Polar Ship Design Standards – State of the Art, and Way Forward

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The IMO Polar Code is moving towards finalization, with implementation planned within the next few years. Under the Code, the IACS Unified Requirements for Polar Class Ships will become the standard for all new construction of vessels intended for operations in polar ice. This paper reviews the history and background of the UR development in the context of IMO’s work. It addresses some aspects of design that often need special consideration to meet owner’s operational requirements, and areas in which the current URs are based on limited knowledge and data. The paper also discusses instrumentation for ice-going ships, and its uses both for operational guidance and for data collection to support future rule and standard development.

KEY WORDS: polar, ice class, scantlings, plastic design

INTRODUCTION

The IACS Unified Requirements for Polar Class Ships (International Association of Classification Societies, 2007) were first published in 2007, and are now incorporated into IACS member class rules as either the sole basis for class for higher ice class ships (e.g. ABS, LR) or as one alternative approach (e.g. DNV, Russian Maritime Register of Shipping). They are being used to develop designs for an increasingly wide range of ship types. However, there is still considerable uncertainty amongst shipowners, shipyards and naval architects as to how the ice classes should be selected, applied in design, and interpreted in operation.

This paper addresses only UR I.1: Polar Class Descriptions and I.2, Structural Requirements. I.3, which addresses machinery is not covered. The paper aims to provide some of the background to the development of the URs, and a discussion of aspects which can be considered “scientific”, empirical, and purely pragmatic. Some guidance is provided on how aspects of the UR approach can be applied to structural design aspects that are not covered explicitly by the URs themselves, and which are interpreted rather differently by various classification societies.

Ship-ice interaction cannot be considered a mature area of engineering, and there are numerous uncertainties in how ice loads are experienced by different areas of the hull under various interaction scenarios. The paper discusses some of these, and suggests how future data collection and research may help improve design efficiency and operational safety.

BACKGROUND

The IACS Unified Requirements for Polar Class Ships (IACS UR I.1-3), first published in 2007, were one of two outcomes from work during the 1990s that aimed to standardize approaches to the regulation of operations in polar waters. The other outcome was the IMO “Guidelines for Ships Operating in Arctic Ice-covered Waters”, which were originally published in December 2002, as MSC Circular 1056/MEPC Circular 399. They were subsequently updated and extended under IMO resolution A.1024 as “Guidelines for Ships Operating in Polar Waters”. Currently, work is in its final stages to replace the Guidelines with a mandatory Polar Code, which will be implemented as a set of amendments to the SOLAS and MARPOL conventions anticipated to come into effect in 2016.

The rationale for the parallel development of IMO and IACS approaches has remained similar throughout this lengthy process. IMO does not, in general, aim to set technical standards. Rather, it provides a framework within which such standards or other methodologies can be applied. Recently, the formal adoption by IMO of the “goal-based” regulations has formalized this expectation. IMO’s goals, supported by functional requirements and (in general) performance-based requirements are expected to be implemented in design and operation by standards such as classification society rules, international standards such as ISO and IEC, etc.

The new Polar Code refers to the IACS URs in Chapter 3, Structure, and Chapter 6, Machinery using standard IMO wording, as follows:

“Scantlings… …shall be approved by the Administration, or a recognized organization accepted by it, taking into account standards acceptable to the Organization1 or other standards offering an equivalent level of safety.”

The footnote reference calls up the URs themselves; “the Organization” is IMO. It can be seen that the use of alternative standards is not rules out, but the onus is put on the shipowner to demonstrate that an equivalent level of safety will be provided. This is likely to increase the use of UR-based rules, and decrease the attractiveness of other approaches.

DEVELOPMENT PRINCIPLES FOR THE URs

The development process for URs I1-3 was quite unlike the normal IACS approach. This was partly because they were intended to be a complement to the IMO work. It was also due

1 Refer to Polar Class 1-5 of IACS Unified requirements for Polar Ships (UR I1 and 13 (Oct.2007) and UI I2 (Nov. 2010))
to the recognition that much of the expertise relevant to their development would come from outside the classification societies themselves. The working groups under IACS therefore had considerable external representation by experts nominated by various National Administrations. The work was extensively documented and debated over a period of many years. Working papers and supporting data cover many metres of shelf space and gigabytes of electronic information.

A key element of the overall development was to agree on the upper and lower capability bounds for polar ships, and to decide on the number of polar classes that would be appropriate. The high end capability was relatively easy to define. This Polar Class (PC) 1 ship was to be capable of operating safely anywhere in the Arctic or Antarctic oceans at any time of year (though safe operation would still require due caution). At the low end, it was acknowledged that much current Arctic and Antarctic summer traffic is carried out by vessels with Baltic ice classes, but also that a number of experienced operators have added features over and above the notional Baltic class requirements. Therefore, the lower threshold was set at a capability level similar to Baltic IA. Between the upper and lower bounds, changes in capability (and therefore cost) should be at manageable increments.

Eventually, seven Polar Classes were adopted, as listed in Table 1. As can be seen, the ice capability descriptions included are rather cursory. This was deliberate, as the wide variety of ways in which ships can be operated in polar waters precludes being overly precise when defining basic classes. One change that is currently under consideration under guidance from the IMO is to make the definitions even more general, by removing any reference to “summer/autumn” operation for the PC 6 and 7. This reflects experience in areas such as Western Greenland, where relatively light ice conditions may be found year round but where operations are definitely “polar” rather than Baltic; due for example to the presence of a great deal of glacial ice and very low temperatures.

<table>
<thead>
<tr>
<th>Polar Class</th>
<th>Ice Description (based on World Meteorological Organization 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>
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<tr>
<td>PC 4</td>
<td>Year-round operation in thick first-year ice which may include old ice inclusions</td>
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<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>

ICE LOADS

Ships interact with ice in various ways, each of which will produce some level of loading on the hull. During the development of the URs, over 70 ice interaction scenarios were defined. Many of these were considered to be unlikely, or avoidable. Ramming an iceberg, for example, is a hazard in polar operation but should not necessarily be treated as a design case.

Ice-capable ship performance usually refers to the level ice thickness that can be broken continuously. The ice loads from this type of icebreaking are typically not the worst case loads for the ship. These are rather represented by impacts against heavy ice features, which may either be deliberate or unavoidable. Ships often have to ram ridges or thicker ice, and the impact velocities will typically be higher than the level icebreaking speed in the same conditions.

An impact load model was therefore developed as the basis for the UR structural requirements. This builds on the classical work of the Russian scientist Popov (Popov, 1967), extended by Daley (Daley, 1999) to provide a more complete and general solution. The ship penetrates into the ice by crushing (Fig. 1), and the maximum force is a function of ship (and ice) shape, velocity, and ice crushing strength, as shown in Equation 1:

\[ F_n = fa \cdot Po^{0.36} \cdot V_{ship}^{1.28} \cdot M_{ship}^{0.64} \] (1)

Where \( fa \) captures the shape terms (full derivation can be found in Daley), \( V \) and \( M \) the ship velocity and displacement, and \( Po \) the ice strength.

For larger ships, the total force may be limited by breaking the ice in bending. Each polar class is therefore defined by ice thickness and crushing and flexural strength, and by an assumed ship speed. All of these parameters are combined into a set of class factors for the PCs 1 to 7. Hull (bow) shape and ship displacement are specific to the ship under consideration.

![Design Ice Impact Scenario](image-url)
factor in ice-capable structural design. Over small areas, ice pressures can be extremely high (up to 50 MPa). However, at a structural design scale of 0.1 m² (e.g. a 0.3 x 0.35 m plate panel) or larger the average pressures are much lower; and by a 1 m² scale average pressures on even larger, high ice class ships are in the 5 MPa range. The UR ice load model provides an average pressure value for the load patch, and uses peak pressure (intensification) factors to adjust this average in the design of smaller structural components.

Loads are derived directly only for the bow region, which is the area of the hull that has been subjected to most extensive experimentation over the years. For other areas of the hull, as shown in Fig. 2, reduced loads are defined using a set of hull area factors. Area factors are common to most previous ice class systems, and the URs use those values that appear to have been appropriate, based on actual service experience. As an example, a class of vessels such as the SA-15 cargo ship or the ‘Terry Fox’ class icebreaker may have more - or less - damage in the bow than in the midbody. The former case would indicate that the midbody was relatively over designed; the latter that it was under designed.

A large database of ice-going vessels was assembled and assessed in this manner in order to select realistic area factors. The other major use of this ship database was to select the overall class factors that define each polar class. Existing ship structures were analyzed against the requirements for PC 1-7, and the known structural performance of the ship was assessed against the broad operational descriptions in Table 2. It was expected (and desired) that a ship such as a Russian nuclear icebreaker would turn out to comply largely with a PC 1 classification, and that some of the Baltic and ‘Baltic plus’ bulk carriers with successful Arctic service experience would meet PC 6 and 7 structural requirements. The bounding class factors were calibrated in this way (see also below). As outlined earlier, the intermediate ice classes/class factors were set at intervals that give relatively consistent increments in capability.

Since the URs first came into effect, there have been a number of other analyses of how existing ice-classed ships compare to the requirements. The USCG ‘Polar Star’, ‘Healy’ and (new) ‘Mackinaw’, all of which were developed using in-house standards of various vintages show different levels of compliance for structural components and hull areas, with the newest (‘Mackinaw’) showing the closest match to the PC requirements at a PC 4 strength level (Yu, 2012). For the older ships, the plating tends to be stronger than the framing when matched to the UR criteria. This is expected and reflects the deliberate approach in the URs to rebalance more traditional structural arrangements. “Good” steel plating has great reserves of strength against overload.

**STRUCTURAL RESPONSE**

The URs approach structural design requirements with a similar philosophy to that utilized in the Russian and Canadian ice class standards developed in the 1990s. Peak ice loads are expected to be relatively infrequent events for any given structural component. Therefore, rather than using first yield as a design point (as in most other ship design standards) the URs for plating and framing are based on the formation of elasto-plastic response mechanisms; i.e. the creation of systems of plastic hinges.

The plate response formulae look reasonably familiar to many structural engineers:

\[
t = 0.5t \sqrt{\frac{p}{FY}} \left(1 + 0.5 \frac{L}{b}\right)
\]

where  
- \(t\) = required plate thickness (mm)  
- \(p\) = pressure (MPa)  
- \(FY\) = yield strength (MPa)  

and dimensions are as shown in Fig 3 below.

Equation (2) defines the onset of the system of hinges shown in Fig. 3, which can vary depending on plate aspect ratio and on whether the plate is fully loaded or strip loaded, as shown.
The frame design equations are more unusual. They reflect a system of hinges some of which combine bending and shear effects, which interact. The distribution of shear stress across a section will reduce its effective section modulus in bending, and bending stresses affect shear capacity. There is thus not a single design point for an ice frame, but a design domain in which various combinations of cross section sheet area and section modulus are possible and can be selected on the basis of availability, configuration, weight and producibility. The system of equations (3) and (4) found in the URs (as equations 22/23 and 24/25 in UR I2) has to be solved iteratively, which can be done quite easily for example in an Excel™ macro.

Minimum shear area, \( A_m = 100^2 \times 0.5 \times LL \times s \times (AF \times PPF_m \times P_{avg}) / (0.577 \times \sigma_y) \) [cm²] \( (3) \)

Minimum section modulus, \( Z_{pm} = 100^3 \times LL \times Y \times s \times (AF \times PPF_t \times P_{avg}) \times a \times A_t / (4 \times \sigma_y) \) [cm³] \( (4) \)

The complex terminology used in these equations is explained fully in the URs themselves, the key term for this discussion being a in equation (4), which is:

\[ a = A_m / A_{it} \]

i.e. the ratio between minimum and actual shear area.

Framing instability is avoided by using a series of equations (5), (6) that apply slenderness ratios and flange outstanding criteria for flat bars, bulb, angle and T-sections.

For flat bar sections:  \( h_w / t_{wn} \leq 282 / (\sigma_y) 0.5 \) \( (5) \)

For bulb, tee and angle sections:  \( h_w / t_{wn} \leq 805 / (\sigma_y) 0.5 \) \( (6) \)

where  \( h_w = \) web height  
\( t_{wn} = \) net web thickness  
\( \sigma_y = \) minimum upper yield stress of the material [N/mm²]

These criteria are drawn from elastic design practice, and have been demonstrated by subsequent experimental to be quite conservative, particularly for flat bars and bulbs. This conservatism is a significant constraint on design options and is one of a number of limitations which it would be desirable to address in future revisions to the URs.

It should be understood – and emphasized – that the ice loads and structural criteria form a “system” that is calibrated against service experience. There is insufficient understanding of ice load mechanisms to allow for the use of finite element (FE) methods to optimize the plate and frame design, and attempts to do so can lead to poor design decisions. It can be necessary to use FE and other techniques to develop other aspects of the design, and this has to be done cautiously (see below).

**LIMITATIONS**

Some of the limitations of the URs have been touched on earlier, but warrant a more detailed explanation.

While the approach to ice loads is physics-based, it is completely reliant on empirical calibration factors. These factors were drawn from a limited population of ships and ship types, most of which were quite small vessels. The rule formulations are extrapolated to larger displacement vessels using coefficients that were selected to be conservative. In recent years much larger ships of high ice class have been designed and built, and it is possible – or even probable – that some if not all areas of these ships are over-designed; certainly there are no known instances of damage to them. It is therefore very important that service data from larger ships is collected and fed back into future updates of the URs. To give an example of the significance of this, in a recent project the shell plate and first level framing weights for an existing Baltic ice class LNG tanker were compared with those needed for various levels of Polar Class. At a PC 4 level, the weight is over 150% of the base case, and at PC 2 this becomes over 300% (an increase of over 7,000 tonnes). The impacts on both construction cost and cargo capacity are obviously very significant.

The scope of the URs covers shell plate and first level framing, and also addresses hull girder strength. However, the URs do not provide much guidance for deep structure such as web frames, stringers, decks and bulkheads. A number of classification societies have developed their own requirements for these components; these are quite different from each other and none has been subjected to much (published) validation. The longest-established procedure is probably that of the Russian Maritime Register, which incorporates an analytical grillage approach for web frames and stringers. ABS has a somewhat similar technique. Neither is well-suited to plate structures. It is generally accepted that the deeper structure should have a larger load reserve capacity than the outer shell, to avoid premature collapse due to mechanisms such as buckling (or fracture). This can be tested by developing non-linear models of the overall structure to check that overall load-bearing capacity continues to increase beyond the design point for the shell plate and framing.

However, few organizations have much experience in developing the types of models that are needed to explore large deflection response with any credibility. They are also relatively expensive to create and to exercise. How to model the ice load itself during a progressive collapse is highly uncertain, as it will migrate along the hull (in any impact scenario) and also be redistributed when the structure deforms. Some work has been undertaken to explore the importance of these aspects of loading (e.g. (Quinton, 2012)), but it is a long way from maturity.

Another key limitation that should be understood is that the URs do not provide much guidance on how to select ice class, or how...
to operate safely. The descriptions in Table 2 are quite generic. The design load for each class results from an impact with a very large and hard ice feature, at a given speed. In real operations, a ship will encounter a wide range of conditions, for some of which its attainable speed may be constrained by its power (icebreaking capability) while in others it should be set by structural safety. However, there is currently no generally accepted system for matching speed to ice conditions, and it is a formidable task to do so. For many years, the Russian administration has required an “Ice Passport” (or Ice Certificate) to be carried on ships using the Northern Sea Route and in other Russian waters. This matches speed to ice conditions using a variant of the Popov approach and a range of assumptions; the methodology is poorly documented and not directly compatible with the UR design approach. More recently, work has been reported by Dolny (Dolny, 2013) to provide a more comprehensive treatment of the problem, but not (yet) to offer a complete solution. Fig. 4 below shows, for a single set of ice floe properties, the impact speeds at which various locations on the bow will exceed the structural design load.

**Figure 4. Limiting speed at various impact locations**

This type of approach can offer some insights into bow loads (and stern loads, for “double acting” ships) but at this point can give no guidance into loads on other waterline areas during ship manoeuvres, or loads below the waterline resulting from forcing ice pieces downwards during icebreaking (or under close escort). As an example of the implications, bilge keels are fitted to a number on Baltic ice class ships. Their track record in Arctic operations is quite poor, with many damage incidents. However, the circumstances in which these damages have taken place are generally quite unclear, and the same applies to most other incidents of lower hull damage.

**INSTRUMENTATION**

Much of what we know about polar ice loads on ships is the result of instrumentation campaigns in the 1980s, when a number of vessels of various types were tested in a variety of ice conditions. Notable examples include the USCG Polar Sea, the CCG Louis St. Laurent, the Oden, various Beaufort Sea icebreaking supply vessels, and the M.V. Arctic. This work was complemented by programs in the Baltic, where many of the techniques used originated.

In recent years there have been relatively few similar instrumentation projects in the Arctic, and their results have generally not been widely disseminated. Instrumentation technology has improved considerably over the period, which makes projects easier and cheaper to implement, and can give any sensor fit much greater potential longevity. New systems can use fibre optic strain gauges, which are inherently more reliable than older types and much less susceptible to electromagnetic interference. Measurement of ship motions, important to the calculation of global loads, used to rely on bulky and highly temperamental gyro-stabilized platforms and can now use solid state accelerometer/inclinometer packages. Speed measurement in ice used to be quite difficult, and in early trials relied on throwing objects over the side and timing the ship’s progress past them. There is now a range of technologies which can do much better than this!

This can be seen in such recent examples as the installations on Norwegian Coast Guard icebreaker KV Svalbard (Fig. 5) and one of the Sovcomflot Varandey shuttle tankers (Fig. 6), both of which are believed to have been operating successfully for a number of years, and thus allowing not only for the collection of dedicated ice trials data but also for the collection of longer-term statistics.

**Figure 5. ILM System on the KV Svalbard (Mejleander-Larsen, Arctic Oil and Gas Operations TEKNA Feb 2008)**
These types of projects are extremely important to the future development of the URs; which as noted earlier are physics-based but wholly reliant on empirical coefficients for calibration. Extrapolations to larger ships, providing more information to owners and operators on the capabilities and limitations of their ships in a wider range of ice conditions, and exploration of how ice loads influence a wider range of structural configurations are all important issues. These systems also provide real-time information to the operators, to assist in adjusting the operation to the prevailing ice conditions. There is a huge amount of scatter in ice load measurements, as so many different parameters affect the total load and local pressure for each individual impact. Also, it is impractical to provide complete sensor coverage of the hull. However, operator guidance systems at the very least can give a general impression of the level of risk posed by the ice conditions, and so whether it is prudent to adjust speed and reduce the aggressiveness of any manoeuvres.

CONCLUSIONS
IACS URs 1 - 3 were developed based on a comprehensive review of the strengths and weaknesses of other ice class rules, and were tested and calibrated against a wide range of experimental data and field experience. As such, they were and are the best available system to use in polar ship design. However, they are neither complete nor perfect as a basis for design, and are only a starting point in providing any guidance for operations. Their use by owners and designers needs to appreciate these limitations.

There is a need for continuing the development of the URs to offer better solutions for larger ships, alternative structural configurations, and other aspects of design. This should be based on continued efforts to develop a better understanding of the ice loads themselves, and how these can be represented both quasi-statically and dynamically. Collection of field data will be a key component of this work. Cooperative research programs involving a range of stakeholders may be the best route towards ensuring that such data is not only collected but that it is made available. National administrations (and Class, acting on their behalf) need to have confidence that design approaches are robust, and that operators will be provided with appropriate guidance on how to operate within their ship’s capabilities and limitations.

ACKNOWLEDGEMENTS
Much of the author’s work in this field has been made possible by the support of the Transport Canada, which has also funded many data collection projects over the last several decades and has contributed greatly to the current state-of-the-art.

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