POAC'13
Espoo, Finland

Proceedings of the 22nd International Conference on
Port and Ocean Engineering under Arctic Conditions
June 9-13, 2013
Espoo, Finland

DEVELOPING A TECHNICAL METHODOLOGY FOR THE EVALUATION OF SAFE OPERATING SPEEDS IN VARIOUS ICE CONDITIONS

John Dolny [1], Han-Chang Yu [2], Claude Daley[3], Andrew Kendrick[4]

[1]ABS Harsh Environment Technology Center, St. John's, NL, CANADA

[2]ABS, Houston, TX, USA

[3]Memorial University of Newfoundland, St. John's, NL, CANADA

[4]STX Canada Marine, Ottawa, ON, CANADA

ABSTRACT

The International Maritime Organization (IMO) has adopted *Guidelines for Ships Operating in Polar Waters* (2010), formally recognizing the need to mitigate the additional risks resulting from increased development of natural resources and marine traffic in the Arctic and Antarctic regions. An effort is underway to develop a mandatory and comprehensive Polar Code. It has been agreed among IMO delegations to require an onboard Polar Water Operational Manual (PWOM) which is to include guidance for safe navigating speeds in ice. Ultimately, this may have significant implications for operators, ship owners and ship builders intending to mobilize assets in Polar regions.

The Russian authorities have long required all Russian Arctic-bound ships to maintain on board an Ice Passport (or Ice Certificate) which contains safe speed guidance as a function of the ship's structural configuration and anticipated ice conditions. This is the only known existing regime which explicitly regulates the speed of ships in ice. Other technical approaches to the concept of safe speed exist. Some are based on probabilistic methodologies while others rely on purely deterministic analysis.

This paper presents an overview of some existing technical approaches for safe speed guidance based on available literature. A proposed framework of a synthesized procedure for the evaluation of safe navigating speeds in various ice conditions is offered and a simple case study is provided for an Ice Class PC5 offshore supply vessel. Directions for future research are outlined with regard to the selection of ship-ice interaction scenarios, the influence of speed on flexural ice failure, and matching safe speed to suitable structural limit states.

INTRODUCTION

The risk of damage to the hull of a ship operating in ice will depend on many factors which include the ice conditions (thickness, strength and concentration), the ship structural particulars (shape of the hull, scantlings and structural arrangement) and the operational profile (speed and maneuvering). The most basic mitigation measure to reduce this risk is compliance with ice strengthening requirements (or ice class rules). These rules, developed and published by classification societies, provide a tiered system of minimum strengthening requirements for ships intended for ice operations. In 2007, the International Association of Classification Societies (IACS), under the guidance of IMO and with participation of concerned coastal state authorities, formally adopted a harmonized system of seven Polar ice classes, known as the Unified Requirements for Polar Ships (Polar UR). The Polar UR represents the latest industry standard, and several major classification societies have replaced their traditional ice notations with this harmonized system (ABS 2011). Furthermore, the current IMO *Guidelines for Ships Operating in Polar Waters* refer to the Polar UR as the primary construction standard.

In order to codify ice strengthening requirements, many assumptions and simplifications are necessary. Typically, a design ship-ice interaction scenario is assumed for the derivation of loading parameters. Values of ice thickness, ice strength and ship impact speeds may not be explicitly presented. Rather, they are often embedded in class-dependent coefficients to reflect a progressive increase in structural capacity for increasing ice classes.

Simple compliance with ice class rules does not provide a full representation of the ship's structural capabilities or limitations in various ice environments or operational modes. Additional analysis procedures are often sought by prudent designers, builders and owners to quantitatively place bounds on the ships' structural capabilities. One such approach is the analysis of safe navigating speeds.

SAFE SPEED ANALYSIS – EXISTING APPROACHES

The idea of an analysis procedure to determine safe navigating speeds in ice conditions is not novel. The earliest concepts of safe speeds were likely postulated by Russian scientists sometime in the 1960s and 1970s during the development of transportation regulations for ships operating in the Russian Arctic. The Ice Passport (often referred to as the Ice Certificate), was first introduced in the mid-1970s. One of its major components is the regulation of speed to mitigate the risk of hull damages due to ice

Russian Ice Passport

Maxutov and Popov (1981) provided a description of Ice Certificate requirements in one of the earliest available publications on its technical basis. They defined the safe limit speed as "the maximum speed under given ice conditions which ensures safe navigation". This limit speed, depicted by simple diagrams (such as the one presented in Figure 1), is determined by the available installed power and limitations in the hull structure. In addition to the limit speeds, other operational guidance is provided by the Ice Passport such as the minimum safe distance in the convoy and ice pressure resistance capabilities. The authors clearly note that while the Ice Certificate can provide the operator useful guidance, it cannot consider every possible ice condition or operating mode and the overall recommendation of operator due caution should be maintained.

In the late 1990s, at the request of Canadian authorities, a detailed report was prepared describing the scientific basis and methodology of the Ice Passport applied to CCG Pierre Radisson (Likhomanov et al. 1997; Likhomanov et al. 1998). The report included the ice load model procedures and the formulations to express the load-bearing capacity of framing members. The technical approach for safe speed guidance in the Ice Passport begins by establishing attainable speed curves in ice (v_{ship} vs. h_{ice}). Empirical and semi-empirical ice resistance formulations for level solid ice, hummocked ice covered in deep snow, high concentration pack ice, and cake ice are formulated considering the full installed main engine power. These attainable speed curves may also be established by model tests or ice trials. Critical state curves are developed to represent the load bearing capacity of local hull structural members. Expressed in terms of pressure, *p*, and load height, *b*, these limit states are derived using analytical beam theory or numerical finite element analyses (linear elastic and nonlinear static) of actual ship grillages. Two separate criteria are applied, first yield (zero plastic deformations) and the ultimate state (the formation of plastic hinges).

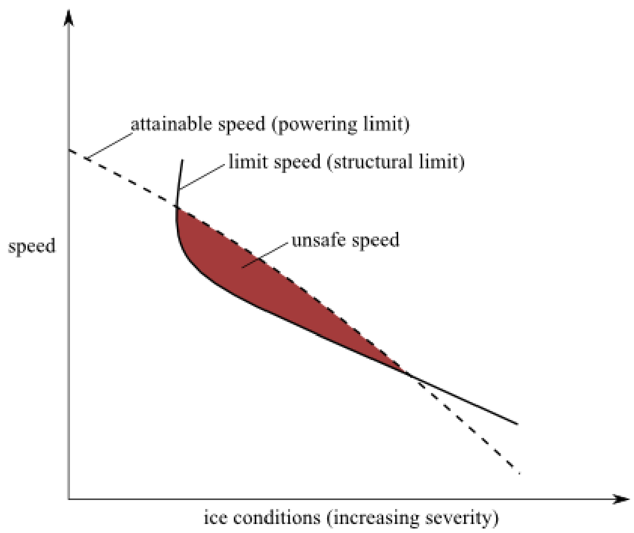


Figure 1. Sketch of safe speed diagram [from Maxutov and Popov (1981)]

The ice load parameters are based on Kurdyumov and Kheisin's velocity-dependent hydrodynamic model for local contact pressure (1976) coupled with Popov-type collision mechanics (Popov et al. 1967). This was one of the first analytical models that produced the basic ice load parameters from a given set of input conditions. The model is used to calculate the load parameters (p and b) over a range of ship speeds (v_{ship} = 2- 20 knots), ice thickness (h_{ice} = 0.25 – 4.0 m), floe size (50 m, 100 m, and infinite level ice), and impact locations (locations on the bow under two draft conditions). A solution scheme is devised to find the speed and ice thickness combinations corresponding to points on the critical state curves. Two different speed conditions are established, safe speed and dangerous speed. The *safe speed* curves, corresponding to the yield criterion, and the *dangerous speed* curves, corresponding to the ultimate state, are calculated for various floe sizes, physical states of structure (with/without wear), impact locations and failure criteria.

Probabilistic Approaches

Tunik et al. (1990) and Tunik (2000) recognized that the safe speed concepts applied in the Ice Passport hinged on pure deterministic analyses. He warned that compounding the most severe combinations of conservatively assumed critical parameters can ultimately lead to even higher levels of conservatism in the safe speeds. As an alternative, a probabilistic approach to safe speed analysis is offered. The impact location on the hull and the environmental ice parameters are treated as random variables and an analysis procedure is proposed to find the probability of load levels which exceed the structural capacity. Available distributions of ice concentrations, thickness, floe size and mechanical properties are utilized; however, it is noted that the parameters can vary significantly between regions. In addition, data availability is scattered and many sources are proprietary.

Recent Approaches

The approaches discussed so far each consider the hydrodynamic model of ice-solid body impact combined with Popov collision mechanics. This model is generally considered as the standard Russian practice and has been employed for over 40 years. Recently, alternative models have been utilized, some of which are tied directly to the pressure-area relationship which underlies the technical background of the Polar UR, which is described in more detail later in this paper.

Daley & Liu (2010) addressed ship ice loads in pack ice by modifying the Polar UR model to consider finite ice floes. Specifically, they explored the secondary impacts on the midbody following bow glancing events. Limiting speeds were established comparing the reflected load parameters with UR design values. This analysis demonstrated that secondary midbody collisions can be critical, especially for thick ice. While the structure was not directly analyzed, this study demonstrated the importance of considering off-design ship-ice interaction scenarios.

Daley & Kim (2010) studied ice collision forces considering structural deformation assuming a linearized plastic component of the structural response. An additional component (structural indentation energy) was introduced to the energy balance. To some degree, this approach circumvents the assumption of a rigid body. A regression analysis of grillages subjected to point loads using the nonlinear finite element analysis method was used to develop this plastic component. Limiting ship speeds were established against various masses of icebergs for different allowable deformation levels. The inclusion of structural deformation into the impact model is a fairly novel concept. It was shown to play a moderate role in the ice load mechanics and could be a direction for a safe speed regime.

In a position paper submitted by Finland and Sweden to IMO, Kolari & Kurkela (2012) consider the case of a bow glancing collision with a spherical glacial ice mass. Their model solves a system of motion equations in the time domain estimating hydrodynamic effects by added mass terms, and adopts a pressure-area model, though one divergent from the Polar UR, as discussed in more detail below. The safety criterion used is the elastic response similar to that of the Russian Ice Passport for *safe speeds*. More significant levels of plastic deformation, for example the three hinge collapse mechanism, could be implemented to establish the *dangerous* operating speeds. The selection of suitable limit states is a key area for debate with regard to safe speeds.

A PROPOSED FRAMEWORK

As discussed above, the concept of safe speeds is not new but there are varying approaches to the problem. At present, the demand for a common framework is being driven by development of international regulations at IMO. Therefore, it is proposed to develop a safe speed framework in line with existing ice strengthening requirements already endorsed by IMO. The technical methodologies should be grounded on modeling approaches adopted by the Polar UR. This will allow for the development of sound and transparent safe speed guidance with well-documented technical background.

Ice Load Model

The Polar UR ice load model was developed following a scientific approach based on a ship-ice collision scenario. Loading parameters are derived considering vessel operational scenarios, hull geometry, the strength of ice and its failure modes. The selected design scenario is a glancing impact with an infinite ice edge. The model incorporates “Popov” collision mechanics, which simplify the ship-ice collision to a single degree-of-freedom problem. This simplification is justified based on the assumption that the duration of the impact event is short and its location along the hull does not change much. The collision model is coupled with a process-pressure area relationship for the formulation of local pressures. It follows a coherent process to fully describe the ice load patch in terms of pressure (p), force (F), line load (Q), load patch width (w) and load height (b). A software tool has been developed to calculate the loading parameters given a unique set of input conditions.

The derivation begins with an energy balance between the initial effective kinetic energy of the ship normal to the impact and the ice crushing energy. The full derivations are described comprehensively in Daley (2000). The effective kinetic energy (1) considers the effective mass of the ship and ice (2). These terms reflect the reduced mass taking into account the location of the impact relative to the respective center of gravity (through directional cosines and moment arms), added mass terms in 6 DOFs, and mass radii of gyration. This is the mass reduction concept originally developed by Popov.

$$KE_n = \frac{1}{2} M_e V_n^2 \tag{1}$$

$$M_e = \frac{1}{\frac{1}{M_{eship}} + \frac{1}{M_{eice}}} \tag{2}$$

The crushing energy (IE) is taken as the integrated normal force over the normal penetrated depth into the ice as expressed in (3).

$$IE = \int_0^{\zeta_{max}} F_n(\zeta) d\zeta \tag{3}$$

In order to relate the force to indentation, a simple process pressure-area model is assumed and shown in (4 and 5). The ice exponent (ex) is assumed -0.1 in the Polar UR and the nominal ice strength (p_o) represents the pressure to crush 1 m^2 (Daley 2000). Figure 2 plots the assumed pressure area relationship for Ice Class PC5 and, as a comparison, the curve presented by Kolari & Kurkela (2012) is included to emphasize their own observation that the exponent (ex) and the nominal pressure have a significant effect on the loading parameters.

$$p = p_0 A^{ex} \tag{4}$$

$$F_n = pA = p_0 A^{1+ex} \tag{5}$$

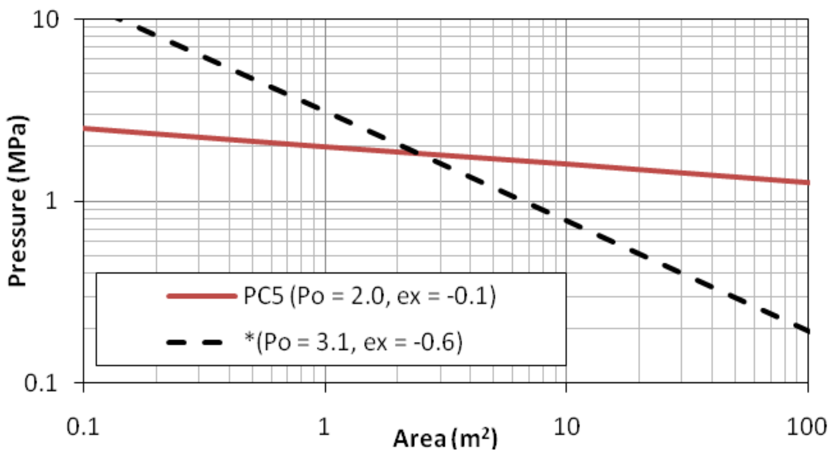


Figure 2. Pressure area relationships
* from Kolari & Kurkela (2012)

The normal contact area, A_n, can be expressed as a function of normal indentation, ζ_n. For a wedge-shaped edge, this function takes the form of (6). A sketch is provided in Figure 3 to further describe the process. This model can be adapted to permit the use of a variety of contact relationships and geometries.

$$A_n = \frac{\zeta_n^2 \tan(\phi/2)}{\sin(\beta')\cos^2(\beta')} \tag{6}$$

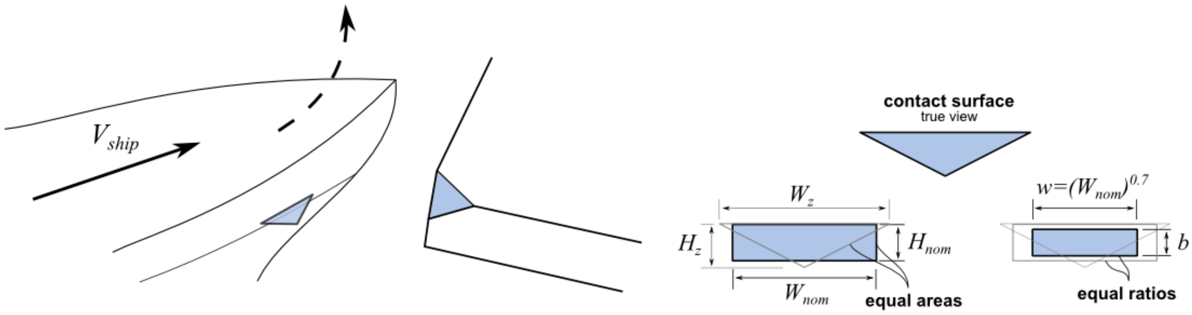


Figure 3. Wedge-edge collision scenario

Equating the kinetic energy and indentation energy considering (4 through 6) produces the following expression for the normal indentation of the collision (pure crushing, limited by momentum).

$$\zeta_n = \left(\frac{KE_n(3+2ex)}{p_o \left(\frac{\tan(\phi/2)}{\sin(\beta')\cos^2(\beta')} \right)^{1+ex}} \right)^{\frac{1}{3+2ex}} \tag{7}$$

The triangular shape of the normal contact surface is not directly applicable as a load patch for structural strength checks or FEA. A simple procedure is applied to translate the shape to a rectangular load patch then further reduced, maintaining a constant aspect ratio, to account for load concentration as ice edges spall off (process shown in Figure 3). The normal force is unchanged; therefore, the average pressure in the patch rises as a result of the reduction. The patch dimensions are calculated in (8 and 9).

$$w = \left(\frac{2 \cdot \zeta_n \tan(\phi/2)}{\sqrt{2}\cos\beta'} \right)^{0.7} \tag{8}$$

$$b = \frac{w}{2 \cdot \tan(\phi/2)\sin\beta'} \tag{9}$$

Flexural Ice Failure

For level ice, a flexural limit force is imposed to cap the maximum force induced by ice crushing. The limit equation assumed in the Polar UR (10) is quite simple, only dependent on ice thickness, flexural strength and the hull form. It simply matches the downward force component from the hull to the beam strength of the ice. The coefficient 1.2 was selected conservatively and considers a 150º wedge ice angle.

$$F_f = 1.2\left(\frac{h_{ice}^2 \cdot \sigma_f}{\sin(\beta')}\right) \quad (10)$$

This expression (or similar variants) is quite common in many ship-ice collision models. For very thick ice, as in the Polar Rules scenario, the simplification is reasonable. As the load progresses (by crushing), the force tends to reach the flexural limit towards the end of the crushing process (which otherwise would be limited by momentum). At this point, the vertical force component can be assumed static. However, for thinner ice and higher speed collisions, horizontal force components and dynamics can dominate. Daley et al. (2011) extended the simple flexural failure model to account for in-plane stresses, friction and speed effects (dynamics). This will prove to be a critical modification when performing a safe speed assessment. During the ship-ice collision process, the force can be divided into vertical and horizontal components. Incorporating a simple coulomb frictional coefficient ($\mu = 0.1$), those components can be expressed as:

$$F_h = F_n \cdot \cos(\beta') + \mu F_n \cdot \sin(\beta') \quad (11)$$

$$F_v = F_n \cdot \sin(\beta') + \mu F_n \cdot \cos(\beta') \quad (12)$$

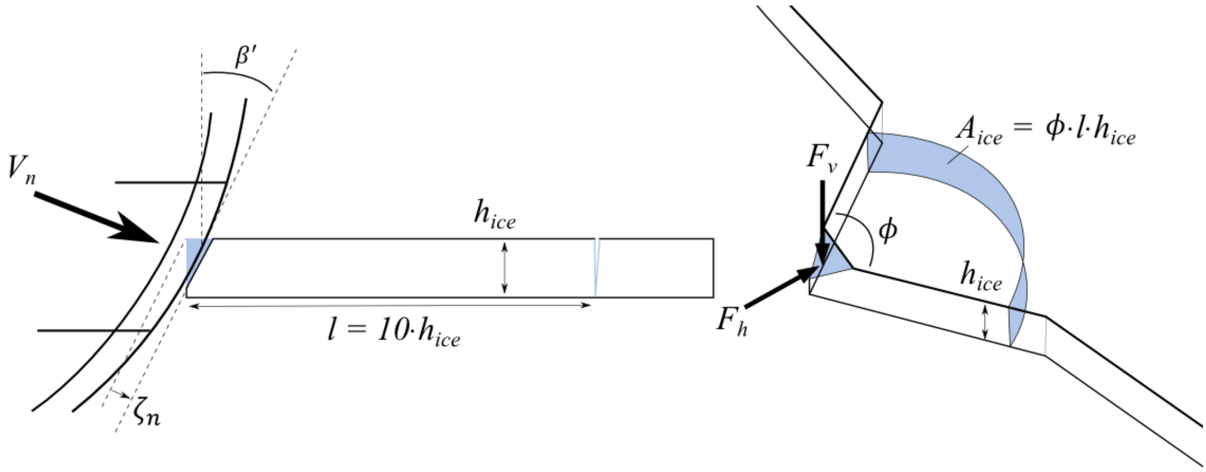


Figure 4. Flexural ice failure modification

The horizontal force component, F_h, will induce in-plane compressive stress, σ_{comp}, through the ice cross-sectional area A_{ice} as expressed in (13 and 14). For simplicity, the length of the cusp, l, is assumed to be 10 times the ice thickness. In fact, the length of the cusp is dependent on several factors including ice thickness, indentation rate, flexural strength, hull geometry, etc. This is an area of on-going research.

$$\sigma_{comp} = \frac{F_h}{A_{ice}} \quad (13)$$

$$A_{ice} = \phi l h_{ice} \quad (14)$$

These in-plane stresses relax the tensile stress induced by the vertical component and effectively increase the flexural limit. The total stress in the ice can then be taken as:

$$\sigma_{total} = \sigma_{bend} - \sigma_{comp} \quad (15)$$

where,

$$\sigma_{bend} = \frac{F_v}{\mathrm{C} \cdot h_{ice}^2 \cdot \phi} \tag{16}$$

$$\sigma_{comp} = \frac{F_h}{\phi \cdot 10 \cdot h_{ice}^2} \tag{17}$$

The normal force considering friction and in-plane stresses, solved by Daley et al. (2011), can be arranged as (18). For a wedge angle of 150, we can assume, C = 0.39.

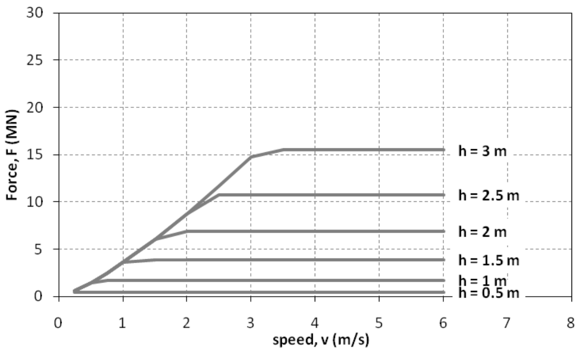
$$F_n = \frac{C \cdot \sigma_f \cdot h_{ice}^2 \cdot \phi}{[\sin(\beta') + \mu\cos(\beta')] - C/10 \cdot [\cos(\beta') + \mu\sin(\beta')]} \tag{18}$$

Daley et al. (2011) also offered a Froude scaling method to consider dynamic support effects of the water on flexural ice failure. This is an area of ongoing research and further work is required to validate the model. In (19 and 20), F_{nd} is the dynamic normal force, FN is the dynamic ice Froude number, and FN_s is a static ice Froude number (chosen as 0.1). The power, n, is hypothetically chosen as 0.33.

$$F_{nd} = F_n \left(\frac{FN}{FN_s}\right)^n \tag{19}$$

$$FN = \frac{V_n}{\sqrt{g \cdot h_{ice}}} \tag{20}$$

General comparisons between the simple static flexural failure model in the Polar UR and the modified formulation offered by Daley et al. (2011) are presented in Figures and for maximum force (F) and line load ($Q = F/w$), respectively. These calculations were performed for the sample ship described in Table 1 at impact location 1. They are based on the assumptions noted above and the ice strength parameters implied for Ice Class PC5 (p_o = 2.0 MPa, ex = -0.1, σ_f = 1.0 MPa). In the pure crushing range (slower speeds, thicker ice), the load parameters remain identical between the static and dynamic models. However, in the dynamic model, the onset of the flexural limit is delayed, especially for faster impact speeds. This causes the rise in the maximum force and line load parameters.



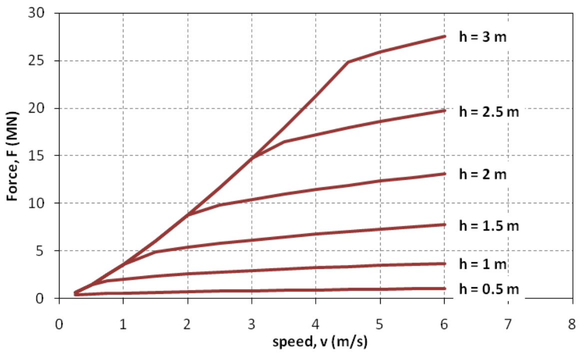


Figure 5. Force vs. speed plots comparing static (left) and dynamic (right) flexural limits

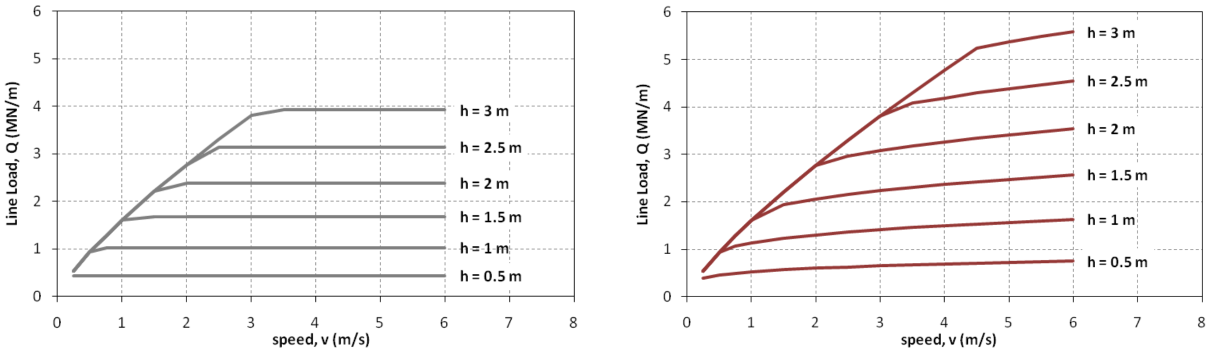


Figure 6. Line load vs. speed plots comparing static (left) and dynamic (right) flexural limits

Structural Limit States

The structural limit states adopted by the Polar Rules provide a set of analytical expressions for the capacity of primary stiffening members (Kendrick & Daley 2000; Daley et al. 2001). These models were derived on the basis of energy methods and make use of plastic limit analysis. They were validated against extensive numerical simulations and physical experiments. For transverse framing, the capacity equations, in terms of pressure, are presented here. It should be understood that these notional "capacities" are in reality well below any ultimate strength due to strain hardening, membrane and many other effects. A robust structure can support 5-10 times the UR design load, as shown by extensive FE and experimental work (Daley et al. 2001; Daley & Hermanski 2009).

The pure shear collapse limit in which the frame will fail by shear at the supports due to a central load patch is shown in (21).

$$p_{lim,shear} = \frac{2 \cdot A_o \cdot \sigma_y}{b \cdot s \cdot \sqrt{3}} \quad (21)$$

Equations (22 and 24) consider pressure applied as a central load which causes the formation of three plastic hinges (one central and two end hinges). For case 1 (22), the total bending capacity is reduced based on a relatively simple quadratic shear-moment interaction.

$$p_{lim,c1} = \frac{1}{12 \cdot Z_{pns} + 1} \cdot \sigma_y \cdot Z_p \cdot \frac{4}{b \cdot s \cdot l \cdot \left(1 - \frac{b}{2 \cdot l}\right)} \quad (22)$$

where,

$$Z_{pns} = \left[\frac{Z_p}{A_w \cdot l \cdot \left(1 - \frac{b}{2l}\right)}\right]^2 \quad (23)$$

Case 2 (24) includes a modification in which the bending capacity is reduced only by the loss of web capacity.

$$p_{lim,c2} = \frac{\left[2 - kw + kw\sqrt{1 - 48Z_{pns}(kw+1)}\right]}{12Z_{pns}kw^2 + 1} \sigma_y Z_p \frac{4}{bsl\left(1 - \frac{b}{2l}\right)} \quad (24)$$

A fourth limit state (25) considers the case of an off-center (end case) or asymmetric load in which plastic hinges form in the flanges along with a shear panel in the web near the load and a large plastic hinge at the far end.

$$p_{lim,e1} = \left[\frac{A_w}{\sqrt{3}} + \frac{Z_p}{l} \cdot fz\right] \cdot \frac{\sigma_y}{b \cdot s\left(1 - \frac{b}{2l}\right)} \tag{25}$$

The capacity of the frame can be considered as the minimum of the four limit states provided above (26).

$$p_{cap} = \min(p_{lim,shear}, p_{lim,c1}, p_{lim,c2}, p_{lim,e1}) \tag{26}$$

When combined with the ice load model, the line load capacity ($Q_{cap} = F_{cap}/s = p_{cap} \cdot b$) can be checked against the line load from the impact with ice.

CASE STUDY

As a case study of the proposed safe speed analysis procedure, let us consider a 90 meter offshore supply vessel (OSV) with particulars listed in Table 1. This analysis only considers the Polar UR design scenario of a glancing impact on the bow shoulder. The dynamic model for the flexural limit state described above is applied in the calculations. The structural configuration and scantlings in the bow region (shown in Table 2) are compliant with Ice Class PC5. Four locations in the bow are selected as shown in Figure 7. For each location, the impact calculation is performed over a range of ice thickness (in this case from 0.5m to 2.5m). At each ice thickness increment, the speed is iterated until the line load exceeds the capacity of the frame.

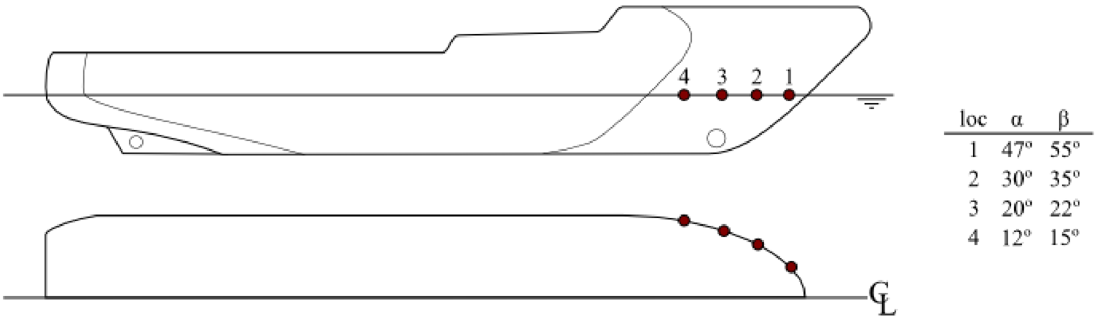


Figure 7. Sketch of PC5 supply vessel indicating impact locations

Table 1. Ship particulars

Length overall	L_{OA}	m	90.0
Length between perpendiculars	L_{BP}	m	85.0
Beam	B	m	18.00
Draft	T	m	6.00
Height	H	m	7.50
Block Coef.	C_B		0.8
Waterplane Coef	C_{wp}		0.94
Midship Coefficient	Cm		0.99
Displacement	M	tons	8000
Vertical distance to CG from keel	KG	m	3.2
Longitudinal distance to CG from MS	LCG	m	1.6

Table 2. Structural particulars

Frame Orientation Type	*FO*	--	Transverse
Material Yield Strength	σ_y	MPa	355
Main Frame Span	*a*	mm	2000
Main Frame Spacing	*s*	mm	600
Thickness of Plate	t_p	mm	27.0
Offered Frame	*frame*	--	BP 340 x 14

The results of the calculations are presented for all four locations in Figure 8 (left). As the impact location moves aft, the unfavorable hull geometry imposes higher structural loads. This analysis suggests while in ice thicknesses as low as 60 – 70 cm, the vessel should consider reducing speeds to below 3.5 m/s or (about 7 knots). As a reference point, the notional scenario implied for PC5 is a 2 m/s (about 4 knots) impact with a 3 m MY ice edge. A constant ice flexural strength (σ_f = 1.0 MPa) was considered for first set of calculations (left). 1.0 MPa is the assumed flexural ice strength for MY ice that is embedded into a class factor in the Polar UR (Ice Class PC5). Figure 8 (right) presents the results considering weaker flexural strength (0.75 MPa). This comparison illustrates the influence of just one factor and emphasizes the need to investigate appropriate ice strength parameters.

The downward sloped section of the technical safe speed curves cover the range of speed-thickness combinations where flexural ice failure governs. The constant limit speed (low speeds) at high and increasing ice thicknesses reflects the momentum limit. In this range the ice load is dominated by pure crushing (no flexural failure). Since the ice is assumed infinitely large in this case study, the increasing thickness has an infinitely small effect on the collision energy. If a discrete and finite sized ice floe is considered, one would expect decreasing limit speeds with increasing thickness in this range.

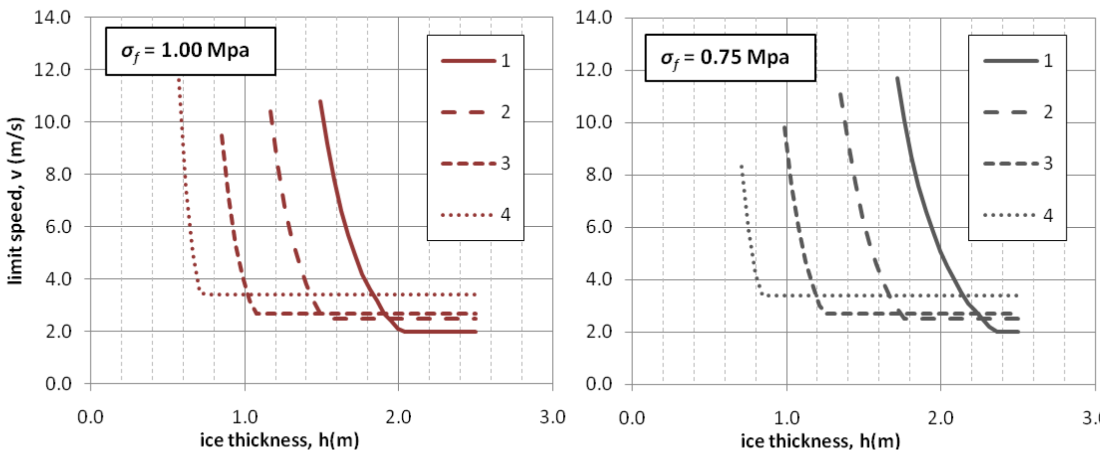


Figure 8. Limit speed versus ice thickness
(left: p_o = 2.0 MPa, *ex* = -0.1, σ_f = 1.0 MPa; right: p_o = 2.0 MPa, *ex* = -0.1, σ_f = 0.75 MPa)

CONCLUSIONS AND RECOMMENDATIONS

This paper presents an overview of existing approaches to the analysis of safe speeds in ice and provides some direction towards the development of a synthesized procedure for matching structural capacity with analytically derived ice load parameters. It is not intended to provide a final solution to the safe speed problem. A PC5-compliant offshore supply vessel was used to demonstrate a procedure for one simple bow impact scenario with the edge of an infinite ice sheet. Several other collision scenarios should be considered to capture a more comprehensive realm of operating modes. This may include interactions with various forms of sea ice or glacial fragments. Glancing collisions with alternative ice geometries could be considered. Reflected collisions on the bow, midbody or stern, ramming scenarios and impacts with the midship or stern during turning maneuvers are all viable scenarios which deserve attention within the context of safe speed. Selection of appropriate structural response criteria needs to consider not only the physics involved, but also the levels of uncertainty that need to be incorporated into factors of safety. Fortunately, many of the technical building blocks to develop such an approach already exist. Input and feedback from vessel operators is invaluable to this kind of analysis. Practical insight into real vessel motions and tactical approaches in various ice regimes can direct development efforts more effectively.

It should be emphasized that the approach presented here is extremely sensitive to the assumptions made. This includes the general assumption of the bow glancing impact but more importantly the ice strength terms (p_o, ex, σ_f). Significant uncertainty arises with regard to ice mechanics (pressure-area relationship, flexural failure mechanisms, and ice geometries) that are treated here in a purely deterministic fashion. To better capture the reality of ice conditions, existing field measurements and observations could be utilized and implemented into the above procedure. In addition, the use of instrumentation systems on ships can both help operator decision making and also inform the development of more accurate models.

Finally, there is always a possibility of ice damage, regardless of the ice class assigned to the ship. Safe speed analysis can potentially provide an overall picture of the capability and limitations of the ship and can facilitate informed tactical decision making to further mitigate risks within the bounds of the ice strengthening requirements. However, operator due caution should always be maintained as the most effective method of risk mitigation.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to ABS for the opportunity and permission to publish this work. The views expressed herein are those of the authors and are not to be construed as the official views of ABS.

REFERENCES

ABS, 2011. *Rules for Building and Classing Steel Vessels*, Houston, TX: American Bureau of Shipping.

Daley, C.G., 2000. *IACS Polar UR Technical Background: Design Ice Loads*,

Daley, C.G. & Hermanski, G., 2009. Investigation of plastic limit states for design of ship hull structures SSC-457. *Ship Structure Committe*, (457).

Daley, C.G., Kendrick, A. & Appolonov, E.M., 2001. Ships, Plating and framing design in the unified requirements for polar class. In *Port and Ocean Engineering Under Arctic Conditions, POAC'01*. pp. 779–791.

Daley, C.G., Kendrick, A. & Quinton, B.W.T., 2011. *Safe Speeds in Ice;* Technical Report: BMT Fleet Technology to NRC-CHC

Daley, C.G. & Kim, H., 2010. Ice collision forces considering structural deformation. In *International Conference on Offshore Mechanics and Arctic Engineering, OMAE'10*. Shanghai, China: ASME.

Daley, C.G. & Liu, J.J., 2010. Assessment of Ship Ice Loads in Pack Ice. In *International Conference And Exhibition On Ships And Structures In Ice, ICETECH'10*. Anchorage, AK, USA: SNAME.

Finland et al., 2012. DE 57/INF.3: Simulation of ship-ice interaction VTT & TRAFI, eds. *IMO Sub-Committee on Ship Design and Equipment, 57th Session, Agenda Item 11, Development of a Mandatory Polar Code*.

Kendrick, A. & Daley, C.G., 2000. *IACS Polar UR Technical Background: Framing Requirements*

Kurdyumov, V.A. & Kheisin, D.E., 1976. Hydrodynamic Model of the Impact of Solid Body Impact Against Ice. *International Applied Mechanics*, 12(10), pp.1063–1068.

Likhomanov, V.A. et al., 1998. Ice Passport for Icebreaker Pierre Radisson and Passport's Concept: Further Development. In *International Offshore and Polar Engineering Conference, ISOPE'98*. Montreal, Canada, pp. 566–571.

Likhomanov, V.A. et al., 1997. *Scientific basis and methodology of the development of an ice passport*, St. Petersburg, Russia.

Maxutov, D.D. & Popov, Y.N., 1981. Development and Implementation of Ship Ice Certificates. In *SNAME STAR Symposium*. pp. 83–86.

Popov, Y.N. et al., 1967. *Strength of ships sailing in ice* FSTC-HT-23rd ed., Leningrad: Sudostroenie Publishing House, U.S. Army Foreign Science and Technology Center (Translation).

Tunik, A.L., 2000. Safe Speeds of Navigation in Ice as Criteria of Operational Risk. *International Journal of Offshore and Polar Engineering*, 10(4), pp.286–291.

Tunik, A.L., Kheisin, D.E. & Kurdyumov, V.A., 1990. Probabilistic Concept of Safe Speeds for Arctic Shipping. In *Ice Technology for Polar Ships*. pp. 295–306.