td>
<td>14.4232</td>
</tr>
<tr>
<td>W</td>
<td>( 3.978 \times 10^{14} )</td>
<td>14.5996</td>
<td>3.0</td>
<td>0.1846</td>
<td>( 1.70 \times 10^{14} )</td>
<td>14.2304</td>
</tr>
</tbody>
</table>
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 Appendix 1, Table 3, are defined to form four (4) pairs. The combinations of load cases are to be used to find the characteristic stress range corresponding to a probability of exceedance of $10^{-4}$, as indicated below.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave Induced Vertical Bending Moment</td>
<td>Sag 100%</td>
<td>Hog 100%</td>
<td>Sag 70%</td>
<td>Hog 70%</td>
<td>Sag 30%</td>
<td>Hog 30%</td>
<td>Sag 40%</td>
</tr>
<tr>
<td>Wave Induced Horizontal Bending Moment</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>Stbd Tens 30%</td>
<td>Port Tens 30%</td>
<td>Stbd Tens 50%</td>
</tr>
<tr>
<td>Wave Induced Torsional Moment</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>(–) 55%</td>
<td>(+) 55%</td>
<td>(–) 100%</td>
</tr>
<tr>
<td>Wave Heading Angle</td>
<td>Head &amp; Follow</td>
<td>Head &amp; Follow</td>
<td>Head &amp; Follow</td>
<td>Head &amp; Follow</td>
<td>Beam</td>
<td>Beam</td>
<td>Oblique</td>
</tr>
</tbody>
</table>

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
Vessels with Either Special Loading Patterns or Special Structural Configuration

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

9 Determination of Wave Induced Stress Range

9.1 General

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

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

9.3 Hatch Corners

9.3.1 Hatch Corners at Decks and Coaming Top

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

\[
f_R = 0.5^{1/7} \times c_f (K_{s1} c_1 f_{RG1} + K_{s2} c_2 f_{RG2}) \quad \text{N/cm}^2 \left( \text{kgf/cm}^2, \text{lbf/in}^2 \right)
\]

where

\[
f_{RG1} = \left| f_{dtvi} - f_{dtvj} \right| + \left| f_{dthi} - f_{dtbj} \right| + \left| f_{dtwi} - f_{dtwj} \right|
\]

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

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

\[
f_{dthi}, f_{dtbj} = \text{wave-induced component of the primary stresses produced by hull girder horizontal bending, in N/cm}^2 \left( \text{kgf/cm}^2, \text{lbf/in}^2 \right), \text{for load case } i \text{ and } j \text{ of the selected pairs of combined load cases, respectively. See 5C-5-3/5.1.3 of the Marine Vessel Rules.}
\]

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

For calculating the wave induced stresses, sign convention is to be observed for the respective directions of wave-induced loads, as specified in Appendix 1, Table 3. These wave-induced stresses are to be determined based on the gross ship scantlings (A1/1.7).
Appendix 1  Full Ship Finite Element Based Fatigue Strength Assessment of Upper Flange Structure

\( f_{d1v} \) 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.

\( \gamma \) 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:

\[
K_{s1} = c_c \alpha_c \alpha_t \alpha_t k_{s1} \\
K_{s2} = \alpha_c \alpha_t k_{s2}
\]

where

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

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

\[ c_t = \begin{cases} 0.8 & \text{for locations where coaming top terminates} \\ 1.0 & \text{for other locations} \end{cases} \]

\[ \alpha_c = \text{adjustment factor for cutout at hatch corners} \]

\[ \alpha_c = \begin{cases} 1.0 & \text{for shapes without cutout} \\ [1 - 0.04(c/R)^{3/2}] & \text{for circular shapes with a cutout} \\ [1 - 0.04(c/r_d)^{3/2}] & \text{for double curvature shapes with a cutout} \\ [1 - 0.04(c/R_1)^{3/2}] & \text{for elliptical shapes with a cutout} \end{cases} \]

\[ \alpha_s = \text{adjustment factor for contour curvature} \]

\[ \alpha_s = \begin{cases} 1.0 & \text{for circular shapes} \\ 0.33[1 + 2(r_1/r_2) + 0.1(r_d/r_1)^2] & \text{for double curvature shapes} \\ 0.33[1 + 2(R_2/R_1) + 0.1(R_1/R_2)^2] & \text{for elliptical shapes} \end{cases} \]

\[ \alpha_{ct} = 1.0 \text{ for shapes without cutout} \]

\[ \alpha_{ct} = 0.5 \text{ for shapes with cutout} \]

\[
\alpha_{t1} = (t_i/t_j)^{1/2} \\
\alpha_{t2} = 6.0/[5.0 + (t_i/t_j)], \text{ but not less than 0.85} \]

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

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

\[ = [3R_t/(R_1 - R_t) + \cos 0]r_{s2}/[3.816 + 2.879R_2/(R_1 - R_2)] \text{ for double curvature shapes in Appendix 1, Figure 4, in mm (in.)} \]

\[ = R_2 \text{ for elliptical shapes in Appendix 1, Figure 5, in mm (in.)} \]

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

\[ = R_2 \text{ for double curvature shapes in Appendix 1, Figure 4, in mm (in.)} \]

\[ = R_2^2/R_1 \text{ for elliptical shapes in Appendix 1, Figure 5, in mm (in.)} \]
\[ r_d = (0.753 - 0.72 \frac{R_2}{R_1})[R_1/(R_1 - R_2) + \cos \theta]r_{e1} \]

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

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

\[ t_i = \text{plate thickness of the strength deck, hatch coaming top or lower deck in way of the hatch corner under consideration, in mm (in.)} \]

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

\( \theta \) for double curvature shapes is defined in Appendix 1, Figure 4.

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

\[
\begin{align*}
r_{e1} &= R & \text{for circular shapes in Appendix 1, Figure 3, in mm (in.)} \\
&= R_2 + (R_1 - R_2)\cos \theta & \text{for double curvature shapes in Appendix 1, Figure 4, in mm (in.)} \\
&= (R_1 + R_2)/2 & \text{for elliptical shapes in Appendix 1, Figure 5, in mm (in.)} \\
r_{e2} &= R & \text{for circular shapes in Appendix 1, Figure 3, in mm (in.)} \\
&= R_1 - (R_1 - R_2)\sin \theta & \text{for double curvature shapes in Appendix 1, Figure 4, in mm (in.)} \\
&= R_2 & \text{for elliptical shapes in Appendix 1, Figure 5, in mm (in.)} 
\end{align*}
\]

\[
\begin{array}{|c|c|c|c|c|c|}
\hline
r_{e1}/w_1 & 0.1 & 0.2 & 0.3 & 0.4 & 0.5 \\
\hline
k_{s1} & 1.945 & 1.89 & 1.835 & 1.78 & 1.725 \\
\hline
\end{array}
\]

\[
\begin{array}{|c|c|c|c|c|}
\hline
r_{e2}/w_2 & 0.1 & 0.2 & 0.3 & 0.4 & 0.5 \\
\hline
k_{s2} & 2.35 & 2.20 & 2.05 & 1.90 & 1.75 \\
\hline
\end{array}
\]

\text{Note: \( k_{s1} \) and \( k_{s2} \) may be obtained by interpolation for intermediate values of \( r_{e1}/w_1 \) or \( r_{e2}/w_2 \).}

where

\[ w_1 = \text{transverse width of the cross deck under consideration, in mm (in.), for hatch corners of the strength deck and lower deck} \]

\[ = 0.1b_1 \text{ for width of cross deck that is not constant along hatch length} \]

\[ w_2 = \text{longitudinal width of the cross deck under consideration, in mm (in.), for strength deck and lower deck} \]

\[ b_1 = \text{width of the hatch opening under consideration, in mm (in.)} \]

\( K_{s1} \) 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 \( \phi \) 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 \( \phi \) 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 \( \phi = \phi_1, \phi_2 \) and three intermediate angles for each pair of the combined load cases considered.

- For circular shapes, \( 25 \leq \phi \leq 55 \)
  
  \[
  c_{L1} = 1 - 0.00045(\phi - 25)^2 \\
  c_{L2} = 0.8 - 0.0004(\phi - 55)^2 
  \]

- For double curvature shapes, \( \phi_1 \leq \phi \leq \phi_2 \)
  
  \[
  c_{L1} = \frac{[1.0 - 0.02(\phi - \phi_1)][1 - 0.015(\phi - \phi_1) + 0.00014(\phi - \phi_1)^2]}{[1 - 0.015(\phi - \phi_1) + 0.00014(\phi - \phi_1)^2]} \quad \text{for} \quad \theta < 55 \\
  = \frac{[1.0 - 0.026(\phi - \phi_1)][1 - 0.03(\phi - \phi_1) + 0.0012(\phi - \phi_1)^2]}{[1 - 0.03(\phi - \phi_1) + 0.0012(\phi - \phi_1)^2]} \quad \text{for} \quad \theta \geq 55 \\
  c_{L2} = 0.8/[1.1 + 0.035(\phi - \phi_2) + 0.003(\phi - \phi_2)^2] 
  \]

  where
  
  \[
  \phi_1 = \mu(95 - 70r_2/r_d) \\
  \phi_2 = 95/(0.6 + r_1/r_d) \\
  \mu = 0.165(\theta - 25)^{1/2} \quad \text{for} \quad \theta < 55 \\
  = 1.0 \quad \text{for} \quad \theta \geq 55 
  \]

- For elliptical shapes, \( \phi_1 \leq \phi \leq \phi_2 \)
  
  \[
  c_{L1} = 1 - 0.00004(\phi - \phi_1)^3 \\
  c_{L2} = 0.8/[1 + 0.0036(\phi - \phi_2)^2] 
  \]

  where
  
  \[
  \phi_1 = 95 - 70R_2/R_1 \\
  \phi_2 = 88/(0.6 + R_2/R_1) 
  \]

The peak stress range, \( f_{R} \), is to be obtained through calculations of \( c_{L1} \) and \( c_{L2} \) at each \( \phi \) along a hatch corner.

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

\[
0.3 \leq R_2/R_1 \leq 0.6 \text{ and } 45^\circ \leq \theta \leq 80^\circ \quad \text{for double curvature shapes} \\
0.3 \leq R_2/R_1 \leq 0.9 \quad \text{for elliptical shapes}
\]

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:

\[
 f_{R} = 0.5^{1/7} \times c(\alpha K_{d1} f_{RG1} + K_{d2} f_{RG2}) \quad \text{N/cm}^2 (\text{kgf/cm}^2, \text{lbf/in}^2) 
\]

where

\[
 f_{RG1} = \text{wave-induced stress range by hull girder vertical and horizontal bending moments and torsional moment at the longitudinal deck girder of hull girder section, in N/cm}^2 (\text{kgf/cm}^2, \text{lbf/in}^2) \\
 = [f_{d1vl} - f_{d1vl}] + [f_{d1hl} - f_{d1hl}] + [f_{d1vl} - f_{d1vl}] + [f_{d1lh} - f_{d1lh}] + [f_{d1lh} - f_{d1lh}]
\]
Appendix 1 Full Ship Finite Element Based Fatigue Strength Assessment of Upper Flange Structure

\[ f_{RG2} = \text{wave-induced stress range by hull girder torsional moment at the connection of the longitudinal deck girder with the cross deck box beam, in N/cm}^2 (\text{kgf/cm}^2, \text{lbf/in}^2) \]
\[ = |f_{d,li} - f_{d,ld}| \]
\[ \alpha_i = 1.0 \text{ for symmetrical section of the longitudinal deck girder about its vertical neutral axis} \]
\[ = 1.25 \text{ for unsymmetrical section of the longitudinal deck girder about its vertical neutral axis} \]

\( c_f \) and \( \gamma \) are as defined in A1/9.3.1 and A1/5.5.

\( f_{d,vi}, f_{d,vj}, f_{d,hi}, f_{d,hj}, f_{d,wi}, \) and \( f_{d,wj} \) 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
\[ k_d = \text{nominal stress concentration factor as given in the table below} \]
\[ \alpha_s = 1.0 \text{ for circular shapes} \]
\[ = 0.33[1 + 2(r_s/r_d) + 0.1(r_d/r_s)^2] \text{ for double curvature shapes} \]
\[ = 0.33[1 + 2(R_2/R_1) + 0.1(R_1/R_2)^2] \text{ for elliptical shapes} \]
\[ \alpha_t = (t_d/t_i)^{1/2} \]

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

\( t_d = \text{flange plate thickness of the longitudinal deck girder clear of the hatch corner under consideration, in mm (in.)} \]
\( t_i = \text{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.

\( \theta \) for double curvature shapes is defined in Appendix 1, Figure 4.

\( r_{s1}, r_d \) 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.

\[ k_d \]

<table>
<thead>
<tr>
<th>( r_{s1}/w_d )</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>( k_d )</td>
<td>2.35</td>
<td>2.20</td>
<td>2.05</td>
<td>1.90</td>
<td>1.75</td>
</tr>
</tbody>
</table>

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

where
\[ w_d = \text{width of the longitudinal deck girder, in mm (in.)} \]
9.3.3 Extent of Reinforced Plate Thickness at Hatch Corners

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

\[
\ell_i = 1.75r_{e1} \quad \text{mm (in.)}
\]
\[
b_i = 1.75r_{e2} \quad \text{mm (in.)}
\]
\[
b_d = 1.1r_{e2} \quad \text{mm (in.)}
\]

for a cut-out radius type,

\[
\ell_{i1} = 1.75r_{e1} \quad \text{mm (in.)}
\]
\[
\ell_{i2} = 1.0r_{e1} \quad \text{mm (in.)}
\]
\[
b_i = 2.5r_{e2} \quad \text{mm (in.)}
\]
\[
b_d = 1.25r_{e2} \quad \text{mm (in.)}
\]

where

\[
r_{e1} = R \quad \text{for circular shapes in Appendix 1, Figure 3, in mm (in.)}
\]
\[
= R_2 + (R_1 - R_2)\cos \theta \quad \text{for double curvature shapes in Appendix 1, Figure 4, in mm (in.)}
\]
\[
= (R_1 + R_2)/2 \quad \text{for elliptical shapes in Appendix 1, Figure 5, in mm (in.)}
\]
\[
r_{e2} = R \quad \text{for circular shapes in Appendix 1, Figure 3, in mm (in.)}
\]
\[
= R_1 - (R_1 - R_2)\sin \theta \quad \text{for double curvature shapes in Appendix 1, Figure 4, in mm (in.)}
\]
\[
= R_2 \quad \text{for elliptical shapes in Appendix 1, Figure 5, in mm (in.)}
\]

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

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

where

\[
f_s = \text{nominal stress range at the joint under consideration}
\]
\[
= f_{RG1} \quad \text{for side longitudinal deck box, as specified in A1/9.3.1, in N/cm}^2 \text{ (kgf/cm}^2, \text{ lbf/in}^2\text{)}
\]
\[
= f_{RG2} \quad \text{for cross deck box beam, as specified in A1/9.3.1, in N/cm}^2 \text{ (kgf/cm}^2, \text{ lbf/in}^2\text{)}
\]
\[
= f_{RG1} + f_{RG2} \quad \text{for longitudinal deck girder, as specified in A1/9.3.2, in N/cm}^2 \text{ (kgf/cm}^2, \text{ lbf/in}^2\text{)}
\]
\[
K_t = 0.25(1 + 3t_i/t_a) \leq 1.25
\]
\[
t_i = \text{plate thickness of inserted plate, in mm (in.)}
\]
\[
t_a = \text{plate thickness of plate adjacent to the inserted plate, in mm (in.)}
\]

\[c_f\] and \[\gamma\] are as defined in A1/9.3.1 and A1/5.5.
FIGURE 2
Hatch Corners at Decks and Coaming Top

(longitudinal direction)

(Strength Deck & Lower Deck)

(Hatch Coaming Top)
**FIGURE 3**
Circular Shape

**FIGURE 4**
Double Curvature Shape

**FIGURE 5**
Elliptical Shape
11 Hot Spot Stress Approach with Finite Element Analysis

11.1 Introduction

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

Hot spot stress is defined as the surface stress at the hot spot. Note that the stress change caused by the weld profile is not included in the hot spot stress, but the overall effect of the connection geometry on the nominal stress is represented. Therefore, in 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

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

Weld hot spot stress can be determined from linear extrapolation of surface component stresses at \( \frac{t}{2} \) and \( 3\frac{t}{2} \) 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](image_url)
The algorithm described in the following is applicable to obtain the hot spot stress for the point at the toe of a weld. The weld typically connects either a flat bar member or a bracket to the flange of a longitudinal stiffener, as shown in Appendix 1, Figure 8.

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

11.3.1
Select two points, \( L \) and \( R \), such that points \( L \) and \( R \) are situated at distances \( t/2 \) and \( 3t/2 \) from the weld toe; i.e.:

\[
X_L = t/2, \quad X_R = 3t/2
\]

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:

\[
C_1 = \frac{(X - X_2)(X - X_3)(X - X_4)}{(X_1 - X_2)(X_1 - X_3)(X_1 - X_4)}
\]

\[
C_2 = \frac{(X - X_1)(X - X_3)(X - X_4)}{(X_2 - X_1)(X_2 - X_3)(X_2 - X_4)}
\]

\[
C_3 = \frac{(X - X_1)(X - X_2)(X - X_4)}{(X_3 - X_1)(X_3 - X_2)(X_3 - X_4)}
\]

\[
C_4 = \frac{(X - X_1)(X - X_2)(X - X_3)}{(X_4 - X_1)(X_4 - X_2)(X_4 - X_3)}
\]

The corresponding stress at Point \( L \) can be obtained by interpolation as:

\[
S_L = C_1 S_1 + C_2 S_2 + C_3 S_3 + C_4 S_4
\]

11.3.3
Let \( X = X_R \) and repeat the step in A1/11.3.2 to determine four new coefficients. The stress at Point \( R \) can be interpolated likewise, i.e.:

\[
S_R = C_1 S_1 + C_2 S_2 + C_3 S_3 + C_4 S_4
\]

11.3.4
The corresponding stress at hot spot, \( S_0 \), is given by

\[
S_0 = \frac{3S_L - S_R}{2}
\]

Notes:
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, \( C_i \) to \( C_4 \), are all cubic polynomials. It is also evident that, when \( X = X_i \), which is not equal to \( X_i \), all of the \( C_i \)’s vanish except \( C_i \) and if \( X = X_i \), \( C_i = 1 \).
11.5 Calculation of Hot Spot Stress at the Edge of **Cutout** or Bracket

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 0.01 cm² (0.0015 in²). 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

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

$$\gamma_S M_{sw} + \gamma_w M_w \leq \frac{M_R}{\gamma_R}$$

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-5-3/5.1.1 of the Marine Vessel Rules for container carriers. For container carriers with $k_w = 1.0$ for wave hogging bending moment and $k_w = 1.84 - 0.56 C_b$ for wave sagging bending moment
- $M_R$ = vertical hull girder residual bending capacity with hatch coaming top and side plates ineffective, in kN-m (tf-m), as defined in the following Subsection
- $\gamma_S = 1.0$ partial safety factor for the still water bending moment
- $\gamma_w = 1.1$ partial safety factor for the vertical wave bending moment covering environmental and wave load prediction uncertainties
- $\gamma_R = 1.0$ partial safety factor for the vertical hull girder bending capacity covering material, geometric and strength prediction uncertainties

5 Vertical Hull Girder Residual Bending Moment Capacity

5.1 General

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

$$\kappa = \frac{\theta}{\ell} \ m^{-1} (\text{ft}^{-1})$$

where,

- $\theta$ = relative angle rotation of the two neighboring cross-sections at transverse frame positions
- $\ell$ = transverse frame spacing, in m (ft) (i.e., span of longitudinals)
The method for calculating the residual hull girder capacity is to identify the critical failure modes of all main longitudinal structural elements. Assuming the hatch coaming top and side plates are ineffective, the remaining longitudinal structural members in the upper flange compressed beyond their buckling limit have reduced load carrying capacity. All relevant failure modes for individual structural elements, such as plate buckling, torsional stiffener buckling, stiffener web buckling, lateral or global stiffener buckling; and their interactions, are to be considered in order to identify the weakest inter-frame failure mode.

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

5.3 Physical Parameters

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

5.3.1 Hull Girder Load and Cross Section Properties

\[ M_i = \text{hull girder bending moment, in kN-m (tf-ft)} \]
\[ F_i = \text{hull girder longitudinal force, in kN (tf)} \]
\[ I_v = \text{hull girder moment of inertia, in m}^4 \text{ (in}^2\text{-ft}^2) \]
\[ SM = \text{hull girder section modulus assuming hatch coaming top and side plates ineffective, in m}^3 \text{ (ft}^3) \]
\[ SM_{dk} = \text{elastic hull girder section modulus at deck at side, in m}^3 \text{ (in}^2\text{-ft)} \]
\[ SM_{kl} = \text{elastic hull girder section modulus at bottom, in m}^3 \text{ (in}^2\text{-ft)} \]
\[ \kappa = \text{curvature of the ship cross section, in m}^{-1} \text{ (ft}^{-1}) \]
\[ z_j = \text{distance from baseline, in m (ft)} \]

5.3.2 Material Properties

\[ \sigma_{yd} = \text{specified minimum yield stress of the material, in N/cm}^2 \text{ (kgf/cm}^2, \text{ lbf/in}^2) \]
\[ E = \text{Young’s modulus for steel, } 2.06 \times 10^7 \text{ N/cm}^2 \text{ (2.1 \times 10}^6 \text{ kgf/cm}^2, 30 \times 10^6 \text{ lbf/in}^2) \]
\[ \nu = \text{Poisson’s ratio, may be taken as 0.3 for steel} \]
\[ \Phi = \text{edge function as defined in A2/5.9.2} \]
\[ \varepsilon = \text{relative strain defined in A2/5.9.2} \]
5.3.3 Stiffener Sectional Properties

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

\[ A_s = \text{sectional area of the longitudinal or stiffener, excluding the associated plating, in } \text{cm}^2 \text{ (in}^2) \]

\[ b_1 = \text{smaller outstanding dimension of flange with respect to centerline of web, in } \text{cm (in)} \]

\[ b_f = \text{total width of the flange/face plate, in } \text{cm (in)} \]

\[ d_w = \text{depth of the web, in } \text{cm (in)} \]

\[ t_p = \text{net thickness of the plating, in } \text{cm (in)} \]

\[ t_f = \text{net thickness of the flange/face plate, in } \text{cm (in)} \]

\[ t_w = \text{net thickness of the web, in } \text{cm (in)} \]

\[ x_o = \text{distance between centroid of the stiffener and centerline of the web plate, in } \text{cm (in)} \]

(see Appendix 2, Figure 2)

\[ y_o = \text{distance between the centroid of the stiffener and the attached plate, in } \text{cm (in)} \]

(see Appendix 2, Figure 2)

**FIGURE 2**

Dimensions and Properties of Stiffeners
5.5 Calculation Procedure

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

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

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

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

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

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

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

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

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

**Step 3** Derive the expected maximum required curvature \( \kappa_F \). The curvature step size \( \Delta \kappa \) is to be taken as \( \kappa_F/300 \). The curvature for the first step, \( \kappa_1 \) is to be taken as \( \Delta \kappa \).

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

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

**Step 5** Determine the new neutral axis position \( z_{NA,i} \) by checking the longitudinal force equilibrium over the whole transverse section. Hence adjust \( z_{NA,i} \) until

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

Note \( \sigma_j \) is positive for elements under compression and negative for elements under tension. Repeat from Step 4 until equilibrium is satisfied. Equilibrium is satisfied when the change in neutral axis position is less than 0.0001 m (0.004 in.).

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

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

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

$$\kappa_F = \frac{3 \max (SM_{d,k} \sigma_{yd} \cdot SM_{d,l} \sigma_{yd})}{EI_y}$$

**5.7 Assumptions and Modeling of the Hull Girder Cross-Section**

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

1. The residual strength is calculated at a hull girder transverse section between two adjacent transverse webs.
2. The hull girder transverse section remains plane during each curvature increment.
3. The material properties of steel are assumed to be elastic, perfectly plastic.
4. The hull girder transverse section can be divided into a set of elements which act independently of each other.
5. The elements making up the hull girder transverse section are:
   - Longitudinal stiffeners with attached plating, the structural behavior is given in A2/5.9.2, A2/5.9.3, A2/5.9.4, A2/5.9.5, and A2/5.9.6
   - Transversely stiffened plate panels, the structural behavior is given in A2/5.9.7
   - Hard corners, as defined below, the structural behavior is given in A2/5.9.1
6. The following structural areas are to be defined as hard corners:
   - The plating area adjacent to intersecting plates
   - The plating area adjacent to knuckles in the plating with an angle greater than 30 degrees.
   - Plating comprising rounded gunwales
7. An illustration of hard corner definition for girders on longitudinal bulkheads is given in Appendix 2, Figure 3.
8. The size and modeling of hard corner elements is to be as follows:
   - It is to be assumed that the hard corner extends up to $s/2$ from the plate intersection for longitudinally stiffened plate, where $s$ is the stiffener spacing
   - It is to be assumed that the hard corner extends up to $20t_{g,r}$ from the plate intersection for transversely stiffened plates, where $t_{g,r}$ is the gross plate thickness.

*Note:* For transversely stiffened plate, the effective breadth of plate for the load shortening portion of the stress-strain curve is to be taken as the full plate breadth, i.e., to the intersection of other plates – not from the end of the hard corner. The area is to be taken as the breadth between the intersecting plates.
5.9 Stress-strain Curves $\sigma-\varepsilon$ (or Load-end Shortening Curves)

5.9.1 Hard Corners

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

5.9.2 Elasto-Plastic Failure of Structural Elements

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

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

where

- $\Phi$ = edge function
- $\Phi = -1$ for $\varepsilon < -1$
- $\Phi = \varepsilon$ for $-1 < \varepsilon < 1$
- $\Phi = 1$ for $\varepsilon > 1$
Appendix 2 Hull Girder Residual Strength

\[ \varepsilon = \text{relative strain} \]
\[ = \frac{\varepsilon_E}{\varepsilon_{yd}} \]
\[ \varepsilon_E = \text{element strain} \]
\[ \varepsilon_{yd} = \text{strain corresponding to yield stress in the element} \]
\[ = \frac{\sigma_{yd}}{E} \]

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

FIGURE 4
Example of Stress Strain Curves $\sigma$-$\varepsilon$

a) Stress strain curve $\sigma$-$\varepsilon$ for elastic, perfectly plastic failure of a hard corner

b) Typical stress strain curve $\sigma$-$\varepsilon$ for elasto-plastic failure of a stiffener
5.9.3 Beam Column Buckling

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

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

where

$$\sigma_{C1} = \text{critical stress, in kN/cm}^2 \text{ (kgf/cm}^2, \text{ lbf/in}^2$$

$$\sigma_{E1} = \frac{\sigma_{E1}}{\varepsilon} \text{ for } \sigma_{E1} \leq \frac{\sigma_{yd}}{2}$$

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

$$\sigma_{E1} = \text{Euler column buckling stress, in kN/cm}^2 \text{ (kgf/cm}^2, \text{ lbf/in}^2$$

$$\ell = \text{unsupported span of the longitudinal, in cm (in.)}$$

$s = \text{plate breadth taken as the spacing between the stiffeners, in cm (in.)}$

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

$b_{eff-s} = \text{effective width, in cm (in.), of the attached plating for the stiffener}$

$$= \frac{s}{\beta_p} \text{ for } \beta_p > 1.0$$

$$= s \text{ for } \beta_p \leq 1.0$$

$$\beta_p = \frac{s}{\ell_p} \sqrt{\frac{\varepsilon \sigma_{yd}}{E}}$$

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

$b_{eff-p} = \text{effective width, in cm (in.), of the plating}$

$$= \left( \frac{2.25}{\beta_p^2} - \frac{1.25}{\beta_p^4} \right)^{\frac{1}{2}} s \text{ for } \beta_p > 1.25$$

$$= s \text{ for } \beta_p \leq 1.25$$

5.9.4 Torsional Buckling of Stiffeners

The equation describing the shortening portion of the stress-strain curve $\sigma_{CR2}$-$\varepsilon$ for the lateral-flexural buckling of stiffeners is to be obtained using the following formula:

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

\[ \sigma_{C2} = \text{critical stress} \]

\[ = \frac{\sigma_{E2}}{\sqrt{2}} \text{ for } \sigma_{E2} \leq \frac{\sigma_{yd}}{2} \]

\[ = \sigma_{yd}\left(1 - \frac{\sigma_{yd}}{4\sigma_{E2}}\right) \text{ for } \sigma_{E2} > \frac{\sigma_{yd}}{2} \]

\[ \sigma_{CP} = \text{ultimate strength of the attached plating for the stiffener} \]

\[ = \left(\frac{2.25}{\beta_p} - \frac{1.25}{\beta_p^2}\right)\sigma_{yd}\text{ for } \beta_p > 1.25 \]

\[ = \sigma_{yd}\text{ for } \beta_p \leq 1.25 \]

\[ \beta_p = \text{coefficient defined in A2/5.9.3} \]

\[ \sigma_{E2} = \text{Euler torsional buckling stress in kN/cm}^2 (\text{kgf/cm}^2, \text{lbf/in}^2), \text{equal to reference stress for torsional buckling } \sigma_{ET} \]

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

\[ K = \text{St. Venant torsion constant for the longitudinal’s cross section, excluding the associated plating} \]

\[ = \left[b_f t_f^3 + d_u t_u^3\right]/3 \]

\[ I_o = \text{polar moment of inertia of the longitudinal, excluding the associated plating, about the toe (intersection of web and plating)} \]

\[ = I_x + ml_y + A_f \left(x_f^2 + y_f^2\right) \text{ in cm}^4 (\text{in}^4) \]

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

\[ m = 1.0 - u(0.7 - 0.1d_u/b_f) \]

\[ u = \text{unsymmetry factor} \]

\[ = 1 - 2b_f/b_f \]

\[ C_o = Et_f^3/3s \]

\[ \Gamma = \text{warping constant} \]

\[ = ml风俗 + d_u t_u^3/36 \]

\[ f_{cl} = \text{critical buckling stress for the associated plating, corresponding to } n \text{-half waves} \]

\[ = \pi^2 E(n/\alpha + \alpha/n)^2(t_f/s)^2/12(1 - \nu^2) \]

\[ \alpha = \ell/s \]

\[ \ell = \text{unsupported span of the longitudinal, in cm (in.)} \]
5.9.5 Web Local Buckling of Stiffeners with Flanged Profiles

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

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

where

$s$ = plate breadth taken as the spacing between the stiffeners, in cm (in.)

$n$ = number of half-wave which yield a smallest $\sigma_{ET}$

5.9.6 Local Buckling of Flat Bar Stiffeners

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

$$
\sigma_{CR4} = \Phi \left( \frac{A_{s} \sigma_{C4} + st_p \sigma_{CP}}{A_{s} + st_p} \right) \text{ kN/cm}^2 \text{ (kgf/cm}^2, \text{ lbf/in}^2)$$

where

$\sigma_{CP}$ = ultimate strength of the attached plating, in kN/cm$^2$ (kgf/cm$^2, \text{ lbf/in}^2$)

$\sigma_{C4}$ = critical stress, in kN/cm$^2$ (kgf/cm$^2, \text{ lbf/in}^2$)

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

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

$\sigma_{E4}$ = Euler buckling stress

$$
\sigma_{E4} = \frac{0.44 \pi^2 E}{12 \left( 1 - \nu^2 \right)} \frac{t_w}{d_w} \varepsilon^2$$
5.9.7 Buckling of Transversely Stiffened Plate Panels

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

$$\sigma_{CR5} = \min \left\{ \sigma_{yd} \Phi, \frac{s}{\ell_{stf}} \left( \frac{2.25}{\beta_p} - \frac{1.25}{\beta^2_p} \right) + 0.115 \left( 1 - \frac{s}{\ell_{stf}} \right) \left( 1 + \frac{1}{\beta^2_p} \right)^2 \right\} \text{ kN/cm}^2 \text{ (kgf/cm}^2, \text{lbf/in}^2)$$

where

$$\beta_p = \text{ coefficient defined in A2/5.9.3}$$

$$\beta_0 = \frac{s}{t \sqrt{E}}$$

$s$ = plate breadth taken as the spacing between the stiffeners, in cm (in.)

$\ell_{stf}$ = span of stiffener equal to spacing between primary support members, in cm (in.)
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

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.

At the discretion of ABS, other approval test results may be requested.

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

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 Guide.

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.
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**
Large-scale (ESSO) 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.
If brittle crack arrest properties are evaluated by ESSO $K_{ca}$, the brittle crack arrest test method is to be in accordance with Appendix 4. The accepted $K_{ca}$ is greater than 6000 N/mm$^{1/2}$ (173 ksi-in$^{1/2}$) at –10°C (14°F) for BCA1 and greater than 8000 N/mm$^{1/2}$ (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 7 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**
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 Guide. 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)
The Y Shape Weld Crack Test method is to be in accordance with recognized national standards such as KS B 0870, JIS Z 3158, or GB 4675.1.

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
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 7 for CAT of this Guide.

11 Approval and Certification
Upon receiving satisfactory results from the survey and tests, approval is granted for grades having the suffix “BCA1” or “BCA2”.

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 alternative 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 General

1.1 Scope
This Appendix specifies the test method for brittle crack arrest toughness (i.e., $K_{ca}$) of steel using fracture mechanics parameters. This Appendix is applicable to hull structural steels with thicknesses of 50 mm (2 in.) to 100 mm (4 in.) specified in this Guide.

1.3 Test Procedure
After setting a temperature gradient in the width direction of a test specimen and applying uniform stress to the test specimen, the test specimen is to be struck to initiate a brittle crack from the mechanical notch at the side of the test specimen, and cause crack arrest (temperature gradient type arrest testing). Using the stress intensity factor, the brittle crack arrest toughness, $K_{ca}$, is to be calculated from the applied stress and arrest crack length. This value is the brittle crack arrest toughness at the temperature of the point of crack arrest (arrest temperature). To obtain $K_{ca}$ at a specific temperature followed by the necessary evaluation, the method specified in Appendix 5 can be used.

As a method for initiating a brittle crack, a secondary loading mechanism can also be used (see Appendix 6 for double tension type arrest test).

1.5 Symbols, Units, and Their Significance
The symbols, units, and their significance as used in this Appendix are shown as follows:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>mm (in.)</td>
<td>Crack length or arrest crack length</td>
</tr>
<tr>
<td>$E$</td>
<td>N/mm²</td>
<td>Modulus of longitudinal elasticity</td>
</tr>
<tr>
<td>$E_i$</td>
<td>J (ft-lbf)</td>
<td>Impact energy</td>
</tr>
<tr>
<td>$E_s$</td>
<td>J (ft-lbf)</td>
<td>Strain energy stored in a test specimen</td>
</tr>
<tr>
<td>$E_t$</td>
<td>J (ft-lbf)</td>
<td>Total strain energy stored in tab plates and pin chucks</td>
</tr>
<tr>
<td>$F$</td>
<td>MN (lbf)</td>
<td>Applied load</td>
</tr>
<tr>
<td>$K$</td>
<td>N/mm² (ksi)</td>
<td>Stress intensity factor</td>
</tr>
<tr>
<td>$K_{ca}$</td>
<td>N/mm² (ksi)</td>
<td>Arrest toughness</td>
</tr>
<tr>
<td>$L$</td>
<td>mm (in.)</td>
<td>Test specimen length</td>
</tr>
<tr>
<td>$L_a$</td>
<td>mm (in.)</td>
<td>Distance between the loading pins</td>
</tr>
<tr>
<td>$L_{pc}$</td>
<td>mm (in.)</td>
<td>Pin chuck length</td>
</tr>
<tr>
<td>$L_{tb}$</td>
<td>mm (in.)</td>
<td>Tab plate length</td>
</tr>
<tr>
<td>$T$</td>
<td>°C (°F)</td>
<td>Temperature or arrest temperature</td>
</tr>
<tr>
<td>$t$</td>
<td>mm (in.)</td>
<td>Test specimen thickness</td>
</tr>
<tr>
<td>$t_{ab}$</td>
<td>mm (in.)</td>
<td>Tab plate thickness</td>
</tr>
<tr>
<td>$t_{pc}$</td>
<td>mm (in.)</td>
<td>Pin chuck thickness</td>
</tr>
<tr>
<td>$W$</td>
<td>mm (in.)</td>
<td>Test specimen width</td>
</tr>
<tr>
<td>$W_{ab}$</td>
<td>mm (in.)</td>
<td>Tab plate width</td>
</tr>
<tr>
<td>$W_{pc}$</td>
<td>mm (in.)</td>
<td>Pin chuck width</td>
</tr>
</tbody>
</table>
Appendix 4  Testing Method for the Brittle Crack Arrest Toughness, $K_{ca}$

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_a$</td>
<td>mm (in.)</td>
<td>Coordinate of a main crack tip in the width direction</td>
</tr>
<tr>
<td>$x_{br}$</td>
<td>mm (in.)</td>
<td>Coordinate of the longest branch crack tip in the width direction</td>
</tr>
<tr>
<td>$y_a$</td>
<td>mm (in.)</td>
<td>Coordinate of a main crack tip in the stress loading direction</td>
</tr>
<tr>
<td>$y_{br}$</td>
<td>mm (in.)</td>
<td>Coordinate of the longest branch crack tip in the stress loading direction</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>N/mm² (ksi)</td>
<td>Applied stress</td>
</tr>
<tr>
<td>$\sigma_{Y0}$</td>
<td>N/mm² (ksi)</td>
<td>Yield stress at room temperature</td>
</tr>
</tbody>
</table>

3  Testing Equipment

The following specifies the testing machine needed for conducting the brittle crack arrest test. The testing machine is used to apply tensile force to an integrated specimen, and impact equipment is used to generate a brittle crack on the test specimen.

3.1 Testing Machine

3.1.1 Loading Method

The tensile force applied to an integrated specimen is to be hydraulically or mechanically applied. The method for loading an integrated specimen by the testing machine is to be a pin type loading method. The stress distribution in the plate width direction is to be made uniform by aligning the centers of the loading pins of both sides and the neutral axis of the integrated specimen.

3.1.2 Loading Directions

The loading directions are to be either vertical or horizontal. In the case of the horizontal direction, test specimen surfaces are to be placed either perpendicular or flat to the ground. However, when using the flat position, care is to be taken so that the temperature difference between the top and bottom surface is within the values specified in A4/7.1iii).

3.1.3 Distance between the Loading Pins

The distance between the loading pins is to be approximately $3.4W$ or more, where $W$ is the width of the test specimen. Since the distance between the loading pins potentially has an effect on the force drop associated with crack propagation, especially for a long arrested crack, the validity of the test results is to be determined by the judgment method described in A4/11.1.

3.3 Impact Equipment

3.3.1 Impact Methods

Methods for applying an impact force to an integrated specimen is to be of a drop weight type or of an air gun type. The wedge is to be hard enough to prevent significant plastic deformation by the impact. The wedge thickness is to be equal to or greater than that of the test specimen, and the wedge angle is to be greater than that of the notch formed in the test specimen and is to have a shape capable of opening up the notch of the test specimen.

5  Test Specimens

5.1 Test Specimen Shapes

The standard test specimen shape is shown in Appendix 4, Figure 1. Appendix 4, Table 1 shows the ranges of test specimen thicknesses, widths and width-to-thickness ratios.

The test specimen length is to, in principle, be equal to or greater than its width.
FIGURE 1
Standard Test Specimen Shape (2021)

TABLE 1
Dimensions of Test Specimens (2021)

<table>
<thead>
<tr>
<th>Test specimen thickness, $t$</th>
<th>$t \leq 100$ mm (4 in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test specimen width, $W$</td>
<td>$350$ mm (14 in.) $\leq W \leq 1000$ mm (40 in.)</td>
</tr>
<tr>
<td></td>
<td>[Standard width: $W = 500$ mm (20 in.)]</td>
</tr>
<tr>
<td>Test specimen width/test specimen thickness, $W/t$</td>
<td>$W/t \geq 5$</td>
</tr>
</tbody>
</table>

5.3 Shapes of Tab Plates and Pin Chucks
The definitions of the dimensions of the tab plates and pin chucks are shown in Appendix 4, Figure 2. Typical examples are shown in Appendix 4, Figure 3.
FIGURE 2
Definitions of Dimensions of Tab Plates and Pin Chucks (2021)

a) Single-pin type

b) Double-pin type
FIGURE 3
Examples of the Shapes of Tab Plates and Pin Chucks (2021)

a) Example 1

b) Example 2

c) Example 3
5.3.1 Tab Plates

The tolerances of tab plate dimensions are shown in Appendix 4, Table 2. When the lengths of the tab plates attached to the two ends of a test specimen are different, the shorter length is to be used as the tab length, $L_{tb}$.

| TABLE 2  
Tolerances of Tab Plate Dimensions (2021) |
<table>
<thead>
<tr>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Tab plate thickness, $t_{tb}$</td>
</tr>
<tr>
<td>Tab plate width, $W_{tb}$</td>
</tr>
<tr>
<td>Total length of a test specimen and tab plates, $L + 2L_{tb}$</td>
</tr>
<tr>
<td>(Total length of a test specimen and a single tab plate $L + L_{tb}$)</td>
</tr>
<tr>
<td>Tab plate length ($L_{tb}$)/Tab plate width, ($W$)</td>
</tr>
</tbody>
</table>
5.3.2 Pin Chucks
The pin chuck width, $W_{pc}$, is in principle to be equal to or more than the tab plate width, $W_{tb}$. The pin chucks are to be designed to have a sufficient force bearing strength. When the pin chucks attached to the two ends of an integrated specimen are asymmetric, the length of the shorter one is to be used as the pin chuck length, $L_{pc}$.

The distance between the pins, $L_p$, is obtained from the following equation. In the case shown in Appendix 4, Figure 3(e), Example 5, $L_p$ is obtained by setting $L_{pc} = 0$.

$$L_p = L + 2L_{tb} + 2L_{pc} \text{ mm (in.)}$$

where

$L_p$ = distance between loading pins, in mm (in.)
$L$ = test specimen length, in mm (in.)
$L_{tb}$ = tab plate length, in mm (in.)
$L_{pc}$ = pin chuck length, in mm (in.)

5.5 Welding of Test Specimen and Tab Plates
The test specimen, tab plates, and pin chucks are to be connected by welding. The welds are to have a sufficient force-bearing strength.

As shown in Appendix 4, Figure 4(a), the flatness (angular distortion, linear misalignment) of the weld between a test specimen and a tab plate is to be 4 mm or less per 1 m (0.144 in. or less per 3 ft). However, when preloading is applied, it is acceptable if the value after preloading satisfies this condition. As shown in Appendix 4, Figure 4(b), the accuracy of the in-plane loading axis is to be 0.5% or less of the distance between the pins, and the accuracy of the out-of-plane loading is to be 0.4% or less of the distance between the pins.
7 Test Methods

The following specifies methods for conducting the brittle crack arrest test.

7.1 Temperature Control Methods

A predetermined temperature gradient is to be established across the test specimen width by soldering at least nine thermocouples to the test specimen for temperature measurement and control.

The temperature gradient is to be established in accordance with the following conditions i) through iii).

i) A temperature gradient of 0.25-0.35°C/mm (11.5-16.0°F/in.) is to be established in a test specimen width range of 0.3W to 0.7W. When measuring the temperatures at the center position of the test specimen thickness, it is to be kept within ±2°C (±3.6°F) for 10 minutes or more, whereas when measuring the temperatures on the front and back surface positions of the test specimen, it is to be kept within ±2°C (±3.6°F) for \((10 + 0.1t)\) minutes or more, considering the time needed for soaking to the center. If the temperature gradient at 0.3W – 0.7W is less than 0.25°C/mm (11.5°F/in.), crack arrest may become difficult, and if the gradient is larger than 0.35°C/mm (16.0°F/in.), the obtained arrest toughness may be too conservative.

ii) At the test specimen width center position (i.e., 0.5W), and in the range of ±100 mm (±4 in.) in the test specimen length direction, the deviation from the temperature at the center position in the length direction is to be controlled within ±5°C (±9°F). However, when temperature measurement is not performed at the center position in the length direction, the average temperature at the closest position is to be used as the temperature at the center position in the length direction.

iii) At the same position in the width direction, the deviation of the temperature on the front and back surfaces is to be controlled within ±5°C (±9°F).

7.3 Crack Initiation Methods

Impact energy is to be applied to a test specimen to initiate a crack. However, if the energy is excessive, it may influence on the test results. In that case, the results are to be treated as invalid data in accordance with the judgment criteria specified in A4/7.1. It is desirable to use the equation below and Appendix 4, Figure 5 as guides for obtaining valid data.

\[
\frac{E_i}{t} \leq 1.2 \sigma - 40 \text{ or } 200 \text{ J/mm, whichever is lower.}
\]

\[
\frac{E_i}{t} \leq 1.2 \sigma - 737 \text{ or } 3685 \text{ ft-lbf/in, whichever is lower.}
\]

where

- \(E_i\) = impact energy, in J (ft-lbf)
- \(t\) = test specimen thickness, in mm (in.)
- \(\sigma\) = applied stress, in N/mm² (ksi)
- \(\min\) = the minimum of the two values
9 Test Procedures

The following specifies the procedures for testing brittle crack arrest toughness.

9.1 Pretest Procedures

i) Install an integrated specimen in the testing machine.

ii) Mount a cooling device on the test specimen. A heating device may also be mounted on the test specimen.

iii) Install an impact apparatus as specified in A4/3.3, on the testing machine. Place an appropriate reaction force receiver as necessary.

Note: The above procedures i) through iii) do not necessarily specify the order of implementation, and they may be completed, for example, on the day before the test.

iv) After checking that all measured values of the thermocouples indicate room temperature, start cooling. The temperature distribution and the holding time are to be as provided in the specifications in A4/7.1.

v) Set an impact apparatus, as specified in A4/3.3 so that it can supply predetermined energy to the test specimen.

vi) Apply force to the test specimen until it reaches the predetermined value. This force is applied after temperature control to prevent autonomous crack initiation during force increase. Alternatively, temperature control may be implemented after loading. The loading rate and applied stress are to satisfy the conditions a) and b) described below, respectively.

a) Loading Rate. There is no specification of loading rate, but it is to be determined considering that an excessively slow loading rate may prolong the temperature control period, thereby allowing the temperature distribution to depart from the desired condition and an excessively fast loading rate may cause over-shooting of the load.

b) Applied Stress/Yield Stress Ratio. Applied stress is to be within the range shown by equation.

\[ \sigma \leq \frac{2}{3} \sigma_{Y0} \text{ N/mm}^2 (\text{kgf/mm}^2, \text{ksi}) \]
where

\[ \sigma = \text{applied stress, in N/mm}^2 \text{ (kgf/mm}^2, \text{ ksi)} \]

\[ \sigma_{Y0} = \text{yield stress at room temperature, in N/mm}^2 \text{ (kgf/mm}^2, \text{ ksi)} \]

As a guide, a value equal to \(\frac{1}{6}\) of \(\sigma_{Y0}\) or more is desirable. If applied stress is larger than that specified by equation, the test may give a non-conservative result.

vii) To initiate a crack, the notch may be cooled further immediately before impact on the condition that the cooling does not disturb the temperature in the range of 0.3\(W\) to 0.7\(W\). The test temperature in this case is to be the measured temperature obtained from the temperature record immediately before the further notch cooling.

viii) Record the force value measured by a force recorder.

9.3 Loading Procedures

i) After holding a predetermined force for 30 seconds or more, apply an impact to the wedge using the impact apparatus. If a crack initiates autonomously and the exact force value at the time of the crack initiation cannot be obtained, the test is invalid.

ii) After the impact, record the force value measured by the force recorder.

iii) When the force after the impact is smaller than the test force, consider that crack initiation has occurred.

\[ \text{Note:} \] An increase in the number of times of impact may cause a change in the shape of the notch of the test specimen. Since the number of impacts has no effect on the value of brittle crack arrest toughness, no limit is specified for the number of impacts. However, because the temperature gradient is often distorted by impact, the test is to be conducted again, beginning from temperature control when applying repeated impacts to the wedge.

iv) When crack initiation, propagation, and arrest are observed, remove the force.

9.5 Procedures after Testing

i) Remove the impact apparatus.

ii) Remove the cooling device, thermocouples, and strain gauges.

iii) Return the temperature of the test specimen to room temperature.

iv) After gas-cutting an uncracked ligament, use the testing machine to cause ductile fracture, as necessary. Alternatively, it is also possible to gas-cut the uncracked ligament after using the testing machine to develop a ductile crack to a sufficient length.

9.7 Observation of Fracture Surfaces

i) Photograph the fracture surfaces and propagation path.

ii) Measure the longest length of the arrest crack tip in the plate thickness direction and record the result as the arrest crack length. The arrest crack length is to include the notch length. In the case where a crack deviates from the direction vertical to the loading direction, the length projected to the plane vertical to the loading line is defined as the arrest crack length. In the following cases, however, judge the results according to the methods described for each case.

a) Crack Re-initiation. In the case where a brittle crack has re-initiated from an arrested crack, the original arrest position is defined as the arrest crack position. Here re-initiation is defined as the case where a crack and re-initiated cracks are completely separated by a stretched zone, and brittle crack initiation from the stretched zone can be clearly observed. In the case where a crack continuously propagates partially in the thickness direction, the position of the longest brittle crack is defined as the arrest position.
b) Crack Branching. In the case where a crack deviates from the direction vertical to the loading direction, the length projected to the plane vertical to the loading line is defined as the arrest crack length. Similarly, in the case of crack branching, the length of the longest branch crack projected to the plane vertical to the loading line is defined as the branch crack length. More specifically, from the coordinates \((x_{a}, y_{a})\) of the arrest crack tip position and the coordinates \((x_{br}, y_{br})\) of the branch crack tip position shown in Appendix 4, Figure 6, obtain the angle \(\theta\) from the \(x\)-axis and define \(x_{a}\) as the arrest crack length, \(a\). Here, \(x\) is the coordinate in the test specimen width direction, and the side face of the impact side is set as \(x = 0\); \(y\) is the coordinate in the test specimen length direction, and the notch position is set as \(y = 0\).

iii) Prepare a temperature distribution curve (line diagram showing the relation between the temperature and the distance from the test specimen top side) from the thermocouple measurement results and obtain the arrest temperature \(T\) corresponding to the arrest crack length.

**FIGURE 6**
Measurement Methods of Main Crack and Branch Crack Lengths (2021)

a) Case of branching from notch

b) Case of branching during brittle crack propagation

11 Determination of Arrest Toughness

11.1 Judgment of Arrested Crack

When an arrested crack satisfies all of the conditions found in A4/11.1.1 through A4/11.1.4 below, as shown in Appendix 4, Figure 7, the length of the arrested crack determined by A4/9.7 is valid. If any of the conditions are not met, the arrest toughness calculated from A4/11.5 is invalid.
11.1.1 Conditions for Crack Propagation Path

The entire crack path from crack initiation to arrest is to be within the range shown in Appendix 4, Figure 8. However, in the case where a main crack tip lies within this range but a part of the main crack passes outside the range, the arrest toughness may be assessed as valid if the temperature at the most deviated position of the main crack in the y direction is lower than that at y = 0 and also K for the main crack falls within ±5% of K for a straight crack of the same a. The calculation method of Ks for the main crack and a straight crack is obtained from the equation below.

\[
K \leq K_1 \cos\left(\frac{\phi}{2}\right) + 3K_1\cos^2\left(\frac{\phi}{2}\right)\sin\left(\frac{\phi}{2}\right) \text{ N/mm}^{3/2} \text{ (ksi-in}^{1/2}\text{)}
\]

where

- \(K\) = stress intensity factor
- \(K_1\) = stress intensity factor for mode I and applied to the crack opening mode
- \(K_{II}\) = stress intensity factor for mode II and applied to the crack shearing mode
- \(\phi\) = angle at crack tip
FIGURE 8
Allowable Range of Main Crack Propagation Path (2021)

11.1.2 Conditions for Arrest Crack Length

\[
0.3 \leq \left( \frac{a}{W} \right) \leq 0.7
\]

\[
\left( \frac{a}{t} \right) \geq 1.5
\]

\[
\left( \frac{a}{L_p} \right) \leq 0.15
\]

where

- \(a\) = crack length or arrest crack length, in mm (in.)
- \(W\) = test specimen width, in mm (in.)
- \(t\) = test specimen thickness, in mm (in.)
- \(L_p\) = distance between loading pins, in mm (in.)

Note: The final equation of the three above equations confirms minimal influence of force drop at the center of the specimen which might be caused by crack propagation and reflection of the stress wave at the two ends of the specimen. However, application of this equation is not necessarily required if the strain and the crack length have been dynamically measured and the value of the strain at the time of arrest is 90% or more of the static strain immediately before crack initiation.

11.1.3 Conditions for Crack Straightness

\(|y_a| \leq 50\) mm (2 in.)

where

- \(y_a\) = coordinate of a main crack tip in the stress loading direction, in mm (in.)

In the case where 50 mm (2 in.) < \(|y_a| \leq 100\) mm (4 in.) and \(|\theta| \leq 30^\circ\), the result is valid only when the temperature at \(x = 0.5W\) and \(y = \pm 100\) mm (4 in.) falls within ±2.5°C (±4.5°F) of that at \(x = 0.5W\) and \(y = 0\).
11.1.4 Conditions for Crack Branching

\[
\left( \frac{x_{br}}{x_a} \right) \leq 0.6
\]

where

- \( x_{br} \) = coordinate of the longest branch crack tip in the width direction, in mm (in.)
- \( x_a \) = coordinate of a main crack tip in the width direction, in mm (in.)

11.3 Assessment of Impact Energy

Impact energy is to satisfy the equation below. If it does not satisfy the equation, the value of arrest toughness calculated from the equations in A4/11.5 is invalid.

Conditions for impact energy:

\[
\frac{E_i}{E_s + E_t} \leq \frac{5a - 1050 + 1.4W}{0.7W - 150} \quad \text{where} \quad 0.3 \leq \frac{a}{w} \leq 0.7
\]

where

- \( E_i \) = impact energy, in J (kgf-m, ft-lbf)
- \( E_s \) = strain energy stored in a test specimen, in J (kgf-m, ft-lbf)
- \( E_t \) = total strain energy stored in tab plates and pin chucks, in J (kgf-m, ft-lbf)

\( E_i, E_s, \) and \( E_t \) are calculated from equations below.

Notes:

1. If the above equation is not satisfied, the influence of impact energy on the stress intensity factor is too large to obtain an accurate arrest toughness.
2. In the case where tab plate widths are tapered as shown in Appendix 4, Figure 3d), calculate the strain energy based on elastostatics.

\[
E_i = mgh \quad \text{J (kgf-m, ft-lbf)}
\]

\( m \) is the mass, \( g \) is the acceleration of gravity, and \( h \) is the height.

\[
E_s = \frac{10^9 F^2}{2E} \frac{L}{W t} \quad \text{J}
\]

\[
= \frac{F^2}{2000 E W t} \quad \text{kgf-m}
\]

\[
= \frac{F^2}{24000 E W t} \quad \text{ft-lbf}
\]

where

\( F \) = applied force, in MN (kgf, lbf)

Note: In the case where the tab plates are multistage as shown in Appendix 4, Figure 3b), calculate and total the strain energy of each tab plate using the equation above.

\[
E_t = \frac{10^9 F^2}{E} \left( \frac{L_{tb}}{W_{tb} t_{tb}} + \frac{L_{pc}}{W_{pc} t_{pc}} \right) \quad \text{J}
\]

\[
= \frac{F^2}{2000 E} \left( \frac{L_{tb}}{W_{tb} t_{tb}} + \frac{L_{pc}}{W_{pc} t_{pc}} \right) \quad \text{kgf-m}
\]
Appendix 4 Testing Method for the Brittle Crack Arrest Toughness, $K_{ca}$

\[
K_{ca} = \frac{F^2}{24000E} \left( \frac{L_{tb}}{W_{tb}t_{tb}} + \frac{L_{pc}}{W_{pc}t_{pc}} \right) \text{ ft-lbf}
\]

where

\[
E = \text{ modulus of elasticity, in N/mm}^2 \text{ (kgf/mm}^2, \text{ ksi)}
\]

\[
L_{tb} = \text{ tab plate length, in mm (in.)}
\]

\[
W_{tb} = \text{ tab plate width, in mm (in.)}
\]

\[
t_{tb} = \text{ tab plate thickness, in mm (in.)}
\]

\[
L_{pc} = \text{ pin chuck length, in mm (in.)}
\]

\[
W_{pc} = \text{ pin chuck width, in mm (in.)}
\]

\[
t_{pc} = \text{ pin chuck thickness, in mm (in.)}
\]

11.5 Calculation of Arrest Toughness

The arrest toughness, $K_{ca}$, at the temperature, $T$, is to be calculated from equation below using the arrest crack length, $a$, and the applied stress, $\sigma$, calculated by A4/11.1.

\[
K_{ca} = \sigma \sqrt{\frac{2W}{\pi a}} \tan \left( \frac{\pi a}{2S} \right)^{1/2} \text{ N/mm}^3\text{ (ksi-in}^{1/2})
\]

Calculate $\sigma$ from the equations below:

\[
\sigma = \frac{10^6 F}{Wt} \text{ N/mm}^2
\]

\[
= \frac{F}{Wt} \text{ kgf/mm}^2
\]

\[
= \frac{F}{1000Wt} \text{ ksi}
\]

If the conditions specified in A4/11.1 and A4/11.3 are not satisfied, the $K_{ca}$ calculated from the equation above is invalid.

The equation above is justified for giving a stress intensity factor for a dynamically propagating, decelerating and arrested crack by dynamic finite-element analyses.

13 Reporting

Using Appendix 4, Table 3, the following items are to be reported:

i) **Test Material**: Steel type and yield stress at room temperature

ii) **Testing Machine**: Capacity of the testing machine

iii) **Test Specimen Dimensions**: Thickness, width, length, angular distortion, and linear misalignment

iv) **Integrated Specimen Dimensions**: Tab plate thickness, tab plate width, integrated specimen length including the tab plates, and distance between the loading pins

v) **Test Conditions**: Applied force, applied stress, temperature gradient, impact energy, and the ratio of impact energy to the strain energy stored in the integrated specimen (sum of test specimen strain energy and tab plate strain energy)
vi) **Test Results**

a) **Judgment of Arrest:** Crack length, presence or absence of crack branching, main crack angle, presence or absence of crack re-initiation, and arrest temperature

b) **Arrest toughness value**

vii) **Temperature Distribution at Moment of Impact:** Thermocouple position, temperature value, and temperature distribution

viii) **Test Specimen Photographs:** Crack propagation path (one side), and brittle crack fracture surface (both sides)

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

*Note:* Item ix) is to be reported as necessary.
### TABLE 3
Report Sheet for Brittle Crack Arrest Test Results (SI Units) (2021)

<table>
<thead>
<tr>
<th>Item</th>
<th>Details</th>
<th>Symbol</th>
<th>Conditions/ Results</th>
<th>Unit</th>
<th>Valid/ Invalid</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Test material</td>
<td>Steel type</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yield stress at room temperature</td>
<td>$\sigma_{Y0}$</td>
<td>N/mm$^2$</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>2 Test equipment</td>
<td>Testing machine capacity</td>
<td>—</td>
<td>MN</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>3 Test specimen dimensions</td>
<td>Thickness</td>
<td>$t$</td>
<td>mm</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Width</td>
<td>$W$</td>
<td>mm</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Length</td>
<td>$L$</td>
<td>mm</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Angular distortion $+$ linear misalignment</td>
<td>—</td>
<td>mm/in</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>4 Integrated specimen dimensions</td>
<td>Tab plate thickness</td>
<td>$t_{tb}$</td>
<td>mm</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tab plate width</td>
<td>$W_{tb}$</td>
<td>mm</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Test specimen length including a tab plate</td>
<td>$L + L_{tb}$</td>
<td>mm</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Distance between loading pins</td>
<td>$L_{p}$</td>
<td>mm</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>5 Test conditions</td>
<td>Applied force</td>
<td>$F$</td>
<td>MN</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Applied stress</td>
<td>$\sigma$</td>
<td>N/mm$^2$</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Temperature gradient</td>
<td>—</td>
<td>°C/mm</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Impact energy</td>
<td>$E_i$</td>
<td>J</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ratio of impact energy to strain energy stored in integrated specimen</td>
<td>$E_i/(E_s + E_t)$</td>
<td>—</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Test results</td>
<td>Judgment of crack propagation/arrest</td>
<td>Crack length</td>
<td>$a$</td>
<td>mm</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Presence/absence of crack branching</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ratio of branch crack length to main crack</td>
<td>$x_{br}/x_a$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Main crack angle</td>
<td>$\theta$</td>
<td>degrees (°)</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Presence/absence of crack re-initiation</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Temperature at crack arrest position</td>
<td>$T$</td>
<td>°C</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Arrest toughness value</td>
<td>$K_{ca}$</td>
<td>N/mm$^{3/2}$</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>7 Temperature distribution at moment of impact</td>
<td>Temperature measurement position</td>
<td>—</td>
<td>Attached</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Temperature at each temperature measurement position</td>
<td>—</td>
<td>Attached</td>
<td>°C</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Temperature distribution curve</td>
<td>—</td>
<td>Attached</td>
<td>—</td>
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</tr>
<tr>
<td>8 Test specimen photographs</td>
<td>Crack propagation path</td>
<td>—</td>
<td>Attached</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Brittle crack fracture surface (both sides)</td>
<td>—</td>
<td>Attached</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>9 Dynamic measurement results</td>
<td>History of crack propagation velocity</td>
<td>—</td>
<td>Attached</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Strain change at pin chucks</td>
<td>—</td>
<td>Attached</td>
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## TABLE 3
Report Sheet for Brittle Crack Arrest Test Results (US Units) (2021)

<table>
<thead>
<tr>
<th>Item</th>
<th>Details</th>
<th>Symbol</th>
<th>Conditions/Results</th>
<th>Unit</th>
<th>Valid/Invalid</th>
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<tr>
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<td>Test material</td>
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<tr>
<td></td>
<td></td>
<td>Yield stress at room temperature</td>
<td>$\sigma_{y0}$</td>
<td>ksi</td>
<td>—</td>
</tr>
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<td>2</td>
<td>Test equipment</td>
<td>Testing machine capacity</td>
<td>—</td>
<td>lbf</td>
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<td>3</td>
<td>Test specimen dimensions</td>
<td>Thickness</td>
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<td>in.</td>
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</tr>
<tr>
<td></td>
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<td>Width</td>
<td>$W$</td>
<td>in.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Length</td>
<td>$L$</td>
<td>in.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Angular distortion + linear misalignment</td>
<td>—</td>
<td>in./ft</td>
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</tr>
<tr>
<td>4</td>
<td>Integrated specimen dimensions</td>
<td>Tab plate thickness</td>
<td>$t_{tb}$</td>
<td>in.</td>
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<td></td>
<td></td>
<td>Tab plate width</td>
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<td>in.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Test specimen length including a tab plate</td>
<td>$L + L_{tb}$</td>
<td>in.</td>
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</tr>
<tr>
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<td></td>
<td>Distance between loading pins</td>
<td>$L_{p}$</td>
<td>in.</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Test conditions</td>
<td>Applied force</td>
<td>$F$</td>
<td>lbf</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Applied stress</td>
<td>$\sigma$</td>
<td>ksi</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Temperature gradient</td>
<td>—</td>
<td>°F/in.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Impact energy</td>
<td>$E_i$</td>
<td>ft-lbf</td>
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<td>Ratio of impact energy to strain energy stored in integrated specimen</td>
<td>$E_i/(E_i + E_t)$</td>
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<tr>
<td>6</td>
<td>Test results</td>
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<td>in.</td>
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<td>Presence/absence of crack branching</td>
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<td>—</td>
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<td></td>
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<td>Ratio of branch crack length to main crack</td>
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<td></td>
<td></td>
<td>Main crack angle</td>
<td>$\theta$</td>
<td>degrees (°)</td>
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<td></td>
<td></td>
<td>Presence/absence of crack re-initiation</td>
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<td>—</td>
</tr>
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<td></td>
<td></td>
<td>Temperature at crack arrest position</td>
<td>$T$</td>
<td>°F</td>
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<tr>
<td></td>
<td>Arrest toughness value</td>
<td>$K_{ca}$</td>
<td>ksi-in(^{1/2})</td>
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<td></td>
</tr>
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<td>7</td>
<td>Temperature distribution at moment of impact</td>
<td>Temperature measurement position</td>
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<td>Attached</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Temperature at each temperature measurement position</td>
<td>—</td>
<td>Attached</td>
<td>°F</td>
</tr>
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<td>Temperature distribution curve</td>
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<td>Test specimen photographs</td>
<td>Crack propagation path</td>
<td>—</td>
<td>Attached</td>
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<tr>
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<td>Brittle crack fracture surface (both sides)</td>
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<tr>
<td>9</td>
<td>Dynamic measurement results</td>
<td>History of crack propagation velocity</td>
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<td>Attached</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Strain change at pin chucks</td>
<td>—</td>
<td>Attached</td>
<td>—</td>
</tr>
</tbody>
</table>
5 Method for Obtaining $K_{ca}$ at a Specific Temperature and the Evaluation (2021)

1 General
This Appendix specifies the method for conducting multiple tests specified in Appendix 4 to obtain $K_{ca}$ value at a specific temperature $T_{D}$.

3 Method
A number of experimental data show the dependency of $K_{ca}$ on arrest temperature, as expressed by the equation below, where $T_{K}(K) = T(°C) + 273$, $c$ and $K_{0}$ are constants.

$$K_{ca} = K_{0} \exp \left( \frac{c}{T_{K}} \right) \text{N/mm}^{3/2} \text{ksi-in}^{1/2}$$

The arrest toughness at a required temperature $T_{D}$, in K, can be obtained using the following procedures.

i) Obtain at least four valid $K_{ca}$ data.

ii) Approximating log $K_{ca}$ by a linear expression of $1/T_{K}$, determine the coefficients log $K_{0}$ and $c$ for the data described above by using the least square method.

$$\log K_{ca} = \log K_{0} + c \left( \frac{1}{T_{K}} \right)$$

iii) Obtain the value of $(K_{ca}/K_{0})^{exp(+c/T_{K})}$ for each data item. When the number of data outside the range of 0.85 through 1.15 is not exceeded, the least square method used in paragraph ii) is considered valid. Obtain an integer by rounding down the value of (number of all data divided by 6). If this condition is not met, conduct additional tests to add at least two data and apply the procedure in paragraph ii) to the data.

iv) The value of $K_{0} \exp(+c/T_{K})$ is defined as the estimated value of $K_{ca}$ at $T_{D}$. The estimated value for the temperature corresponding to a specific value of $K_{ca}$ can be obtained from $T_{K} = +c/\log(K_{ca}/K_{0})$. If the condition specified in paragraph iii) is not met, these estimated values are treated as reference values.

5 Evaluation
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 5, 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 5, 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 $-10^\circ$C (2021)

FIGURE 2
Example for Evaluation of Temperature Corresponding to the Required $K_{ca}$ (2021)
APPENDIX 6  Double Tension Type Arrest Test (2021)

1  Features of this Test Method

A double tension type arrest test specimen consists of a main plate and a secondary loading tab. The main plate is a test plate for evaluating brittle crack arrest toughness. The secondary loading tab is a crack starter plate for assisting a brittle crack to run into the main plate. After applying a predetermined tension force and a temperature gradient to the main plate, a secondary force is applied to the secondary loading tab by a secondary loading device to cause a brittle crack to initiate and run into the main plate. The arrest toughness is evaluated from the arrest temperature and the crack length in the main plate.

The narrow connection part of the main plate and the secondary loading tab in this test suppress the flow of the tension stresses of the secondary loading tab into the main plate. The values of arrest toughness obtained by this method can be considered the same as the results obtained by the brittle crack arrest toughness test specified in Appendix 4.

The specifications described in Appendix 4 are to be applied to conditions not mentioned in this Appendix.

3  Test Specimen Shapes

The recommended shapes of the entire double tension type arrest test specimen and the secondary loading tab are shown in Appendix 6, Figures 1 and 2, respectively. Subsection A4/5 is applied to the shapes of the tab plates and pin chucks.

Note: Because of the narrowness of the connection part, slight crack deviation may lead to failure of the crack to enter the main plate. The optimum shape design of the secondary loading tab depends on the type of steel and testing conditions.
5 Temperature Conditions and Temperature Control Methods

In order to evaluate the brittle crack arrest toughness, a temperature gradient in the main plate is to be established. The specifications for temperature gradients and methods for establishing the temperature gradient are described in Subsection A4/7. In addition, in the double tension type arrest test, the secondary loading tab must be cooled. The secondary loading tab is cooled without affecting the temperature gradient of the main plate. As in the cooling method for test specimens described in Appendix 4, cooling may be applied using a cooling box and a coolant. The temperature of the secondary loading tab can be measured using thermocouples as described in Appendix 4.

7 Secondary Loading Method

A secondary loading device is used to apply force to the secondary loading tab. The secondary loading device is to satisfy the conditions below.

7.1 Holding Methods of Secondary Loading Device

To avoid applying unnecessary force to the integrated specimen, the secondary loading device is to be held in an appropriate manner. Suspension type or floor type holding methods can be used. In the suspension type method, the secondary loading device is suspended and held by using a crane or a similar device. In the floor type method, the secondary loading device is lifted and held by using a frame or a similar device.

7.3 Loading System

A hydraulic type loading system is most suitable for applying a force to the secondary loading tab. However, other methods may be used. A4/5.3 is applied to the shapes of the tab plates and pin chucks.

7.5 Loading Method

The method of loading the secondary loading tab is to be a pin type loading method. A loading method other than a pin type may be used by agreement among the parties concerned. The loading rate is not specified because it does not have a direct influence on the crack arrest behavior of the main plate.
Appendix 7: Outline of Requirements for Undertaking Isothermal Crack Arrest Temperature (CAT) Test (2021)

1 Scope

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 Appendix 4.

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

The following symbols, units, and significance specific to the isothermal tests supplement Appendix 4.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t$</td>
<td>mm (in.)</td>
<td>Test specimen thickness</td>
</tr>
<tr>
<td>$L$</td>
<td>mm (in.)</td>
<td>Test specimen length</td>
</tr>
<tr>
<td>$W$</td>
<td>mm (in.)</td>
<td>Test specimen width</td>
</tr>
<tr>
<td>$a_{MN}$</td>
<td>mm (in.)</td>
<td>Machined notch length on specimen edge</td>
</tr>
<tr>
<td>$LSG$</td>
<td>mm (in.)</td>
<td>Side groove length on side surface from the specimen edge. $LSG$ is defined as a groove length with constant depth except a curved section in depth at side groove end.</td>
</tr>
<tr>
<td>$d_{SG}$</td>
<td>mm (in.)</td>
<td>Side groove depth in section with constant depth</td>
</tr>
<tr>
<td>$LEB_{min}$</td>
<td>mm (in.)</td>
<td>Minimum length between specimen edge and electron beam re-melting zone front</td>
</tr>
<tr>
<td>$LEB_{-1}, -2$</td>
<td>mm (in.)</td>
<td>Length between specimen edge and electron beam re-melting zone front appeared on both specimen side surfaces</td>
</tr>
<tr>
<td>$LTG$</td>
<td>mm (in.)</td>
<td>Local temperature gradient zone length for brittle crack runaway</td>
</tr>
<tr>
<td>$a_{arrest}$</td>
<td>mm (in.)</td>
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<td>$T_{Target}$</td>
<td>°C (°F)</td>
<td>Target test temperature</td>
</tr>
<tr>
<td>$T_{test}$</td>
<td>°C (°F)</td>
<td>Defined test temperature</td>
</tr>
<tr>
<td>$T_{arrest}$</td>
<td>°C (°F)</td>
<td>Target test temperature at which valid brittle crack arrest behavior is observed</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>N/mm² (ksi)</td>
<td>Applied test stress at cross section of $W \times t$</td>
</tr>
<tr>
<td>SMYS</td>
<td>N/mm² (ksi)</td>
<td>Specified minimum yield strength of the tested steel grade to be approved</td>
</tr>
<tr>
<td>CAT</td>
<td>°C (°F)</td>
<td>Crack arrest temperature, the lowest temperature, $T_{arrest}$, at which running brittle crack is arrested</td>
</tr>
</tbody>
</table>
5 Testing Equipment

The test equipment to be used is to be of the hydraulic type of sufficient capacity to provide a tensile load equivalent to \( \frac{2}{3} \) 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 \( \pm 2^\circ C \) (\( \pm 3.6^\circ F \)) from \( T_{\text{target}} \).

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 specified in A4/3.

7 Testing Specimens

7.1 Impact Type Crack Initiation

Test specimens are to be in accordance with A4/5, unless otherwise specified in this Appendix.

Specimen dimensions are shown in Appendix 7, 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 \( \pm 1 \) mm (\( \pm 0.04 \) in.).

Requirements for side grooves are described in A7/7.7.

**FIGURE 1**

Test Specimen Dimensions for an Impact Type Specimen (2021)

Notes:

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**
Reference is to be made to Appendix 6 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.

*Notes:* 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**
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 of 150 mm (6 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 7, 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.
7.9 Nominal Length of Embrittled Zone

The length of the embrittled zone is to be nominally equal to 150 mm (6 in.) in both systems of EBW and LTG.

The EBW zone length is calculated by three measurements on the fracture surface after testing, as shown in Appendix 7, Figure 3: $L_{EB\text{-}min}$ between specimen edge and EBW front line, and $L_{EB\text{-}s1}$ and $L_{EB\text{-}s2}$.

The minimum length between the specimen edge and EBW front line, $L_{EB\text{-}min}$, is to be no smaller than 150 mm (6 in.). However, it can be acceptable even if $L_{EB\text{-}min}$ is no smaller than 150 mm – 0.2t (6 in. – 0.2t), where t is the specimen thickness. When $L_{EB\text{-}min}$ 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 $L_{EB\text{-}s1}$ and $L_{EB\text{-}s2}$. Both $L_{EB\text{-}s1}$ and $L_{EB\text{-}s2}$ are to be no smaller than 150 mm (6 in.).

In the LTG system, $L_{LTG}$ is set as 150 mm (6 in.).
7.11 Tab Plate/Pin Chuck Details and Welding of Test Specimen to Tab Plates

The configuration and size of tab plates and pin chucks are to be as defined in A4/5.3. 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 A4/5.5.

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 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 7, 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, $T_{\text{target}}$.

When all measured temperatures across the range of 0.3W~0.7W have reached $T_{\text{target}}$, steady temperature control is to be kept at least for $10 + 0.1 \times t$ mm (0.4 + 0.004 × $t$ 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 7, 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 7, Figure 5.

**FIGURE 5**

Detail of LTG Zone and Additional Thermocouple \( A_0 \) (2021)

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

\[
\begin{align*}
T \text{ at } A_3, T \text{ at } B_3 &< T_{\text{target}} - 2°C \\
T \text{ at } A_2 &< T \text{ at } A_3 - 5°C \\
T \text{ at } B_2 &< T \text{ at } B_3 - 5°C
\end{align*}
\]

Once the all measured temperatures across the range of 0.3\( W \text{-} 0.7W \) have reached \( T_{\text{target}} \), 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, 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 7, Figure 6.
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 7, Table 1.

### TABLE 1
**Acceptable LTG Range** (2021)

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

*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 7, Table 2 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
Prior to testing, a target test temperature ($T_{target}$) is to be selected.

Test procedures are to be in accordance with A4/9 except that the applied stress is to be $2/3$ of SMYS of the steel grade tested.
Appendix 7  Outline of Requirements for Undertaking Isothermal Crack Arrest Temperature (CAT) Test

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 7, 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 7, 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.

13 Judgment of “ Arrest” or “ Propagate”

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 A4/9.5 and A4/9.7.

ii) If the specimen was not broken into two pieces during testing, the arrested crack length, \(a_{\text{arrest}}\), 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 \(a_{\text{arrest}}\).

iii) For LTG and EBW, \(a_{\text{arrest}}\) is to be greater than \(L_{\text{LTG}}\), \(L_{\text{EB-s1}}\), \(L_{\text{EB-s2}}\) or \(L_{\text{EB-max}}\). 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 $a_{\text{arrest}}$. If re-initiation is not visibly evident, the test is judged as “propagate”.

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

15 $T_{\text{test}}, T_{\text{arrest}}$ and CAT Determination

15.1 $T_{\text{test}}$ 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 $T_{\text{target}} \pm 2^\circ C$ ($T_{\text{target}} \pm 3.6^\circ F$) at brittle crack initiation. If not, the test is to be considered as invalid. However, the temperature measurement at $0.3W$ (location of A3 and B3) in the LTG system is to be exempted from this requirement.

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

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

The final arrest judgment at $T_{\text{test}}$ is concluded by at least two tests at the same test condition which are judged as “arrest”.

15.3 $T_{\text{arrest}}$ Determination

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

15.5 CAT Determination

When CAT is determined, one “propagate” test is needed in addition to two “arrest” tests. The target test temperature, $T_{\text{target}}$ for “propagate” test is to select $5^\circ C$ ($9^\circ F$) lower than $T_{\text{arrest}}$. The minimum temperature of $T_{\text{arrest}}$ is determined as CAT.

With only the “arrest” tests, without a “propagation” test, it is decided only that CAT is lower than $T_{\text{test}}$ 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 $a_{\text{MN}}$, side groove details if machined

iv) Embritted 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 A7/15.5.
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 coamings. 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 coamings 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 A8/1.1.

3  Fracture Mechanics Analysis

Fracture mechanics analysis (FMA) is to be carried out for the flaws in critical areas identified in A8/1.3. 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 8, Figure 1.
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 8, Figure 2. The crack orientation is assumed to be perpendicular to the principal stress direction.
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 8, Figure 3. The crack orientation is assumed to be perpendicular to the principal stress direction.

![Initial Embedded Flaws inside Coaming Top Plate (2021)](image)

3.5 Load Distribution

3.5.1 Maximum Hull Girder Stress

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-5-3/5.1 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

\[
k_1 = 10 \ (10, 2240)
\]

\[
M_{w-Hog} = \text{vertical wave induced hogging bending moments, in kN-m (tf-m, Ltf-ft), in accordance with 5C-5-3/5.1 of the Marine Vessel Rules}
\]

\[
M_{w-Sag} = \text{vertical wave induced sagging bending moments, in kN-m (tf-m, Ltf-ft), in accordance with 5C-5-3/5.1 of the Marine Vessel Rules}
\]

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

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

\[
z = \text{vertical distance from baseline to considered location (i.e., side hatch coaming top), in m (ft)}
\]

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

\[
\sigma_{total} = c_f (\sigma_{SWBM} + \sigma_{w-Hog})
\]
where

\[ \sigma_{SWBM} = \text{hull girder bending stress due to maximum hogging still water bending moment, in N/mm}^2 \text{ (kgf/mm}^2, \text{ psi)} \]
\[ c_f = \text{adjustment factor to reflect a mean wasted condition, taken as 0.95} \]

3.5.2 Long Term Stress Range

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 \( \gamma \) are the scale and shape parameters of the Weibull distribution, respectively.

The shape parameter of the Weibull distribution \( \gamma \) is determined in accordance with 5C-5-A1/5.5 of the Marine Vessel Rules.

The scale parameter is determined by:

\[
A = \frac{\Delta \sigma_w}{(\ln N_R)^{1/\gamma}}
\]

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, \( \Delta \sigma \) is calculated as follows:

\[
\Delta \sigma = c_f |\sigma_{w-Hog} - \sigma_{w-Sag}|
\]

where \( \sigma_{w-Hog} \) and \( \sigma_{w-Sag} \) are described in A8/3.5.1 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 8, 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:

\[ N_T = \frac{f_0 \cdot D_L}{4 \log L} \]

where

\[ f_0 = \text{factor for net time at sea} \]
\[ = 0.85 \]
\[ L = \text{scantling length of vessel, in m} \]
\[ D_L = \text{design life in seconds} \]

For 20 year ship design life \( (T_{\text{Design}}) \), the design life \( (D_L) \) is \( 6.31 \times 10^8 \) seconds. For 25 year ship design life, the design life \( (D_L) \) is \( 7.88 \times 10^8 \) 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:

\[ \Delta K = (Y \Delta \sigma) \sqrt{a} \]

where

\[ Y \Delta \sigma = M_f \cdot \{ M_{km} \cdot M_m \cdot \Delta \sigma_m + M_{kb} \cdot M_b \cdot (\Delta \sigma_b + (k_m - 1) \cdot \Delta \sigma_m) \} \], in N/mm\(^2\)

\[ M = \text{bulging correction factor} \]
\[ = 1 \quad \text{for surface and embedded cracks in plate} \]
\[ f_w = \text{finite width correction factor} \]
\[ M_{km}, M_{kb} = \text{weld toe notch factors} \]
\[ M_m, M_b = \text{stress intensity magnification factors} \]
\[ \Delta \sigma_m = \text{remote uniform tensile stress, in N/mm}^2 \]
\[ \Delta \sigma_b = \text{remote bending stress in, N/mm}^2 \]
\[ k_m = \text{misalignment factor} \]
\[ a = \text{crack length} \]

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 8, Figure 5, is described as follows:

Step 1: Specify an initial surface crack with length, \(2c_0\), and height, \(a_0\), as described in A8/3.3.

Step 2: Perform crack propagation analysis on a surface crack using Paris’ law with stress intensity factor range as described in A8/3.7.

Step 3: Repeat Step 2 to calculate crack propagation for each group of load spectra as described in A8/3.5 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.

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

\[
\frac{da}{dN} = C (\Delta K_a)^m \\
\frac{da}{dN} = 0 \\
\frac{dc}{dN} = C (\Delta K_c)^m \\
\frac{dc}{dN} = 0
\]

for \(\Delta K_a > \Delta K_{th}\) and \(\Delta K_a \leq \Delta K_{th}\),

for \(\Delta K_c > \Delta K_{th}\) and \(\Delta K_c \leq \Delta K_{th}\),

where

\(dc/dN, da/dN\) = crack propagation rate, in mm/cycle

\(C, m\) = Paris’ law constants

\(\Delta K_a, \Delta K_c\) = 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

\(\Delta K_{th}\) = 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.
Appendix 8  Engineering Critical Assessment for Hatch Coamings

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, \( \sigma_y \), and tensile strength, \( \sigma_u \), 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, \( \sigma_y \), and tensile strength, \( \sigma_u \) 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:

\[
K_{IC} = \frac{m \delta \sigma_f E}{(1-\nu^2)}
\]

where

- \( \delta \) = CTOD value, in mm
- \( E \) = Young’s modulus of the material, in N/mm\(^2 \)
- \( \nu \) = Poisson’s ratio of material
- \( \sigma_f \) = flow stress, in N/mm\(^2 \)
  
  \( \sigma_f = (\sigma_y + \sigma_u)/2 \) and \( \sigma_f \leq 1.2 \sigma_y \)
- \( \sigma_y \) = yield stress of the material, in N/mm\(^2 \)
- \( \sigma_u \) = tensile strength of material in N/mm\(^2 \)
- \( m = 1.517 \left( \frac{\sigma_y}{\sigma_u} \right)^{-0.3188} \) for \( 0.3 < \frac{\sigma_y}{\sigma_u} < 0.98 \)
- \( \sigma_y \) = yield strength of the material tested, determined at the fracture toughness test temperature, in N/mm\(^2 \)
- \( \sigma_u \) = 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 8, Table 1 following BS 7910:2013 for assessing the welded joints of steels in air.

### TABLE 1

Details of Paris’ Law Parameters (2021)

<table>
<thead>
<tr>
<th>Threshold of Stress Intensity Factor Range ( \Delta K_0 ) N/mm(^{3/2} )</th>
<th>( m ) (stage A)</th>
<th>( C ) (stage A)*</th>
<th>Transition Point ( \Delta K ) N/mm(^{3/2} )</th>
<th>( m ) (stage B)</th>
<th>( C ) (stage B)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>63</td>
<td>5.10</td>
<td>2.10 \times 10^{-17}</td>
<td>144</td>
<td>2.88</td>
<td>1.29 \times 10^{-12}</td>
</tr>
</tbody>
</table>

*Note: For \( d/dN \) in mm/cycle and \( \Delta K \) 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 8, 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 \( \sigma_{ref} \) is the reference stress in accordance with Annex P from BS 7910:2013 and \( \sigma_y \) 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.

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**FIGURE 6**

Option 1 Failure Assessment Diagram (FAD) (2021)
Appendix 8  Engineering Critical Assessment for Hatch Coamings

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 A8/3.3. The remaining life ($T_{RL}$) can be calculated for each assumed initial flaw size configuration following A8/3.5 through A8/3.13. 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 8, 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)

![Diagram showing the allowable zone for initial surface flaw size](image)

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 A8/3.5 through A8/3.13, 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 of Hull Welds. 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 of Hull Welds.

During construction, any detected flaw on the hatch coaming top is to be evaluated in accordance with A8/3.15 for allowable initial single flaw size. Adjacent flaws separated by less than 2$\ell$ of sound metal ($\ell$ equals length of longest discontinuity) are to be considered as a single flaw. Multiple flaws ($\geq$ two flaws) are evaluated in accordance with ABS Guide for Nondestructive Inspection of Hull Welds.
5.3 Construction Monitoring Plan

The defined areas in A8/1.3 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 A8/3.15 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 in this Guide.

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 Guidance Notes on Structural Monitoring using Acoustic Emissions.