E-9093
Ice Class Ship Structures

by
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Part 2 – Overview of Polar Rules
Development of Polar Rules

Work began as a “Harmonization: effort

1993 – 2006 work at IMO/IACS to rationalize and simplify ice classes

IMO Guidelines provide framework for design and operation

IACS Unified Requirements provide specific structural and machinery requirements
Development of Polar Rules

The Polar classes have been developed by IACS to establish a common system of ice classes.
PC classes bring together the experiences of many prior rule systems, including those of several Classification societies and Governments, including:

- Canadian ASPPR/CAC (9 Classes)
- Russian MRS/NSR (9 Classes, 4 Icebreaker)
- Finnish/Swedish (Baltic) (5 Classes)
- ABS (USCG) (5 Polar, 5 Baltic Classes)
- DNV (3 Icebreaker, 3 Polar, 5 Baltic Classes)
- LR (5 Polar, 5 Baltic Classes)
- Other classification societies
### Polar Class descriptions

<table>
<thead>
<tr>
<th>Polar Class</th>
<th>Ice Description (based on WMO Sea Ice Nomenclature)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC 1</td>
<td>Year-round operation in all Polar waters</td>
</tr>
<tr>
<td>PC 2</td>
<td>Year-round operation in moderate multi-year ice conditions</td>
</tr>
<tr>
<td>PC 3</td>
<td>Year-round operation in second-year ice which may include multi-year ice inclusions.</td>
</tr>
<tr>
<td>PC 4</td>
<td>Year-round operation in thick first-year ice which may include old ice inclusions</td>
</tr>
<tr>
<td>PC 5</td>
<td>Year-round operation in medium first-year ice which may include old ice inclusions</td>
</tr>
<tr>
<td>PC 6</td>
<td>Summer/autumn operation in medium first-year ice which may include old ice inclusions</td>
</tr>
<tr>
<td>PC 7</td>
<td>Summer/autumn operation in thin first-year ice which may include old ice inclusions</td>
</tr>
</tbody>
</table>
Polar Classes

In many circumstances class selection will depend on an analysis of ice statistics, owners experience, ice expertise and financial/economic considerations. The Polar Rules give on general guidance. All Polar classes can find ice that will damage the structure. Class selection is a balance among ice conditions, operational requirements and cost.
Class Selection

Selection of class can be easy or difficult, depending on the situation.

When the ship is intended for a specific route and operation in one of the controlled arctic shipping regions, the required class is set by the shipping control regime.

For example:
- Russia – ice passport, NSR regulations
- Baltic – FMA escort regulations
- Canada – ice numeral system
PC Concept of Loads

Polar Rules are based on the concept that ice loads can be rationally linked to a design scenario. The design scenario is a glancing collision with an ice edge (edge of a channel, edge of a floe). This scenario is valid for both independent and escorted operations.
PC Ice Load Concept

Scenario: ship striking an ice edge.
Ice Load Derivation

Normal Kinetic Energy = Ice Indentation Energy

↓

Find indentation → Find force, area, pressure.

Exact Solution Simplifies to:

\[ F_n = fa \cdot P_0^{0.36} \cdot V_{ship}^{1.28} \cdot M_{ship}^{0.64} \]

Becomes Rule Equation:

\[ F = fa \cdot CFc \cdot D^{0.64} \]
Ice Load Derivation

Ice edge indentation.
Ice Load Derivation

Normal Kinetic Energy = Ice Indentation Energy

Find indentation → Find force, area, pressure.

\[ KE_{normal} = IE_{ice} \]

\[ \frac{1}{2} M_e \cdot V_n^2 = \int_0^{\delta_m} F_n(\delta) \cdot d\delta \]

\[ \frac{1}{2} \frac{M_{ship}}{Co} \cdot (V_{ship} \cdot l)^2 = Po \cdot ka^{1+ex} \int_0^{\delta_m} \delta^{2+2\cdot ex} \cdot d\delta \]

Solve for \( \delta \) → then solve for Force

Ice Class Ships pt 2
Ice Load Derivation

Exact Solution is:

\[ F_n = (3 + 2 \cdot ex)^{2+2\cdot ex \over 3+2\cdot ex} \cdot Po^{1 \over 3+2\cdot ex} \cdot \left( {\tan(\phi / 2) \over \sin(\beta') \cdot \cos^2(\beta')} \right)^{1+ex \over 3+2\cdot ex} \cdot \left( {1 \over 2} \Delta_n \cdot V_n^2 \right)^{2+2\cdot ex \over 3+2\cdot ex} \]

Simplifies to:

\[ F_n = fa \cdot Po^{0.36} \cdot V_{ship}^{1.28} \cdot M_{ship}^{0.64} \]

Becomes Rule Equation:

\[ F = fa \cdot CFc \cdot D^{0.64} \]
Ice Load Derivation

Also from $\delta$ and Force:

- Pressure: $p = F_{n}^{2.22} \cdot CF_{D}^{2} \cdot AR^{0.3}$
- Line load: $Q = F_{n}^{-61} \cdot CF_{D} \cdot AR^{-0.35}$
- Width: $w = F / Q$
- Height: $b = Q / p$
Class Factors

The higher class factors represent increasing ice thickness, ice strength and ship speed.

<table>
<thead>
<tr>
<th>Polar Class</th>
<th>Crushing Failure Class Factor (CFc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC1</td>
<td>17.69</td>
</tr>
<tr>
<td>PC2</td>
<td>9.89</td>
</tr>
<tr>
<td>PC3</td>
<td>6.06</td>
</tr>
<tr>
<td>PC4</td>
<td>4.50</td>
</tr>
<tr>
<td>PC5</td>
<td>3.10</td>
</tr>
<tr>
<td>PC6</td>
<td>2.40</td>
</tr>
<tr>
<td>PC7</td>
<td>1.80</td>
</tr>
</tbody>
</table>
Rule Load:

The whole bow is to be designed with one load patch. To arrive at the design load, 4 specific values are calculated. The largest of $F$, $Q$ and $p$ are used in the assembles bow design load.

\[
F = \max(F_1, F_2, F_3, F_4)
\]
\[
Q = \max(Q_1, Q_2, Q_3, Q_4)
\]
\[
p = \max(p_1, p_2, p_3, p_4)
\]

\[
w = \frac{F}{Q}, \quad b = \frac{Q}{p}
\]
Hull Areas

The areas other than the bow are designed for a portion of the bow load. The hull areas are defined based on the shape and waterlines of the vessel.
Hull Area Factors

The hull area factors are applied to a standard (for all vessel shapes) bow load patch.

<table>
<thead>
<tr>
<th>Hull Area</th>
<th>Area</th>
<th>Polar Class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>PC1</td>
</tr>
<tr>
<td>Bow (B)</td>
<td>All</td>
<td>B</td>
</tr>
<tr>
<td>Bow</td>
<td>Icebelt</td>
<td>Bli</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Bli</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>Blb</td>
</tr>
<tr>
<td>Midbody (M)</td>
<td>Icebelt</td>
<td>Ml</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Ml</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>Mb</td>
</tr>
<tr>
<td>Stern (S)</td>
<td>Icebelt</td>
<td>Sl</td>
</tr>
<tr>
<td></td>
<td>Lower</td>
<td>Sl</td>
</tr>
<tr>
<td></td>
<td>Bottom</td>
<td>Sb</td>
</tr>
</tbody>
</table>
Polar Class Structural Rules

• Ice loads based on ice mechanics
  – Rectangular load patch, with horizontal orientation
  – Uniform pressure patch, with P/A effects in pressure term
• Structural design based on realistic plastic response
  – analytical (energy) solutions, verified by FE analysis (and lab tests)
  – plate folding for shell plate
  – bending/shear considerations for frames
  – Simple buckling-based slenderness limits
Plate requirements

– plate folding based on perfectly plastic hinge formation
– equate internal plastic work with external work
– gives nominal plastic capacity (>2 x yield)
– small plastic strains (shown by FE analysis)
– substantial membrane & material reserve (little chance of rupture)
Plate requirements

\[ t = 0.5s \sqrt{\frac{p}{FY}} \cdot \frac{1}{1 + 0.5 \frac{s}{b}} \]

similar to plastic collapse formula for uniformly loaded plate

s/b term reflects load height effect
12.4 - Shell Plate Requirements

12.4.1 The required minimum shell plate thickness, t, is given by:

\[ t = t_{net} + t_s \text{[mm]} \]  \hspace{1cm} \text{[Equation 16]}

where  \( t_{net} \) = plate thickness required to resist ice loads according to 12.4.2 [mm]
\( t_s \) = corrosion and abrasion allowance according to 12.11 [mm]

12.4.2 The thickness of shell plating required to resist the design ice load, \( t_{net} \), depends on the orientation of the framing.

In the case of transversely-framed plating (\( \Omega \geq 70 \text{ deg} \)), including all bottom plating, i.e. plating in hull areas \( B_{fb}, M_b \) and \( S_{fb} \), the net thickness is given by:

\[ t_{net} = 500 * s * \left( \frac{(AF * \text{PPF}_p * P_{av})}{\sigma_y} \right)^{0.5} / (1 + s / (2 * b)) \text{[mm]} \]  \hspace{1cm} \text{[Equation 17a]}

where  \( s \) = transverse frame spacing in transversely-framed ships [m]
\( AF \) = Hull Area Factor from Table 3
\( \text{PPF}_p \) = Peak Pressure Factor from Table 2
\( P_{av} \) = average patch pressure according to Equation 15 [MPa]
\( \sigma_y \) = minimum upper yield stress of the material [N/mm²]
\( b \) = height of design load patch [m], where \( b \leq (a - s/4) \) in the case of [Equation 17a]
\( l \) = distance between frame supports, i.e. equal to the frame span as given in 12.5.5, but not reduced for any fitted end brackets [m]. When a load-distributing stringer is fitted, the length \( l \) need not be taken larger than the distance from the stringer to the most distant frame support.
Frame requirements

• **3 limit states checked**
  - Two involve shear/bending resulting in interaction effects
  - Third is pure shear

• **Frame design allows tradeoffs**
  - Over-capacity in web area allows saving in modulus and v.v.

• **Design point is post-yield, but still quasi-elastic**
  - Permanent deflections are \(~0\), with significant strength reserve.
Frame requirements

- Design point is onset of permanent deflections.

![Graph showing 'Simple' Plastic Theory and Actual Structural Behavior]
Frame requirements

1\textsuperscript{st} limit state – 3 hinge formation

Rule requirement for plastic modulus:

\[ Z_p = \frac{P \cdot b \cdot S \cdot L}{8 \cdot \sigma_y} \left(1 - \frac{b}{2 \cdot L}\right) \cdot \frac{2}{2 + kw \cdot \sqrt{1 - \left(\frac{A_o}{A_w}\right)^2} - 1} \]
Frame requirements

2\textsuperscript{nd} Limit state: shear panel formation

Rule requirement for plastic modulus:

$$Z_p = \frac{P \cdot b \cdot S \cdot L}{8 \cdot \sigma_y} \left(1 - \frac{b}{2 \cdot L}\right) \frac{8}{(1.1 + 5.75 \cdot k\gamma^7)} \left[1 - \frac{Aw}{2 \cdot Ao \left(1 - \frac{b}{2 \cdot L}\right)}\right]$$
Frame requirements

3rd Limit state : end shear

Rule requirement for min web area: $Aw = Ao$
Frame requirements

- 3 limits in the design space for modulus and area.

3 hinge:

\[
\frac{Z_p}{Z_o} = \frac{1}{2 + k_w \sqrt{1 - \left(\frac{A_o}{A_w}\right)^2} - 1}
\]

end shear:

\[
\frac{Z_p}{Z_o} = \frac{4}{(1.1 + 5.75 \cdot k_z^7)} \left[ 1 - \frac{A_w}{A_o} \cdot \frac{1}{2 \cdot \left(1 - \frac{b}{2 \cdot L}\right)} \right]
\]
Experimental validation

- Experimental results show stable post-yield behavior

Load-deflection curves for points under the load patch
**STePS² Structures Experiments:**
Ship Grillage can withstand 10x yield, 6x PC load, with minor effect (dent but no fracture) true limit not reached.
UR structural requirements - summary

– plastic capacity with substantial reserve at design load levels
– analytical energy methods give useful design equations
– validation by non-linear FE analysis, and experimentation
– multiple limit states for frames (improved mechanics)
– ‘design’ effort required (by users) to satisfy multiple and interacting effects
  • gives flexibility for designer
  • more realistic structural behavior
  • aim: safer, economical structures.
end of introduction to PC rules