Guidance Notes On

# Ice Class

ABS

October 2024

GUIDANCE NOTES ON

# ICE CLASS
# OCTOBER 2024

American Bureau of Shipping
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# Foreword *(1 October 2024)*

The purpose of these Guidance Notes is to provide ship designers and owners/operators with guidance on ice class selection, as well as guidance on certain aspects of ice class ship design and analysis.

- Chapter 1 provides an introduction to ice class.
- Chapter 2 provides guidance for selecting an appropriate ice class.
- Chapter 3 provides guidance on certain aspects of ice class ship design and analysis.

The October 2024 edition updates the Guidance Notes to align with current practice and provides an introduction to ice class, helps with ice class selection, and provides guidance on aspects of ice class ship design and analysis. This edition is a complete rewrite of the Guidance Notes. Therefore, the new text is not marked in red.

These Guidance Notes become effective on the first day of the month of publication.

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

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

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GUIDANCE NOTES ON

# ICE CLASS

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CHAPTER 1

# Introduction

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# CHAPTER 1
# Introduction

## SECTION 1
## Ice Class Rules

### 1 Background

Ice class rules are a set of construction standards that provide additional requirements beyond those for open water operations to enable a ship to withstand loads induced by interaction with ice. The rules contain construction standards that provide varying levels of structural and machinery strengthening to withstand ice loads. Ice class rules have evolved over the decades from a simple structural strength addition(s) for light ice applications to structural and machinery requirements for highly capable polar transiting ships including today's modern specialized icebreakers.

Ice class rules have existed for many decades in Classification Society Rules and in Polar coastal nation rules. The different rule sets prescribed requirements which were dependent on the local ice conditions for a specific country's waters or the Classification Societies' school of thought. The large number of ice class rule sets led to confusion for ship owners/operators and significant work for regulators to determine if a vessel was compliant with a specific rule set. This led to many efforts to determine "equivalency" between ice class rule sets but often led to more confusion and disagreement between stakeholders.

A major harmonization of rule sets was done by the International Association of Classifications (IACS) and the signatory countries of the International Maritime Organization (IMO). The two main ice class rule sets in the ABS *Rules for Building and Classing Marine Vessels (Marine Vessel Rules)* after this harmonization are the Finnish-Swedish Ice Class Rules (FSICR) and the Polar Class (PC) Rules. Many Classification Societies have additional rules for lighter ice conditions, such as **Ice Class ID** and **Ice Class IE** in Section 6-1-4 of the *Marine Vessel Rules*.

Note that an ice class notation is verification that the hull and machinery are strengthened to withstand ice loads to a level corresponding to the vessel's associated ice class. An ice class notation does not guarantee efficient performance in ice. The hull form, installed power, and crew capability/knowledge govern the ship's performance in ice. Ice class rules do not prescribe requirements governing the hull form design.

The Subsections below outline the underlying principles for both the FSICR and Polar Class Rules.

### 2 Finnish-Swedish Ice Class Rules

The FSICR requirements are located within Section 6-1-4 of the *Marine Vessel Rules* but have been renamed to the First Year Ice Class Rules to include the ABS-specific low ice classes. The basis for the FSICR is to maintain commercial traffic to the ports of Finland and Sweden during the winter navigation season. Baltic Sea ice is naturally first year ice due to the geography of the Baltic Sea. Therefore, the principles behind the FSICR Rules do not include contact with hard multi-year ice floes. The FSICR have been used widely for other areas of the world that have seasonal first year ice such as the Great Lakes, the Caspain Sea, and the Bohai Sea.

The FSICR Rules have powering requirements, which are baseline minimums to keep ships moving within a convoy of ships with minimal icebreaker assistance. The load model is assumed to produce a thin load patch that acts more like a line load than a classical rectangular patch, and has been validated via several years of ice load monitoring studies in the Baltic Sea.

There are four FSICR ice classes. These ice classes are (in the ABS Rules) **Ice Class IC**, **Ice Class IB**, **Ice Class IA**, and **Ice Class IAA**, from lowest to highest. The ice classes correspond to a nominal ice thickness that the ship can resist/expect to encounter within a channel broken by the convoy. As mentioned previously, the Rules do not govern hull form, they provide strengthening requirements for the structure and machinery to withstand ice loads. The nominal ice thicknesses are outlined in 1-1/Table 1 for each FSICR ice class. Note that the design philosophy of the FSICR is set around an elastic response of the structure and machinery. The prescribed ice loads in the Rules should not lead to any permanent deformations.

### TABLE 1
### FSICR Nominal Thickness

| *FSICR Ice Class* | *ABS Notation* | *Nominal Ice Thickness m (ft)* |
|---|---|---|
| IA Super | **Ice Class IAA** | 1.0 (3.28) |
| IA | **ice Class IA** | 0.8 (2.62) |
| IB | **Ice Class IB** | 0.6 (1.97) |
| IC | **Ice Class IC** | 0.4 (1.31) |

## 3 Polar Class Rules

The Polar Class Rules are the highest ice classes recognized by the IMO and IACS members. The Rules were designed around operations in Polar waters (generally at or above 60 degrees latitude) where multi-year ice is likely present. The polar classes range from operations in shoulder seasons only (**Ice Class PC7**) to all year-round operations in the high Arctic (**Ice Class PC1**). 1-1/Table 2 provides a basic operational description for each Polar Class. Note that old ice includes both second year ice (ice that has survived only one melt season) and multi-year ice (ice that has survived two or more melt seasons).

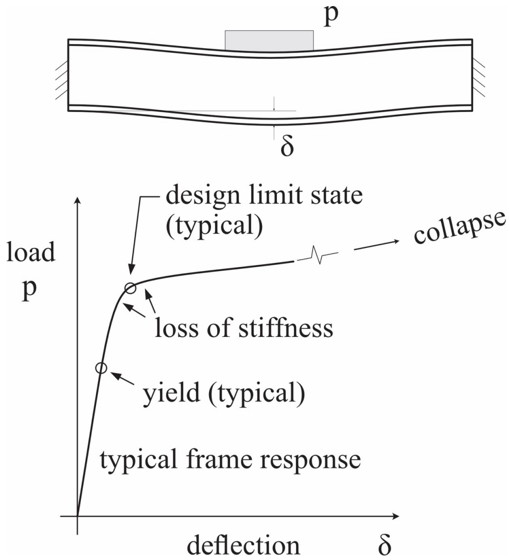
### TABLE 2
### Polar Class Descriptions

| *Polar Class* | *Ice Description (based on World Meteorological Organization Sea Ice Nomeclature)* |
|---|---|
| **Ice Class PC1** | Year-round operation in all Polar waters |
| **Ice Class PC2** | Year-round operation in moderate multi-year ice conditions |
| **Ice Class PC3** | Year-round operation in second-year ice which may include multi-year ice inclusions |
| **Ice Class PC4** | Year-round operation in thick first-year ice which may include old ice inclusions |
| **Ice Class PC5** | Year-round operation in medium first-year ice which may include old ice inclusions |
| **Ice Class PC6** | Summer/autumn operation in medium first-year ice which may include old ice inclusions |
| **Ice Class PC7** | Summer/autumn operation in thin first-year ice which may include old ice inclusions |

The design load for Polar Class ships takes a physics-based approach so that ice loads can be rationally linked to a specified ship/ice interaction scenario. The design scenario is a glancing collision with an ice edge, such as the edge of a channel or of a floe. The form of the load equation is derived from the solution of an energy-based collision model in which the available kinetic energy (assuming a specific ship speed) is equated to energy expended into failure via ice crushing and/or bending. Ice thickness, ice crushing strength, hull form, ship size, and ship speed are all considered. The flexural failure of the ice sheet is also considered as a force limit state during the collision. The results of the model are in close agreement with a variety of past studies and operational experience. The forces generated during a glancing impact are represented in ways that allow them to be used in developing scantlings for individual structural elements, grillages, and supporting structure.

Although most traditional ship structural rule formulations are based on elastic criteria, the Polar Class Rules incorporate a plastic design criteria. These plastic design criteria are very near to the yield point, at the onset of plasticity before deformations that require repair have occurred. Plastic design methods typically result in a better balance of material distribution to resist extreme loads than elastic design methods. This is particularly important due to the risk of unintended extreme ice loads in multi-year ice which may be well in excess of design values. In plastic design, there are many possible limit states ranging from yield through to rupture. The Polar Class Rules use a design limit state representing a condition of substantial plastic stress, prior to the development of large plastic strains and deformations. 1-1/Figure 1 shows a typical load deflection curve for a frame at the plastic design point in the Polar Class Rules.

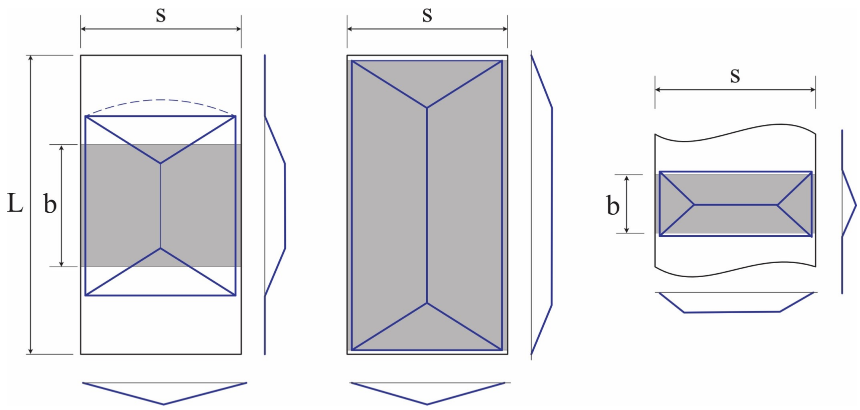
## FIGURE 1
## Load Deflection Curve




Source: Dr. Claude Daley

The shell plate thickness requirements are derived using ultimate strength criterion where the ultimate state is determined when plastic folding occurs due to perfect plastic hinge formation, without considering membrane action. 1-1/Figure 2 shows the ice load application and deformed shell plate transition in the ultimate state for three potential different loading conditions (square patch load, entire bay between frames, rectangular patch load) within the Polar Class Rules.

## FIGURE 2
## Plating Plastic Limit State

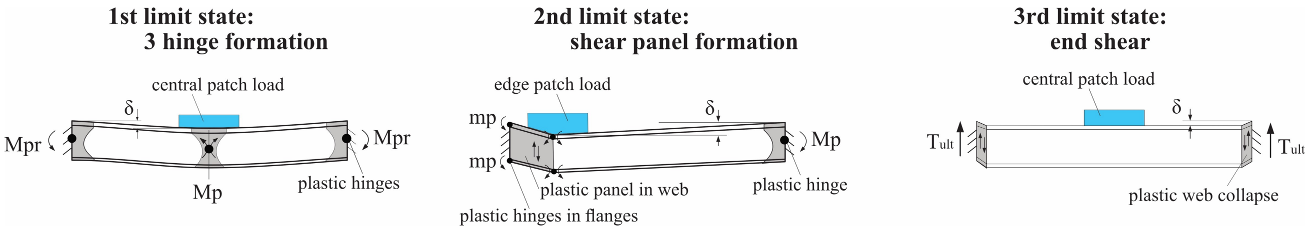



Source: Dr. Claude Daley

***Note:*** The dashed line represents the actual deformed shape, $L$ is the frame span, $s$ is the distance between frames, and $b$ is the load height.

The frames are dimensioned such that the combined effects of shear and bending do not cause the development of a plastic collapse mechanism. The plastic section modulus requirement is derived from an analytical energy method considering three limit-states shown in 1-1/Figure 3. The Polar Class Rules rigorously treat bending and shear interaction by considering actual section shape in the calculation procedure. The application of an iterative procedure may be advantageous for the designer to optimize the frames for the shear and plastic section modulus requirements. The scantling requirements are provided for both transversely and longitudinally framed structures.

## FIGURE 3
## Framing Plastic Limit States




Source: Dr. Claude Daley

***Note:*** $Mp$, $Mpr$, and $mp$ are the bending moments at the plastic hinges, $T_{ult}$ is the maximum shear stress, and $\delta$ is the displacement.

The Polar Class Rules provide specific machinery requirements related to the strength of main propulsion, steering gear, emergency, and other essential auxiliary support systems. Propeller ice interaction load formulas form the basis of the propulsion line component strength calculations. The calculated loads are the expected, single occurrence, maximum value(s) for a ship's entire service life in normal operation conditions. The propeller blades should be designed with respect to two overall limit states, namely static and fatigue. The static criterion is based on the calculated maximum expected loads applied via finite element analysis with acceptance criteria for permissible stress levels. The propeller blade fatigue criterion is based on a load distribution for the ship service life and a nominal S-N curve of the blade material. The propulsion line components should be designed according to the "selective strength principle" so that the first damage does not cause significant risk to the ship's safety and other shaft line components.

ABS has developed Guidance Notes to help designers and engineers with the design of Polar Class azimuthing propulsors. The Guidance Notes outline various load cases/scenarios that can be used for extreme load analysis. Please see the ABS *Guidance Notes on Ice Loads on Azimuthing Propulsion Units* for more details.

CHAPTER 2

# Ice Class Selection

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CHAPTER 2
# Ice Class Selection

SECTION 1
## Operational Profile

### 1 Defining an Operational Profile

Selecting an appropriate ice class for a vessel is instrumental in providing the vessel with sufficient strength to resist the expected ice loads.

The first step is to define the operational area the vessel will sail in. This includes both the geographical location and the time of year. It is the responsibility of the owner/operator to define the operational profile, which will in turn define the ice class. Most ice-covered waters are ice free during the summer months. During the ice-free periods, these waters are frequently traveled by non-ice classed vessels. If the vessel will operate in an area and time of year where very little ice is present, the vessel may only need a low (or no) ice class.

For example, a northern Canadian mine generally has vessels call during the ice-free, warm air months during the North American summer, with most of the vessels calling at the port having low or no ice class. However, the vessels calling at the port in the shoulder seasons when ice is present generally have a higher ice class. If the vessel owner/operator only intends to operate during the ice-free months, having a higher ice class would make the vessel less competitive in the open market, as the ship will be carrying less cargo due to increased lightship. However, if the vessel does not have a high enough ice class, the vessel may sustain damage during ice operations and require costly repairs, or worse, such as loss of the ship, crew, or significant damage to the environment.

Once the operational profile has been defined, the applicable hazards (ice, cold air temperatures, ice accretion, etc.) can be determined using available environmental data. These Guidance Notes will only consider the ice risk with guidance on selecting an ice class.

CHAPTER 2
# Ice Class Selection

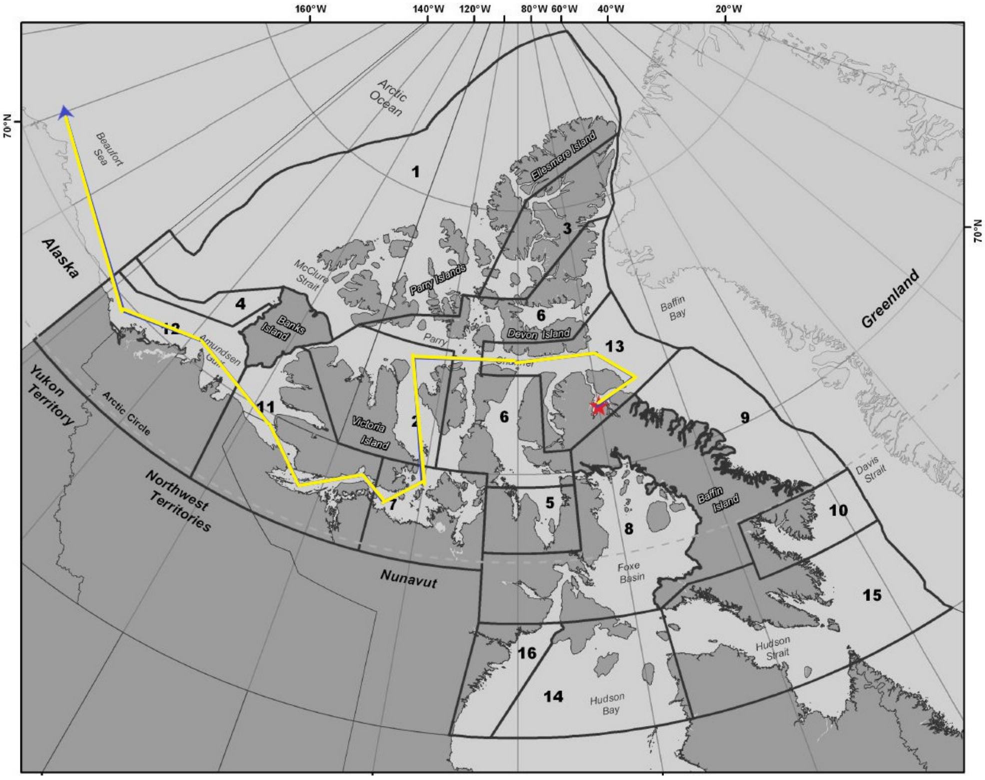
SECTION 2
# Selection Methods

## 1 Canadian Zone/Date System

The Canadian Zone/Date System (Z/DS) has been used in the Canadian Arctic for decades. It was developed as a tool to contribute to safe shipping in the Canadian Arctic and to help enable the regulation of the Canadian Arctic. The system was first introduced in the now repealed Arctic Shipping Pollution Prevention Regulations but remains in force under the current Arctic Shipping Safety and Pollution Prevention Regulations.

The zones are defined in the Shipping Safety Control Zones Order (C.R.C., 356). For the fully defined zone definitions, see C.R.C., 356 or 2-2/Figure 1 below. Note that the red star and yellow line in 2-2/Figure 1 are used in the following Subsection as part of an example. They are not part of the zones.

## FIGURE 1
## Canadian Z/DS Zones




Source: C.R.C., 356

## TABLE 1
## Canadian Z/DS Date Ranges for First Year Ice Classes

| Ice Class | Zone 1 | Zone 2 | Zone 3 | Zone 4 | Zone 5 | Zone 6 | Zone 7 | Zone 8 | Zone 9 | Zone 10 | Zone 11 | Zone 12 | Zone 13 | Zone 14 | Zone 15 | Zone 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| IAA | No Entry | No Entry | Aug. 20 to Sept. 10 | Aug. 20 to Sept. 20 | No Entry | Aug. 15 to Oct. 15 | Aug. 1 to Oct. 25 | Aug. 1 to Nov. 10 | Aug. 1 to Nov. 20 | Jul. 25 to Nov. 20 | Jul. 10 to Oct. 31 | June 15 to Nov. 10 | June 25 to Oct. 22 | June 25 to Nov. 30 | June 25 to Dec. 5 | June 20 to Nov. 20 |
| IA | No Entry | No Entry | Aug. 20 to Sept. 5 | Aug. 20 to Sept. 15 | No Entry | Aug. 25 to Sept. 30 | Aug. 10 to Oct. 15 | Aug. 10 to Oct. 31 | Aug. 10 to Oct. 31 | Aug. 1 to Oct. 31 | Jul. 15 to Oct. 20 | Jul. 1 to Oct. 25 | Jul. 15 to Oct. 15 | Jul. 1 to Nov. 30 | Jul. 1 to Nov. 30 | June 20 to Nov. 10 |
| IB | No Entry | No Entry | No Entry | No Entry | No Entry | Aug. 25 to Sept. 25 | Aug. 10 to Oct. 10 | Aug. 10 to Oct. 25 | Aug. 10 to Oct. 25 | Aug. 1 to Oct. 25 | Jul. 15 to Oct. 15 | Jul. 1 to Oct. 25 | Jul. 15 to Oct. 10 | Jul. 1 to Nov. 25 | Jul. 1 to Nov. 25 | June 25 to Nov. 10 |
| IC | No Entry | No Entry | No Entry | No Entry | No Entry | No Entry | Aug. 10 to Oct. 5 | Aug. 15 to Oct. 20 | Aug. 15 to Oct. 20 | Aug. 5 to Oct. 20 | Jul. 15 to Oct. 10 | Jul. 1 to Oct. 20 | Jul. 30 to Sept. 30 | Jul. 10 to Nov. 10 | Jul. 5 to Nov. 10 | Jul. 1 to Oct. 31 |
| None | No Entry | No Entry | No Entry | No Entry | No Entry | No Entry | Aug. 10 to Sept. 30 | Aug. 20 to Oct. 20 | Aug. 20 to Oct. 15 | Aug. 10 to Oct. 20 | Jul. 15 to Sept. 30 | Jul. 1 to Oct. 20 | Aug. 15 to Sept. 20 | Jul. 20 to Oct. 31 | Jul. 20 to Nov. 5 | Jul. 1 to Oct. 31 |

Source: SOR/2017-286

## TABLE 2
## Canadian Z/DS Date Ranges for Polar Ice Classes

| Ice Class | Zone 1 | Zone 2 | Zone 3 | Zone 4 | Zone 5 | Zone 6 | Zone 7 | Zone 8 | Zone 9 | Zone 10 | Zone 11 | Zone 12 | Zone 13 | Zone 14 | Zone 15 | Zone 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PC1 | All year | All year | All year | All year | All year | All year | All year | All year | All year | All year | All year | All year | All year | All year | All year | All year |
| PC2 | Jul. 1 to Oct. 15 | All year | All year | All year | All year | All year | All year | All year | All year | All year | All year | All year | All year | All year | All year | All year |
| PC3 | Aug. 15 to Sept. 15 | Aug. 1 to Oct. 31 | Jul. 15 to Nov. 30 | Jul. 15 to Nov. 30 | Aug. 1 to Oct. 15 | Jul. 15 to Feb. 28 | Jul. 1 to Mar. 31 | Jul. 1 to Mar. 31 | All year | All year | Jul. 1 to Mar. 31 | All year | All year | All year | All year | All year |
| PC4 | Aug. 20 to Sept. 15 | Aug. 20 to Sept. 30 | Jul. 25 to Oct. 15 | Jul. 20 to Nov. 5 | Aug. 20 to Sept. 25 | Aug. 1 to Nov. 30 | Jul. 20 to Dec. 15 | Jul. 20 to Dec. 31 | Jul. 20 to Jan. 20 | Jul. 15 to Jan. 25 | Jul. 5 to Dec. 15 | June 10 to Dec. 31 | June 10 to Dec. 31 | June 20 to Jan. 10 | June 20 to Jan. 31 | June 5 to Jan. 10 |
| PC5 | No Entry | No Entry | Aug. 15 to Sept. 30 | Aug. 1 to Oct. 31 | No Entry | Aug. 15 to Nov. 20 | Aug. 1 to Nov. 20 | Aug. 1 to Nov. 30 | Aug. 1 to Dec. 20 | Jul. 25 to Dec. 20 | Jul. 10 to Nov. 20 | June 15 to Dec. 5 | June 25 to Nov. 22 | June 25 to Dec. 10 | June 25 to Dec. 20 | June 10 to Dec. 10 |
| PC6 | No Entry | No Entry | Aug. 20 to Sept. 10 | Aug. 20 to Sept. 20 | No Entry | Aug. 15 to Oct. 15 | Aug. 1 to Oct. 25 | Aug. 1 to Nov. 10 | Aug. 1 to Nov. 20 | Jul. 25 to Nov. 20 | Jul. 10 to Oct. 31 | June 15 to Nov. 10 | June 25 to Oct. 22 | June 25 to Nov. 30 | June 25 to Dec. 5 | June 20 to Nov. 20 |
| PC7 | No Entry | No Entry | Aug. 20 to Sept. 5 | Aug. 20 to Sept. 15 | No Entry | Aug. 25 to Sept. 30 | Aug. 10 to Oct. 15 | Aug. 10 to Oct. 31 | Aug. 10 to Oct. 31 | Aug. 1 to Oct. 31 | Jul. 15 to Oct. 20 | Jul. 1 to Oct. 25 | Jul. 15 to Oct. 15 | Jul. 1 to Nov. 30 | Jul. 1 to Nov. 30 | June 20 to Nov. 10 |

Source: SOR/2017-286

2-2/Table 1 is taken from the Canadian Arctic Shipping Safety and Pollution Prevention Regulations (SOR/2017-286) that were amended on June 7, 2023. This table covers **Ice Class IAA** down to non-ice strengthened vessels.

2-2/Table 2 is based on Schedule 1 from the Canadian Arctic Shipping Safety and Pollution Prevention Regulations (SOR/2017-286) that were amended on June 7, 2023. Links between the CAC ice classes, and the Polar Classes is made by reference to Transport Canada's Safety Bulletin No 04/2009. In this case the following links are made:

## TABLE 3
## Canadian Arctic Classes - Polar Class

| *Canadian Arctic Class* | *Polar Class* |
|---|---|
| CAC1 | **Ice Class PC1** |
| CAC2 | **Ice Class PC2** |
| CAC3 | **Ice Class PC3** |
| CAC4 | **Ice Class PC4** |
| Arctic Class 2 | **Ice Class PC5** |
| Type A | **Ice Class PC6** |
| Type B | **Ice Class PC7** |

The above referenced bulletin states that an **Ice Class PC5** is somewhere between a Type A and a CAC4. An Arctic Class 1 has tighter date windows than the Type A, and an Arctic Class 1A has a window opening after that of a Type A, therefore Arctic Class 2 dates are used for an **Ice Class PC5**.

### 1.1 Using the Z/DS to Determine an Ice Class

With the operational profile for the vessel known, the areas and times of operation are determined. To determine the recommended ice class, the user must identify the zones in which the ship will operate, then identify the dates the ship will be within those zones. Select an ice class that has a window adequate for the intended operational profile.

For example, assume a bulk carrier will go into Milne Inlet (Zone 13, red star in 2-2/Figure 1), between July 15th and October 15th, and transit the Northwest Passage (Zones 13, 6, 2, 7, 11, and 12) between September 1st and the 15th (yellow line in 2-2/Figure 1).

**Part 1:** Milne Inlet (Zone 13) between July 15th and October 15th: An **Ice Class IA** is the lowest ice class that has date ranges for Zone 13.

**Part 2:** NWP, Zones 13, 6, 2, 7, 11, and 12, between September 1st and the 15th. Zone 2 is the most onerous of these. Therefore, focusing on the dates in Zone 2 shows that the First Year Ice Classes do not have any available date ranges. The lowest ice class that has a date opening for Zone 2 is an **Ice Class PC4**.

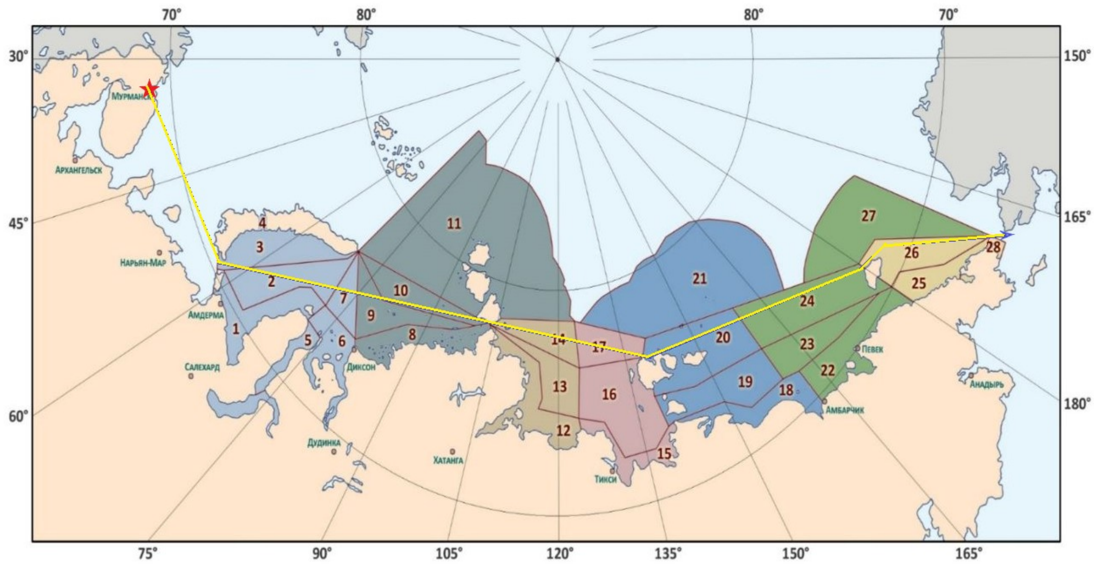
It is worth noting that the above is based on the system published by Transport Canada, many **Ice Class IA** ships have transited the NWP. The tables given here are intended as an initial estimate of what Ice Class is needed for the given zone or route through multiple zones. Systems such as POLARIS can be used to operate outside the Z/DS, which is how the **Ice Class IA** ships have passed through the NWP.

Please contact the ABS Polar Team at Polar@eagle.org for assistance selecting an ice class.

## 2 Russian Northern Sea Route

The Russian Northern Sea Route (NSR) has been claimed as an alternative to the traditional routes through the Panama or Suez canals. As the waters can be ice covered, the Russians have implemented a system of icebreaker escorts. The requirements for escort or the possibility of operation in the NSR are established in a similar method to that used in the Canadian Arctic. Russian Federation Resolution #1487 contains the requirements for navigating the Russian NSR, with zones like the Canadian Arctic. For the fully defined zone definitions, see Resolution #1487 or 2-2/Figure 2 below. Note that the red star and yellow line in 2-2/Figure 2 are used in the following Subsection as part of an example. They are not part of the zones.

**FIGURE 2**
**Russian NSR Zones**




Source: Rosatom Northern Sea Route General Administration

The following tables are found in Russian resolution #1487, dated 18 September 2020, with the ice classes altered to align with the ABS ice class notations. The approximate correspondence between the ice classes is provided in 2-2/Table 4.

## TABLE 4
## Ice Class Approximate Correspondance

| *Russian Ice Class* | *ABS Ice Class* | *Comments* |
|---|---|---|
| Without ice class | None | - |
| Ice1 | **Ice Class ID** | Russian Rules for hull areas show bow strengthening only, as does ABS Rules and Table 14 from the 2017 FSICR equivalent ice classes. |
| Ice2 | **Ice Class IC** | Table 14 from the 2017 FSICR equivalent ice classes. |
| Ice3 | **Ice Class IB** | Table 14 from the 2017 FSICR equivalent ice classes. |
| Arc4 | **Ice Class PC7** | Table 14 from the 2017 FSICR equivalent ice classes. |
| Arc5 | **Ice Class PC6** | Table 14 from the 2017 FSICR equivalent ice classes. |
| Arc6 | **Ice Class PC4** | Central Marine Research and Design Institute (CNIIMF) of Russian Federation (For Ice Certificate / Ice Passport) for LU6. |
| Arc7 | **Ice Class PC3** | Central Marine Research and Design Institute (CNIIMF) of Russian Federation (For Ice Certificate / Ice Passport) for LU6. |
| Arc8 | **Ice Class PC2** | Central Marine Research and Design Institute (CNIIMF) of Russian Federation (For Ice Certificate / Ice Passport) for LU6. |

In 2-2/Table 5 and 2-2/Table 6, the numbers in the second row represent the zones accross the NSR. The third row with H, M, L, C are the type of ice conditions. 2-2/Table 5 and 2-2/Table 6 below use the following notations:

| | | |
|---|---|---|
| H | = | heavy type of ice conditions |
| M | = | medium type of ice conditions |
| L | = | light type of ice conditions |
| C | = | clean water |
| + | = | navigation of the vessel is allowed |
| - | = | navigation of the vessel is prohibited |
| * | = | independent navigation is allowed from July 1st to November 30th |

## TABLE 5
## Ice Class IB and Below from July 1 to November 15

| Ice Class | Ice navigation method | Water area of the Northern Sea Route | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1, 2, 3, 4, 5, 6, 7 | | | | 8, 9, 10, 11 | | | | 12, 13, 14 | | | | 15, 16, 17 | | | | 18, 19, 20, 21 | | | | 22, 23, 24, 27 | | | | 25, 26, 28 | | | |
| | | H | M | L | C | H | M | L | C | H | M | L | C | H | M | L | C | H | M | L | C | H | M | L | C | H | M | L | C |
| None | Independent | - | - | - | + | - | - | - | + | - | - | - | + | - | - | - | + | - | - | - | + | - | - | - | + | - | - | - | + |
| | w/Icebreaker | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + |
| ID | Independent | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + |
| | w/Icebreaker | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + |
| IC | Independent | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + |
| | w/Icebreaker | - | + | + | + | - | + | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + |
| IB | Independent | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + |
| | w/Icebreaker | - | + | + | + | - | + | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | + | + | + |

Source: Russian Federation Resolution #1487

## TABLE 6
## Ice Class PC7 and Above

| Ice Class | Ice navigation method | Water area of the Northern Sea Route | | | | | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1, 2, 3, 4, 5, 6, 7 | | | | 8, 9, 10, 11 | | | | 12, 13, 14 | | | | 15, 16, 17 | | | | 18, 19, 20, 21 | | | | 22, 23, 24, 27 | | | | 25, 26, 28 | | | |
| | | H | M | L | C | H | M | L | C | H | M | L | C | H | M | L | C | H | M | L | C | H | M | L | C | H | M | L | C |
| PC7 | Independent | - | * | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | * | + | + |
| | w/Icebreaker | + | + | + | + | + | + | + | + | - | + | + | + | - | + | + | + | - | + | + | + | - | + | + | + | - | + | + | + |
| PC6 | Independent | - | * | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | - | + | + | - | * | + | + |
| | w/Icebreaker | + | + | + | + | + | + | + | + | - | + | + | + | - | + | + | + | - | + | + | + | - | + | + | + | - | + | + | + |
| PC4 | Independent | * | + | + | + | - | * | + | + | - | * | + | + | - | * | + | + | - | * | + | + | - | * | + | + | - | * | + | |
| | w/Icebreaker | + | + | + | + | + | + | + | + | - | + | + | + | - | + | + | + | - | + | + | + | - | + | + | + | - | + | + | + |
| PC3 | Independent | + | + | + | + | * | + | + | + | * | + | + | + | * | + | + | + | * | + | + | + | * | + | + | + | * | + | + | + |
| | w/Icebreaker | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| PC2 | Independent | + | + | + | + | + | + | + | + | * | + | + | + | * | + | + | + | * | + | + | + | * | + | + | + | + | + | + | + |
| | w/Icebreaker | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| PC1 | Independent | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| | w/Icebreaker | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |

Source: Russian Federation Resolution #1487

## 2.1 Use the Russian System to Determine an Ice Class

Like selecting an ice class using the Canadian Z/DS, the Russian system can be used to estimate the required ice class for operations in the Russian Arctic.

The operational profile for the vessel will detail the zones in which operation is required. The profile will also identify the times of the year the vessel will be required to operate in those areas.

For the purposes of ice class selection, a "+" or a "*" in 2-2/Table 5 or 2-2/Table 6 is desired. It is recommended that the intended operation drive the ice conditions and with or without icebreaker escort.

For example, most commercial operators opt for the lightest ice class, which implies light ice conditions. It is up to the owner/designer to decide the scenario used behind the ice class selection.

For example, using the above tables to select an ice class, it will be assumed that the vessel will operate independently in "L" or "C" conditions (lighter blue cells). For example a vessel starting on the west side of Russia (red star in 2-2/Figure 2) and transiting the NSR passing through zones 3, 2, 7, 9, 10, 14, 17, 20, 24, 26, and 28 (yellow line in 2-2/Figure 2). (Note these zones are only for example purposes and are not representative of any recommended route). It is assumed that this example ship with perform the NSR transits in the month of September only. Referencing 2-2/Table 5, an ABS **Ice Class ID** has "+" markers for all zones. Therefore, for this example operational profile, an ABS **Ice Class ID** will be the starting point for ice class selection.

However, if conditions worsen or are slightly worse than expected to an "M" or "H" level, the **Ice Class ID** vessel becomes a "-", even if icebreaker escort is requested. This may not be an acceptable risk, and therefore, re-examining the tables looking for a "+" for all the applicable zones for independent operations in "L" or "C" conditions, and "+" for "M" ice conditions with icebreaker escort is recommended. This enables the vessel to call for icebreaker support if the ice conditions become worse than expected. In this revised scenario, the suggested ice class is an **Ice Class PC7**.

# 3 Ice Data and IMO POLARIS

## 3.1 Description

With the publishing of the Polar Code, the IMO introduced a methodology for assessing the risks of operating in ice conditions. This methodology is described in MSC.1/Circ.1519 and is called the Polar Operational Limit Assessment Risk Indexing System (POLARIS). The system incorporates experience and best practices from the Canadian Arctic Ice Regime Shipping System (AIRSS) system and the Russian Ice Certificate concept, with additional input provided by other coastal administrations with experience regulating marine traffic in ice conditions. The basis of POLARIS is an evaluation of the risks posed to the ship by ice conditions using the World Meteorological Organization (WMO) nomenclature and the ship's assigned ice class (or lack thereof).

POLARIS can be used for voyage planning or on-board decision-making in real time on the bridge. As with any methodology, it is not intended to replace an experienced Master's judgement. POLARIS assesses ice conditions based on a Risk Index Outcome (RIO) which is determined by the following simple calculation:

$$RIO \quad = \quad (C_1 \times RV_1) + (C_2 \times RV_2) + (C_3 \times RV_3) + (C_4 \times RV_4)$$

where

$C_1$ through $C_4$ are the concentrations of ice types within the ice regime

$RV_1$ through $RV_4$ are the corresponding risk index values for the given ice class

The Risk Values (RV) are a function of ice class, season of operation, and operational state (i.e., independent operation or icebreaker escort). An example table of RVs is shown in 2-2/Table 7. Risk levels are higher with increasing ice thickness and decreasing ice class. POLARIS establishes RVs for the seven (7) IACS Polar Classes, four (4) Finnish-Swedish Ice Classes, and non-ice strengthened ships. For example, for a non-ice strengthened category C ship, only the bottom row of risk values needs to be considered.

A positive RIO indicates an acceptable level of risk where operations may proceed normally. A negative RIO indicates an increased risk level, potentially to unacceptable levels. Criteria is established, as shown in

2-2/Table 8. For negative RIOs, the system suggests that operations should both be stopped and reassessed or proceed cautiously with reduced speeds (IMO terminology is "subject to special consideration").

## TABLE 7
## POLARIS Risk Values (winter)

Increasing Ice Thickness (severity)

WINTER RISK VALUES (RVs)

| POLAR SHIP CATEGORY | ICE CLASS | ICE FREE -- | NEW ICE 0-10 cm | GREY ICE 10-15 cm | GREY WHITE ICE 15-30 cm | THIN FIRST YEAR 1ST STAGE 30-50 cm | THIN FIRST YEAR 2ND STAGE 50-70 cm | MEDIUM FIRST YEAR 1ST STAGE 70-95 cm | MEDIUM FIRST YEAR 2ND STAGE 95-120 cm | THICK FIRST YEAR 120-200 cm | SECOND YEAR 200-250 cm | LIGHT MULTI YEAR 250-300 cm | HEAVY MULTI YEAR 300+ cm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | PC1 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 1 | 1 |
| | PC2 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 1 | 1 | 0 |
| | PC3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 1 | 0 | -1 |
| | PC4 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 1 | 0 | -1 | -2 |
| | PC5 | 3 | 3 | 3 | 3 | 2 | 2 | 1 | 1 | 0 | -1 | -2 | -2 |
| B | PC6 | 3 | 2 | 2 | 2 | 2 | 1 | 1 | 0 | -1 | -2 | -3 | -3 |
| | PC7 | 3 | 2 | 2 | 2 | 1 | [illegible] | 0 | -1 | -2 | -3 | -3 | -3 |
| C | IAA | 3 | 2 | 2 | 2 | 2 | 1 | 0 | -1 | -2 | -3 | -4 | -4 |
| | IA | 3 | 2 | 2 | 2 | 1 | 0 | -1 | -2 | -3 | -4 | -5 | -5 |
| | IB | 3 | 2 | 2 | 1 | 0 | -1 | -2 | -3 | -4 | -5 | -6 | -6 |
| | IC | 3 | 2 | 1 | 0 | -1 | -2 | -3 | -4 | -5 | -6 | -7 | -8 |
| | NO ICE CLASS | 3 | 1 | 0 | -1 | -2 | -3 | -4 | -5 | -6 | -7 | -8 | -8 |

Decreasing Ice Class

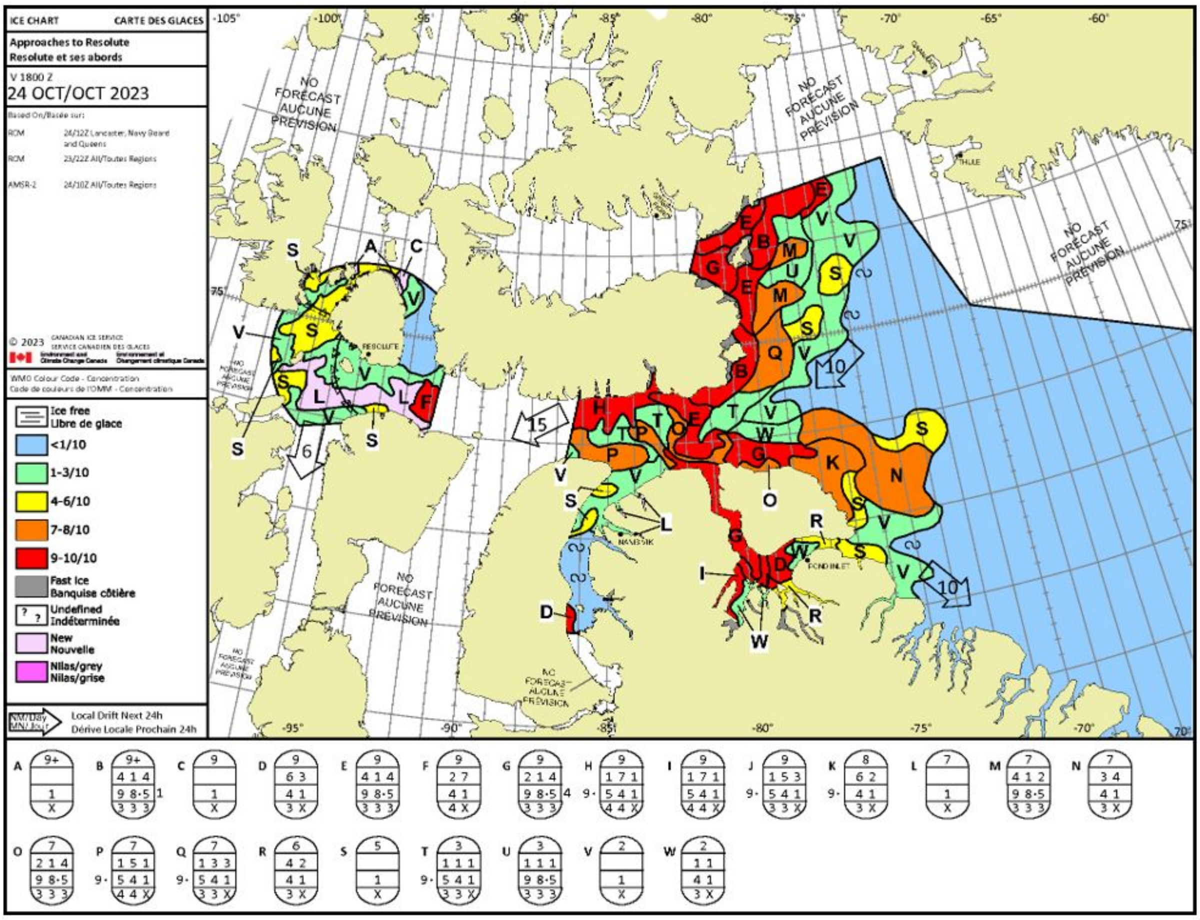
Increased Risk

## TABLE 8
## POLARIS Risk Index Outcome (RIO) Criteria

| $RIO_{SHIP}$ | Ice classes PC1-PC7 | Ice classes below PC 7 and ships not assigned an ice class | Color Code |
|---|---|---|---|
| 20 ≤ RIO | Normal operation | Normal operation | |
| 10 ≤ RIO < 20 | | | |
| 0 ≤ RIO < 10 | | | |
| -10 ≤ RIO < 0 | Elevated operational risk | Operation subject to special consideration | |
| -20 ≤ RIO < -10 | Operation subject to special consideration | | |
| -30 ≤ RIO < -20 | | | |

Ice charts are available for many areas that frequently have ice coverage. An example ice chart is shown below in 2-2/Figure 3. Each ice regime shown on the ice chart is described using the WMO egg code, which are arranged in rows at the bottom of this example chart.

## FIGURE 3
## Example Canadian Ice Services Chart




Source: Canadian Ice Service

### 3.2 Reading an Egg Code

Ice charts consolidate all available information on ice cover using the egg code, which in most sea areas will be developed using WMO principles and terminology. An example of an egg code is given in 2-2/ Figure 4. Each egg code defines an ice regime.

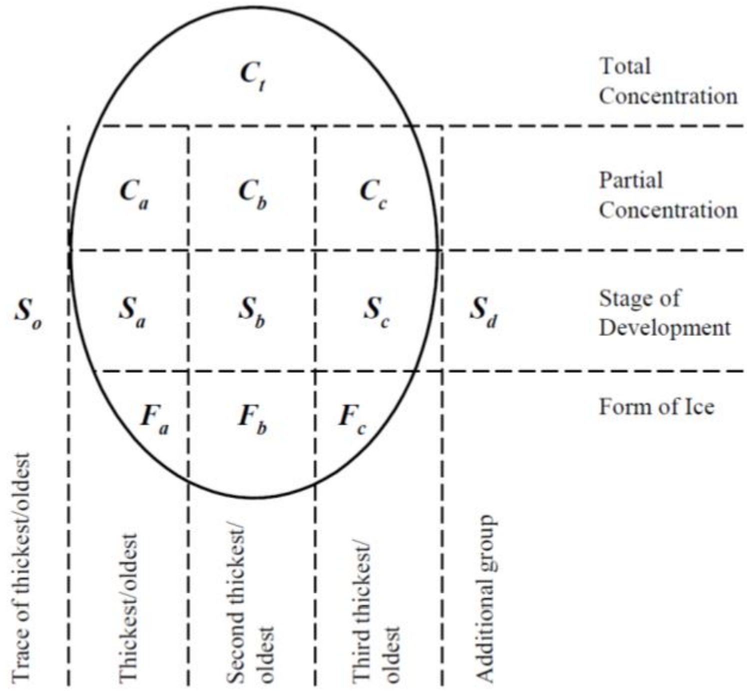
The top row represents the total concentration ($C_t$) of ice in tenths. For example, if the water is half covered in ice and half open water, the $C_t$ value would be 5. A value of 5 means 5/10 or 50%.

The second row is the partial concentrations. The most severe ice (lower row on 2-2/Table 9) in the ice regime is given in the leftmost column, followed by the second most severe ice type in the middle and the third most severe ice type in the right column. Some ice services, such as the Canadian Ice Service, may have additional information with more than three partial concentrations. These are given outside of the egg. Like the total concentration, the partial concentrations are given in tenths. When only one ice type is present, the partial concentration is not used, and the total concentration represents the left most column.

The third row in the egg code represents the stage of development of the ice. The values for stage of development are given in TABLE 9. Sometimes a significant ice type is present but in concentrations less than 1/10 concentration. If this is the case, the stage of development of such ice is indicated outside the egg code. The three values inside the egg code are the stages of development for the ice types referred to by partial concentrations on the second row (i.e., $C_a$ and $S_a$ define the partial concentration and stage of development of one type of ice in the egg code). As the leftmost ice type is always the more severe ice type, if a dot is used in the egg code in the middle or right column, the dot is also applied to the stage of development in the left columns. For example, if row 3 was ($S_a$ $S_b$ $S_c$) = (7 4. 9), the 7 is actually stage of development "7." which refers to “Old Ice”.

The fourth row is for the form of the ice. This is the part of the egg code that gives information on the size of the ice floes in the regime. The three values given correspond to the partial concentration and stage of development above. Coding for the forms of ice is given in 2-2/Table 10.

## FIGURE 4
## WMO Egg Code




## TABLE 9
## Sea Ice Stages of Development

| *Description* | *Thickness* | *WMO Code* |
|---|---|---|
| New ice | < 10 cm | 1 |
| Nilas; ice rind | 0-10 cm | 2 |
| Young ice | 10-30 cm | 3 |
| Grey ice | 10-15 cm | 4 |
| Grey-white ice | 15-30 cm | 5 |
| First year ice | 30-200 cm | 6 |
| Thin first year ice | 30-70 cm | 7 |
| Thin first year ice first stage | 30-50 cm | 8 |
| Thin first year ice second stage | 50-70 cm | 9 |
| Medium first year ice | 70-120 cm | 1. |

| Description | Thickness | WMO Code |
|---|---|---|
| Thick first year ice | 120-200 cm | 4. |
| Old ice | | 7. |
| Second year ice | | 8. |
| Multi year ice | | 9. |
| Ice of land origin | | . |
| Undetermined or unknown | | x |

## TABLE 10
## Forms of Ice

| Description | Width | Code |
|---|---|---|
| Pancake ice | - | 0 |
| Small ice cake, brash ice, agglomerated brash | < 2 m | 1 |
| Ice cake | 2-20 m | 2 |
| Small floe | 20-100 m | 3 |
| Medium floe | 100-500 m | 4 |
| Big floe | 500-2000 m | 5 |
| Vast floe | 2-10 km | 6 |
| Giant floe | > 10 km | 7 |
| Fast ice | - | 8 |
| Icebergs, growlers, floebergs | - | 9 |
| Undetermined, unknown or no form | - | X |

### 3.3 Using POLARIS to Determine an Ice Class

This method is more universal and can be applied anywhere ice data is available.

With the vessel's operational profile established, the location and time of expected operation in an area is known. Ice charts for the area of operation can be obtained from years past that closely align with the time of the intended operation. ABS recommends using at least the last five years of ice data for this assessment. The ice charts are then analyzed/processed using POLARIS for the expected route.

The ice types do not perfectly align between those used in the egg codes (WMO) and the tables in the IMO circular. It is recommended to link the ice types based on thickness as is shown in 2-2/Table 11.

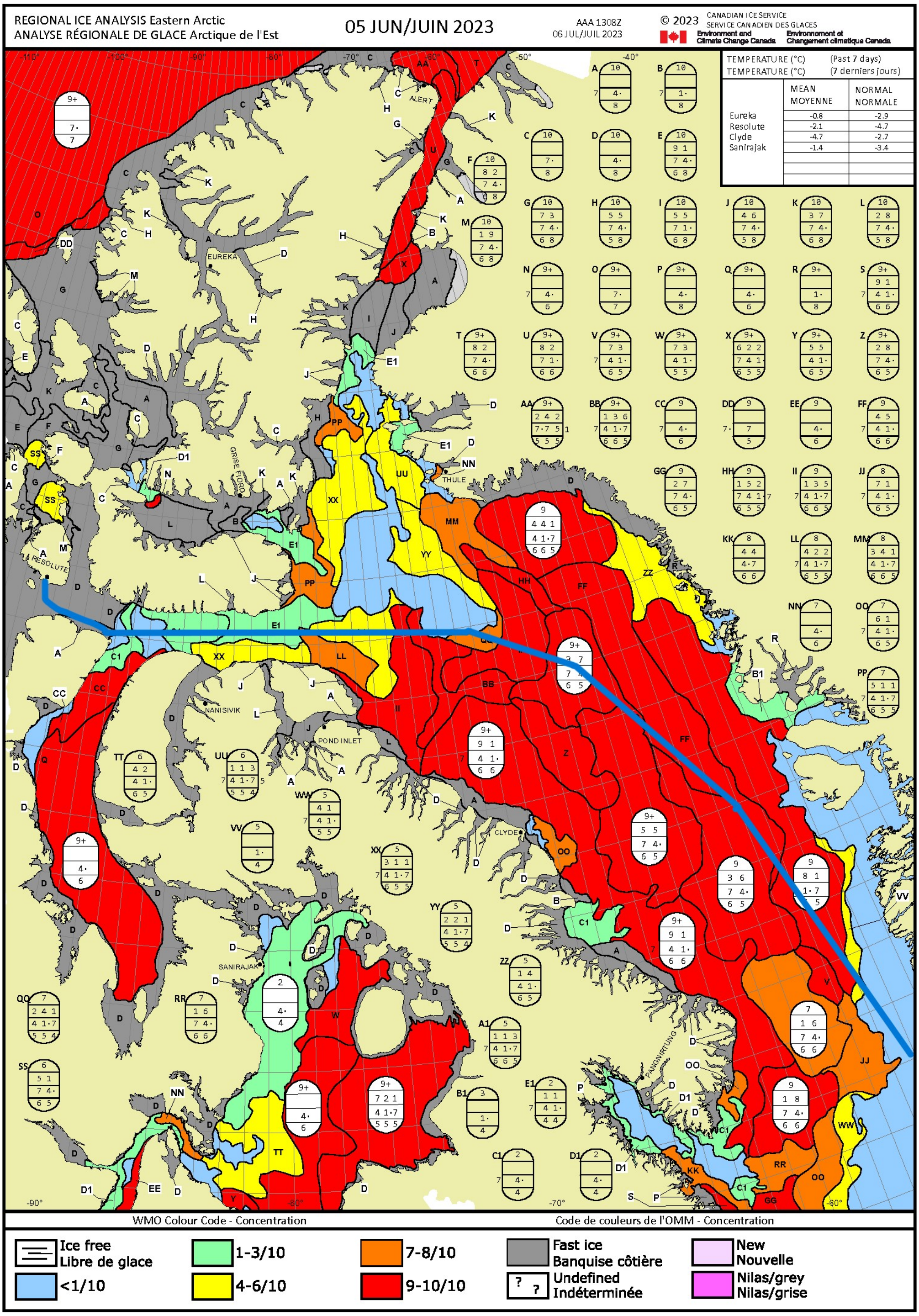
## TABLE 11
## WMO Ice Types to POLARIS Ice Types

| Stage of Development | Thickness | Egg Code | Suggested POLARIS Ice Type |
|---|---|---|---|
| Ice Free | | - | Ice free |
| No stage of development | | - | Ice free |
| New ice | | 1 | New ice |
| Nilas, Ice rind | < 10 cm | 2 | New ice |

| *Stage of Development* | *Thickness* | *Egg Code* | *Suggested POLARIS Ice Type* |
|---|---|---|---|
| Young ice | 10-30 cm | 3 | Grey white ice |
| Grey ice | 10-15 cm | 4 | Grey ice |
| Grey white ice | 15-30 cm | 5 | Grey white ice |
| First year ice | 30-200 cm | 6 | Thick first year ice |
| Thin first year ice | 30-70 cm | 7 | Thin first year ice (2nd stage) |
| Thin first year ice stage 1 | 30-50 cm | 8 | Thin first year ice (1st stage) |
| Thin first year ice stage 2 | 50-70 cm | 9 | Thin first year ice (2nd stage) |
| For later use | | - | Medium first year ice (<1 m) |
| Medium first year ice | 70-120 cm | 1. | Medium first year ice |
| For later use | | - | Thick first year ice |
| Thick first year ice | >120 cm | 4. | Thick first year ice |
| For later use | | - | Light multi year ice |
| Old ice | | 7. | Light multi year ice |
| Second year ice | | 8. | Second year ice |
| Multi year ice | | 9. | Heavy multi year ice |
| Glacier ice | | . | Heavy multi year ice |

For example, assume a vessel needs to call at Resolute, Canada, in mid-June. In this example, several years of ice charts for the first week of June are obtained. An example route is plotted in blue and shown in 2-2/ Figure 5.

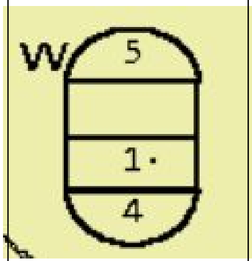
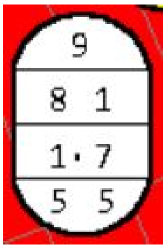
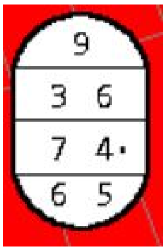
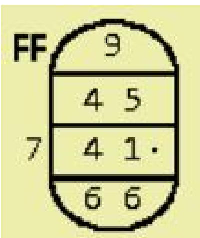
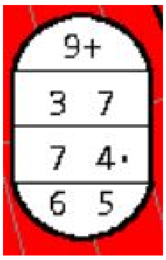
## FIGURE 5
## Ice Chart with Example Route

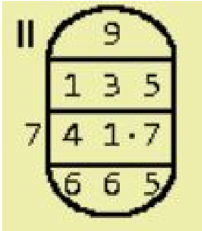
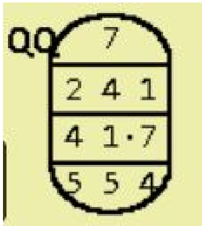
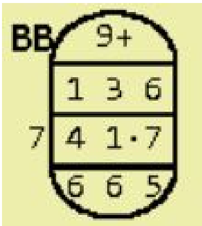
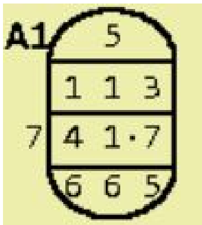
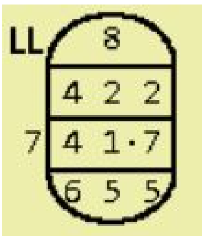
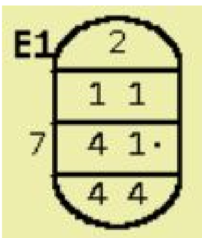


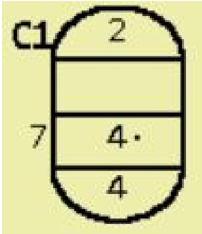
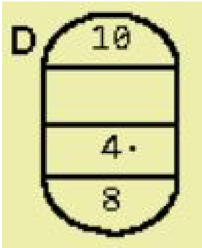

Source: Canadian Ice Service

The example route (blue line) for this chart crosses several ice regimes. Assuming winter risk values and no icebreaker escort, the egg codes are converted to POLARIS RIOs in 2-2/Table 12 for the lowest ice class that has a positive (or zero) RIO.

## TABLE 12
## POLARIS RIO Example Calculation

| *Egg Code* | *Lowest Ice Class with Positive RIO* | *RIO Calculation* |
|---|---|---|
|  | **Ice Class IB** | (5 x -3) + (0 x 0) + (0 x 0) + (5 x 3) = 0 |
|  | **Ice Class PC6** | (8 x 0) + (1 x 1) + (0 x 0) + (1 x 3) = 4 |
|  | **Ice Class PC4** | (3 x -1) + (6 x 1) + (0 x 0) + (1 x 3) = 6 |
|  | **Ice Class PC5** | (4 x 0) + (5 x 1) + (0 x 0) + (1 x 3) = 8 |
|  | **Ice Class PC4** | (3 x -1) + (7 x 1) + (0 x 0) + (0 x 3) = 4 |

| *Egg Code* | *Lowest Ice Class with Positive RIO* | *RIO Calculation* |
|---|---|---|
|  | **Ice Class PC7** | (1 x -2) + (3 x -1) + (5 x 1) + (1 x 3) = 3 |
|  | **Ice Class PC7** | (2 x -2) + (4 x -1) + (1 x 1) + (3 x 3) = 2 |
|  | **Ice Class PC7** | (1 x -2) + (3 x -1) + (6 x 1) + (0 x 3) = 1 |
|  | **Ice Class IC** | (1 x -5) + (1 x -4) + (3 x -2) + (5 x 3) = 0 |
|  | **Ice Class PC6** | (4 x -1) + (2 x 0) + (2 x 1) + (2 x 3) = 4 |
|  | No Ice Class | (1 x -6) + (1 x -5) + (0 x 0) + (8 x 3) = 13 |

| *Egg Code* | *Lowest Ice Class with Positive RIO* | *RIO Calculation* |
|---|---|---|
|  | No Ice Class | (2 x -6) + (0 x 0) + (0 x 0) + (8 x 3) = 12 |
|  | **Ice Class PC5** | (10 x 0) + (0 x 0) + (0 x 0) + (0 x 0) = 0 |

This analysis should be repeated for at least five years of ice charts (if available). The simplest solution for the ice class selection is to select the lowest ice class that has positive RIOs for all ice regimes, for all the data considered. This will result in a conservative approach which may be appropriate for selecting an icebreaker's ice class but may be overly conservative for a commercial cargo ship. For commercial vessels, the likelihood of the ice regime changing and becoming more difficult to traverse and thus requiring a higher ice class or icebreaker escort should be considered.

CHAPTER 3
# Design and Analysis Guidance

## CONTENTS

CHAPTER 3
**Design and Analysis Guidance**

SECTION 1
**Structure**

# 1 Hull Areas and Materials

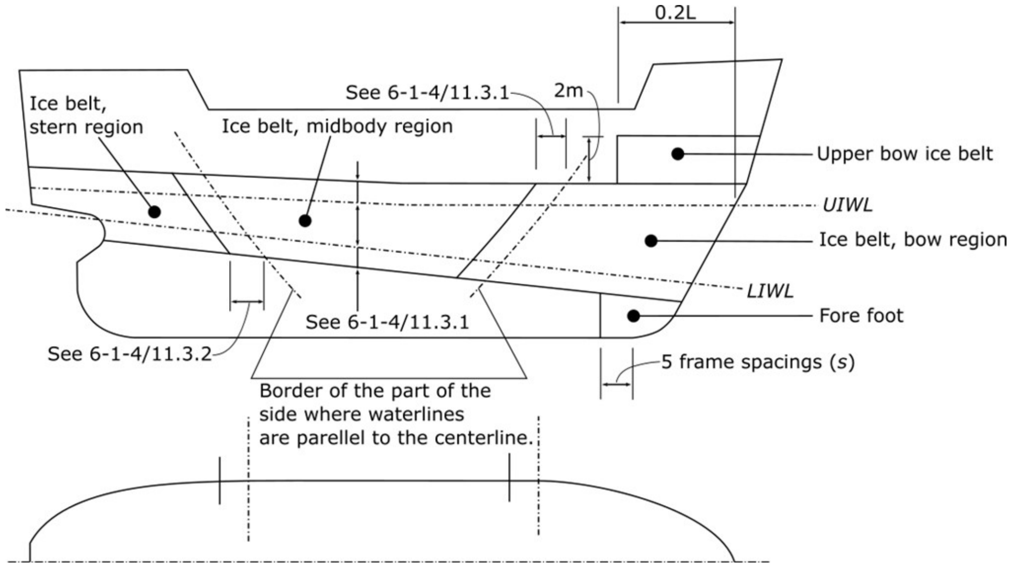
## 1.1 Hull Areas

The structure of an ice classed vessel or platform has strengthening in addition to that required for open water to resist the increased loads due to collision with ice. Depending on the Ice Class (and associated rules) the hull is broken up into different hull areas, with the scantlings of the structure differing depending on the hull area.

The requirements of the most widely used ice class rule set, the Finnish-Swedish Ice Class Rules (FSICR), are located within Seciton 6-1-4 of the *Marine Vessel Rules* and referred to as the "ABS First Year Ice Classes" (prior to 2024 they were titled the "Baltic Rules"). This Rule set divides the hull longitudinally into three hull areas: Bow, Midbody, and Stern. Vertically, there is a single hull area, referred to as the icebelt. The vertical extent of the icebelt is dependent on the deepest and shallowest drafts (referred to as the Upper Ice Waterline [UIWL] and Lower Ice Waterline [LIWL] respectively), the structural member (plating or framing), ice class, and hull area. For the bow hull area, there is also a fore foot and upper bow area which are both considered as part of the icebelt, see 3-1/Figure 1. The longitudinal extent of the hull areas is defined by the hullform. The structure above and below the icebelt does not need to be strengthened to resist ice loads but should be transitioned appropriately.

For an ABS First Year Ice Class vessel, the Bow hull area extends longitudinally from where the UIWL touches the stem to 0.04*L* (where *L* is the length on the upper ice waterline) aft of where the waterline becomes parallel with the vessel centerline. The 0.04*L* overlap with the parallel midbody need not exceed 6 m (19.7 ft) for an **Ice Class IAA** or **Ice Class IA**, and 5 m (16.4 ft) for **Ice Class IB** or **Ice Class IC**. The Midbody hull area extends from the bow boundary to 0.04*L* aft of the point where the waterline is no longer parallel with the vessel centerline towards the stern. The remaining hull aft of the midbody area is the Stern hull area. 3-1/Figure 1 outlines the the hull area defintions for an ABS First Year Ice Class vessel.

## FIGURE 1
## First Year Ice Class Hull Areas

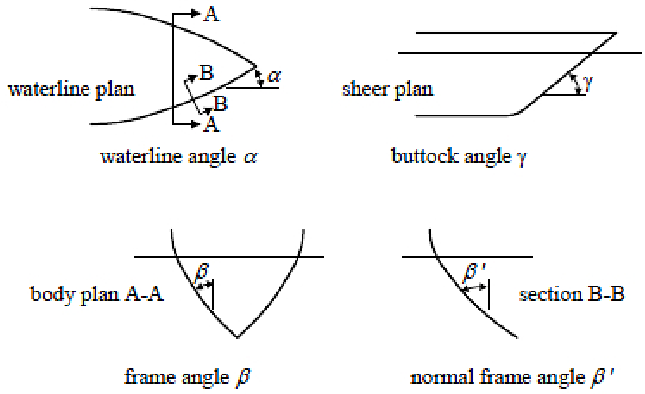



The Polar Class (PC) Rules, published in Section 6-1-2 and 6-1-3 of the *Marine Vessel Rules*, divide the hull longitudinally into four hull areas for vessels that will operate ahead only in ice. These hull areas are the Bow, Bow Intermediate, Midbody, and Stern. For a vessel that will operate both ahead and astern, there are five hull areas longitudinally: Bow, Bow Intermediate, Midbody, Stern Intermediate, and Stern. The Stern Intermediate hull area is added since a vessel that will operate astern is more likely to load the stern quarters near the midbody at higher speeds. Government icebreakers often operate astern, such as backing along a beset vessel to reduce ice pressure or during milling operations. Note operating astern is defined as breaking ice continuously when going astern. It does not include operations like backing back down a channel to allow the ship to gain enough forward momentum to continue forward progress.

The Polar Class Rules divide each of the longitudinal hull areas into three vertical hull areas: icebelt, lower, and bottom. This is true for all hull areas except the bow, which is considered only icebelt. If the vessel will operate ahead and astern, the stern is also considered only icebelt.

The Polar Class Rules utilize waterline angles ($\alpha$) to determine the boundaries for the various hull areas longitudinally. The Bow hull area comprises all structure forward of the location where the waterline angle ($\alpha$) is 10 degrees (on the UIWL) or where the line of the stem reaches the baseline, whichever is further aft. The Bow Intermediate hull area is from the Bow boundary to $0.04L_{ui}$ aft of the location where the waterline angle ($\alpha$) becomes 0 (i.e., where the waterline is parallel with the centerline). The aft boundary of the midbody is either 70% of the distance from the aft perpendicular ($b$) to the maximum half breadth on the UIWL (measured along the centerline) or $0.15L_{ui}$, whichever is greater. The Stern hull area is the remainder of the hull aft of the after midbody boundary. For the hull angle definitions, see 3-1/Figure 2.

## FIGURE 2
## Definition of Hull Angles

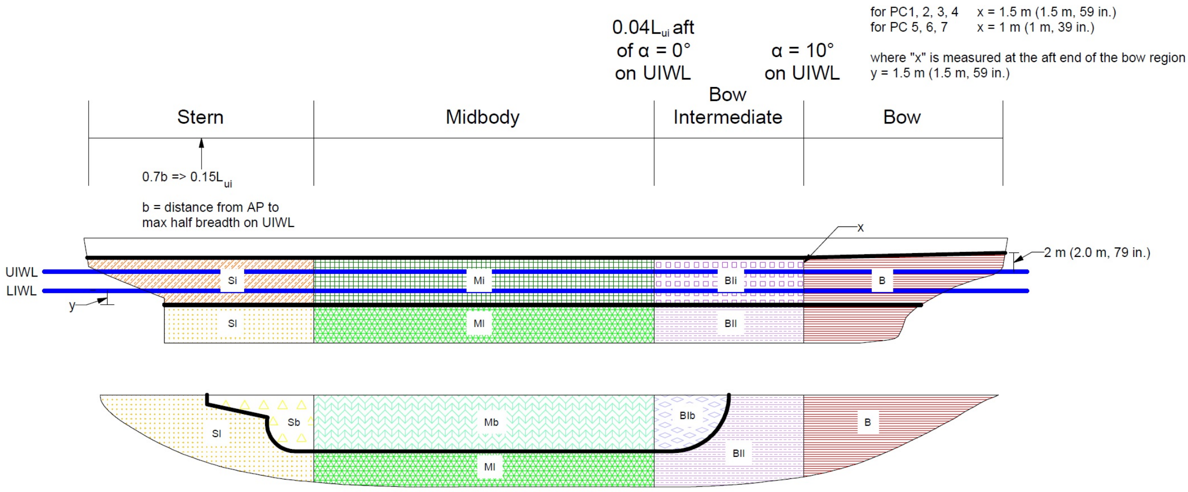



For a vessel that operates ahead and astern, the hull areas change slightly. The vessels' hull areas are essentially mirrored from the midship plane. This causes the Stern Intermediate to have the same definition as the Bow Intermediate, and similarly, the Stern to have the same definition as the Bow. For vessels that operate ahead and astern in ice the hullform when viewed on the waterline tends to have an odd concave shape. This shape is usually due to the need to have "ice knives" in line with the propulsor(s) which cause the ice to break in flexural failure. Developing an astern icebreaking vessel is challenging, contact ABS subject matter experts at Polar@eagle.org for additonal guidance.

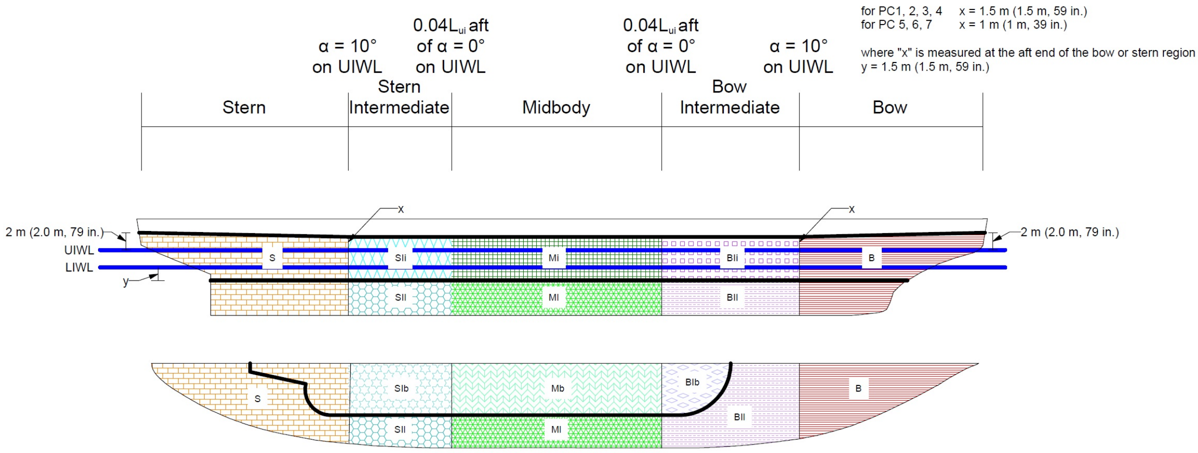
The Polar Class Rules have an optional notation, the **Ice Breaker** notation, that extends the Stern hull area forward to $0.04L_{ui}$ forward of the point where the waterline angle ($\alpha$) becomes 0 (i.e., where the waterline is parallel with the centerline). Due to the stern requiring thicker plating and larger framing, the **Ice Breaker** notation provides the operator with more flexibility, which is required for the more aggressive operations that icebreakers tend to perform.

The vertical boundaries in the Polar Class Rules are easily defined. The icebelt extends 1 m (3.3 ft) above the UIWL for **Ice Class PC7**, **Ice Class PC6**, and **Ice Class PC5**, and 1.5m for **Ice Class PC4** and above. For all Polar Classes the icebelt extends 1.5 m (4.9 ft) below the LIWL. The lower icebelt extends from the bottom of the icebelt down to where the hull becomes the flat of bottom. From the turn of the bilge (which is defined as the point where the frame angle ($\beta$) becomes greater than 7 degrees) to the centerline is the Bottom hull area. Note that for the Bow hull area (and the Stern hull area for vessels that will operate ahead and astern), the vertical extent of the icebelt at the stem increases to 2 m (6.6 ft).

## FIGURE 3
## Polar Class Hull Areas - Ahead Only

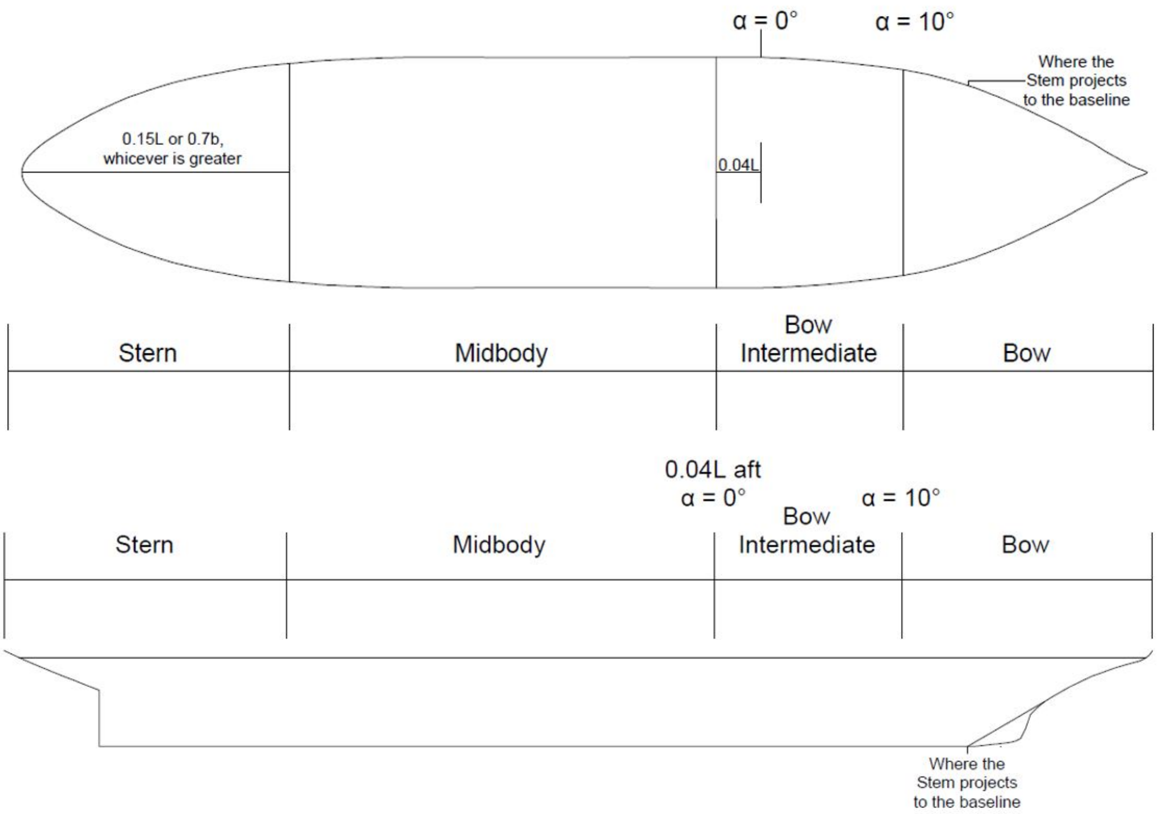



## FIGURE 4
## Polar Class Hull Areas - Ahead and Astern



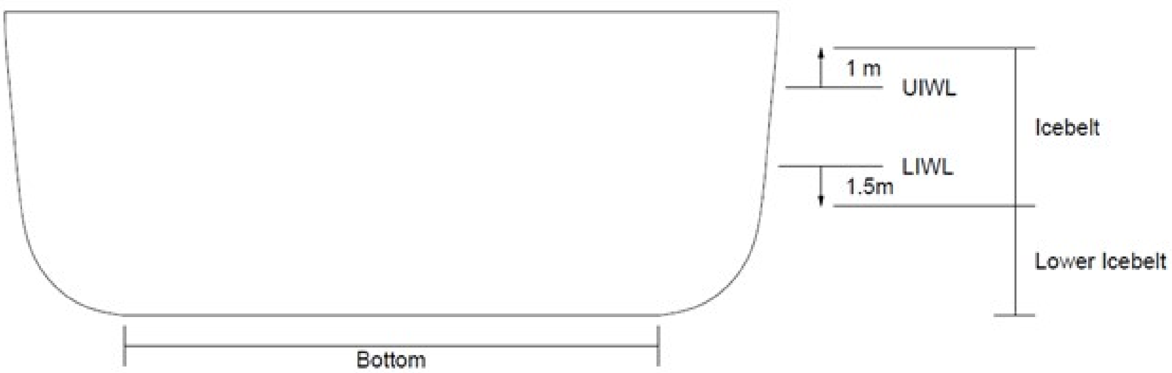

An example on how to divide a hull into the various Polar Class Rules hull areas is provided below. The example vessel is assumed to be **Ice Class PC7**, with an UIWL length of 95 m (311 ft), breadth on the UIWL of 19.5 m (64 ft), an UIWL of 7.4 m (24.3 ft) above baseline (ABL), and LIWL of 6.2 m (20.3 ft) ABL. First, the Bow area is determined, which is either the location where the waterline angle ($\alpha$) becomes 10 degrees or where the stem line reaches (or projects) to the baseline, whichever is further aft. In this example the 10-degree waterline angle is further aft. The Bow Intermediate area is located from the aft end of the Bow area to $0.04L_{ui}$ aft of where the waterline angle becomes 0 (i.e., when the parallel midbody begins). Finally, the Stern/Midbody boundary is located either $0.15L_{ui}$ or $0.7b$, whichever is greater, forward from the aftmost point on the UIWL. In this example $0.15L_{ui}$ was the greater distance.

**FIGURE 5**
**Example Polar Class Longitudinal Hull Area Determination**




The vertical divisions are easier to determine than the longitudinal hull areas. For this **Ice Class PC7** example vessel, the icebelt is 1 m (3.3 ft) above the UIWL down to 1.5 m (4.9 ft) below the LIWL. The lower icebelt hull area is from the bottom of the icebelt down to the flat of bottom. As mentioned above the bottom hull area is from the centerline out to the point where the angle of the plating to the baseline reaches 7 degrees, but for practical purposes, the bottom hull area can be considered just the flat of bottom. Note that for all Polar Classes, the Bow icebelt hull area goes up to 2 m (6.6 ft) above the UIWL at the stem. If the vessel will operate ahead and astern, the icebelt in the stern would also increase up to 2 m (6.6 ft) above the UIWL at the stern frame.

**FIGURE 6**
**Example Polar Class Vertical Hull Area Determination**



The optional **Icebreaker*** notation can modify the extent of the hull areas (and the associated hull area factors). These modifications are determined based on the operational profile determined by the designer or owner/operator. For further information on the **Icebreaker*** notation see Section 6-1-5 of the *Marine Vessel Rules*.

## 1.2 Materials

Ice class vessels often operate in areas where cold air temperatures occur. The materials used to construct the hull, machinery, and equipment must be selected to resist the air temperatures for the area of operation and time of year. For example, if a vessel will operate in the Arctic during the summer months when the air temperature is above 0°C, it does not require low air temperature steel. ABS has processed air temperature data and offers isothermal plots in Appendix 10 of the ABS *Guide for Vessels Operating in Low Temperature Environments (LTE Guide)*. These figures can be referenced for estimation of appropriate design temperatures.

Parts 3 and 5C of the *Marine Vessel Rules* contain material requirements for all steel vessels, regardless of ice class. The material requirements depend on the thickness, type of structure, and intended design temperature. Some Ice Class Rule sets, such as the Polar Class Rules, also contain material requirements which depend on the location of the structure under consideration, the thickness of the plating or framing, and the Polar Class. Where the requirements in Part 3, Part 5C (as applicable), and Part 6 differ, the more onerous requirement is to be applied.

For example, the Bow icebelt plating for an **Ice Class PC7** at the waterline would be classified as Material Class II in the Polar Class Rules as per 6-1-2/Table 11 of the *Marine Vessel Rules*. Using 6-1-2/Table 12 of the *Marine Vessel Rules* and an assumed thickness of 22 mm (0.87 in.), the required material grade is either Grade B, Grade AH, or Grade AQ depending on if the designer uses regular, high strength, or extra high strength steel respectively. Note that temperature is not considered for the material requirements in the Polar Class Rules.

**TABLE 11**
**Material Classes for Structural Members of Polar Class Vessels** *(2021)*

| *Structural Members* | *Material Class* |
|---|---|
| Shell plating within the bow and bow intermediate icebelt hull areas (B, $BI_i$) | II |
| All weather and sea exposed SECONDARY and PRIMARY, as defined in 3-1-2/Table 2, structural members outside $0.4L_{UI}$ amidships | I |
| Plating materials for stem and stern frames, rudder horn, rudder, propeller nozzle, shaft brackets, ice skeg, ice knife and other appendages subject to ice impact loads | II |
| All inboard framing members attached to the weather and sea-exposed plating including any contiguous inboard member within 600 mm (600 mm, 23.6 in.) of the plating | I |
| Weather-exposed plating and attached framing in cargo holds of vessels which by nature of their trade have their cargo hold hatches open during cold weather operations | I |
| All weather and sea exposed SPECIAL, as defined in 3-1-2/Table 2, structural members within $0.2L_{UI}$ from FP | II |

**TABLE 12**
**Steel Grades for Weather Exposed Plating[1, 2]** *(2021)*

| *Thickness, t mm (in.)* | *Material Class I* | | | | | | *Material Class II* | | | | | | *Material Class III* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | PC1-5 | | | PC6 &7 | | | PC1-5 | | | PC6 &7 | | | PC1-3 | | | PC4 & 5 | | | PC6 &7 | | |
| | *MS* | *HT* | *XHT* | *MS* | *HT* | *XHT* | *MS* | *HT* | *XHT* | *MS* | *HT* | *XHT* | *MS* | *HT* | *XHT* | *MS* | *HT* | *XHT* | *MS* | *HT* | *XHT* |
| $t \le 10$<br>$t \le 0.394$ | B | AH | AQ | B | AH | AQ | B | AH | AQ | B | AH | AQ | E | EH | EQ | E | EH | EQ | B | AH | AQ |
| $10 < t \le 15$<br>$0.394 < t \le 0.591$ | B | AH | AQ | B | AH | AQ | D | DH | DQ | B | AH | AQ | E | EH | EQ | E | EH | EQ | D | DH | DQ |
| $15 < t \le 20$<br>$0.591 < t \le 0.787$ | D | DH | DQ | B | AH | AQ | D | DH | DQ | B | AH | AQ | E | EH | EQ | E | EH | EQ | D | DH | DQ |
| $20 < t \le 25$<br>$0.787 < t \le 0.984$ | D | DH | DQ | B | AH | AQ | D | DH | DQ | B | AH | AQ | E | EH | EQ | E | EH | EQ | D | DH | DQ |
| $25 < t \le 30$<br>$0.984 < t \le 1.18$ | D | DH | DQ | B | AH | AQ | E | EH | EQ | D | DH | DQ | E | EH | EQ | E | EH | EQ | E | EH | EQ |
| $30 < t \le 35$<br>$1.18 < t \le 1.38$ | D | DH | DQ | B | AH | AQ | E | EH | EQ | D | DH | DQ | E | EH | EQ | E | EH | EQ | E | EH | EQ |
| $35 < t \le 40$<br>$1.38 < t \le 1.58$ | D | DH | DQ | D | DH | DQ | E | EH | EQ | D | DH | DQ | ø | FH | FQ | E | EH | EQ | E | EH | EQ |
| $40 < t \le 45$<br>$1.58 < t \le 1.77$ | E | EH | EQ | D | DH | EQ | E | EH | EQ | D | DH | DQ | ø | FH | FQ | E | EH | EQ | E | EH | EQ |
| $45 < t \le 50$<br>$1.77 < t \le 1.97$ | E | EH | EQ | D | DH | EQ | E | EH | EQ | D | DH | DQ | ø | FH | FQ | ø | FH | FQ | E | EH | EQ |
| *ø Not Applicable* | | | | | | | | | | | | | | | | | | | | | |

Using Part 3 with the assumptions made above and a design temperature of -20°C (-4°F), the plating would be considered "Side Plating Above the BWL (Ballast Water Line)" outside of the midship 0.4*L*. Therefore, the plating would be Material Class I as per 3-1-2/Table 3 of the *Marine Vessel Rules*, and require a minimum of Grade D or Grade DH steel for regular or high strength steel respectively as per 3-1-2/Table 4 of the *Marine Vessel Rules*. Since the Part 3 material requirements are more onerous than the Part 6 requirements, the vessel would require Grade D or DH steel.

## TABLE 3
## Application of Material Classes and Grades – Structures Exposed at Low Temperatures *(1 July 2019)*

| *Structural Member Category* | *Material Class* | |
|---|---|---|
| | *Within 0.4L Amidships* | *Outside 0.4L Amidships* |
| Secondary<br>Deck plating exposed to weather, in general<br>Side plating above BWL<br>Transverse bulkheads above BWL(5)<br>Cargo tank boundary plating exposed to cold cargo(6) | I | I |
| Primary<br>Strength deck plating (1)<br>Continuous longitudinal members above strength deck, excluding longitudinal hatch coamings<br>Longitudinal bulkhead above BWL(5)<br>Top wing tank bulkhead above BWL(5) | II | I |
| Special<br>Sheer strake at strength deck (2)<br>Stringer plate in strength deck (2)<br>Deck strake at longitudinal bulkhead (3)<br>Continuous longitudinal hatch coamings (4) | III | II |

## TABLE 4
## Material Grade Requirements for Classes I, II and III at Low Temperatures Class I *(1 July 2019)*

| *Thickness, in mm (in.)* | *–11 to –15°C (12 to 5°F)* | *–16 to –25°C (4 to –13°F)* | *–26 to –35°C (–14 to –31°F)* | *–36 to –45°C (–32 to –49°F)* | *–46 to –55°C (–50 to –68°F)* |
|---|---|---|---|---|---|
| $t \le 10$ ($t \le 0.39$) | A, AH | A, AH | B, AH | D, DH | D, DH |
| $10 < t \le 15$ ($0.39 < t \le 0.60$) | A, AH | B, AH | D, DH | D, DH | D, DH |
| $15 < t \le 20$ ($0.60 < t \le 0.79$) | A, AH | B, AH | D, DH | D, DH | E, EH |
| $20 < t \le 25$ ($0.79 < t \le 0.98$) | B, AH | D, DH | D, DH | D, DH | E, EH |
| $25 < t \le 30$ ($0.98 < t \le 1.18$) | B, AH | D, DH | D, DH | E, EH | E, EH |
| $30 < t \le 35$ ($1.18 < t \le 1.38$) | D, DH | D, DH | D, DH | E, EH | E, EH |
| $35 < t \le 45$ ($1.38 < t \le 1.80$) | D, DH | D, DH | E, EH | E, EH | -, FH |
| $45 < t \le 50$ ($1.80 < t \le 1.97$) | D, DH | E, EH | E, EH | -, FH | -, FH |

The *LTE Guide* contains many different temperature plots for the various ice-covered waters of the world. These plots can be used for selecting an appropriate design temperature. Alternatively, the ABS Harsh Environment Technology Center (HETC) can provide a range of environmental data and services for any ice-covered region of the world, for more information please contact Polar@eagle.org.

## 2 Stringers and Web Frames

Stringers and web frames for ice class ships tend to be quite large, especially at higher ice classes. It is often not practical to meet the buckling requirements for stringers and web frames, in which case, stiffeners and other structural details can be added to the stringer or web frame to mitigate the chance of failure. The Finnish-Swedish Ice Class Rules have design equations for both stringers and web frames. The Polar Class Rules do not.

Instead of design equations, the Polar Class Rules allow the user to perform either linear or nonlinear structural analysis. The web frame or stringer must meet specific acceptance criteria, which differ depending on the type of analysis. Although linear analysis is easier to perform, it often leads to overly stiff and heavier web frames and stringers. Using nonlinear analysis will result in a structure that has significant reserve past the yield point while allowing the designer to optimize the structure, thus reducing the weight.

### 2.1 Worked Example

The ABS structural requirements for Polar Class vessels in Part 6, Chapter 1 of the *Marine Vessel Rules* require the use of Finite Element Analysis (FEA) to determine compliance with the appropriate acceptance criteria (linear or nonlinear) for load-carrying stringers, web frames, and other deep members, such as floors. FEA can be difficult to perform for inexperienced users, especially Nonlinear Finite Element Analysis (NLFEA), which requires a much more in-depth knowledge of the finite element method. ABS has developed the ABS *Guidance Notes on Nonlinear Finite Element Analysis of Marine and Offshore Structures* which provide background information on the finite element method along with many worked examples for a variety of different loading scenarios and structures.

The example provided below is for an **Ice Class PC7** icebreaker. The grillage has been assumed to be in the bow region but for modeling simplicity, the curvature of the shell plating has been removed and replaced with a flat plate. In general, FEA models should contain as many design details as possible to closely match the actual structure. Note that including the curvature will increase the complexity of the model.

The principal particulars and grillage scantlings for the example vessel are provided in 3-1/Table 1 and 3-1/Table 2, respectively. Snapshots of the structural 3-D and Finite Element (FE) model are provided in 3-1/Figure 7 and 3-1/Figure 8. All material has been assumed to be ABS AH36, with a bilinear material model. A bilinear model is generally sufficient for a simple nonlinear structural grillage analysis. See the ABS *Guidance Notes on Non-linear Finite Element Analysis of Marine and Offshore Structures* for other types of material models that can be used for NLFEA. The assumed material properties are outlined in 3-1/Table 3.

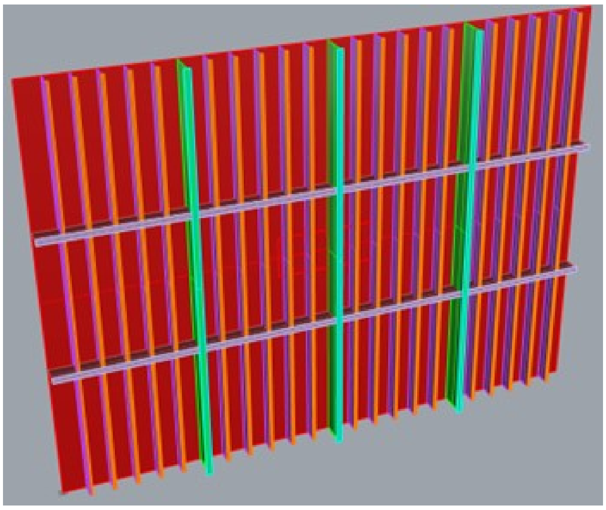
**TABLE 1**
**Example Ship Principal Particulars**

| | |
|---|---|
| Polar Class | **Ice Class PC7** |
| Displacement (metric tonnes) | 3259 |
| $L_{ui}$ (m) | 63.4 |
| $B_{ui}$ (m) | 16 |

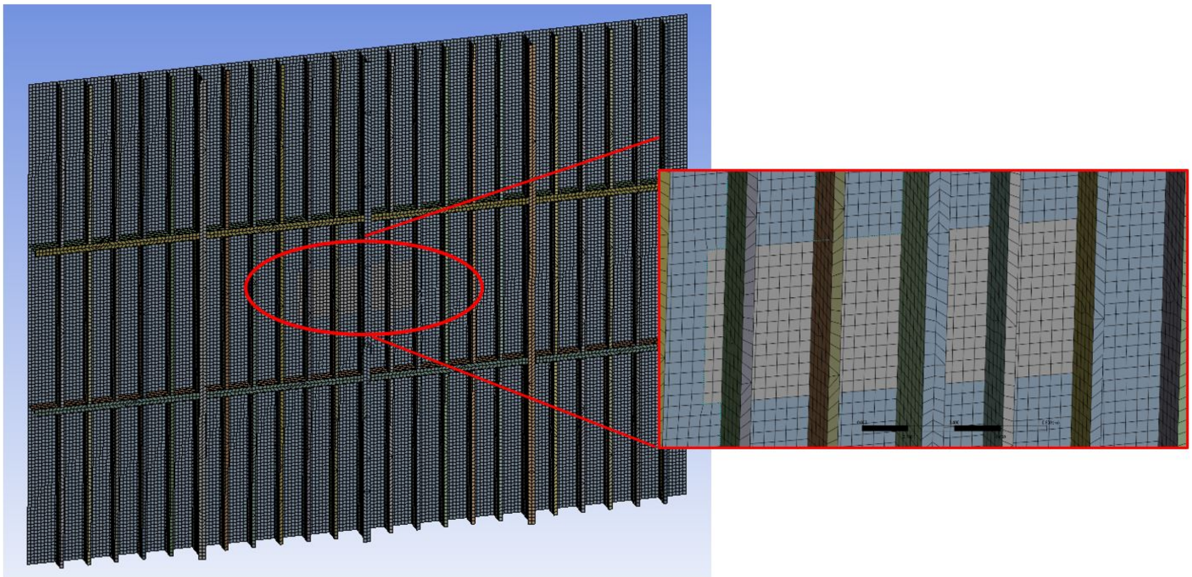
## TABLE 2
## Example Grillage Scantlings

| | |
|---|---|
| Shell plating thickness (mm) | 16 |
| Framing system | Transverse |
| Frame spacing (mm) | 400 |
| Frame scantlings (mm) | 260 x 12 Bulb Profile |
| Frame span (mm) | 2800 |
| Stringer type | T |
| Stringer spacing (mm) | 2800 |
| Stringer scantlings (mm) | 350 x 10 web, 100 x 10 flange |
| Stringer span (mm) | 2400 |
| Web frame type | T |
| Web frame spacing (mm) | 2400 |
| Web frame scantlings (mm) | 500 x 14 web, 100 x 14 flange |
| Web frame span (mm) | 2800 |

## FIGURE 7
## Example 3-D Model



## FIGURE 8
## Example Meshed FEA Model



## TABLE 3
## Example Grillage Material Properties

| | |
|---|---|
| Density (kg/m$^3$) | 7850 |
| Young's Modulus (GPa) | 200 |
| Poisons Ratio | 0.3 |
| Yield Strength (MPa) | 355 |
| Tangent Modulus (MPa) | 1000 |

Loads can be applied in many ways in a finite element analysis. For structural grillages, the load is often applied as either a force or pressure. In most finite element codes, a force is applied in a specific direction, with the force spread uniformly over the number of nodes selected by the user. The user can define the force vectors to apply the load in a particular direction or set the force to follow the deformation of the structure.

Pressures are applied over a prescribed area, with the pressure being applied uniformly over the number of elements selected by the user. Pressures are applied normal to the surface. If the structure begins to deform, the direction of the applied pressure will change to be applied normal to the surface. Pressures can sometimes be referred to as “follower” loads as they change direction to follow the deformation of the structure.

The ABS Polar Class Rules require that the loads be applied as a uniform pressure for both the linear and nonlinear FEA. For this worked example, the load was applied via a uniform pressure patch, centered on the middle of the span of the central web frame. The patch had the same dimensions as the design load patch for the bow hull area as defined in 6-1-2/5.9 of the *Marine Vessel Rules*.

Boundary conditions must be applied so that the model does not exhibit rigid body motion when the load is applied. The boundary conditions should match as closely as possible to the actual boundary conditions of the structure. When the boundary conditions are too complex to model accurately, the model extent/size can be increased and fully fixed boundary conditions can be applied to the outside edges. When performing a NLFEA, it is critical that no plastic strains occur at the boundary elements/nodes (or where the boundary conditions have been applied) as it would invalidate the model. For this worked example, the model boundary conditions were fully fixed in all six degrees of freedom around the outside edges of the model. The model extent was made large enough so that no plastic strains were present at the boundary elements/nodes.

The ABS *Guidance Notes on Nonlinear Finite Element Analysis of Marine and Offshore Structures* provides guidance on mesh size but also suggests that a mesh sensitivity/convergence analysis be performed. It is important to note that the mesh must be small enough to capture the expected behavior. For example, if the web of a frame is only two elements deep, it will not be possible to determine if the web has buckled under the load.

The following steps can be taken to determine the mesh size when the results have converged:

*i)* Create an initial coarse mesh. Record the mesh size.

*ii)* Select a convergence criterion. In general, displacement is the preferred criteria as it is not as susceptible to concentrations like stress or strain.

*iii)* Determine the tolerance for the convergence criterion. The tolerance is dependent on the required accuracy and complexity of the model, but in general, 5% is an acceptable tolerance.

*iv)* Apply the load to the model.

*v)* Record the convergence criteria when the simulation has finished.

*vi)* Reduce the mesh size.

*vii)* Repeat steps iv through vi until the change in convergence criteria is less than the tolerance. The mesh is now considered converged and does not need to be reduced in size.

For this worked example, a mesh sensitivity/convergence analysis was undertaken to determine the mesh size where the results converged and were no longer dependent on the mesh size while also optimizing the computational time. For this example, the mesh converged at a mesh size of 25 mm.

The linear analysis requires two different pressures to be applied, the design pressure and the overload pressure. The overload pressure is a scaled design pressure, where the scale factor depends on the Polar Class and the structural layout. For the nonlinear analysis, an additional pressure must also be applied, the reserve pressure. The reserve pressure is simply 1.25 times the overload pressure. See below or 6-1-2/15.7 of the *Marine Vessel Rules* for more details on the required pressures.

- Design: The load patch and pressure specified in 6-1-2/5 of the *Marine Vessel Rules*.
- Overload: The design load pressure multiplied by the Polar Class dependent Overload Capacity Factor ($CF_o$), specified in 6-1-2/Table 8 of the *Marine Vessel Rules* is to be applied to the design load patch.
- The Overload case pressure multiplied by 1.25 is to be applied to the design load patch.

## TABLE 4
## Overload Capacity Factor

| *Polar Class* | *Overload Capacity Factor ($CF_o$)* | |
|---|---|---|
| Structure has both web frames and load-carrying stringers? | No - has only one type of structural member | Yes - has both types of structural members |
| **Ice Class PC1** - **Ice Class PC3** | 1.20 | 1.10 |
| **Ice Class PC4** - **Ice Class PC5** | 1.25 | 1.15 |
| **Ice Class PC6** - **Ice Class PC7** | 1.30 | 1.20 |

### 2.1.1 Linear Criteria and Analysis

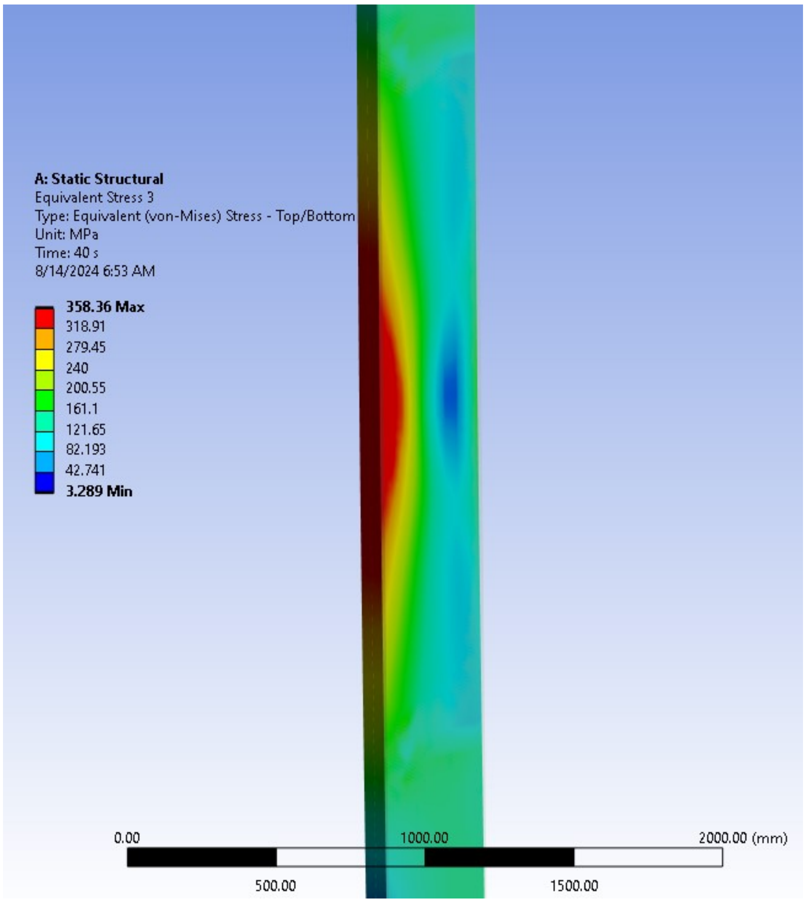
The following acceptance criteria have been taken verbatim from 6-1-2/15 of the *Marine Vessel Rules*.

For a linear finite element analysis, the deep member must meet the following criteria as per 6-1-2/15.9 of the *Marine Vessel Rules*:

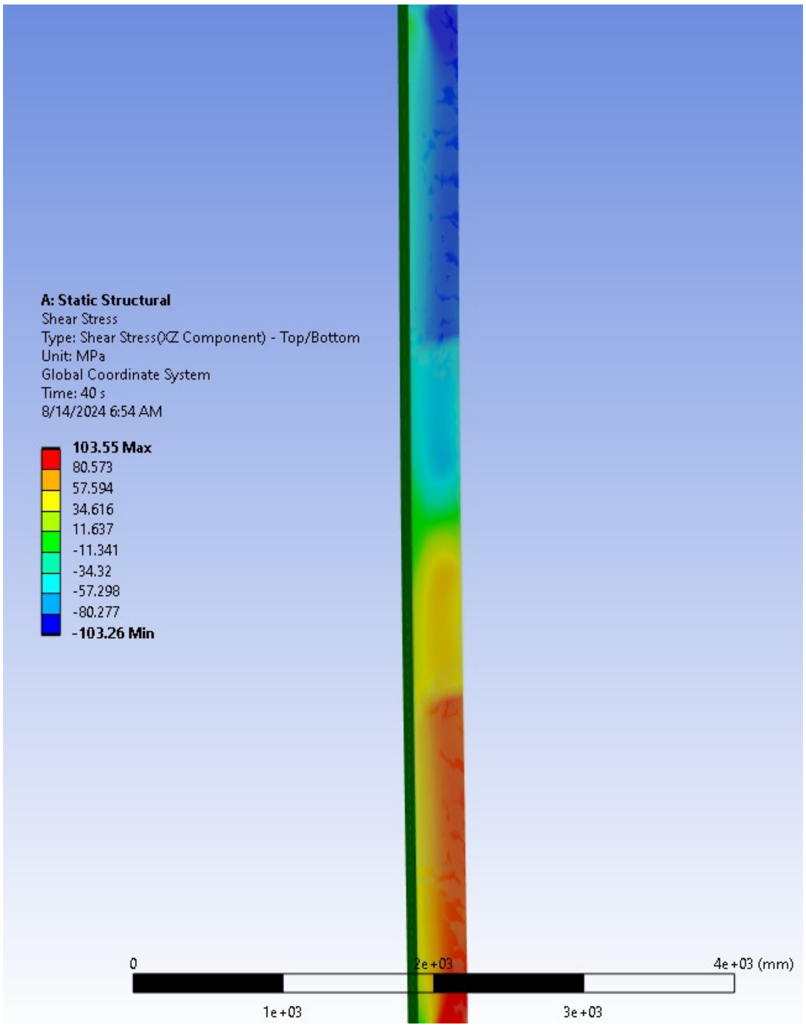
- Nominal shear stresses in member web plates is to be less than $0.577\sigma_y$ at the design load.
- Nominal von Mises stresses in member flanges is to be less than $1.15\sigma_y$ at the design load.
- Web plate and flange elements in compression and shear do not exhibit signs of elastic buckling at the overload load case.

$\sigma_y$ is the yield stress of the material. The design pressure was applied, and the shear and von Mises stress in the web frame web and flange were extracted from the model, respectively. The allowable web shear stress and allowable von Mises stress in the flange was 204.8 MPa and 408.25 MPa, respectively for ABS AH36 steel. At the design load, the max shear stress in the web was 103.55 MPa for a utilization of 51%, the max von Mises stress in the flange was 358.36 MPa for a utilization of 88%. As both utilizations were below 100%, both criteria were met. Visual inspection of the web and flange of the web frame at the overload pressure showed no signs of elastic buckling. As all criteria have been met, the web frame passed the linear criteria. See 3-1/ Figure 9 and 3-1/Figure 10 for the max von Mises and shear stresses, respectively. Note that only the web frame results have been presented for this worked example.

**FIGURE 9**
**Linear Analysis - Max von Mises Stress**



## FIGURE 10
## Linear Analysis - Max Shear Stress




### 2.1.2 Non-linear Criteria and Analysis

Unlike the linear criteria which focuses on stresses, the nonlinear criteria are displacement-based and relate to construction tolerances as per International Association of Classification Societies (IACS) Recommendation 47. The following criteria must be met for a nonlinear analysis:

- The maximum permanent set ($\delta_p$) after unloading from the design load case pressure specified in 6-1-2/15.7.i of the *Marine Vessel Rules* must be less than 0.3% of the web frame or load-carrying stringer span under consideration.
- The maximum permanent set ($\delta_p$) after unloading from the overload load case pressure specified in 6-1-2/15.7.ii of the *Marine Vessel Rules* must be less than 0.9% of the web frame or load-carrying stringer span under consideration.
- The slope of the maximum load deflection curve must be positive and no structural instability has occurred at the reserve load case pressure specified in 6-1-2/15.7.iii of the *Marine Vessel Rules*.

For the web frame being analyzed, the span is 2400 mm. See 3-1/Table 5 for the allowable and the actual permanent set for the design and overload load cases. The utilization at the design and overload cases is 16% and 22%, respectively. The load deflection curve was analyzed for the reserve case. As the slope of the load deflection curve at the reserve load is still positive, the web frame passed all the nonlinear criteria. See 3-1/Figure 11 through 3-1/Figure 13, which outline the displacements for the design and reserve load cases, and the load deflection curve which contains all three load cases.

## TABLE 5
## Web Frame Permanent Set

| *Load Level* | *Allowable Permanent Set* | *Actual Permanent Set* |
|---|---|---|
| Design | 7.2 mm | 1.1 mm |
| Overload | 21.6 mm | 4.8 mm |

This difference in utilization from the linear to nonlinear acceptance criteria highlights the advantage of performing a nonlinear analysis, as the structure can be better optimized while confirming the member has significant capacity beyond the yield point.

## FIGURE 11
## Non-linear Analysis - Permanent Set, Design Case

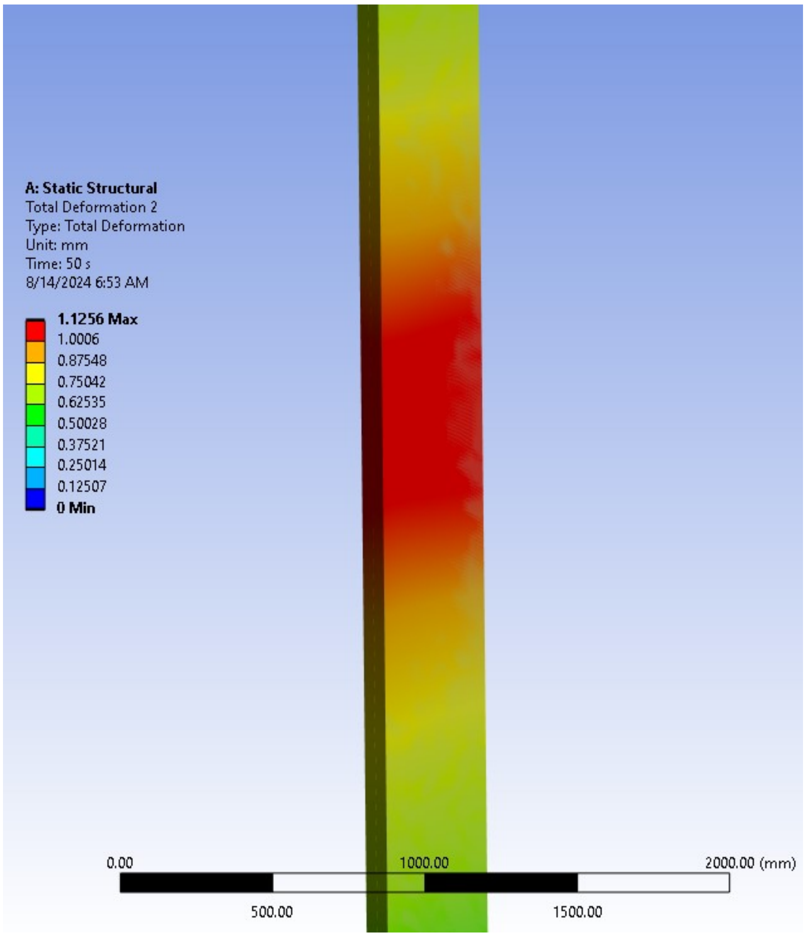


**FIGURE 12**
**Non-linear Analysis - Permanent Set, Overload Case**

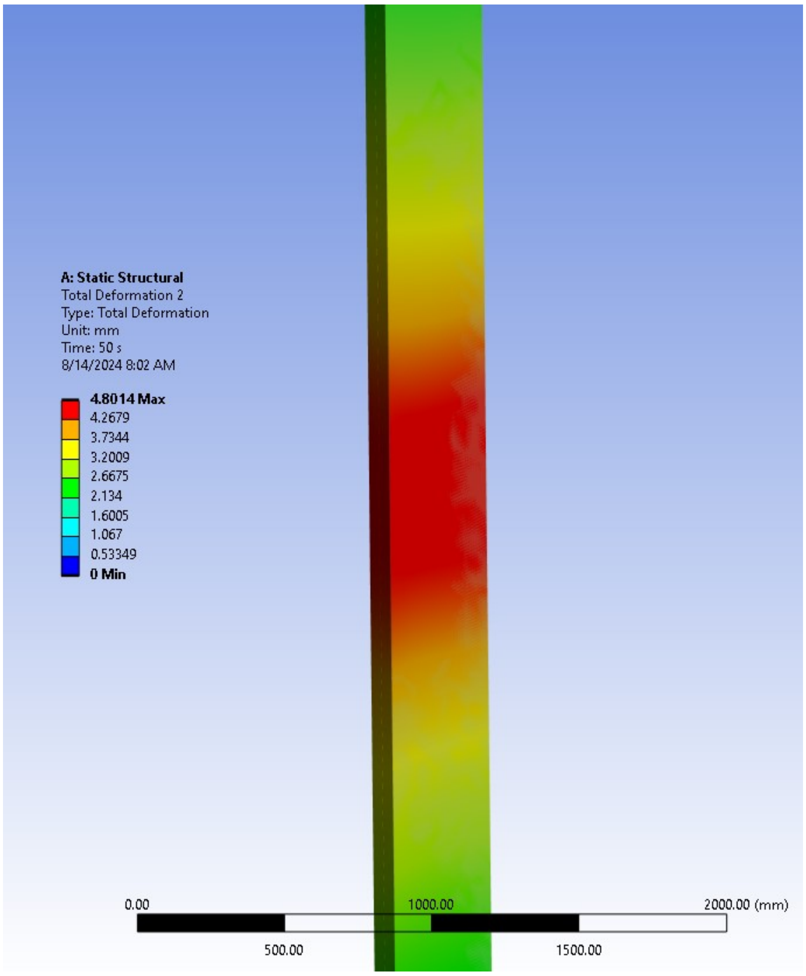
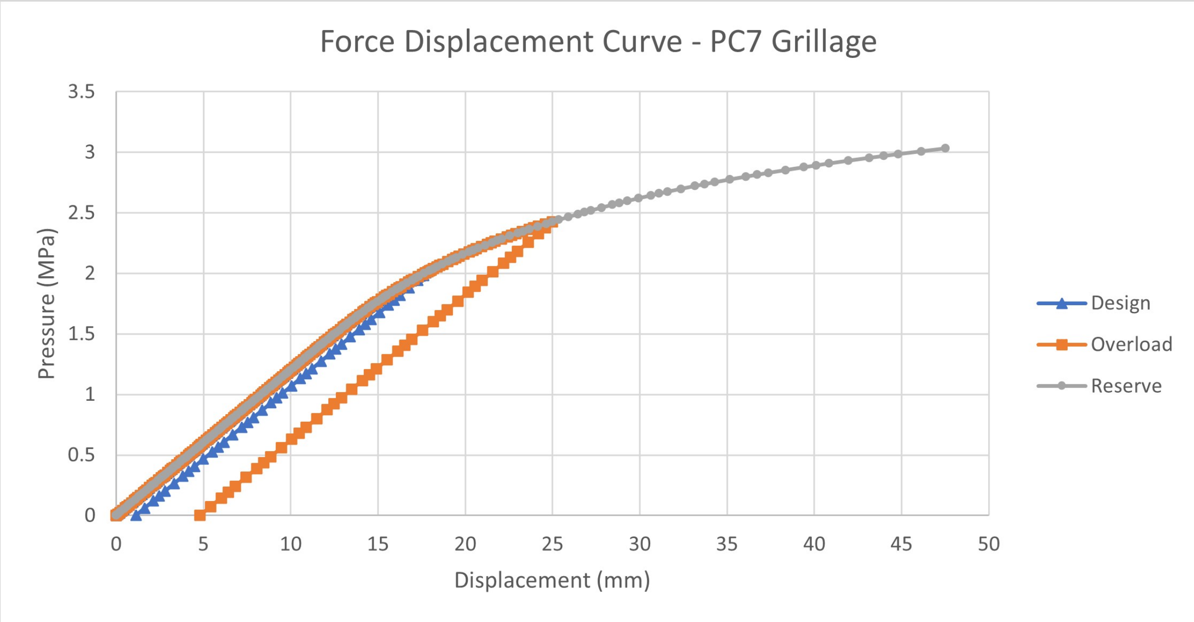


**FIGURE 13**
**Non-linear Analysis - Load Deflection Curves**




# 3 Polar Class Decks

The Polar Class Rules do not have design equations for deck plating, deck transverses, and deck beams. The stringer plating of the deck would need to meet the requirements in 6-1-2/15 of the *Marine Vessel Rules* for stringers through the use of FEA, and all the deck structure would need to meet the relevant requirements in Parts 3 and 5 (if applicable) of the *Marine Vessel Rules*. The following Paragraphs can be used for the initial sizing of the deck scantlings for decks or parts of decks situated within the icebelt and refined in later stages of the design spiral.

## 3.1 Deck Plating

The thickness of the stringer plate may be determined using the following equation:

$$t = k(s^2bP)^{1/3} \quad mm \quad (in.)$$

where

$k$ = 0.12 (0.257, 0.00523)

$s$ = distance between the deck beams, in mm (in.)

$b$ = as defined in 6-1-2/5.9 of the *Marine Vessel Rules*, in m (ft) for the particular hull area ($b_{Bow}$ or $b_{NonBow}$)

$P$ = $C_1 P_{avg} AF$

$C_1$ = 0.6 for the Bow hull area (and the stern hull area for vessel that operate ahead and astern)

= 0.5 for all other areas

$P_{avg}$ = as defined in 6-1-2/5.11 of the *Marine Vessel Rules* for the particular hull area

$AF$ = Hull Area Factor from 6-1-2/5.13 of the *Marine Vessel Rules* for the particular hull area

It is suggested that the width of the stringer plate be not less than five times the depth of the main frame for **Ice Class PC1** and **Ice Class PC2**, and four times the main frame depth for **Ice Class PC3** to **Ice**

**Class PC7**. Also, it is suggested that the thickness of the deck plating be not less than 0.75 times the required thickness of the stringer plate.

## 3.2 Deck Transverses and Beams

### 3.2.1 Transversely Framed Decks

It is suggested that partial beams or brackets be fitted at every intermediate frame for **Ice Class PC1** to **Ice Class PC5**. These partial beams or brackets should extend from the frames to a deck longitudinal or deck girder. The length of these partial beams or brackets should be not less than the width of the stringer plate.

### 3.2.2 Longitudinally Framed Decks

It is suggested that deck transverses be fitted at every web frame and, in addition, ideally at every second main frame for **Ice Class PC1** to **Ice Class PC4** or every third main frame for ice classes **Ice Class PC5** to **Ice Class PC7**.

It is suggested that partial beams or brackets be fitted at all other main frames and at every intermediate frame for all polar classes. The partial beams or brackets should extend from the frames to a deck longitudinal or deck girder

### 3.2.3 Scantlings

The sectional area of the beams and deck transverses may be calculated using the following equations:

$$A = K_1 s b\left(\frac{P}{\sigma_y}\right)\cos(\beta) \quad \text{cm}^2$$

$$A = 1.2K_1 s b\left(\frac{P}{\sigma_y}\right)\cos(\beta) \quad \text{in}^2$$

The moment of inertia of the beams may be calculated using the following equation:

$$I = kK_2 s\ell^2 bP\cos(\beta') \quad \text{cm}^4 \quad (\text{in}^4)$$

where

| | | |
|---|---|---|
| $k$ | = | 1 (9.81, 0.1191) |
| $\ell$ | = | span of the beam, measured in m (ft), between the inboard edge of the frame and the deck longitudinal or deck girder supporting the beam |
| $\sigma_y$ | = | minimum upper yield stress of the material, in N/mm$^2$, but not greater than 690 N/mm$^2$ (70 kgf/mm$^2$, 100000 psi) |
| $\beta'$ | = | as defined in 6-1-2/5.5 of the *Marine Vessel Rules*, in degrees, for the particular area |
| $K_1$ | = | 8.5 for **Ice Class PC1** to **Ice Class PC5** |
| | = | 6.6 for **Ice Class PC6** and **Ice Class PC7** |
| $K_2$ | = | 0.24 for **Ice Class PC1** to **Ice Class PC5** |
| | = | 0.13 for **Ice Class PC6** and **Ice Class PC7** |

It is suggested that the beams and the partial beams be bracketed to the deck longitudinals or deck girders. It is suggested that beams or partial beams or brackets fitted at the web frames be reinforced so that their section modulus ($SM$) is not less than:

$$SM = K_3 SM_{wf}\ell_{wf}/\ell \quad \text{cm}^3 \quad (\text{in}^3)$$

where

$SM_{wf}$ = section modulus of the web frame in $cm^3$ ($in^3$)

$\ell_{wf}$ = span of the web frame, measured in m (ft), between supports, with no reduction for fitted end brackets, if any

$K_3$ = 0.8 for **Ice Class PC1** to **Ice Class PC5**

= 0.5 for **Ice Class PC6** and **Ice Class PC7**

When calculating the section modulus and the moment of inertia of a framing member, net thickness of the web, flange (if fitted) and attached shell plating should be used.

### 3.3 Decks with Wide Openings (60% of the breadth or greater)

Within the Bow Intermediate and Midbody areas of the icebelt, the cross-sectional area of the deck outside the line of openings may be calculated using the following equation:

$$A = Kb\ell\left(\frac{P}{\sigma_y}\right) \cdot 10^3 \quad cm^2$$

$$A = 14.4Kb\ell\left(\frac{P}{\sigma_y}\right) \quad in^2$$

where

$\ell$ = length of the opening, in m (ft), but need not be taken as more than $0.1L_{ui}$

$L_{ui}$ = as defined in 6-1-2/1.3 of the *Marine Vessel Rules*, in m (ft)

$K$ = 8.2 for **Ice Class PC1** to **Ice Class PC5**

= 6.2 for **Ice Class PC6** and **Ice Class PC7**

## 4 Polar Class Bulkheads

Like deck structures, the Polar Class Rules do not provide bulkhead design equations. The bulkhead plating attached to the shell would need to meet the requirements in 6-1-2/15 of the *Marine Vessel Rules* for web frames through the use of FEA and the relevant requirements in Parts 3 and 5 (if applicable) of the *Marine Vessel Rules*.The following suggestions can be used for inital sizing and refined in later stages of the design spiral.

It is suggested that the thickness of the part of the bulkhead adjacent to the side shell be not less than the thickness of the adjacent frames or of the stringers connected to the bulkhead, whichever is greater. It is suggested that the width of these parts of the bulkhead be not less than shown in 3-1/Table 6. It is suggested that these parts of the bulkhead adjacent to the shell within the icebelt be fitted with stiffeners normal to the shell plating. It is suggested that the stiffeners be welded to a vertical bulkhead stiffener and welded and bracketed to the side longitudinals. Where the shell is transversely framed, it is suggested that brackets be welded to the shell and extended and attached to adjacent frames. Alternatively, bulkhead stiffening may be terminated with a minimum of 4:1 taper.

If a vessel is intended to operate astern in ice regions, it is suggested that the width of the reinforced parts of the bulkhead adjacent to the Stern and Stern Intermediate icebelt areas be not less than that required for Bow and Bow Intermediate Areas shown in 3-1/Table 6.

**TABLE 6**
**Minimum Width of Reinforced Bulkhead Plating**

| *Ice Class* | *Area of the Icebelt* | | | |
|---|---|---|---|---|
| | *Peaks m (ft)* | *Bow and Bow Intermediate m (ft)* | *Midbody m (ft)* | *Stern m (ft)* |
| **Ice Class PC1** through **Ice Class PC4** | 1.6 (5.2) | 1.4 (4.6) | 1.2 (4) | 1.4 (4.6) |
| **Ice Class PC5** through **Ice Class PC7** | 1.2 (4) | 1.2 (4) | 1 (3.3) | 1 (3.3) |

# 5 Stem and Stern Frames

Like deck and bulkhead structures, the Polar Class Rules do not provide stem and stern frame design equations. The stem and stern frames would be required to meet the shear and bending loads calculated in 6-1-2/25 of the *Marine Vessel Rules* and the relevant requirements in Parts 3 and 5 (if applicable) of the *Marine Vessel Rules*. The following section can be used for initial sizing of the stem and stern frame scantlings and refined in later stages of the design spiral.

It is suggested that the stem and stern frame for ice class **Ice Class PC1** through **Ice Class PC5** be constructed of rolled bar, cast or forged steel instead of shaped plate.

## 5.1 Stem

### 5.1.1 Solid Stem

The cross-sectional area of a stem made of rolled bar, cast or forged steel from the center vertical keel to $0.01L_{ui}$ above the icebelt may be calculated using the following equation:

$$A = K_1 \;\; D_{ui}^{1/3}(L_{ui} - 61) + A_0 \quad \text{cm}^2$$

$$A = 0.0473K_1 \;\; D_{ui}^{1/3}(L_{ui} - 200) + A_0 \quad \text{in}^2$$

where

| | | |
|---|---|---|
| $K_1, A_0$ | = | as given in 3-1/Table 7 |
| $D_{ui}$ | = | as defined in 6-1-2/1.3 of the *Marine Vessel Rules* |
| $L_{ui}$ | = | as defined in 6-1-2/1.3 of the *Marine Vessel Rules*, in m (ft) but not less than 61 m (200 ft) |

The equation above assumes the steel is regular carbon (non-high strength) steel. If higher strength steel is used the cross-sectional area may be reduced using the $Q$ variable in 3-2-1/5.3 of the *Marine Vessel Rules* and the formula below.

$$A_{hsm} = AQ$$

where

| | | |
|---|---|---|
| $A_{hsm}$ | = | cross-sectional area of the solid stem using higher strength material |
| $Q$ | = | as defined in 3-2-1/5.3 of the *Marine Vessel Rules* |
| $A$ | = | the cross-sectional area of the solid stem using non-high strength material |

## TABLE 7
## Solid Stem Bar Coefficients

| *Ice Class* | $A_0$ *cm*$^2$ *(in*$^2$*)* | $K_1$ |
|---|---|---|
| **Ice Class PC1** | 750 (116.2) | 0.28 |
| **Ice Class PC2** | 750 (116.2) | 0.28 |
| **Ice Class PC3** | 700 (108.5) | 0.27 |
| **Ice Class PC4** | 500 (77.5) | 0.24 |
| **Ice Class PC5** | 200 (31) | 0.18 |
| **Ice Class PC6** | 62 (9.6) | 0.13 |
| **Ice Class PC7** | 62 (9.6) | 0.13 |

### 5.1.2 Shaped Plate Stem

Thickness of shaped plate stems within the bow area may be calculated using the following equation:

$$t = 0.8s\sqrt{\left(P/\sigma_y\right)} + t_s \quad \text{but not less than 0.04R}$$

where

$s$ = distance between frames, brackets (breast hooks) or stiffeners, in mm (in.)

$P$ = $0.75P_{bow}$, as defined in 6-1-2/5.5 of the *Marine Vessel Rules*

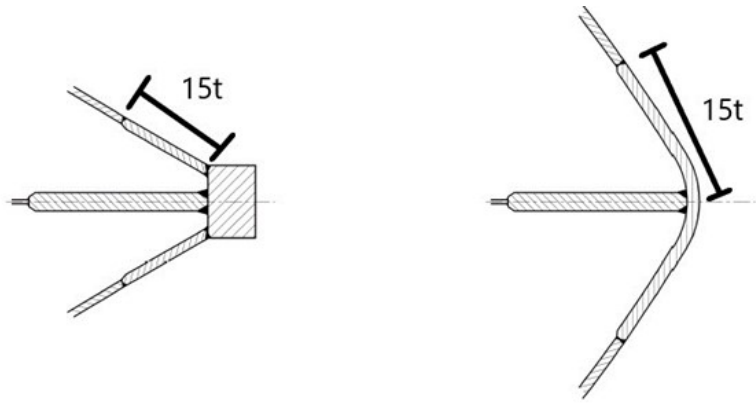
$\sigma_y$ = minimum upper yield stress of the material, in N/mm$^2$ (kgf/mm$^2$, psi), but not greater than 690 N/mm$^2$ (70 kgf/mm$^2$, 100 psi)

$t_s$ = corrosion/abrasion addition for the bow area, as defined in 6-1-2/21 of the *Marine Vessel Rules*, in mm

$R$ = inside radius of the stem at the given section, in mm (in.). Need not be taken greater than 625 mm (24.6 in.) for **Ice Class PC6** and **Ice Class PC7**

It is suggested that at any section, the fore and aft length of the stem plate be not less than 15*t*.

## FIGURE 14
## Shaped Plate Stem Example




Source: Finnish Swedish Ice Class Rules 2021

#### 5.1.3 Arrangement

The following is suggested for stems of polar class vessels:

- The outer surface of connections of the shell plating to the stem be flush.
- The stem be supported by floors, webs, frames, breasthooks or brackets spaced not more than 610 mm (24 in.).
- Shaped plate stems be supported on the centerline by a plate, web or bulkhead having the same thickness as the center vertical keel and a width not less than 610 mm (24 in.).

### 5.2 Stern

For a double acting vessel, see the stem requirements.

For all non-double acting vessels, it is suggested that the stern post be of size obtained from 3-2-13/3.3 through 3-2-13/3.11 of the *Marine Vessel Rules*, with all thicknesses increased by coefficient $K$, as given in 3-1/Table 8. In addition, factors $C_f$ and $C_c$ in 3-2-13/3.3 of the *Marine Vessel Rules* should be multiplied by $K$.

## TABLE 8
## Stern Post Coefficient

| *Ice Class* | *K* |
|---|---|
| **Ice Class PC1** | 2 |
| **Ice Class PC2** | 1.9 |
| **Ice Class PC3** | 1.8 |
| **Ice Class PC4** | 1.6 |
| **Ice Class PC5** | 1.4 |
| **Ice Class PC6** | 1.2 |
| **Ice Class PC7** | 1.2 |

# 6 Other Structural Guidance

Ice-going vessels are uniquely loaded compared to traditional open-water vessels. The ice can produce extremely high concentrated loads on the local structure and produce large global loads during ridge ramming. The hullform of an ice-going vessel must clear the ice away from the vessel to avoid the extreme ice loads from damaging the propulsion machinery and other appendages. If an appendage is not strengthened sufficiently and becomes damaged, it can lead to the surrounding hull structure also becoming damaged. See the ABS *Guidance Notes on Ice Loads on Azimuthing Propulsion Units* and the TRAFICOM *Guidelines for the application of the Finnish-Swedish Ice Class Rules.*

## 6.1 Bilge Keels

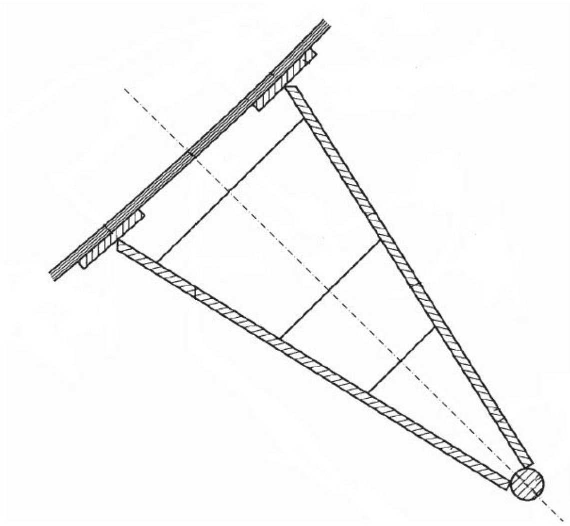
The following text and images have been copied verbatim from the TRAFICOM *Guidelines for the application of the 2017 Finnish-Swedish Ice Class Rules.* It is suggested that bilge keels not be fitted to higher ice class vessels when possible, due to the increased lilelihood of being damaged. For ship-shaped ice classed offshore assets such as Floating Production Storage and Offloading (FPSO) units that will require bilge keels, see the relevant ABS offshore Rules and Guides for more information and guidance.

*Bilge keels are often damaged or ripped off in ice, see 3-1/Figure 15. The reason for this is that ice floes roughly follow the buttock lines when the ship is proceeding in ice. The connection of bilge keels to the hull should be designed to minimize the risk of damage to the hull if the bilge keel is damaged. A construction often described as an "A-type" bilge keel is recommended due to its strength. An example of this kind of construction is shown in 3-1/Figure 16. To limit the damage which occurs when a bilge keel is partly damaged, it is recommended that bilge keels are split into several shorter, independent lengths. The forward and aft parts of the bilge keels should also be pointed towards the oncoming ice when going forward or astern, respectively.*

**FIGURE 15**
**Damaged Bilge Keel**

Source: Guidelines for the application of the 2017 Finnish-Swedish Ice Class Rules

**FIGURE 16**
**Type A Bilge Keel**



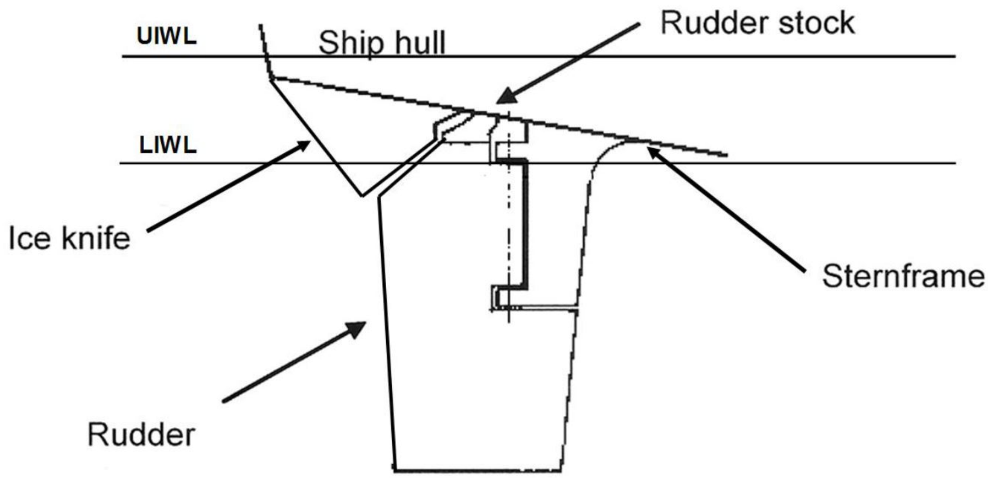
Source: Guidelines for the application of the 2017 Finnish-Swedish Ice Class Rules

## 6.2 Ice Knife

The following text and image have been copied verbatim from the TRAFICOM *Guidelines for the application of the 2017 Finnish-Swedish Ice Class Rules* with a small addition to include the Polar Classes.

*When going astern, level ice will be broken by the stern and the ice floes will be forced under the ship. The function of the ice knife is to push ice floes approaching the rudder downwards, so that the rudder is not subject to head-on impacts with ice floes and large forces that deviate the rudder out the amidships position occur less frequently. Attention should be paid to the strength and shape of the ice knife with regard to its function. A properly shaped ice knife is shown in 3-1/Figure 17: the lowest part of the ice knife should be below water for all draughts. However, if it is not intended that the ship will go astern in ice at some draughts, a smaller ice knife could be used.* An ice knife is recommended for all ships with an **Ice Class IAA** or **Ice Class IA** and all Polar Classes.

**FIGURE 17**
**Example Ice Knife**




Source: Guidelines for the application of the 2017 Finnish-Swedish Ice Class Rules

## 6.3 Rudder Turning Mechanism

The following text has been copied verbatim from the TRAFICOM *Guidelines for the application of the 2017 Finnish-Swedish Ice Class Rules.*

*When going astern, a large turning moment will be applied to the rudder, especially if it is allowed to deviate from the amidships position. In order to avoid a situation where the rudder is forced sideways, the operators should pay attention to keeping the rudder amidships when going astern. At the same time, rudder stoppers should be installed in order to avoid excessive movement of the rudder(s).*

*When the rudder is turned sideways, a great deal of pressure will act on the rudder turning mechanism. The relief valves for hydraulic pressure in the turning mechanism must therefore be effective. The components of the steering gear should be dimensioned to withstand loads corresponding to the required diameter of the rudder stock.*

## 6.4 Bow Thrusters

The following text has been copied verbatim from the TRAFICOM *Guidelines for the application of the 2017 Finnish-Swedish Ice Class Rules.*

*In general, bow thrusters are not used in ice, because ice floes can damage the thruster blades. Of course, thrusters can be specifically designed for ice loading, as some manufacturers have done. Ice floes can become jammed in the tunnel entrance, making operation of the thrusters impossible. Sometimes, a grid is recommended at the tunnel entrance in order to prevent ice floes from entering the tunnel. On the other hand, this can diminish the thruster's performance when used in open water.*

## 6.5 Sea Chests and Sea Bays

Sea chests and bays provide water to critical systems. They can become clogged when the water within the chests/bays begins to freeze, turning the sea water into very thin slushy sea ice, or when ice is ingested. This thin slush-like sea ice can clog the chests and bays, not allowing the cooling water to reach the various equipment, which can lead to overheating, loss of power, and potentially catastrophic failure of the equipment.

Grating on the chests will help reduce thicker sea ice from entering and clogging the chest. Recirculation systems can also be used to melt any slush or ice that has formed. The arrangement and design of the sea chests and bay can significantly reduce the likelihood of the water freezing within the chests/bays. Designing the chests with an ice box above the waterline and a hatch to be accessible will allow the crew to clear out the ice if the chests begin to freeze or melt the ice using a steam lance or recirculation system. See IMO MSC/Circ. 504 "Guidance of Design and Construction of Sea Inlets under Slush Ice Conditions" or Appendix 4 of the ABS *Guide for Vessels Operating in Low Temperature Environments* for further guidance. Note that ABS requires that at least two sea chests are arranged as ice boxes for **Ice Class PC5** through **Ice Class PC1**, and only one ice box for **Ice Class PC6** and **Ice Class PC7**.

CHAPTER 3
# Design and Analysis Guidance

SECTION 2
# Propeller Strength Analysis Procedure

## 1 Propeller Design Loads

The design loads on propeller blades are calculated using simple formulas in the *Marine Vessel Rules*. The design equations for the Polar Class Rules (Section 6-1-3 of the *Marine Vessel Rules*) and First Year Ice Class Rules (Section 6-1-4 of the *Marine Vessel Rules*) are the same but differ in magnitude. The magnitude of the applied forces is dependent on the blade particulars and ice class.

The ice-blade interactions models are based on two primary interactions, contact with ice and non-contact with ice. Typically, the propeller contacts ice during a milling event. This typically results in a backwards bending force on a propeller blade. The rules also consider the forces as a result of non-contact but close proximity. The proximity of the ice can create a hydrodynamic blocking effect often resulting in a forward bending force.

There are two main propeller design load equations for both ice class rule sets, the backward ($F_b$) and forward ($F_f$) blade bending forces. The equations can be found in Section 6-1-3 of the *Marine Vessel Rules* for the Polar Classes and Section 6-1-4 of the *Marine Vessel Rules* for the First Year Ice Classes. The propeller blade load equations and calculated loads are provided below for an assumed **Ice Class PC4** vessel with two controllable pitch propellers.

3-2/Table 1 contains example propeller blade particulars and the calculated design loads for demonstration purposes.

### TABLE 1
### Example Propeller Particulars and Design Blade Loads (Ice Class PC4)

| *Variable* | *Description* | *Value* | *Units* |
|---|---|---|---|
| $D$ | Propeller diameter | 4.8 | m |
| $n$ | Rotational speed | 130 | RPM |
| $EAR$ | Expanded blade area ratio | 0.55 | - |
| $Z$ | Number of propeller blades | 4 | - |
| $d$ | Propeller hub diameter | 2 | m |
| $P_{07}$ | Propeller pitch at 0.7R | 4.998 | m |

| *Variable* | *Description* | *Value* | *Units* |
|---|---|---|---|
| $S_{ice}$ | Ice Strength Index | 1.1 | - |
| $H_{ice}$ | Design Ice Thickness | 2.5 | m |
| $F_b$ | Backward Blade Force | 1244 | kN |
| $F_f$ | Forward Blade Force | 792 | kN |

*Backwards Blade Force:*

The backwards bending force results in the most common ice related propeller damage. It is a result of the curved suction side of the blade being loaded during an ice milling event.

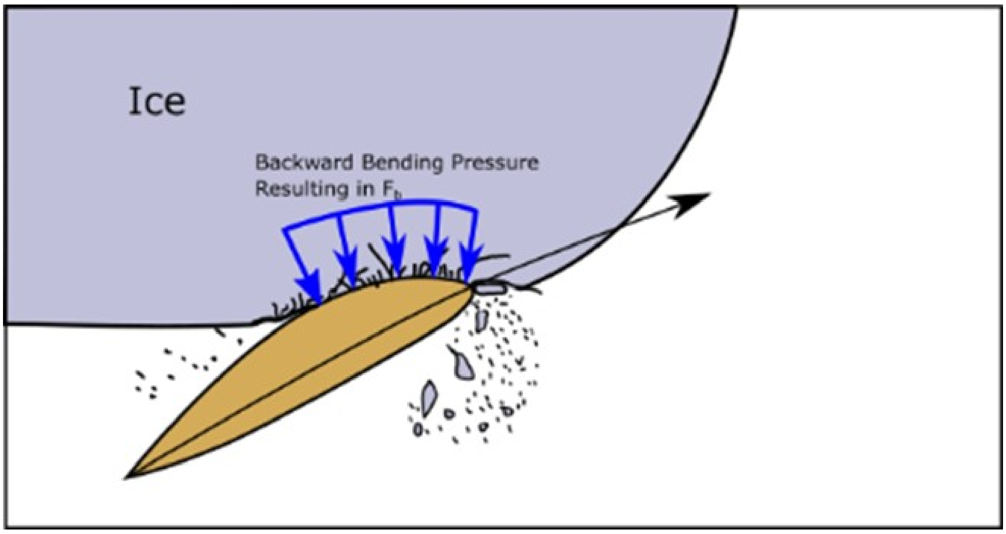
$$F_b = c_0 S_{ice}[n \cdot D]^{0.7} \cdot \left[\frac{EAR}{Z}\right]^{0.3} \cdot D^2 \quad \text{when} \quad D < D_{limit}$$

$$F_b = c_1 S_{ice}[n \cdot D]^{0.7} \cdot \left[\frac{EAR}{Z}\right]^{0.3} \cdot [H_{ice}]^{1.4} \cdot D^2 \quad \text{when} \quad D \geq D_{limit}$$

where

| | | |
|---|---|---|
| $D_{limit}$ | = | $c_2 \cdot [H_{ice}]^{1.4}$ m (ft) |
| $C_0$ | = | 27 (2.753, 0.1096) |
| $C_1$ | = | 23 (2.345, 0.0580) |
| $C_2$ | = | 0.85 (0.85, 0.528) |
| $n$ | = | nominal rotational speed, in rev/s, (at MCR free running condition) for CP propeller and 85% of the nominal rotational speed (at MCR free running condition) for a FP-propeller (regardless driving engine type) |
| $D$ | = | propeller diameter, in m (ft) |
| $EAR$ | = | expanded blade area ratio |
| $Z$ | = | number of propeller blades |
| $S_{ice}$ | = | Ice Strength Index |
| $H_{ice}$ | = | Design Ice Thickness (machinery specific ice thickness) |

**FIGURE 1**
**Backward Blade Bending Force Diagram**




Source: Dr. Brian Veitch

*Forward Blade Force:*

The forward bending force is a result of very close proximity of an ice block and propeller blade pressure side.

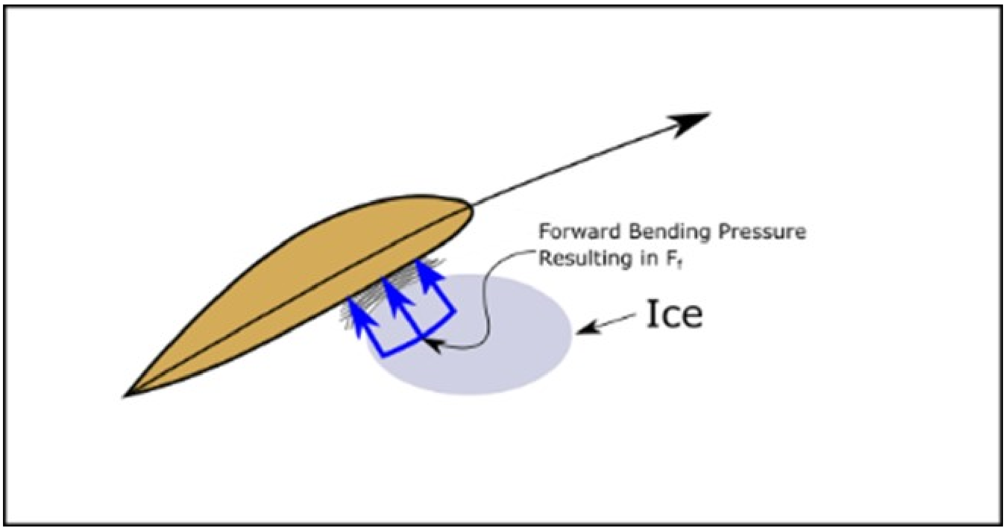
$$F_f = c_3 \cdot \left[\frac{EAR}{Z}\right]^{0.3} \cdot D^2 \quad \text{when} \quad D < D_{limit}$$

$$F_f = 2c_3 \cdot \left[\frac{1}{1 - d/D}\right] \cdot [H_{ice}] \cdot \left[\frac{EAR}{Z}\right] \cdot D \quad \text{when} \quad D \geq D_{limit}$$

where

| | | |
|---|---|---|
| $D_{limit}$ | = | $\left[\frac{2}{1 - d/D}\right] \cdot [H_{ice}]$ m (ft) |
| $C_3$ | = | 250 (25.493, 2.331) |
| $d$ | = | propeller hub diameter, in m (ft) |
| $D$ | = | propeller diameter, in m (ft) |
| $EAR$ | = | expanded blade area ratio |
| $Z$ | = | number of propeller blades |
| $H_{ice}$ | = | Design Ice Thickness (machinery specific ice thickness) |

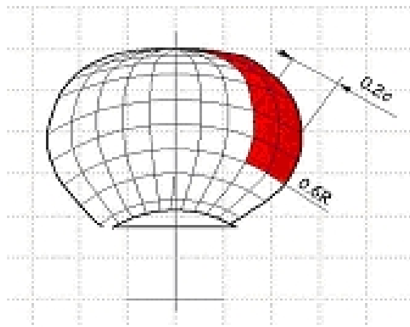
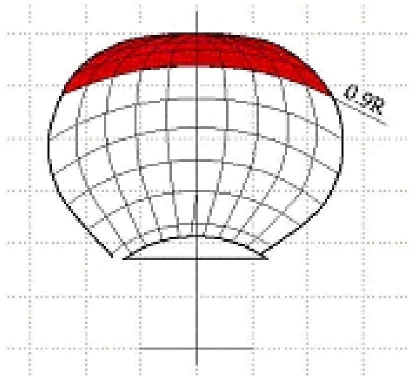
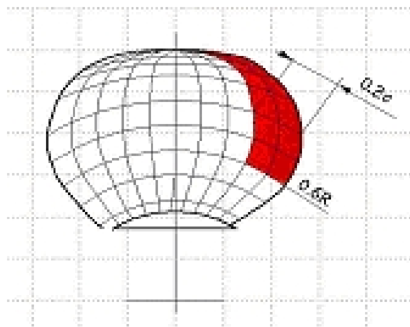
**FIGURE 2**
**Forward Blade Bending Force Diagram**

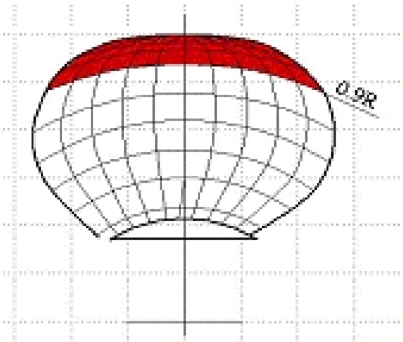
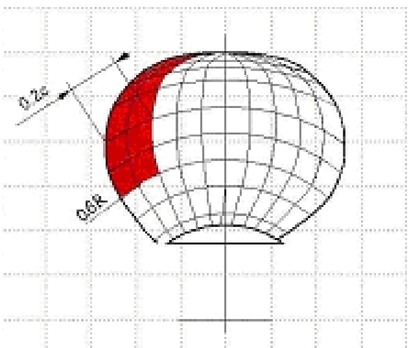



Source: Dr. Brian Veitch

There are five design load cases in Part 6, Chapter 1 of the *Marine Vessel Rules* that must be assessed. Two cases use the backward force, two use the forward force, and the fifth is only applicable for reversing propellers. The reversing case uses a load of 60% of whichever force is greater. See 3-2/Table 2 highlighting the five load cases.

## TABLE 2
## Load Cases for Open Propeller

| | *Force* | *Loaded Area* | *Right handed propeller blade seen from back* |
|---|---|---|---|
| Load case 1 | $F_b$ | Uniform pressure applied on the back of the blade (suction side) to an area from 0.6$R$ to the tip and from the leading edge to 0.2 times the chord length |   |
| Load case 2 | 50% of $F_b$ | Uniform pressure applied on the back of the blade (suction side) on the propeller tip area outside of 0.9$R$ radius. |   |
| Load case 3 | $F_f$ | Uniform pressure applied on the blade face (pressure side) to an area from 0.6$R$ to the tip and from the leading edge to 0.2 times the chord length. |   |

| | *Force* | *Loaded Area* | *Right handed propeller blade seen from back* |
|---|---|---|---|
| Load case 4 | 50% of $F_f$ | Uniform pressure applied on propeller face (pressure side) on the propeller tip area outside of 0.9$R$ radius. |   |
| Load case 5 | 60% of $F_f$ or 60% of $F_b$ whichever is greater | Uniform pressure applied on propeller face (pressure side) to an area from 0.6$R$ to the tip and from the trailing edge to 0.2 times the chord length |   |

The Rules require that the calculated design loads be applied as a uniform pressure as described in the load cases above. There are several ways to apply the uniform pressure. One such way is to split the blade into the correct areas using the 3D model, both radially and along the chord, to correctly apply the load. For the worked example the propeller is a Controllable Pitch Propeller (CPP) on a **Ice Class PC4** vessel. Therefore, it is not a backing blade, thus only the first four load cases are applicable. The area for each of the load cases, along with the calculated force and uniform pressure is provided in 3-2/Table 3 below.

## TABLE 3
## Forces and Pressure for Load Cases

| *Load Case* | *Force (kN)* | *Area ($m^2$)* | *Pressure (MPa)* |
|---|---|---|---|
| 1 | 1244 | 0.358 | 3.475 |
| 2 | 622 | 0.333 | 1.869 |
| 3 | 792 | 0.355 | 2.231 |
| 4 | 396 | 0.326 | 1.215 |

# 2 Propeller Material Properties

The materials used for propeller blades must be strong enough to resist the expected hydrodynamic and ice loads and be resistant to corrosion and fatigue, while also being able to be shaped into complex geometries. Propellers are often made from a bronze casting of varying alloy composition (see Section 2-3-14 of the

ABS *Rules for Materials and Welding (Part 2)*) or austenitic stainless steel propeller castings (see Section 2-3-15 of the ABS *Rules for Materials and Welding (Part 2)*). For this worked example, the material properties are assumed to be for a Type 4 propeller composed of Mn-Ni-Al Bronze and provided in 3-2/ Table 4.

## TABLE 4
## Example Propeller Material Properties

| *Property* | *Value* | *Units* |
|---|---|---|
| Density | 7590 | $kg/m^3$ |
| Tensile Strength ($\sigma_u$) | 590 | MPa |
| Yield Strength ($\sigma_y$) | 245 | MPa |
| Modulus of Elasticity (Youngs Modulus) | 130 | GPa |
| Poissons Ratio | 0.3 | - |
| Minimum Elongation | 15 | % |

Using the tensile strength, yield strength, and minimum elongation a tangent modulus can be calculated. The tangent modulus can be used to create a bilinear model which can in turn be used in a nonlinear finite element analysis. Bi-linear models have been shown to be sufficient during early design phases when material stress strain test data is not available. The tangent modulus can be calculated using the following equation:

$$Tangent \quad Modulus \quad = \quad \frac{\sigma_u - \sigma_y}{Elongation - {}^{\sigma_y}/_{E}}$$

For the example propeller, the tangent modulus was calculated to be 2300 MPa using the material properties in 3-2/Table 4.

# 3 Propeller Non-linear Finite Element Analysis

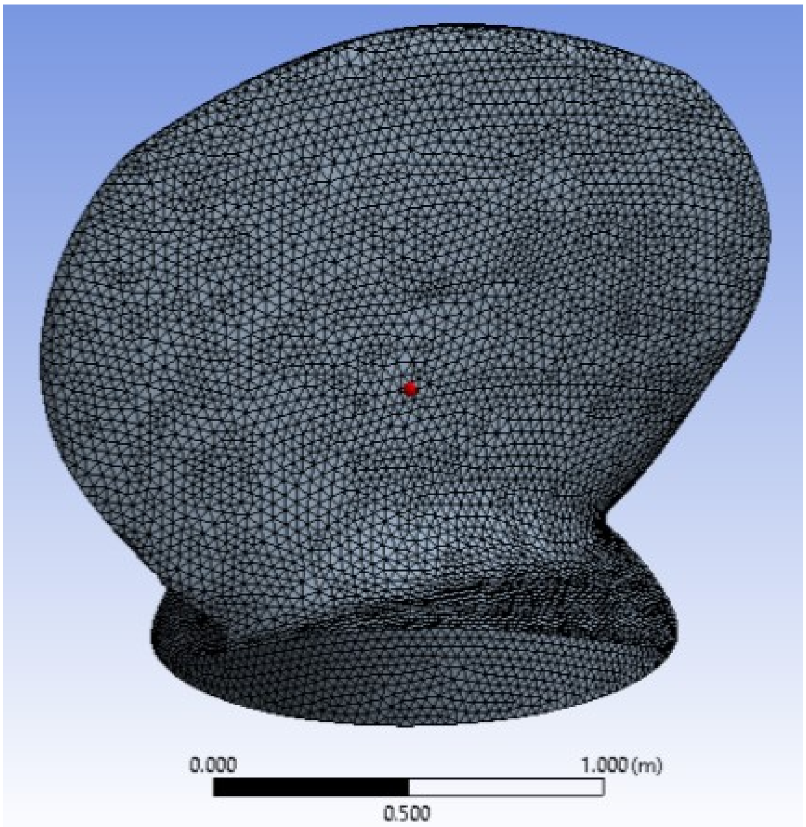
## 3.1 Mesh Convergence and Boundary Conditions

To determine compliance with the Rules, a Nonlinear Finite Element Analysis (NLFEA) must be undertaken. There are several different forms of nonlinearities. For the analysis required by Sections 6-1-3 and 6-1-4 of the *Marine Vessel Rules*, only material and large deflection nonlinearities are required. For more details on how to perform an NLFEA, see the ABS *Guidance Notes on Nonlinear Finite Element Analysis of Marine and Offshore Structures*.

Once the 3-D model has been imported into the FEA software, the model must be meshed. For a propeller analysis, it is suggested to use solid elements, and more specifically, tetrahedron solid elements, due to the complex curvature of the blades. Different FEA solvers have different element types. It is up to the user to select the most appropriate element type. The size of the elements (generally referred to as element size) must be small enough to capture the correct behavior of the propeller blade under load but not so small that the computational cost becomes too great. The process of determining the optimal mesh size is often referred to as a mesh sensitivity/convergence analysis. See Chapter 3, Section 1 for details on how to perform a mesh sensitivity/convergence analysis.

For this worked example, an initial mesh size of 50 mm was used. The mesh was reduced in size by 10 mm until the results converged. The mesh converged at a size of 30 mm, when the change in the total displacement was less than 5% when the backward bending force was applied. See 3-2/Figure 3 showing the final meshed model.

**FIGURE 3**
**Final Meshed Model - 30 mm**




The model boundary conditions should match as closely to the "real" conditions as possible. However, it is often sufficient to apply fully fixed boundary conditions (no translations or rotations) where the palm connects to the hub. Often ice class propeller blades have bolted connections between the palm and the hub to allow for easy replacement in the case of damage. However, modeling the bolted connections when performing the blade analysis is often not required. It is up to the user performing the analysis to determine the required boundary conditions that will allow for an accurate analysis. For the worked example, the blade has been fully fixed at the base of the palm.

## 3.2 Stress Acceptance Criteria

For polar class vessels, the maximum blade stress criteria states that the highest calculated stresses ($\sigma_{calc}$) (von Mises or principal) in the FE analysis are not to exceed the allowable stress, $\sigma_{all}$:

$$\sigma_{calc} < \sigma_{all} = {}^{\sigma_{ref}}\!/_{S}$$

where

| | | |
|---|---|---|
| $\sigma_{ref}$ | = | reference stress, which is the lesser of: |
| | = | $0.7\sigma_u$ or |
| | = | $0.6\sigma_{0.2} + 0.4\sigma_u$ |
| $\sigma_u$ | = | specified maximum ultimate tensile strength in MPa (kgf/mm$^2$, psi) |
| $\sigma_{0.2}$ | = | specified maximum yield or 0.2% proof strength in MPa (kgf/mm$^2$, psi) |
| $S$ | = | 1.5 |

For vessels with a FSICR ice class notation, there is a simplified formula for estimating the blade stresses for all propellers at the root area ($r/R$ < 0.5). The root area dimensions will be accepted even if the FEM analysis would show greater stresses at the root area. The simplified equation to calculate the blade stress is provided below:

$$\sigma_{st} = C_1 \frac{M_{BL}}{k \cdot ct^2} \quad \text{MPa} \quad (\text{kgf/cm}^2, \quad \text{psi})$$

The following criterion for calculated blade stresses must be met:

$$\frac{\sigma_{ref2}}{\sigma_{st}} \geq 1.3$$

where

| | | |
|---|---|---|
| $C_1$ | = | $\sigma_{actual}/\sigma_{beam}$ |
| | = | If the actual value is not available, $C_1$ should be taken as 1.6. |
| $\sigma_{actual}$ | = | von Mises stress measured from FEA in MPa (kgf/cm$^2$, psi) |
| $\sigma_{beam}$ | = | $M_{BL} \cdot y / c_2 \cdot I$ in MPa (kgf/cm$^2$, psi) |
| $M_{BL}$ | = | $\left(0.75 - \frac{r}{R}\right) \cdot R \cdot F$ for relative radius r/R<0.5 |
| $y$ | = | distance from extreme fiber to neutral axis in m (ft) |
| $I$ | = | moment of inertia in m$^4$ (ft$^4$) |
| $c_2$ | = | $10^3$ ($10^4$, 144) |
| $F$ | = | maximum of $F_b$ and $F_f$, whichever is greater |
| $k$ | = | $10^2$ ($10^3$, 14.4) |
| $c$ | = | actual chord length in m (ft) |
| $t$ | = | thickness, in m (ft), of the cylindrical root section of the blade at the weakest section outside root fillet, typically at the termination of the fillet into the blade profile. |
| $\sigma_{ref2}$ | = | $\sigma_{ref}$ |
| $\sigma_{st}$ | = | calculated stress for the design loads. If FE analysis is used in estimating the stresses, von Mises stresses shall be used. |

Determing the bending stress within a propeller blade section using simple beam bending equations is challenging due to the curvature of the blade, as it is difficult to determine the moment of inertia and a specific radius/section. ABS suggests that the $C_1$ factor simply be set to 1.6 to avoid the additonal beam bending claculations which can be a time consuming process for very little (if any) gain.

For the worked example and assumed material properties, the reference stress, $\sigma_{ref}$, is 383 MPa with an allowable stress, $\sigma_{all}$, of 255.3 MPa for a safety factor of 1.5.

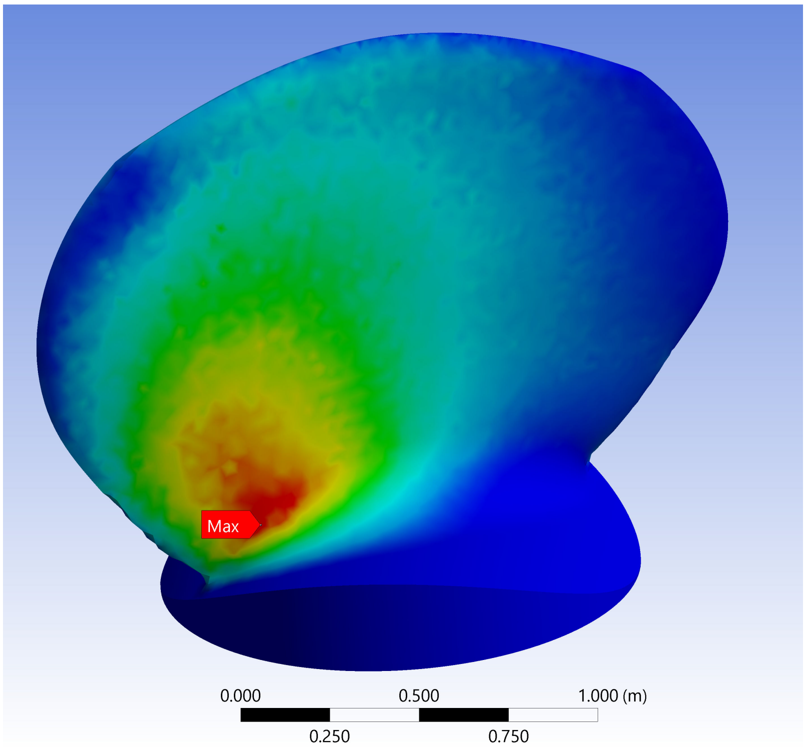
## 3.3 Stress Analysis Results

Each of the applicable load cases (Load Case 1 through 4) was applied to the blade and the equivalent and maximum principal stress were extracted. A comparison was made between the extracted stresses and the allowable stress. As the extracted stresses are all below the allowable stress for each load case, the propeller meets the **Ice Class PC4** propeller blade strength requirements.

### TABLE 5
### Blade Stress Analysis Results

| *Load Case* | *Max Principal Stress (MPa)* | *Max von Mises Stress (MPa)* | *Allowable Stress (MPa)* | *Pass/Fail* |
|---|---|---|---|---|
| 1 | 251.8 | 212.0 | 255.3 | Pass |
| 2 | 117.8 | 102.6 | 255.3 | Pass |
| 3 | 154.9 | 139.7 | 255.3 | Pass |
| 4 | 69.2 | 67.0 | 255.3 | Pass |

### FIGURE 4
### Load Case 3 Equivalent Stress Results




## 4 Propeller Failure Load Case

Sections 6-1-3 and 6-1-4 of the *Marine Vessel Rules* require that the propeller blade's failure load be calculated. This load is used to evaluate other areas of the propulsion line, but this requirement has no bearing on the vessel's ice class. There are two approaches given in the Rules, with the lowest of the two taken as the blade failure load.

The first method is simply using the equation provided in Sections 6-1-3 and 6-1-4 of the *Marine Vessel Rules*. The equation is provided below for reference. Note that the constants in the formula below differ slightly between Sections 6-1-3 and 6-1-4 of the *Marine Vessel Rules*. However, they are functionally the same.

$$F_{ex} = 0.3 \cdot \frac{c \cdot t^2 \cdot \sigma_{ref}}{0.8D - 2r} \cdot 10^3$$

where

$\sigma_{ref}$ = $0.6\sigma_{0.2} + 0.4\sigma_u$

$\sigma_u$ = specified maximum ultimate tensile strength in MPa (kgf/mm$^2$, psi)

$\sigma_{0.2}$ = specified maximum yield or 0.2% proof strength in MPa (kgf/mm$^2$, psi)

$c$ = actual chord length in m (ft)

$t$ = thickness, in m (ft), of the cylindrical root section of the blade at the weakest section outside root fillet, typically at the termination of the fillet into the blade profile.

$r$ = radius, in m (ft), of the cylindrical root section of the blade at the weakest section outside root fillet, typically at the termination of the fillet into the blade profile.

$D$ = diameter of the propeller, in m (ft)

Note that differs slightly from the design load cases discussed in the previous sections. For the example propeller:

$$\sigma_{ref} = 0.6\sigma_{0.2} + 0.4\sigma_u = 0.6 \cdot 245 + 0.4 \cdot 590 = 383 \quad \text{MPa}$$

The values for $c$, $t$, and $r$ are taken for the radius under consideration at the weakest section. The user may need to iterate over the radius of the propeller to find the weakest section, and thus the lowest force to cause failure. Example iterative results are provided in 3-2/Table 6.

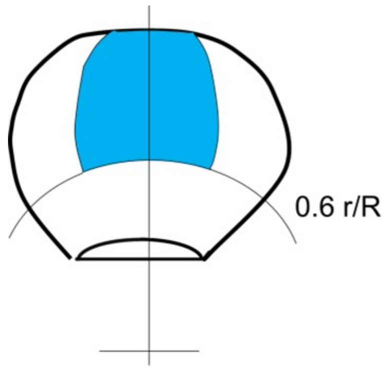
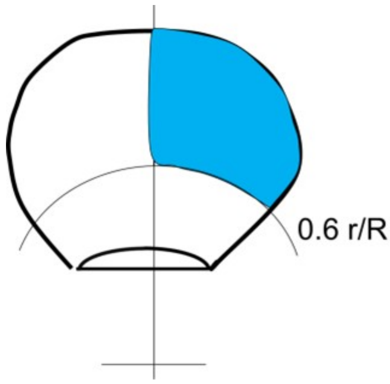
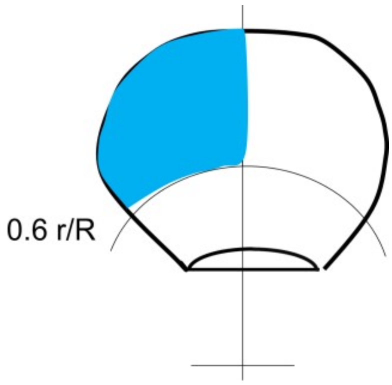
## TABLE 6
## Example $F_{ex}$ Iterative Calculation

| $r/r_0$ | $r$ | $t$ | $c$ | $F_{ex}$ |
|---|---|---|---|---|
| 0.42 | 1.008 | 0.240 | 1.233 | 4,488 |
| 0.5 | 1.200 | 0.198 | 1.556 | 4,846 |
| 0.6 | 1.440 | 0.161 | 1.850 | 5,706 |
| 0.7 | 1.680 | 0.136 | 2.073 | 9,136 |
| $F_{ex}$ (formula) | | | | 4,488 |

The second option is to use finite element analysis (elastic analysis) to determine the load when the blade fails. For the FE analysis, failure occurs when the stress in any blade element reaches $1.5\sigma_{ref}$, which for the example blade is 574.5 MPa.

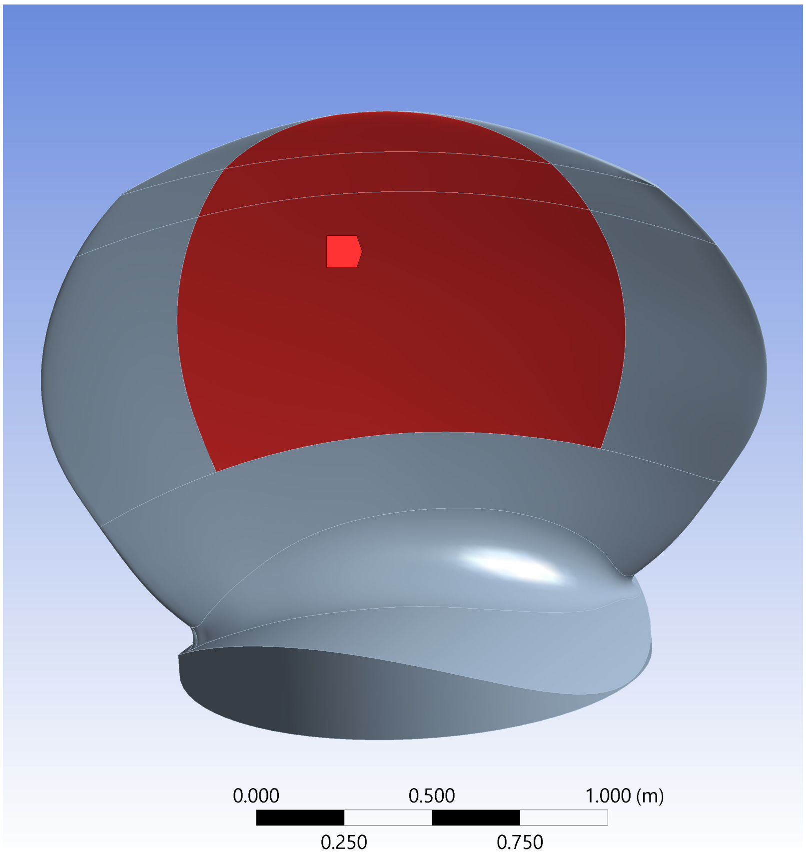
A blade failure force as determined from an FE analysis can be applied as a point load or as a pressure patch centered over 0.8R and a spindle arm 1/3 distance from the axis of blade rotation of the leading and trailing edge, whichever is the greatest. Stresses in way of the applied load should not result in reaching the failure criteria, as it is expected that the blade failure will occur near the root fillet. The pressure patch may be applied using the following three load cases in 3-2/Table 7. Each case should be applied on the pressure and suction sides to determine the weaker direction.

## TABLE 7
## Blade Failure Load Cases

| *Load Case* | *Description* | *Location of Pressure* |
|---|---|---|
| Load Case $F_{ex1}$ | Constant pressure in the area above 0.6 $r/R$. Chord wise until 50% towards leading edge and 50% towards trailing edge. |   |
| Load Case $F_{ex2}$ | Constant pressure in the area above 0.6 $r/R$ but only on the leading edge half of the propeller blade. |   |
| Load Case $F_{ex3}$ | Constant pressure in the area above 0.6 $r/R$ but only on the trailing edge half of the propeller blade. |   |

Ramped loads in the form of uniform surface pressures (normal to the surface) were applied to the example blade for each of the three load cases, on both the pressure and suction side, until an element in the model reached an equivalent stress of 574.5 MPa. The pressure side for Load Case 1, shown in 3-2/Figure 5, required a load of 4,438 kN to reach the failure stress of 574.5 MPa. The suction side required slightly more load (4,520 kN) to reach the failure stress. The other load cases required even larger loads. Therefore, the $F_{ex}$ from the finite element analysis is 4,438 kN.

**FIGURE 5**
**Failure Load FEA - Pressure Side Load Case $F_{ex1}$**




As the $F_{ex}$ from the FEA was lower than the calculated failure load, the $F_{ex}$ for the example propeller blade would be 4,438 kN.

## 5 Additional Analysis

The ABS Ice Class Rules (Part 6, Chapter 1 of the *Marine Vessel Rules*) require several additional machinery analyses to be compliant with the Rules. These analyses include propeller fatigue, shafting strength, shaft fatigue, and shaft vibrations. These analyses can be difficult to perform and are arrangement dependent. Please contact Polar@eagle.org for guidance on these analyses.