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STRUCTURAL CHALLENGES FACED BY ARCTIC SHIPS

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2011

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STRUCTURAL CHALLENGES FACED BY ARCTIC SHIPS

A warming climate, retreating ice and increased interest in exploring the Arctic Ocean for undeveloped resources has changed the shipping situation in the Arctic Ocean. The Arctic Marine Shipping Assessment released by the intergovernmental Arctic Council reflects this viewpoint and presents a variety of scenarios for future shipping operations. The increased commercial interest and recent updates and development of polar codes for ship design highlight the need for cutting edge research focused on improving vessel structural strength for service in the harsh environment. This project surveys the current status of expertise, the literature available and presents applicable research to evaluate vessel structures for operation in an arctic environment. Challenges are categorized into five primary areas of research with multiple topics and sub-topics for each:

- Changing Arctic Environmental Conditions,
- Ice Loads on Ships,
- Material and Structural Behavior,
- Hazard and Risk Assessment, and
- Regulatory Issues.

These topics help characterize and organize the challenges faced by marine structures, identify existing knowledge gaps, and provide potential future areas of research the Ship Structure Committee may wish to pursue for vessels operating in arctic environments in fulfilling a mission to enhance the safety of life at sea.

We thank the authors and Project Technical Committee for their dedication and research toward completing the objectives and tasks detailed throughout this paper.

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16. Abstract

This report represents a scoping study, identifying issues related to the challenges for the structural safety of ships navigating in the Arctic Ocean. The work undertaken has included an extensive literature survey of areas such as: changing Arctic environmental conditions, ice loads on ships, material issues, risk and hazard assessment, and regulatory developments. The survey comments on the current state of the art and on areas of continued uncertainty. From this work, an issues map of Arctic ship structural safety has been developed. A set of recommendations for future research in areas particularly relevant to the SSC's mandate has been developed, focusing on ice loads, materials and structural response.

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To convert from	to	Function	Value
LENGTH			
inches	meters	divide	39.3701
inches	millimeters	multiply by	25.4000
feet	meters	divide by	3.2808
VOLUME			
cubic feet	cubic meters	divide by	35.3149
cubic inches	cubic meters	divide by	61,024
SECTION MODULUS			
inches^2 feet^2	centimeters^2 meters^2	multiply by	1.9665
inches^2 feet^2	centimeters^3	multiply by	196.6448
inches^4	centimeters^3	multiply by	16.3871
MOMENT OF INERTIA			
inches^2 feet^2	centimeters^2 meters	divide by	1.6684
inches^2 feet^2	centimeters^4	multiply by	5993.73
inches^4	centimeters^4	multiply by	41.623
FORCE OR MASS			
long tons	tonne	multiply by	1.0160
long tons	kilograms	multiply by	1016.047
pounds	tonnes	divide by	2204.62
pounds	kilograms	divide by	2.2046
pounds	Newtons	multiply by	4.4482
PRESSURE OR STRESS			
pounds/inch^2	Newtons/meter^2 (Pascals)	multiply by	6894.757
kilo pounds/inch^2	mega Newtons/meter^2 (mega Pascals)	multiply by	6.8947
BENDING OR TORQUE			
foot tons	meter tons	divide by	3.2291
foot pounds	kilogram meters	divide by	7.23285
foot pounds	Newton meters	multiply by	1.35582
ENERGY			
foot pounds	Joules	multiply by	1.355826
STRESS INTENSITY			
kilo pound/inch^2 inch^{½}(ksi√in)	mega Newton MNm$^{3/2}$	multiply by	1.0998
J-INTEGRAL			
kilo pound/inch	Joules/mm^2	multiply by	0.1753
kilo pound/inch	kilo Joules/m^2	multiply by	175.3

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ACRONYMS

ACIA	Arctic Climate Impact Assessment
AIRSS	Arctic Ice Regime Shipping System
AMSA	Arctic Marine Shipping Assessment
AMSR-E	Advanced Microwave Scanning Radiometer – Earth Observing System
ASPEN	Arctic Shipping Probability Evaluation Network
ASPPR	Arctic Shipping Pollution Prevention Regulations
AVHRR	Advanced Very High Resolution Radiometer
AUV	Autonomous Underwater Vehicles
CCG	Canadian Coast Guard
CCGA	Canadian Coast Guard Auxiliary
CCGS	Canadian Coast Guard Ship
CLIP	Catalog of Local Ice Pressures
CReSIS	Centre for Remote Sensing of Ice Sheets
CVN	Charpy Vee Notch
DMSP	Defence Meteorological Satellite Program
ECA	Emission Control Area
EEZ	Exclusive Economic Zones
ESMR	Electrically Scanning Microwave Radiometer
Envisat	"Environmental Satellite" is an Earth-observing satellite
EPA	Environmental Protection Agency
FE	Finite Element
FD	Finite Difference
FRP	Fibre Reinforced Plastics
FY	First-year
G&M	German and Milne
GCM	Global Climate Model
GPR	Ground Penetrating Radar
HAZ	Heat Affected Zone
HAZID	Hazard Identification
HAZOP	Hazard and Operability
IACS	International Association of Classification Societies
IACS UR I	International Association of Classification Societies, Unified Requirements, Polar Class
ICESat	Ice, Cloud and Land Elevation Satellite
IMD	Institute for Marine Dynamics
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
LNG	Liquified Natural Gas
MARAD	Maritime Administration
MARPOL	International Convention for the Prevention of Pollution from Ships
MCoRDS	Multichannel Coherent Radar Depth Sounder
MODIS	Moderate Resolution Imagine Spectroradiometer
MOTAN	inertial motion measurement system
MPa	Mega Pascal

MY	Multi-year
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NO_x	Nitrogen Oxide
NRC	National Research Council of Canada
NRC-CHC	National Research Council of Canada Iceberg Canadian Hydraulics Centre Management Database
NRC-IOT	National Research Council of Canada Iceberg Collisions Database
NSIDC	National Snow and Ice Data Centre
NSIDC-IIP	National Snow and Ice Data Centre Iceberg Sightings Database
NSR	Northern Sea Route
OLS	Operational Linescan System
PTC	Project Technical Committee
RADARSAT	Earth observation satellite to monitor environmental changes and the planet's natural resources
RoRo	Roll on Roll off
RMRS	Russian Maritime Register of Shipping
SAR	Synthetic Aperture Radar
SCICEX	Scientific Ice Expeditions
sgof	strain-gage-on-frames
smhr	surface mounted high resolution
SMMR	Scanning Multi-channel Microwave Radiometer
SO_x	Sulphur Oxide
SPS	Sandwich Plate System
SSC	Ship Structure Committee
SSMI	Special Sensor Microwave Imagers
TMCP	Thermo-Mechanical Control Process
UNCLOS	United Nations Convention on the Law of the Sea
UR	Unified Requirements
URL	Uniform Resource Locator
USCGC	United States Coast Guard Cutter
USN	United States Navy
VTT	Valtion Technilinen Tuktimukeskus (Technical Research Centre of Finland)

1. INTRODUCTION

1.1 General

This project has been undertaken on behalf of the inter-agency Ship Structures Committee (SSC) through a contract let by the U.S. Maritime Administration (MARAD), and overseen by a Project Technical Committee (PTC) comprising representatives from various organizations and individuals from around the world.

The stated primary objective of the project is:

"…a scoping study… identifying issues related to the challenges with regard to structural safety of ships navigating in the Arctic Ocean, which may be undergoing climatic changes. A detailed literature review will be undertaken ... to recommend future research required to ensure continued safety..."

With the review as a base, the project has tabulated the changes and challenges and has proposed directions for research to address the most critical issues. These proposals are focused on areas where the SSC is best suited to play a leading research role.

1.2 Background

The Arctic Ocean is the least travelled of all the world's major seas. Ice, winter darkness, great distances, environmental challenges and jurisdictional issues are continuing impediments to shipping. And despite all these issues, the arctic shipping situation is changing. The climate is warming, the ice is retreating and ship traffic is likely to increase. There is increasing public and professional awareness of the sensitivities associated with the arctic. The environmental, social, political and security issues are numerous and interrelated. The recent release of the Arctic Marine Shipping Assessment (AMSA) by the intergovernmental Arctic Council consolidates recent work on a number of these issues, and presents a range of scenarios for future arctic shipping operations (see http://arcticportal.org/en/pame/amsa-2009-report).

There are several factors which are driving the likelihood of increased shipping. The primary issue is the wealth of the resources in the region. The Arctic is said to comprise approximately 25% of the Earth's undeveloped resources. This includes non-renewable mineral and petroleum resources as well as renewable resources such as the fishery. Tourism is another significant driver, growing steadily in recent years. Other key drivers are public sector activities in science, regional management and development, as well as defense and security. While all these aspects are significant, the petroleum resources must be considered the single largest factor when considering the future of arctic shipping.

"The U.S. Geological Survey (USGS) has completed an assessment of undiscovered conventional oil and gas resources in all areas north of the Arctic Circle. Using a geology-based probabilistic methodology, the USGS estimated the occurrence of undiscovered oil and gas in 33 geologic provinces thought to be prospective for petroleum. The sum of the mean estimates for each province indicates that 90 billion barrels of oil, 1,669 trillion cubic feet of natural gas, and 44 billion barrels of natural gas liquids may remain to be found in the Arctic, of which approximately 84 percent is expected to occur in offshore areas." - US Geological Survey report 2008

At today's prices (2010) this represents a traded commodity value of 14 Trillion dollars. In terms of total economic activity, the importance of the arctic is exceptionally large. When added to the environmental and strategic concerns, the arctic represent a challenge and opportunity of nearly unparalleled significance.

Numerous current projects by governments, shipbuilders and resource companies are contemplating a range of vessels; tankers, bulk carriers, support vessels, science ships, military patrol ships, cruise ships and emergency evacuation craft. With the climatic and commercial changes in the arctic, even our limited range of operational experience may be of little use in predicting the structural challenges that future vessels will face. The aim of this project is to take a forward looking view to develop a listing of issues, challenges and needed research to try to ensure viable arctic shipping in the years ahead. The particular focus is on ship structural questions, including but not limited to:

- Will changes in the arctic climate tend to lead to increased or decreased ice loads?
- As arctic ice retreats and shipping seasons are extended, will cold-embrittlement, or various material degradation issues (corrosion, fatigue) become significantly larger issues?
- Will developments in the arctic lead to more local infrastructure, or will development need to continue as fully self sufficient remote operations?
- Will improvements in material grades, welding standards and overall design have a significant positive impact on arctic ship structural risks?
- Will changes in design methods, standards and corporate policies contribute to improved safety levels?
- Are there likely to be a sufficient number of adequately trained people to perform the design, operation, research and regulation activities that will be initiated?

The main topics have been grouped in to five primary areas, each with multiple topics and sub-topics. For each sub-topic, a description is presented below. In the appendix, the actual references are found. For some aspects of the report, footnotes are used to identify URLs for websites that are sources of data or for information that may change with time; e.g., environmental conditions, regulations and standards.

2. OUTLINE OF AREAS AND TOPICS

The topics listed in the proposal have been grouped and subdivided as shown below. Section 3 expands on this list.

Area	Topic	Sub Topics	Key Issues
Changing Environmental Conditions	Climate Change		
		Environmental Changes	Coverage, Thickness, Loss of MY ice
		Potential Impacts	More variability, uncertainty
	Ice Cover		
		First Year Ice	
		Multiyear Ice	Differentiation of MY thicknesses
		Thickness	
		Pressure	Identification and prediction of pressure
		Pressure Ridges	
		Rubble Ice	
		Consolidation	
		Lead Systems	
Ice Load	Ice Loads		Extreme loads on larger ships
			Load patterns
			Load following
Scenarios	Mechanical Properties	Computer Simulation	
	Load Measurements		
Material / Structural Response	Materials	Material Grades	Tearing
		Corrosion	Temperature and strain rate influences
		Material Behaviour	
		Sandwich Plate System	
		Coatings	
	Design /Assessment	Plastic Design	Collapse mechanisms
Risk and Hazard	Key Risks	Simulation	Human factors
		Sensing	Data collection
		Databases	
Assessment	Assessment Methods		
Regulatory and	Regulation	International	
		National	
		Classification Societies	
Other Factors	Remote Facilities	Search and Rescue	
		Environmental Protection	
		Vessel repair	
	People		
	Information Technology		

3. TOPIC OUTLINE

3.1 Changing Environmental Conditions

3.1.1 Climate Change

Numerous sources of data suggest that the average annual quantity of Arctic sea ice is declining (see Figure 3.1). These data sources include nuclear submarine sonar data stretching back to the 1950s; satellite data such as the Scanning Multi-channel Microwave Radiometer (SMMR) on the Nimbus 7 satellite, and the Special Sensor Microwave Imagers (SSMIs) on the Defence Meteorological Satellite Program (DMSP) satellites; and observations of sailors who lived and worked in the Arctic since the early twentieth century. *Science Magazine* reports "Satellite monitoring revealed a 5% decrease in the extent of the ice between 1978 and 1998" (Kerr, R.A., 1999). Old sailors say that there is much less ice in the Arctic now than there used to be. For this reason, there is very limited value in using old ice data such as historical ice atlases to plan current and future operations.

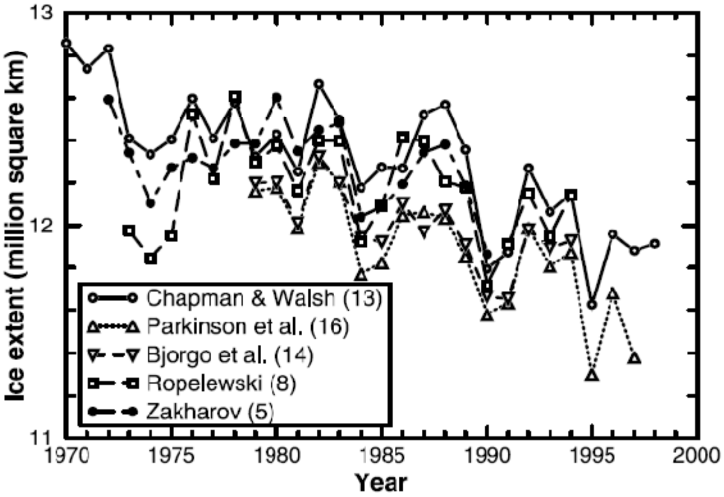


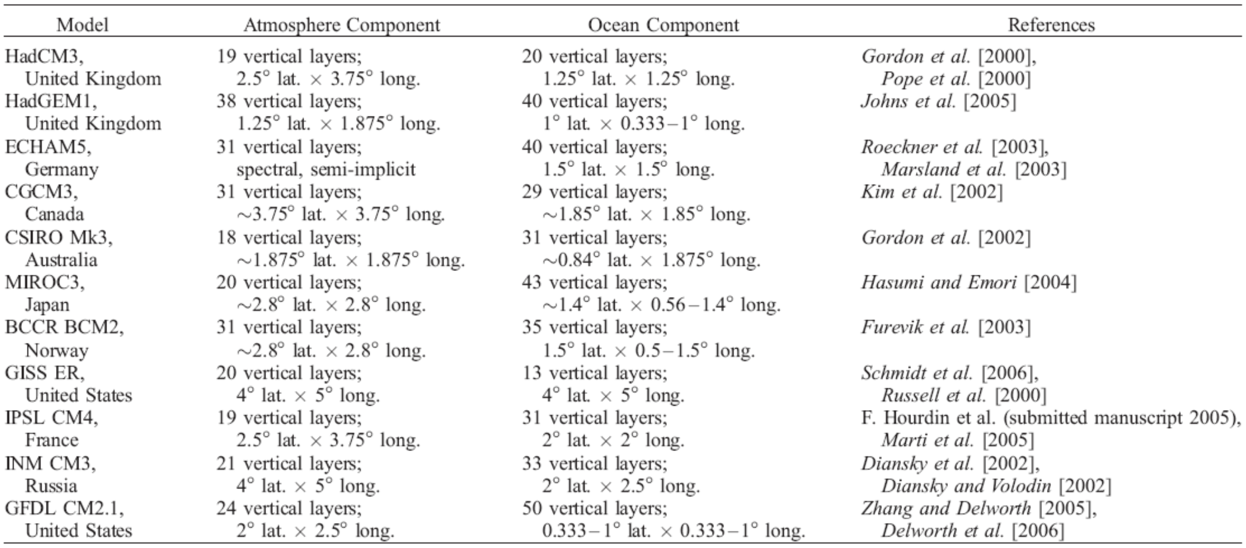
Figure 3.1: Observed Northern Hemisphere Sea Ice Extent (Source: Vinnikov et al, 1999)

3.1.1.1 Projected Changes

Polar regions are amongst the most extensively modelled areas of the world for climate change forecasting. These models are usually extremely complex, involving (broadly) an atmosphere component, an ocean component, the ability to deal with sea ice cover, and anthropogenic forcing (e.g., greenhouse gasses and sulphate aerosols). There is a strong coupling between sea ice and the rest of the climate system. This means that errors in the simulation of sea ice cover will be propagated to errors in the simulated atmosphere and simulated ocean too (Parkinson et al, 2006). The strong coupling between sea ice cover and the rest of the climate system springs from the influence of sea ice cover on the following: exchanges of heat, mass, and momentum between the ocean and atmosphere; reflection of solar radiation; net transport of cold fresh water towards the equator; and the salinity and density structure of the ocean.

A 2006 study (Parkinson et al.) evaluated eleven of the world's leading Global Climate Models (GCMs) based on their ability to deal with sea ice. Table 3.1 lists these GCMs. This study showed that each model does well simulating the annual ice extent cycle; the best model overall was not any one model in particular, but an average of all eleven models.

Table 3.1: Model Particulars for Eleven Global Climate Models (Parkinson et al, 2006, p 5).



Model	Atmosphere Component	Ocean Component	References
HadCM3, United Kingdom	19 vertical layers; 2.5° lat. × 3.75° long.	20 vertical layers; 1.25° lat. × 1.25° long.	*Gordon et al.* [2000], *Pope et al.* [2000]
HadGEM1, United Kingdom	38 vertical layers; 1.25° lat. × 1.875° long.	40 vertical layers; 1° lat. × 0.333–1° long.	*Johns et al.* [2005]
ECHAM5, Germany	31 vertical layers; spectral, semi-implicit	40 vertical layers; 1.5° lat. × 1.5° long.	*Roeckner et al.* [2003], *Marsland et al.* [2003]
CGCM3, Canada	31 vertical layers; ∼3.75° lat. × 3.75° long.	29 vertical layers; ∼1.85° lat. × 1.85° long.	*Kim et al.* [2002]
CSIRO Mk3, Australia	18 vertical layers; ∼1.875° lat. × 1.875° long.	31 vertical layers; ∼0.84° lat. × 1.875° long.	*Gordon et al.* [2002]
MIROC3, Japan	20 vertical layers; ∼2.8° lat. × 2.8° long.	43 vertical layers; ∼1.4° lat. × 0.56–1.4° long.	*Hasumi and Emori* [2004]
BCCR BCM2, Norway	31 vertical layers; ∼2.8° lat. × 2.8° long.	35 vertical layers; 1.5° lat. × 0.5–1.5° long.	*Furevik et al.* [2003]
GISS ER, United States	20 vertical layers; 4° lat. × 5° long.	13 vertical layers; 4° lat. × 5° long.	*Schmidt et al.* [2006], *Russell et al.* [2000]
IPSL CM4, France	19 vertical layers; 2.5° lat. × 3.75° long.	31 vertical layers; 2° lat. × 2° long.	F. Hourdin et al. (submitted manuscript 2005), *Marti et al.* [2005]
INM CM3, Russia	21 vertical layers; 4° lat. × 5° long.	33 vertical layers; 2° lat. × 2.5° long.	*Diansky et al.* [2002], *Diansky and Volodin* [2002]
GFDL CM2.1, United States	24 vertical layers; 2° lat. × 2.5° long.	50 vertical layers; 0.333–1° lat. × 0.333–1° long.	*Zhang and Delworth* [2005], *Delworth et al.* [2006]

Five[1] GCMs were used in the Arctic Climate Impact Assessment and the Intergovernmental Panel on Climate Change Fourth Assessment Report (2007). In general, these GCMs predict continuous declines in sea ice coverage through the 21st century. At the extreme, some simulations show that by the middle of the century, the entire Arctic Ocean could be ice-free for a short period in the summer. However, it is also important to note that no simulations have indicated that the winter sea ice cover of the Arctic Ocean will disappear during this century.

On a more local basis, the Canadian Arctic Archipelago is predicted to retain significant summer ice coverage and large concentrations of multi-year ice for longer than any other area of the Arctic.

3.1.2 Ice Cover

There has been a substantial decrease in sea ice cover over the past few decades. Since the 1950s, there is a reduction in sea ice coverage by 10-15% (IPCC – Intergovernmental Panel on Climate change). The extent of sea ice cover is maximum in March and minimum in September. There is a twofold increase/decrease in sea cover between March and September (IPCC). The ocean and atmosphere play an intrinsic role in the extent of sea ice cover. A negative trend is apparent in the time series of the variability of ice extent at 2% in March and 7% in September

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[1] CGCM2, CSM_1.4, ECHAM4/OPYC3, GFDL-R30_c, and HadCM3.

(Richter-Menge et al., 2008). The mean ice edge position retreated significantly over a period of 150 years with greater retreat during the last century (Shapiro et al., 2001).

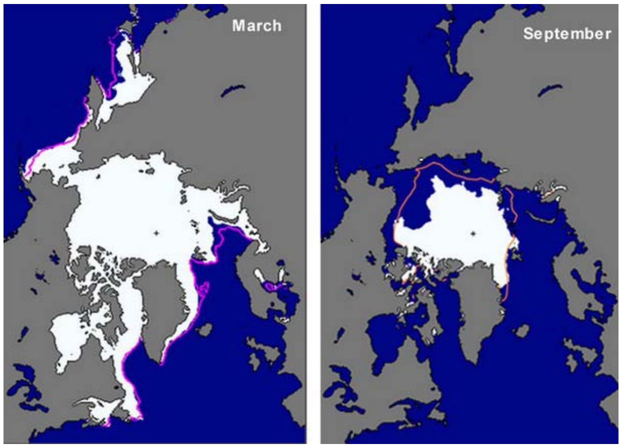


Figure 3.2: Sea Ice Extent during March and September (2009)
(Source: Richter-Menge et al)

3.1.2.1 Types

Sea ice is comprised of both first year and multiyear ice. The presence of multiyear ice adds a significant dimension to the design issues. Since multiyear ice concentration has been showing a declining trend in the past decade, its implication to Arctic shipping is vital. The presence of less multiyear ice means there is a probability of extended Arctic navigation season. Passive and active microwave satellite remote sensing observations are used to monitor the extent and concentration of sea ice. It has been found out that two different ice regimes were not differentiable by microwave remote sensing under similar climatic conditions.

3.1.2.2 Thickness

Thickness of sea ice is one of the main restricting factors in commercial Arctic shipping and it is poorly documented. The speed at which commercial vessels can go through ice is directly related to the thickness of the ice. The thickness also plays a very important role in the structural design of the ship. The thickness of the ice also decreases with ice cover area during the melt season. It is more difficult to monitor ice thickness. Measurements of ice thickness can be made in situ. Satellite based techniques such as ICESat (Ice, Cloud and Land Elevation Satellite) altimeter (Kwok *et al.*, 2006) and obtaining ice thickness from satellite based estimates of ice freeboard (Laxon *et al.*, 2003) are already in use, but these observations have been spatially and temporally limited. Ice thicknesses have also been measured by using submarines. Scientific Ice Expeditions (SCICEX) program have acquired many ice draft data in the 1990s (Gossett, 1999) (Margo, H et al., 2003). Data from submarine based observations indicate that at the end of the melt season the permanent ice cover thinned by an average of 1.3 m between 1956– 1978 and the 1990s, from 3.1 to 1.8 m (Rothrock *et al.*, 1999).

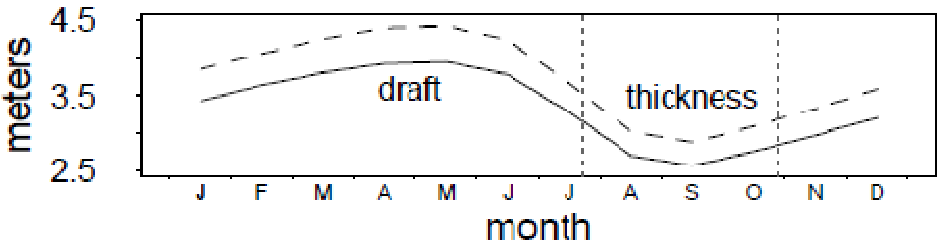


Figure 3.3: Modeled Seasonal Cycle of Ice Thickness (Source: Rothrock et al., 1999)

There is a significant loss of older, thicker multiyear ice drifting out of the Arctic through the Fram Strait (Rigor and Wallace, 2004). On the other hand, measurements of the seasonal ice cover do not indicate any statistically significant change in thickness in recent decades (Melling *et al.*, 2005). The thickness of first year ice in level floes ranges from a few tenths of a meter near the southern margin of the marine cryosphere to 2.5 m in the high Arctic at the end of winter. In the present climate, old multi-year ice floes without ridges are about 3 m thick at the end of winter (ACIA).

Table 3.2: Level Ice Thickness (Source: S. Løset et al., 1999)

Reference	Sea	Month							
		11	12	1	2	3	4	5	6
Sanderson (1988)	Beaufort	0.48	0.80	1.10	1.34	1.50	1.65	1.74	1.70
Croasdale (1977)	Beaufort	0.30	0.60	0.90	1.20	1.40	1.60	1.70	1.75
Mironov et al. (1994) (average)	West Pechora	0.40	0.60	0.80	1.00	1.00	1.10	1.10	1.00
	East Pechora	0.40	0.70	1.00	1.20	1.30	1.40	1.45	1.30
Riska (1995)	Pechora	0.30	0.50	0.70	0.90	1.10	1.20	1.20	–
	Kara	0.60	0.90	1.20	1.40	1.60	1.70	1.80	–
Vinje (1985)	North Barents[a]	0.40	0.45	0.55	0.70	0.80	1.00	1.05	1.10

The above table shows the measurement of monthly level ice thickness in various regions. The air temperature regimes play a role in the overall thickness of ice.

3.1.2.3 Ice Pressure

Ice pressure is dependent upon many factors such as wind speed, current direction and current speed, etc. The sea ice under pressure has the potential to stop the ship in its tracks by inhibiting its forward motion. Since most of the shipping will be done near coastal areas, fast ice is an inherent danger which can strand a ship.

3.1.2.4 Ridge Rubble Consolidation

Ice ridges are formed when sea ice floes collide with each other under pressure. These can happen near the sea ice land interface too. The ridges form when the floes buckle and break into blocks due to the compression of the ice pack. These ridges can be up to 30 m thick (Arctic Climate Impact Assessment - ACIA). Waves are an additional cause of ridging near open water, notably in the Labrador, Greenland, and Barents Seas. Because of ridging and rafting, the average thickness of first-year sea ice is typically twice that achievable by freezing processes alone (Melling and Riedel, 1996). Heavily deformed multi-year floes near the Canadian Archipelago can average more than 10 m thick.

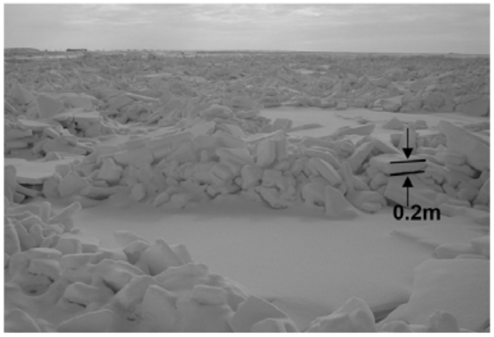


Figure 3.4: Rubble Fields
(Source: M.L. Druckenmiller et al., 2009)

A multiyear ridge is fully consolidated and has low salinity. The sail height of ridges can reach up to 6 m in height.

3.1.2.5 Lead Systems

Leads are ice free areas between ice floes which the ship can use for transit. Since a ship is like a vehicle, the lead systems can be used to navigate the ship through ice floes without sustaining any structural damage. Lead systems are short lived; unlike polynyas, which are regularly occurring ice-free areas generated by wind, current and upwelling conditions.

3.2 Ice Loads on Ships

3.2.1 Introduction

Ice loads represent the main structural challenge faced by ships in the arctic. And even after years of study, ice loads continue to be poorly understood and difficult to predict. This uncertainty stems from several causes, including:

- **Complexity of ice loads** – Ice forces arise when breaking a brittle solid. The ice fractures in many ways and creates highly localized and dynamic local pressures. The direct contact pressures are difficult to observe visually or measure electronically. Only recently have technologies been developed to observe the complex reality of the contact, and such observations have only taken place in controlled laboratory conditions. Field tests on ships have given useful data, but have always been difficult to analyze, understand and generalize.

- **Inadequate modeling methods** – While there are ice tanks that perform tests of ships in ice, the focus is on level icebreaking and resistance. Local ice pressures are not modeled with any available model ice materials. Numerical techniques are used for modeling local loads, but such methods are unable to represent the complexities observable in laboratory tests. Models, whether physical or numerical, tend to reflect the views and biases of the model's author. There are many different models and little agreement among specialists.
- **Shortage of specialists** – The field of ship structures is not particularly large when compared with some engineering fields. The sub-field of ice-class ship structures is quite small. A handful of specialists from a handful of arctic countries cover the field. Research in the area is relatively limited when compared to Naval Architecture as a whole.

The following sections will expand on these topics to illustrate the challenges and uncertainties.

3.2.2 Ice Mechanical Properties and Load Measurements

When ship-ice interaction occurs, local and global loads occur on the ship. The loads will depend on the mechanical behavior of ice, and thus the mechanical properties of ice are certainly relevant. Empirical evidence of ice loads on ships shows that the ship-ice interaction process is quite complex. It is not easy to show a strong link between mechanical properties of ice measured in a lab (or field) and the load phenomena on ships. Nevertheless, mechanical properties of ice are a starting point.

3.2.2.1 Compressive Strength

Local ice contact with ice will always involve compression of the ice edge. The standard test arrangement for measuring the uni-axial compressive strength of ice is shown in Figure 3.5 (Timco and Weeks, 2010). Both freshwater and glacial ices have no salt, and yet the compressive strength at high (i.e., brittle) strain rates is noticeably different as shown in Figure 3.6 (Jones, 2007). There are several issues that this plot highlights. The trend lines appear to indicate that freshwater ice gets significantly stronger (almost 2x) as the strain rate rises from 10^3 to 10^1 /s. Over the same range the iceberg ice appears to get about 20% weaker. And yet when all the data is examined without reference to the trend line, it is clear that the scatter in the data overwhelms the trend of the mean. At the high strain rates (typical of ship impact events) the uniaxial strength of freshwater ranges from 3.5 to 18 MPa, a 5x increase. The iceberg ice, taken has a whole, shows a 4x increase from lowest to highest. When considering that these tests all involved prepared standard samples, tested in a simple way in controlled conditions, the scatter is quite curious.

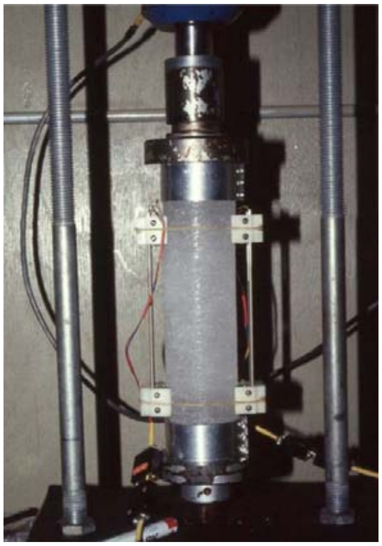


Figure 3.5: Typical Lab Test Arrangement for Uni-axial Compression Strength Test of Sea Ice (Source: Timco and Weeks, 2010

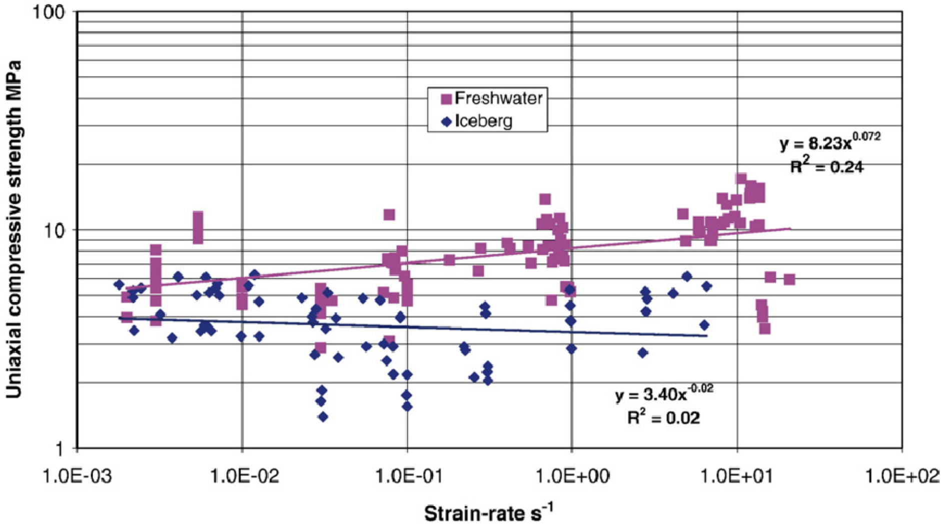


Figure 3.6: Uni-axial Compressive Strength Data for Iceberg and Fresh Water Ice at -10°C (Source: (Jones, 2007)

The strength of saline ice (sea ice) under combined bi-axial stresses is shown in Figure 3.7 (Iliescu and Schulson, 2004). It shows that while uni-axial strength may be only around 5 MPa, biaxial stresses (confining stresses) can raise the apparent strength to over 20 MPa. When ships strike ice edges, the contact can become large and the ice towards the center is confined. Biaxial strength tests are more complicated to conduct and are thus less available. As an attempt to address the need for a more appropriate confined strength test, the borehole jack was developed for ice (Masterson and Graham 1996). Figure 3.8 shows the use of a borehole jack device for measuring in-situ confined compressive strength of ice. Masterson et. al., (1997) discuss the relationship between bore-hole jack tests and uni-axial tests. Figure 3.9 shows how strength (as measured by borehole jack) decays in first-year, second-year and multi-year ice during the decay season (Johnston et.al., 2003). As ice decays in spring and summer, the strength diminishes markedly. First year ice decays more due to the presence of brine in the ice. Multi-year ice, which has almost no brine, maintains its strength to a much greater extent. This is an important factor when considering ship operations in the arctic in late spring and summer. Figure 3.10 shows how borehole jack strength in old ice varies with temperature (i.e., from winter to summer) and can be nearly 40MPa (Johnston et.al., 2003). Once again, one of the most interesting aspects of Figure 3.10 is the very wide range of the data. At warmer temperatures, the borehole jack (confined) pressures range from 3 to 25 MPa, approximately an 8x range. At colder temperatures the range is from 10 to 40 MPa. Given both the small sample size and the relatively controlled conditions for such data, this represents a remarkable range. Could it be that material properties of ice do vary over such a wide range? Or is there something about the tests or their interpretation that tends to generate random results?

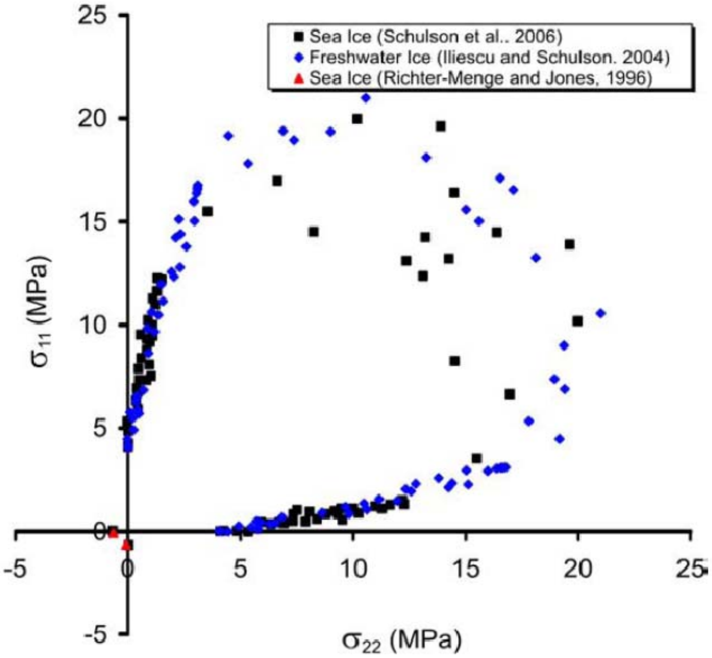


Figure 3.7: Failure Envelope for the Brittle Strength of Saline Ice (Iliescu and Schulson, 2004)

Figure 3.8: Borehole Jack for In-Situ Compression Test in Ice (Source: Photo by Lanthier from Timco and Weeks, 2010)

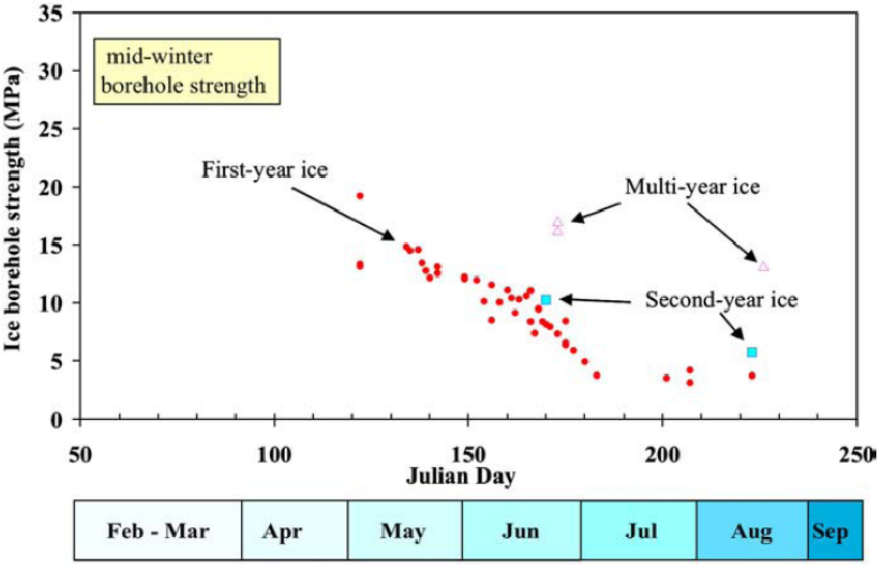


Figure 3.9: Comparison of First-Year, Second-Year and Multi-Year Borehole Strength during the Decay Season (Johnston et. al., 2003)

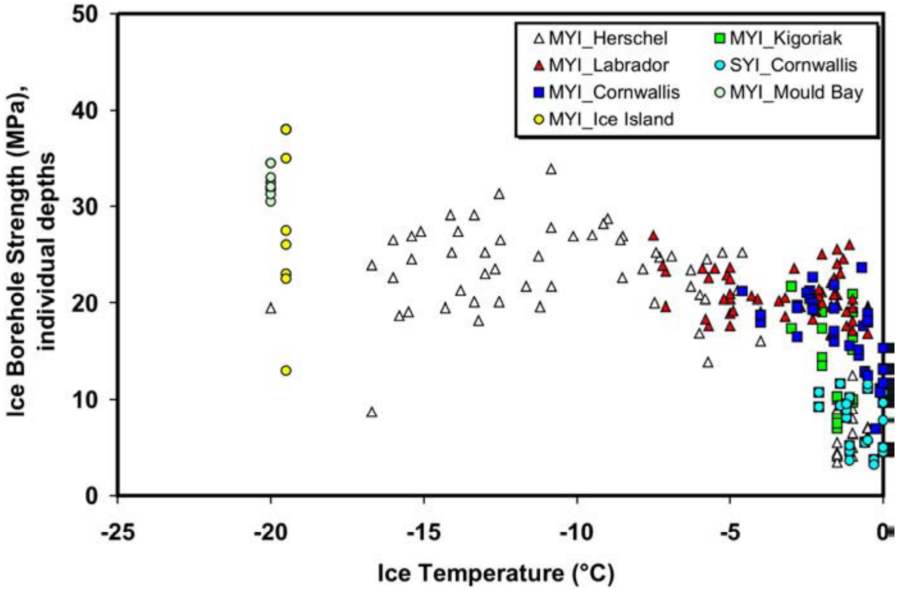


Figure 3.10: Multi-Year Borehole Strength as a Function of Temperature (Johnston et.al., 2003)

3.2.2.2 Other Types of Ice Strength

A comprehensive review of various mechanical properties of ice is presented in Hooke at. al., (1980). Timco and Weeks, (2010) present a more recent review of mechanical properties. Fracture properties of ice at high strain rates are reviewed in Dutta et. al. (2004). Ice load and pressure measurements are often observed with ice, and are the subject of much continuing debate. Scale affects are discussed in Gagnon et. al. (2001) and Goldstein et.al. (2009). Flexural strength is a key parameter for ice loads on ships in normal operations. The flexural strength of first year sea ice in the Barents Sea is discussed in Krupina et.al. (2007)

3.2.3 Ice Load Measurements

An understanding of the safety of ships in ice relies on an understanding of the ice loads that occur in various situations. Field measurements of ice loads are essential sources of information to permit rational design and risk assessment. Ice loads have been measured on many ships since the 1970s. The approaches used have varied and improved over the years, though strain gauges applied to framing have been the most common method. Sensor technologies have improved significantly since the 1970s. Many of the early trials focused on monitoring locations where the strains were thought to be highest. The data was collected in analog form and later examined to try to assess loads (e.g., German and Milne 1973). Beginning with the Kigoriak trials (Ghoneim and Keinonen 1983), a new approach was taken, one which aimed to use strain gauges to convert the vessel into a pressure sensor. Gauges were placed to ensure the most unique relationship between the desired load measurement and the response. Practically all ice loads trials since the Kigoriak have used a similar philosophy. Combined with digital data acquisition, it is now typical that ice loads data can be derived and presented in real time during the voyage.

The ‘standard’ way to measure ice loads on ships is to instrument the framing with strain gauges (e.g., Daley, et.al. 1984, Muller and Payer 1987, Kujala 1989, Ritch et al. 1999, Mejlaender-Larsen and Nyseth 2007). There have been improvements in the technology over the years. Improved finite element model tools have permitted more accurate system design. Modern systems have far greater data storage capacity and typically record data at higher sampling frequencies. And yet the improvements in the standard approach can only be described as modest. The system characteristics suffer from the same fundamental shortcomings as existed with the systems on the Kigoriak and Polar Sea in the early 1980s. The key weakness of these systems is the lack of spatial resolution, coupled with the inherent challenges of trying to use a stiffened panel as the ‘structure’ of a force transducer. A design aim for any transducer (sensor) is to achieve a high level of fidelity between the ‘true’ and ‘measured’ quantities. All strain-gage-on-frames (sgof) ice load panels on ships suffer from inherent ‘cross-talk’ between frames, which both limits the spatial resolution of the data and amplifies errors. And since ice pressures contain complex patterns and sharp peaks, sgof systems are incapable of providing anything but a blurred impression of the loads. Figure 3.11 illustrates how the lack of adequate spatial resolution can blur patterns to the point of completely misrepresenting their meaning. Structurally significant ice pressures can occur in line-like patterns with dimensions (line widths) as small as a few cm. (Riska, Rantala and Joensuu, 1990). The spatial resolution typical of sgof systems is 35cm to 50cm, and would be completely incapable of resolving fine patterns of ice load.

Figure 3.11: Illustration of Effect of Spatial Resolution on Patterns

The newest approaches to ice load measurements in the field involve surface mounted high resolution (smhr) ice load panels (e.g., Gagnon et. al. 2008, see Figure 3.12). The Terry Fox trials of 2001 were the first to examine full scale collisions between a ship and iceberg fragments (called bergy-bits). The trials were novel and advanced in several aspects. Three separate ice load measurement systems (Figure 3.12) were deployed:

(1) the MOTAN system that attempted to estimate forces from the accelerations of the vessel;
(2) a strain gauged panel (a sgof system) covering 6m^2 with a spatial resolution of 0.08m^2 to 0.24 m^2 sampled at 500hz; and

(3) a novel optical pressure panel, covering 4m^2 mounted outside the hull (a smhr system) with a spatial resolution of approximately .0004m^2 , measured at 60hz. (the IMD panel).

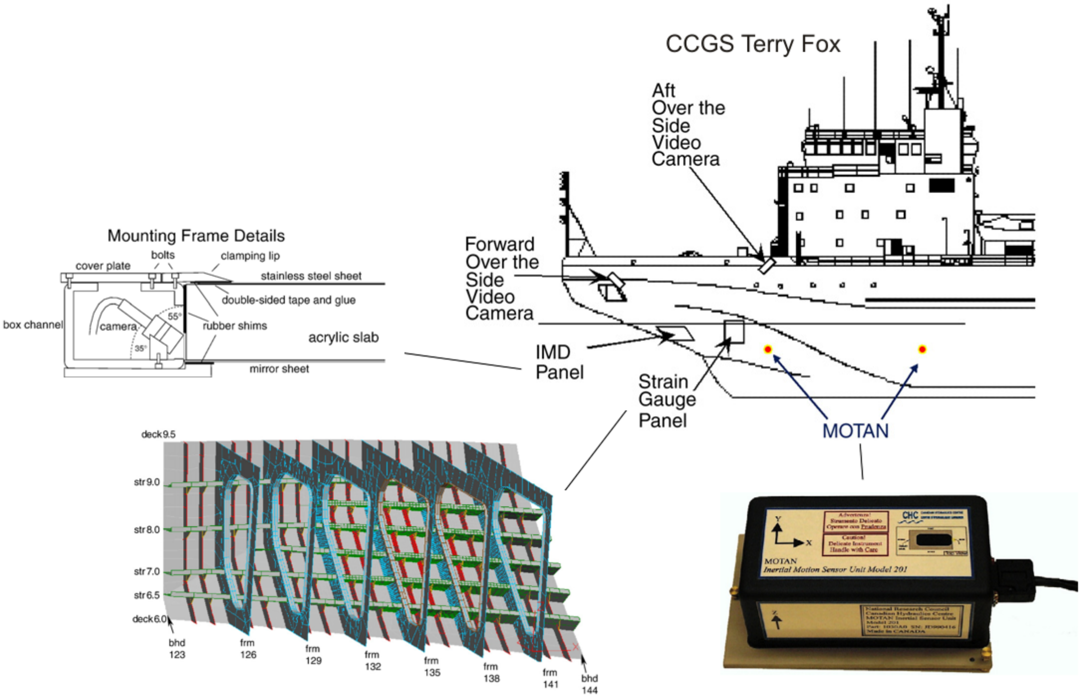


Figure 3.12: Multiple Sensor Systems for Bergy Bit Impact Tests on CCG Terry Fox (Gagnon et al 2008)

The vessel was deliberately collided with bergy bits (see Figure 3.13) that had been profiled to determine shape and mass.

Interestingly, the strain gauge panel on the Terry Fox measured the highest local pressure of 11.3 MPa on an area of 0.12m^2. This corresponds surprisingly well to the highest measurement on the Polar Sea in multiyear ice in 1983 of 11.3 MPa on an area of 0.15m^2 (see Daley et. al. 1984).

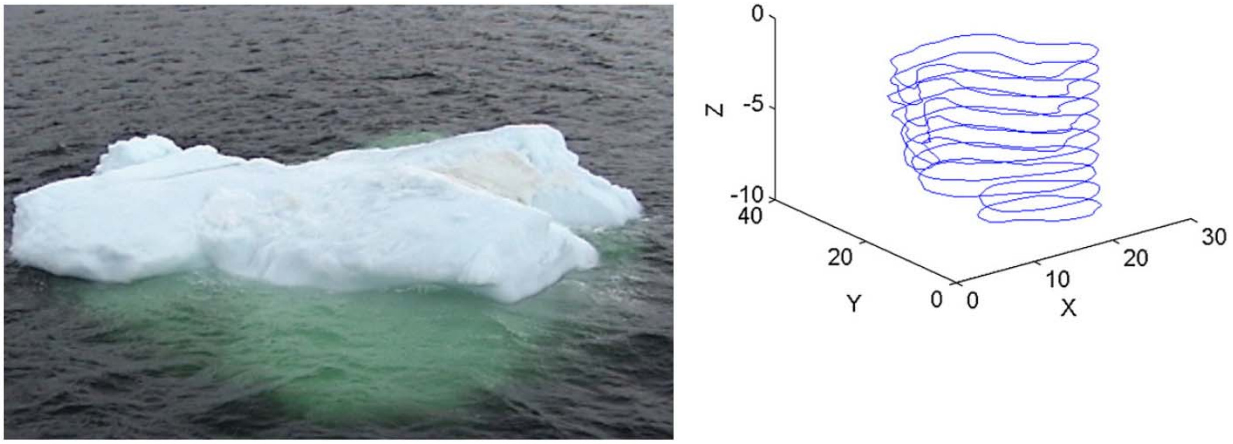


Figure 3.13: Profiled Ice from Bergy Bit Impact Tests on CCG Terry Fox (Ralph et al 2008)

Table 3.3 gives a list of ship instrumented, along basic test information. The data collected on these trials has had a very significant impact on ice class construction standards.

A useful reference for field measurements of ice pressure on ships is the Catalog of Local Ice Pressures (CLIP) maintained by the Nation Research Council of Canada (NRC) (see Frederking and Collins, 2005). The data from many of the trials conducted in North America and Europe are included as well as data from several offshore structures (see Figure 3.14).

Ship	Year
CCGS Louis S. St. Laurent	1980, 1994, 1995
Oden	1991, 1996
Kigoriak	1981, 1983
CCGS Terry Fox	2001
M.V. Arctic	1984, 1986
USCGC Polar Sea	1982-86
Robert Lemeur	1983, 1990
USCGC Healy	2000
R.V. Polarstern	1984

Structure	Type	Year
Molikpaq – Amauligak I-65	Caisson, 100m wide	1985-86
Tarsiut	Caisson, 100 m wide	1981-82, 1982-83
SSDC – Uviluk, etc	Caisson, 160 m wide	1982-83 through 1987-88
Yamachiche	Lighthouse, 75° cone	1985-86, 1987-88, 1988-89
Curve 1	Lighthouse, 45° cone	1987-88, 1988-89
Confederation Bridge	Pier, 52° cone	1997-98 through to 2004-05
LOLEIF/STRICE - Norströmsgrund	Lighthouse, cylindrical	2000 through to 2003
JZ-20 – Bohai Bay	Jacket	1990

Figure 3.14: Ship and Offshore Structure Data included in the CLIP data set (Frederking and Collins 2005)

Table 3.3: Ice Load Measurement Programs on Ships

Ship Name:	Louis S St. Laurent		
Location(s):	Lancaster Sound	Instrumentation:	Small through-hull Pressure sensors
Year(s):	1977,1980	Comments:	25 Pressure sensors recorded point pressures up to 75MPa over very small areas.
References:	Glen, I.F., Blount, H., 1984 Measurement Of Ice Impact Pressures And Loads Onboard CCGS Louis S. St. Laurent., Proc. OMAE 1984 Symposium, 3, New Orleans, pp. 246-252.		

Ship Name:	Sisu		
Location(s):	Baltic	Instrumentation:	Frame gauges and ice pressure gauge
Year(s):	1979-1984	Comments:	234 days of operations in ice, with 670,000 measured peaks
References:	Kujala, P., Vuorio, J., "Results and Statistical Analysis of Ice Load Measurements On Board Icebreaker SISU in Winters 1979 to 1985", Winter Navigation Research Board Report 43, 52p., 1986		

Ship Name:	Polar Sea		
Location(s):	Beaufort, Chukchi, Bering Seas and Antarctic	Instrumentation:	Strain gauges applied to frames (compression normal to shell) to create 60 sub-panels, each of 0.15m2, covering 9m2 on bow shoulder.
Year(s):	1982 - 1984	Comments:	Approx 3700 recorded impacts in FY and MY ice.
References:	Daley, C., St. John, J.W., Brown, R., Glen, I.F., 1990. "Ice Forces and Ship Response to Ice - Consolidation Report", Ship Structures Committee Report SSC-340.		

Ship Name:	MV Arctic		
Location(s):	Baffin Bay	Instrumentation:	Hull Girder Strain Gauges to determine Ram forces and Bending Moments
Year(s):	1984	Comments:	146 Head-on Rams, most of which causes the ice to break in bending.
References:	Riska, K., "On the Mechanics of the Ramming Interaction between a Ship and a Massive Ice Floe", Thesis for degree of Doctor of Technology, Technical Research Centre of Finland, Publications 43, Espoo, Finland, 1987.		

Ship Name:	Polar Star		
Location(s):	Beaufort Sea	Instrumentation:	Strain gauges on decks for hull girder bending, plus accelerometer package in the bow.
Year(s):	1985 - 1986	Comments:	Approx 80 impacts in ice floes and ridges. Mainly symmetrical head-on rams
References:	Minnick, P., St. John, J.W., Cowper, B., Edgecombe, M., 1990. Global Ice Forces and Ship Response to Ice, Ship Structural Committee Report SSC-341. Minnick, P., St. John, J.W., 1990. Global Ice Forces and Ship Response to Ice – A Second Season, Ship Structural Committee Report SSC-343,		

Ship Name:	ODEN		
Location(s):	Arctic Ocean (North Pole)	Instrumentation:	Shear difference frame gauges in 2 separate panels in the bow, as well as global hull loads
Year(s):	1991	Comments:	A 50 day ice transit from Spitsbergen to the North Pole. Triggered recording of load events. Hourly observations of ice conditions.
References:	Edgecombe, M., St. John, J., Liljestrom, G. and Ritch, R., 1992. Full scale measurements on hull-ice impact loads and propulsion machinery response onboard icebreaker Oden during the 1991 International Arctic Ocean Experiment, Transport Canada TP 11252E		

Ship Name:	Nathanial B. Palmer		
Location(s):	Antarctic	Instrumentation:	4 Strain gauge panels, on bow, bottom fwd, side aft and stern (transom). Approx 60 gauges measuring compression normal to shell.
Year(s):	1992	Comments:	Approx 800 recorded impacts in FY and SY ice.
References:	St. John, J.W., Minnick, P., 1995. Ice Load Impact Study on NSF R/V Nathanial B. Palmer, Ship Structural Committee Report SSC-376,		

Ship Name:	Louis St. Laurent		
Location(s):	Arctic Ocean (North Pole)	Instrumentation:	Shear difference frame gauges in 3 separate panels
Year(s):	1994	Comments:	A 35 day transit, with USCGC Polar Sea, from Alaska, across the Arctic Ocean to Svalbard. Triggered recording of loads and hourly observations of ice conditions.
References:	Ritch, R., St. John, J., Browne, R., Sheinberg, R. 1999. Ice Load Impact Measurements on the CCGS Louis S. St. Laurent during the 1994 Arctic Ocean Crossing, *Proc of the 18th OMAE*. July 11-16, St. John's Newfoundland, paper OMAE99/P&A-1141 Frederking, R. 2000 Local Ice Pressures from the Louis S. St. Laurent 1994 North Pole Transit *Technical Report*, HYD-TR-054. Canadian Hydraulics Centre, NRC, Ottawa		

Ship Name:	Healy		
Location(s):	Labrador Sea and Davis Straight	Instrumentation:	
Year(s):	2000	Comments:	
References:	Santos-Pedro, V.M., Timco, G.W. 2001. Canadian Involvement in the USCGC HEALY Ice Trials, POAC 01, August 12-17, Ottawa Canada		

Ship Name:	Terry Fox		
Location(s):	Newfoundland	Instrumentation:	3 load and pressure systems: Strain Gauge Panel, exterior optical pressure panel and MOTAN Motion/Loads package
Year(s):	2001	Comments:	These were dedicated bergy-bit collision trials, with 3 load measuring approaches.
References:	Gagnon, Robert, David Cumming, Ron Ritch, Robin Browne, Michelle Johnston, Robert Frederking, Richard McKenna, and Freeman Ralph. 2008. Overview accompaniment for papers on the bergy bit impact trials. Cold Regions Science and Technology 52, (1): 1-6.		

3.2.3.1 Local Loads

The term local ice loads refers to ice load cases that relate to local structural response, both shell plating and framing, as well as loads on appendages. Most ice loads of structural interest arise from collision events. A head-on ram may cause both local and global responses. Shoulder and other ice impacts will typically only be of local structural interest, with the potential damage confined to the local area of the impact.

There have been many ship trials to measure local loads in ice, with a partial list shown in Table 3.3. The load measurements have been found to be quite non-uniform, varying significantly from panel to panel. As a way to express the spatial variability of the pressures, the concept of the pressure-area relationship was developed as a way to quantify and present the spatial variability of ice pressures (see Sanderson 1988, Frederking 1998, Daley 2007, Jordaan et al 2010). There continues to be some debate and controversy about the pressures-area relationship (see Daley 2007). There are those who appear to believe that the currently available data (meaning the measured pressures on various ships and structures in the arctic) represent values of pressure that cannot be exceeded. In the introductory remarks of (Jordaan et. al. 2010) the authors state:

> *Thus the ship's rams and indentor impact tests represent in all cases the ultimate strength of the ice in practical situations of confined compression.*

The authors then propose a design pressure-area curve (see Figure 3.15) that is derived from a statistical assessment of the available pressure data with inclusion of 'exposure'. The proposed pressure-area curve just happens to go through the highest measured values of pressure.

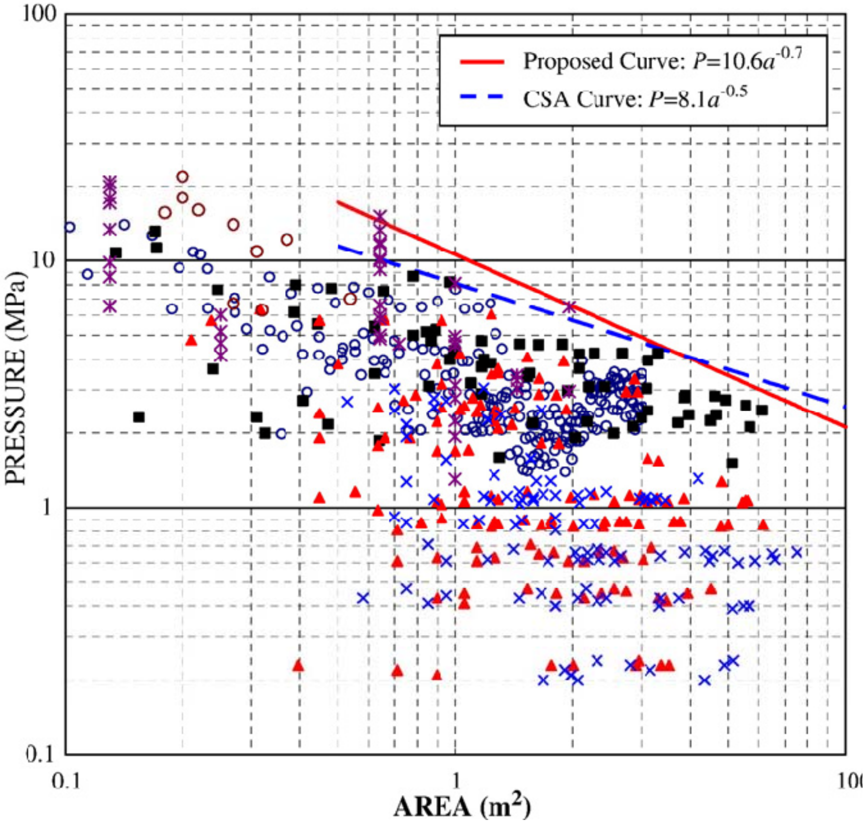


Figure 3.15: Local Pressure-Area Curves (Jordaan et.al. 2010)

In contrast to the view that the existing local pressure data represents the 'ultimate strength of ice' and thus is representative of maximum possible ice pressures, there are some authors who remain to be convinced. The key to the debate lays in the influences that parameters such as force, velocity, mass and interaction shape on ice pressures. Sanderson (1988) speculated as to whether ice pressures may be just a function of area, and relatively independent of other factors. This would be true if local ice pressure were primarily controlled by ice material properties. In such a case, both large and small ships, fast and slow ships, would experience similar pressures when operating in similar ice.

If, on the other hand, local ice pressures are significantly influenced by factors such as the overall force level, and total area of contact, then larger, faster ships would not only experience larger forces, but would also experience larger pressures. To address this question, Daley (2004, 2007) re-analyzed the measured data from the USCGC Polar Sea (Daley et al. 1990), with the aim of examining the relationships between force, total area of contact and local pressures. The results clearly showed that the local pressures are strongly correlated to total contact area and force. Figure 3.16 shows the trends from a single impact. The ten largest impacts all showed similar results. Gagnon (2008) finds a similar link in the Terry Fox iceberg impact pressure data.

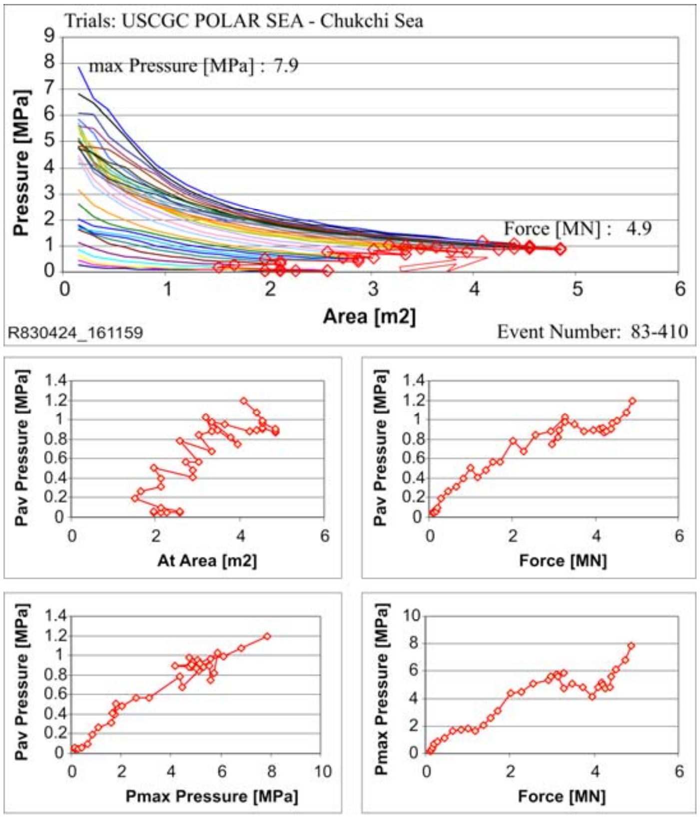


Figure 3.16: Local Pressure Data from Event #410 on the USCGC Polar Sea, from 1983 (Daley 2007)

A topic that has arisen recently in the literature is the question of ‘exposure’. Frederking and Johnston (2008), and Jordaan et. al. (2010) both discuss the matter of the definition and influence of exposure. The explanation by Jordaan is as follows:

Exposure can be measured in a number of different ways. One can think of exposure in the case of a Weibull “weakest link” problem. In this case we could have a chain with many links, all with random strength. The strength of the chain is only as strong as that of the weakest link. Exposure *can be considered here as the number of links in the chain. The greater the number of links in the chain, the greater the likelihood of having a link with a low strength to initiate failure. For the design of offshore structures in an ice environment, exposure can be considered as a function of time. One can compare the effect of floe sizes which could impact the Molikpaq structure. A floe that is 1000 m long would have a greater exposure than a floe with a diameter* *of only 100 m. Here the duration of the impact with a 1000 m ice floe would be much longer than that of a 100 m ice floe, resulting in a greater likelihood of exceeding a particular load or pressure threshold.*

The difficulty with the above explanation is that it seems to be an attempt to define a new term to describe something that needs no definition, and in doing so merely confuses the matter. All statements about probability require context. It is meaningless to give any probability without the context.

Nevertheless, the focus on 'exposure' or context does serve a useful purpose. There are many examples in the literature in which probabilities of ice pressure have been presented with insufficient description of context. Frederking and Johnston (2008) serves as an example of this issue. Figure 3.17 presents a comparison of plots of the cumulative probability for various level of local pressure. The data is taken from pressure measurements from both glacial and multiyear ice and for both ships and a pressure panel attached to a cliff in Labrador. In all the cases the pressure data represents the maximum observed pressure on a sensing area of approximately 0.3m^2, for one 'event'. The probability of exceeding the pressure Y is determined by ordering the data of N samples, and then using the rank of the Y sample (n_Y);

$$P(Y) = \frac{\text{n}_\text{Y}}{N+1}$$

The five data sets shown in Figure 3.17 all use this simple form of probability to generate the plots from the measured data. For each set of tests the probability context is an 'event', where an event is one impact. It is clear that the data from the different tests follows different trends. The differences include the ice type, temperature, strength (as measured in the lab), as well as the mass speed and shapes of the impacting bodies. All data was scaled using a pressure-area relationship, of the form;

$$P(A) = \text{C}\left(\frac{\text{A}}{\text{A}_\text{o}}\right)^{-.5}$$

Unfortunately, there was no correction for factors such as mass, shape and velocity. It might be inferred that Frederking and Johnston do not expect that such factors influence ice pressure.

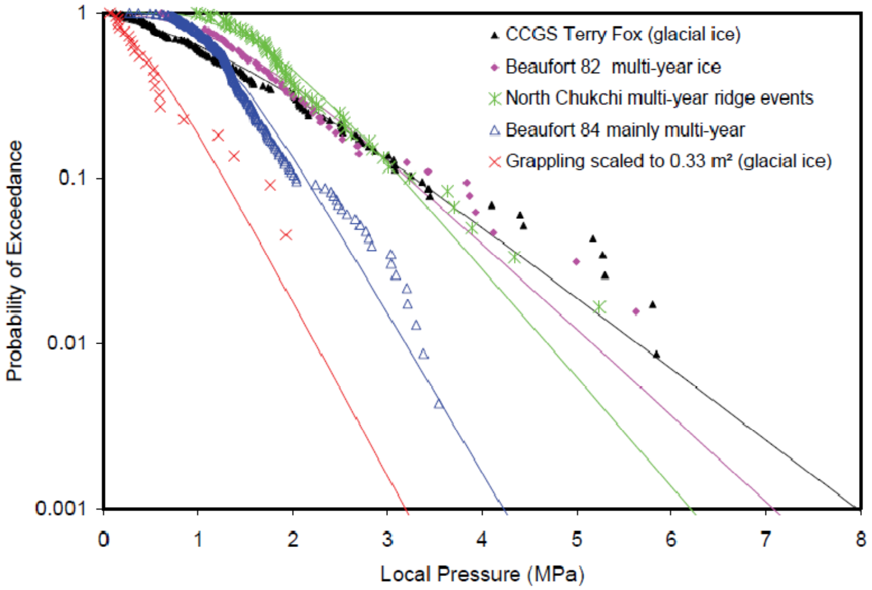


Figure 3.17: Comparison of Local Pressures from Tests on Terry Fox, Polar Sea and Grappling Island (Frederking and Johnston 2008)

The authors do, however, make one additional correction to the data, which they describe as accounting for exposure. They seek to express the probability of pressure on a single sub-panel of 0.3 m^2. In the case of the Polar Sea data, which had an overall sensing area of 9m^2, the authors divided all probabilities by a factor of 30 (=9/.3). The 'corrected' probabilities are shown in Figure 3.18. In doing so the authors were trying to express the chance that any individual panel of 0.3m^2 would experience a given pressure in a single event. While this may at first seem reasonable, it is actually not correct, or at least not at all useful. The purpose of correcting for exposure is to place all the data to be compared on a valid common base. In the case here, the statistics for the maximum pressure were divided by the total number of measuring panels. This is, in this case, inappropriate, as it implicitly assumes that all the panels are equally likely to experience the load. Only if the loads were equally and randomly distributed over all panels would it be reasonable to assess the risk on a per-panel basis. It would presumably be relatively easy to use the data to see if the panels were equally likely to experience a peak. Otherwise there would be little value in estimating the average risk for all panels. The practical concern should be the risk to the ship of damage to any plate.

This issue deserves a significant amount of discussion, not only to clarify a complex matter, but because there is a significant trend towards probability based design.

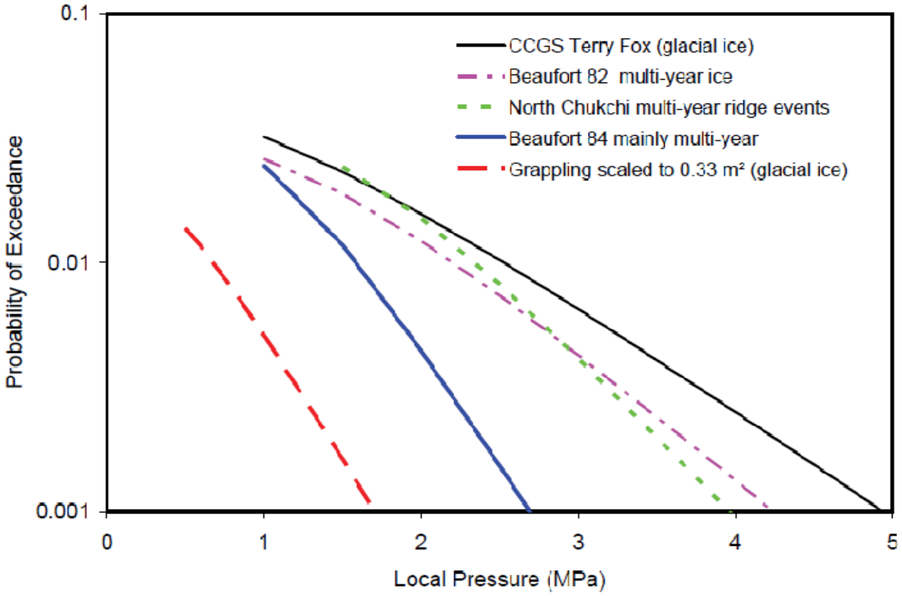


Figure 3.18: Comparison of Local Pressures from Tests on Terry Fox, Polar Sea and Grappling Island, Corrected to a Common 'Exposure' of One Sub-panel (Frederking and Johnston 2008)

3.2.3.2 Global Loads

The term 'global loads', in the case of ships, normally refers to those loads that cause a global structural response in the hull girder. The term can also refer to the total force of impact, although since most ice impacts occur over a small area, there is little need to separate local load from total impact forces. In the case of the Terry Fox bergy-bit impact trials (Gagnon et.al. 2008), one of the sensors, the MOTAN system, used the global rigid body response of the vessel to determine the total ice impact force (see Figure 3.13).

The major global load and response of interest is hull girder stress that arises from a head-on ram into very heavy ice features. This interaction formed the design basis for the Canadian Arctic Shipping Pollution Prevention Regulations (ASPPR). There was a great deal of research conducted on this topic in the 1980s. Key field programs are reported in Ghoneim et.al. (1984), German and Milne and VTT (1985). Ramming model tests are reported in Riska and Daley (1986) and Howard et. al. (1989). Mathematical models are described in Daley (1984), Vaughn (1986), Riska (1987) and Daley (1999). The global load and strength requirements of the IACS Polar Rules are presented in Daley (2000). The ramming forces and vessel response for the case of a ship ramming heavy ice are now quite well understood, and require little further study. There is limited sensitivity of global loads to the pressure/area effect discussed above, vital as these are to local loads.

3.3 Materials, Structural Response and Fabrication

3.3.1 Material Grades

Ships operating in the polar regions are subjected to highly concentrated loading from ice features and air temperatures down to -50°C. For this reason, large load carrying capacity and high ductility are required. Additionally, the necessity of weight reduction for saving material and lowering production costs, construction time and buoyancy leads to the employment of different materials and enforces their development for these special environmental conditions.

3.3.1.1 Steel

Steel is preferred over other construction materials for arctic going ships because of its high strength, processability, availability and its relatively low price. The required steel grade for a particular application will depend on (Riska et al. 1997):

- Design minimum temperature
- Associated wind speed
- Likelihood of exposure of the structural member to impact loads at low temperatures
- Stress category of the member, and anticipated strain rate
- Steel thickness
- Stress relieving and post-welded heat treatment
- Amount of cold-forming (unless its effects have been nullified)
- Accessibility to structural components for welding inspection and periodic surveys
- Weld acceptance criteria
- Provision of artificial means of heating (Rapo 1983)

In 1996, the International Association of Classification Societies (IACS) issued new unified requirements, UR S6 (rev. 3), pertaining to the use of steel grades for various hull members. Included were requirements for structures exposed to low air temperatures. By these rules, the selection of steel grades is to be made on the basis of the design temperature, material thickness and the structural category. This coupled with drivers from industry in the form of increased material property demands for liquefied natural gas (LNG) and container ships as well as corrosion resistant crude tank material have lead to the development of new steels through new manufacturing processes. Specific industrial demands on steel grades are (Ohkita and Oikawa 2007):

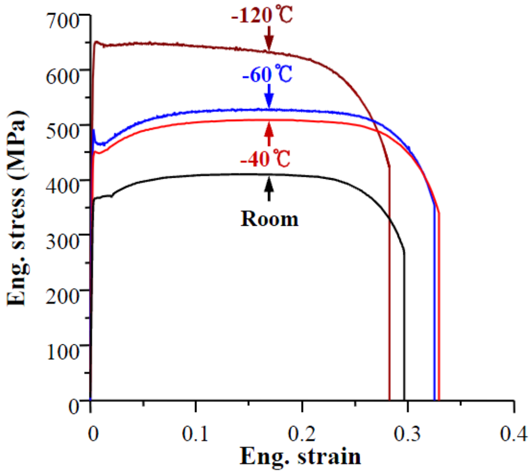
- Heat Affected Zone (HAZ) toughness
- Crack arrest properties
- High heat input weldability
- High tensile strength
- Small distortions
- High efficiency fabrication
- Corrosion resistance, and
- Fatigue strength

The process by which these new steels are made is called the *thermo-mechanical control process* (TMCP). TMCP now uses online accelerated cooling devices during steel production. In addition to online cooling, heat affected zone (HAZ) grain size is controlled through thermal stabilization of TiN particles; and HAZ grain microstructure is controlled through advanced microalloying technology (i.e., microalloyed with one or more of nickel, chromium, copper, niobium and boron) (Um et al. 2008; Suzuki, Ichimiya, and Akita 2005; Nie et al. 2010; Kang 2005; Basu, Tripathi, and Modak 2005).

Steels created with these new processes are optimized for high heat input welding, high strength and low temperature fracture toughness. (Stern, Wheatcroft, and Ku 1985; Um et al. 2008; Suzuki, Ichimiya, and Akita 2005; Nie et al. 2010; Kang 2005; Stern, Wheatcroft, and Ku 1985; Kim, Suh, and Kang 2007b). These steels are available in an "as rolled" condition; rather than in a quenched and tempered state (Basu, Tripathi, and Modak 2005). In particular, high heat input welding versions of grades EH36, EH40 and EH47 are now available (Um et al. 2008; Stern, Wheatcroft, and Ku 1985; Kim, Suh, and Kang 2007a). These EH-grade heavy shipbuilding steels are expected to have long crack arrestibility for brittle cracks in a base plate or welded joint. At least one paper (Inoue et al. 2007) has shown that while this is the case for longitudinally stiffened panels loaded to stresses less than 200MPa, this was not the case when these stresses exceeded 200 MPa.

Of these new steels, much research in niobium bearing steels in particular has been carried out. Published works generally report that niobium bearing steels provide improved toughness (including at low-temperatures), fracture resistance and weldability. (Jansto 2008; Yang et al. 2008); however McPherson (2009) suggests that niobium imparts no beneficial effects in the HAZ and Ichimiya et al (2008) state that the *reduction* of carbon, silicon and niobium improves HAZ toughness.

The above experiments were performed at room temperature, as has been normally done in such experiments. The plastic behavior of steel grillages and structures at cold temperatures has not been widely explored and is significant concern for arctic ships. Recent research into the effect of cold temperatures on ship steels has shown that the yield strength can be significantly enhanced at colder temperatures and that fracture strain is not strongly affected, although the testing methodology (involving dry ice and acetone versus liquid nitrogen) does have a significant effect. This is significant because the dry ice/acetone environment is supposed to more closely resemble an arctic environment than the liquid nitrogen setup; implying that other previous laboratory experiments into the effect of cold temperatures on steel material behavior (which mostly used liquid nitrogen cooling) may be overestimating the quasi-static failure strain (Kim et al, 2009, 117-124).



Liquid nitrogen cooled system

Figure 3.19: Stress-strain Behavior for Tests at Various Temperatures (Kim et. al. 2009)

Another area of research applicable to arctic ship structures is the effect of cold temperatures on material strain rate effects. Hot rolled mild steel is notoriously strain-rate sensitive (Marsh and Campbell 1963), as are other steels. For steel, this strain rate sensitivity manifests itself in the form of increased yield strength (i.e., dynamic yield strength) with increasing strain rate, and decreasing fracture strain with increasing strain rate. Dynamic yield stress for various materials may be described by the following regression equation proposed by Cowper and Symonds (Jones 1983; Cowper and Symonds 1957):

$$\sigma_D = \sigma_y \left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/p}\right]$$

where: σ_D is the dynamic yield stress

σ_y is the static yield stress

C and p are constants called the *Cowper-Symonds Parameters*

C and p for hot-rolled mild steel are:

$$C = 40.4 \quad \text{and} \quad p = 5$$

Values for other materials are given in the following table (Jones 1983):

Material	C [-/s]	p
Stainless Steel 304	100	10
Alpha-Titanium (Ti-50A)	120	9
Aluminum	6500	4

Figure 3.20 shows the behavior of hot-rolled mild steel versus that of other materials.

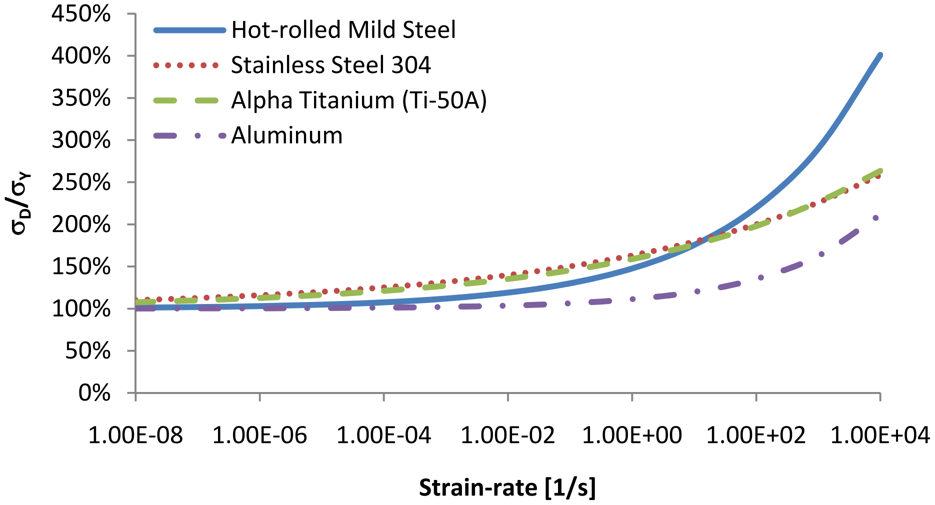


Figure 3.20: Yield Stress Scale Factor for Various Materials for Various Strain Rates

This dynamic increase in yield strength for various ship building materials can be quite dramatic (even at quasi-static strain rates). Quantifying the increased yield strength for various ship building materials at various temperatures would allow the substitution of this dynamic yield stress into design equations for specific load scenarios where the strain rate can be assumed; thus preventing the overdesign of structural members in some cases.

It should be noted that the Cowper-Symonds relationship given above has gained nearly universal acceptance because of the remarkable agreement between analytical and numerical predictions with experimental data (Jones 1983).

Other factors to consider are the post dynamic yield stress-strain relationship and the effect of strain rate on fracture strain.

One potential pitfall of using the Cowper-Symonds formula lies in assuming it is valid for any strain. Note in Figure 3.21 that for the static case, plastic design using a perfectly plastic stress-strain relationship assumes that the structural stresses will never exceed the static yield stress for any strain up to fracture. This provides a very conservative estimate a structure's energy absorbing capacity. For the 0.02 strain rate case, the actual stress beyond the yield strain promptly drops significantly. In this case if a perfectly plastic assumption is used based on the Cowper-Symonds formula, it will over-predict the structure's energy absorbing capacity (see the Erroneous Dynamic Perfectly Plastic Assumption line in the figure). A general rule is that for cases where the expected strains are only a few percent, it is acceptable to use the Cowper-Symonds formula; if strains are expected to be greater, than Cowper-Symonds formula may still be used, but with new *C* and *p* parameters that provide a more conservative scale factor on the static yield stress. Even at room temperature, little data exists regarding the Cowper-Symonds parameters for large strains.

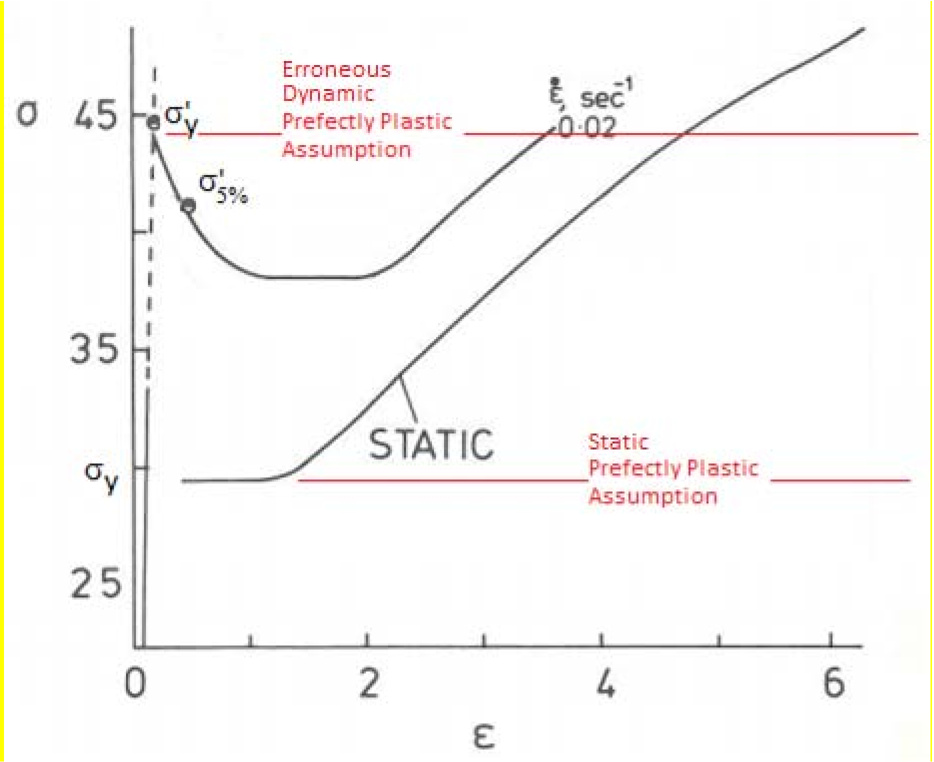


Figure 3.21: Mild Steel Stress-strain Curves for Two Strain Rates (1 unit of ordinate is 10^3 lb in^{-2}) (modified from Jones 1983).

The effect of strain rate on fracture strain affects the energy absorption capacity of a structure. The energy required to fracture steel is proportional to the area under the stress-strain curve up to the fracture strain. Fracture strain is sensitive to strain-rate but does not necessarily decrease with increasing strain rate; it can be significantly higher than the static fracture strain. Fracture strain is also sensitive to temperature. Much research has been done regarding the effect of elevated temperatures on structural steels, however similar experiments on ship building steels at reduced temperatures are lacking. More research is needed to determine the combined effects of strain-rate and reduced temperatures on ship-building steels so that an assessment of the energy absorption capacity of arctic ship structures may be made.

3.3.1.2 Selection of Steel Grades Based Design Temperature

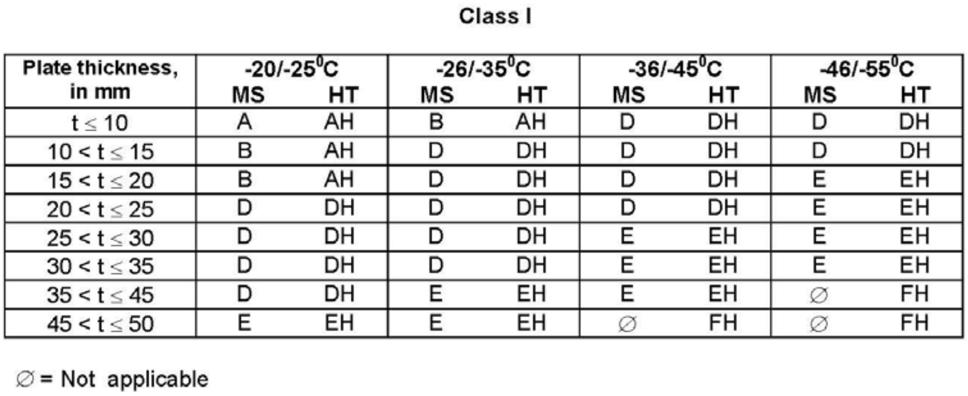
Steels for hull structures subject to the direct action of ice have to possess high resistance to brittle fracture under impact loads and high stresses at low temperatures. According to established practice and IACS unified requirements (UR W11), steel grades A, B, D and E of normal strength; and AH, DH, EH and FH of higher strength are distinguished based on their impact test requirements. The only difference is in the CVN-test temperature and the amount of steel to be tested for the steel grades.

All the factors influencing the ductile-to-brittle transition are greatly variable and all are essentially random in nature. No scientifically based formulas or proven empirical relationships exist for selecting the appropriate steel grades as a function of these parameters. After Japanese studies started in the late 1970’s (Yajima and Tada 1981 and others) remarkable progress has been made in this field (e.g., Sumpter and Caudrey 1995; Malik et al. 1997), however this progress has not yet translated into commonly agreed scientific criteria for selecting a steel grade.

There are a number of existing regulations, as well as the recently adapted IACS rules, for structures exposed to low air temperatures. The Baltic Rules contain virtually no requirements other than an introductory remark that the hull materials are to be adequate for operation in -30°C. Material selection in all non-Baltic rules is based on the concept that structural members operating in cold environment under high impact loads are to be made of higher steel grades. However, the specific material requirements by different regulatory bodies differ considerably from each other both in approach and in detail. As a result, in spite of the limited list of steel grades, different rules do not always require the same steel grade for a structural member of a ship.

This is an area of uncertainty and controversy, best illustrated by the contrast between the two IACS URs, S6.2[2] and I2[3] as shown in Tables 3.4 and 3.5 below. During the development of the (later) I2 various stakeholders pointed to the absence of fracture problems on existing high ice class ships and offshore structures despite lack of conformity to S6.2 standards. There was an absence of material to justify the requirements of the (earlier) S6.2 scientifically. The resulting steel grade requirements in I2 represented a compromise solution. However, several classification societies have now published various forms of “winterization” guidelines (e.g., ABS) that re-introduce the S6.2 requirements for items not covered by I2. The paradoxical result is to require higher steel grades for some non-safety critical components than for the hull itself.

Table 3.4: Material Grades from IACS S6.2



Class I

Plate thickness, in mm	-20/-25^{0}C		-26/-35^{0}C		-36/-45^{0}C		-46/-55^{0}C	
	MS	HT	MS	HT	MS	HT	MS	HT
t ≤ 10	A	AH	B	AH	D	DH	D	DH
10 < t ≤ 15	B	AH	D	DH	D	DH	D	DH
15 < t ≤ 20	B	AH	D	DH	D	DH	E	EH
20 < t ≤ 25	D	DH	D	DH	D	DH	E	EH
25 < t ≤ 30	D	DH	D	DH	E	EH	E	EH
30 < t ≤ 35	D	DH	D	DH	E	EH	E	EH
35 < t ≤ 45	D	DH	E	EH	E	EH	∅	FH
45 < t ≤ 50	E	EH	E	EH	∅	FH	∅	FH

∅ = Not applicable

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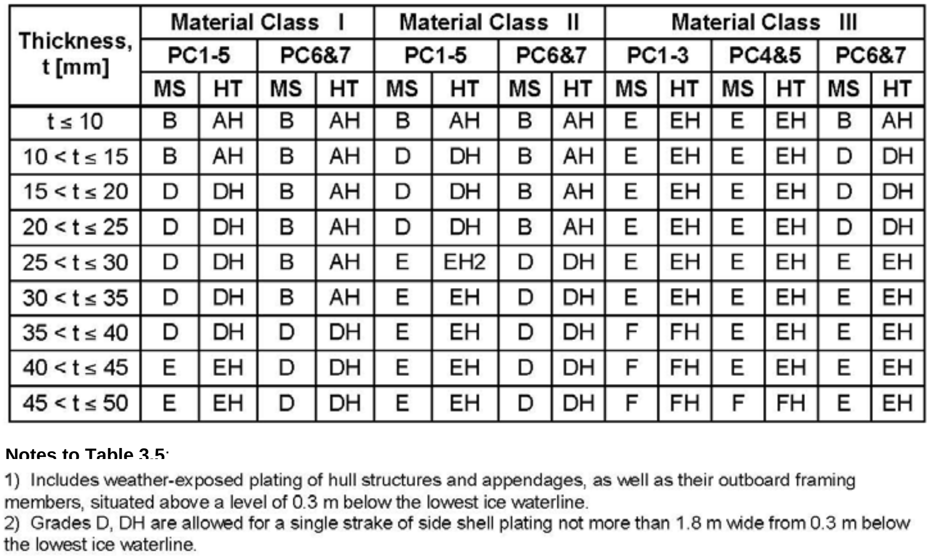
[2] http://www.iacs.org.uk/document/public/Publications/Unified_requirements/PDF/UR_S_pdf158.PDF

[3] http://www.iacs.org.uk/document/public/Publications/Unified_requirements/PDF/UR_I_pdf410.pdf

Table 3.5: Material Grades from IACS I2



Thickness, t [mm]	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	MS	HT	MS	HT	MS	HT	MS	HT	MS	HT	MS	HT
t ≤ 10	B	AH	B	AH	B	AH	B	AH	E	EH	E	EH	B	AH
10 < t ≤ 15	B	AH	B	AH	D	DH	B	AH	E	EH	E	EH	D	DH
15 < t ≤ 20	D	DH	B	AH	D	DH	B	AH	E	EH	E	EH	D	DH
20 < t ≤ 25	D	DH	B	AH	D	DH	B	AH	E	EH	E	EH	D	DH
25 < t ≤ 30	D	DH	B	AH	E	EH2	D	DH	E	EH	E	EH	E	EH
30 < t ≤ 35	D	DH	B	AH	E	EH	D	DH	E	EH	E	EH	E	EH
35 < t ≤ 40	D	DH	D	DH	E	EH	D	DH	F	FH	E	EH	E	EH
40 < t ≤ 45	E	EH	D	DH	E	EH	D	DH	F	FH	E	EH	E	EH
45 < t ≤ 50	E	EH	D	DH	E	EH	D	DH	F	FH	F	FH	E	EH

Notes to Table 3.5:

1) Includes weather-exposed plating of hull structures and appendages, as well as their outboard framing members, situated above a level of 0.3 m below the lowest ice waterline.

2) Grades D, DH are allowed for a single strake of side shell plating not more than 1.8 m wide from 0.3 m below the lowest ice waterline.

3.3.1.3 Aluminium

Aluminium alloys are generally useable for different structures that experience low temperatures. Examples of these structures are cars, trains, aerospace and space technology, gas tanks, ships and offshore structures. Unlike common non-austenitic steels for ship and offshore structures, the mechanical properties of aluminium alloys suitable for use in sea water improve with lower temperatures. The shear and Young's moduli go up. The tensile strength increases; but in a higher grade than the yield strength. This means that the plastic reserve of the material increases too, providing a higher durability against impacts (Ostermann 1998). Toughness and deformability increase at lower temperatures as well. The fatigue strength of the basis material, as well as the welding, seems to show higher values at lower temperatures too.

The classification societies have specified a number of aluminium alloy grades for use in ship construction. These are the non- heat treatable 5XXX- group and some of the heat treatable 6XXX grades. The alloys of the 5XXX- group plate materials have a high corrosion resistance and are suited for underwater use as hull plating, while the alloys of the 6XXX- group are used for extruded profiles, commonly used for internal applications.

Aside from a 14m, 14.7 tonne displacement aluminium pilot boat (Beecham 2000), a literature search reveals little else regarding aluminium hulled vessels specially designed for Polar Regions. This is because: (a) aluminium alloys are preferred for marine applications because of their relatively low density, but there is little reason for weight saving in ice breaking vessels in this regard; (b) the relatively high material costs; (c) the processability is somewhat more difficult than for steel; (d) the higher risk of corrosion due to destructed coating (especially in the ice belt); and (e) the relatively low fire resistance. With increasing fuel costs and the development of suitable coatings, the above disadvantages may be negated. This may allow aluminium to be considered for greater use in polar vessels. It must be stressed, however, that current polar class ship design methods cannot be simply adjusted for use with aluminum. There are many practical matters, including issues of welding, heat-affected zones, fatigue, and general arctic durability for which there is little or no field experience. Aluminum in polar applications will need to be carefully tested and initially used with care.

3.3.1.4 Fibre Reinforced Plastics

Fibre reinforced plastics (FRP) are increasingly being used to reinstate/strengthen steel structures (Liu et al. 2009; Zhao and Zhang 2007) and their use may be warranted in arctic ship structures. Further, arctic-related FRP research (for use in ice-capable lifeboats and ship superstructures among other areas) is currently underway regarding FRP structure-ice interaction (Ré, Kuczora, and Veitch 2008) and the effects of cold temperatures on FRP material properties (see below).

FRP is attractive for arctic application because of its corrosion resistance, light weight, fatigue resistance and the ability to tailor its structural and mechanical response (Wilde et al. 1996). The question is whether these benefits exist under the environmental conditions in the arctic. Compared to pure metallic structural materials, composites have a lower thermal conductivity, lighter weight, higher strength and stiffness, and better fatigue and vibration damping characteristics.

Special tests were performed to determine the material behavior of FRP at low temperatures (Dutta 1994; Ritter 1995; Shen and Springer 1977; Jang et al. 1987; Aboudi 1991). Generally, when a glass fibre is embedded in an annulus of cured resin, the resin exerts a radial compression on the fibre as the temperature lowers. This compression produces a better contact at the interface of the resin and fiber; and the effect is to hold the fiber tighter during a fiber pull out test (Jang et al. 1987). Additionally, the resin gives a more effective support to the fiber against local buckling.

By theoretical treatment and experimental testing, it was shown that the Young's modulus of just the polymer resin matrix increases with decreasing temperature. The change of matrix modulus also causes a change of the composite modulus (Jang et al. 1987; Hartwig 1979; Tsai and Hahn 1980; Dutta 1989). The shear modulus of the polymer matrix increases approximately linearly with reduction of temperature (Kreibich, Lohse, and Schmid 1979). The comparison of shear strength of a unidirectional carbon fibre reinforced epoxy at +20°C and -196°C shows that the shear strength doubles at low temperatures (Ritter 1995). The estimation of yield strength by compression tests shows that the strength increases at lower temperatures.

There are two important effects that influence the behavior of unidirectional composites in compression at low temperatures: first, the increase of thermal residual stresses that must be overcome by the matrix and second, the increase in matrix stiffness that causes an increase in the critical fibre stress before failure (Dutta 1994). The ultimate tensile strength of a unidirectional carbon fibre reinforced epoxy decreases at lower temperatures (Ritter 1995). Tests show that samples of glass- and carbon-fibre reinforced laminates impact loaded at -196°C always have impact energy values greater than identical samples tested at 23°C (Jang et al. 1987). This higher impact energy seems to go hand-in-hand with a greater degree of macroscopic delamination and a larger amount of microdelamination or microcracking. The reduction of impact energy for Aramid-fibre-epoxy biaxial systems loaded at low temperature may be attributed to Aramid fibres having a higher transverse thermal expansion coefficient than the epoxy resin. Of interest is the influence of moisture on FRP at low temperatures. Moisture accumulates mainly in pores. Evidently a minimum volume is necessary to lead to an impairment of the laminate (Ritter 1995; Shen and Springer 1977). A careful optical microscopic examination reveals that very few microcracks are apparent in all samples exposed or unexposed to moisture attack (before impact loading). This implies that the thermal stresses and/or the moisture-induced stresses (if any) are not sufficient to cause microcracking at room temperature. A microscope cold stage was designed and used to observe if microcracking occurred at -196°C. No apparent microcracking was found (Jang et al. 1987).

As with aluminium, the interesting and potentially beneficial material properties of FRPs may lead them to be considered for greater use in polar vessels. Again it must be stressed, however, that current polar class ship design methods cannot be simply adjusted for use with FRP. There are many practical matters, including issues of bond strength and general arctic durability for which there is little or no field experience. FRPs in polar applications will need to be carefully tested and initially used with care.

3.3.2 Corrosion

Corrosion is a destructive electrical or electro-chemical attack on a material by reaction with its environment. The arctic environment is dominated by cold water, relatively clean air and the sun’s radiation. The corrosive nature of seawater has already been widely documented. The main factors which make seawater such a corrosive fluid are divided in two groups: (bio) chemical (i.e., oxygen, carbonate, salts, organic compounds, biochemical activity and pollutants) and physical (i.e., temperature, flow velocity, potential pressure and light) (European Federation of Corrosion and Institute of Materials 1993). As a general rule, the corrosion reaction rate in seawater increases as the temperature is increased. This rule applies only to the effect of temperature on the corrosion assuming all other variables are unchanged. The solubility of oxygen decreases as the temperature is increased. Biological activity generally increases with increasing temperature, and calcareous deposits and other protective scales are also more likely to form/deposit on metal surfaces at higher temperatures (Baboian 1995). Thus the cold arctic waters are generally less corrosive than warmer waters, but the corrosion protection systems, especially coatings, are highly loaded and often damaged by external forces.

On metal arctic structures, higher corrosion rates can be expected in the area of the water (ice) line by permanent abrasion of the corroded layer. This acts normally as a kind of corrosion protection. Field and laboratory tests (European Federation of Corrosion and Institute of Materials 1993) conducted on stainless steels and aluminium alloys in Antarctica allow the following preliminary conclusions:

- Oxygen reduction depolarization induced by biofilm growth on the surface of stainless steels, similar to that observed in other seas, was also found in Antarctica with a seawater temperature close to 0°C.
- Nevertheless, in comparison with the Mediterranean Sea, some differences in the final shape of cathodic curves, when the surface of stainless steels has been covered by biofilms, can be observed.

- The differences point to a decrease in the probability of localized corrosion initiation in Antarctica, although once started the rate of propagation of localized corrosion in the two regions is about the same.
- A rise in temperatures above 30°C tends to delay the oxygen reduction depolarisation induced by biofilm growth on the surface of stainless steels.
- The corrosion of aluminium alloys is heavily affected by the seawater temperature: thus under 10°C localized corrosion, in the form of both crevice and pitting corrosion, is easily enhanced with the propagation sustained by the oxygen reduction. Above 10°C only uniform corrosion, sustained by hydrogen reduction, occurs.

The new low-carbon Nb microalloyed steels mentioned above are reputed to have better corrosion resistance in sea water than that of niobium-free steel (Wang, Yang, and Zhuang 2007; Li et al. 2009).

3.3.3 Coatings

There are many requirements for a coating in arctic operations (Makinen 1994):

- Be smooth
- Have good wear resistance
- Have good bond strength with the base material
- Give good corrosion protection for the base material
- Sustain high normal pressures
- Withstand the deformations of the base material
- Withstand low temperatures, temperature changes and temperature gradients
- Maintain its properties in the arctic environment
- Be reasonably priced
- Should have antifouling properties (with limits of environmental issues)
- Applicable on a large scale
- Application method must be practicable in yard construction
- Not inhibit the possibility of repairs after installation

Ultraviolet considerations may also play a factor, depending on the base material. Sun light is about 95% absorbed and about 5% reflected by open sea water. If the water is ice and snow covered, these two values can be exchanged. This leads to much higher ultraviolet radiation in snow covered regions. This radiation is additionally increased by the depletion of the ozone layer over the polar regions. Ultraviolet radiation causes embrittlement of many duro- and thermoplastics. Therefore the need of special coatings for ultraviolet stabilized materials is greater (Domininghaus 1992).

One solution for coating the area of the water (ice) line of arctic structures is to use stainless steel cladded plates; which are offered by different manufacturers. In Makinen et al. (1994), friction coefficients of different coatings are compared. Katoh et al. (1989) investigated adhesion strength and wear by ice on various coatings in order to develop coated steel piles suitable for use in sea ice regions. Polyethylene and polyurethane coatings were found to be the best because these two coatings were durable against impact and the compressive forces of ice; as well adhesion strength and wear by ice were smallest.

Research has been initiated to evaluate coatings which can be applied to offshore structures and service vessels to minimize the bond between spray ice and the surfaces of these structures and vessels (Sackinger et al. 1988). A field program to collect naturally formed spray sea ice on vertical cylinders is described, and crystallographic evidence of four distinct crystal types (formed under differing atmospheric conditions) is presented. Bond strength of this ice to several coatings was measured, with the lowest values given by a graphite paint and polyethylene.

A major area of uncertainty for coatings – both external and internal – is resistance to deformation (strain) of the base material. While some of the ice-resistant external coatings such as Inerta 160^{TM} and its competitors have displayed good adhesion on moderately deformed external plating, internal ballast tank coatings on a number of vessels have performed much less well. This is considered to be an area in which additional research is needed (see Section 4).

3.3.4 Plastic Design

Plastic design has become the new norm for ice class ship design. The new IACS unified polar rules (IACS UR I), the Canadian Administration (ASPPR 1996) and the Russian Maritime Register (MRS 1999) all employ plastic design methods. There are several elements to the rationale for the use of plastic design for ice-structure interaction (Kendrick and Daley 2000). These include:

- Plastic design can ensure a better balance of material distribution to resist design and extreme loads. This is important because extreme ice loads can be considerably in excess of design values. This is more likely for ice loads than (e.g.) for wave loadings. The use of plastic methods ensures a considerable strength reserve, which may or may not be the case with elastic design.
- Plastic design can allow considerably lighter structure, particularly when the return period for design loads is relatively long and when cumulative damage (deformation, fatigue cracking, etc.) is not a major consideration.
- Plastic design methods are more applicable to damage analysis, which allows the assumptions in the URs to be tested against experience and refined in the future as necessary.

These considerations tie in well with actual operating practice for ice class ships. Occasional local deformation (denting) has tended to be an acceptable consequence of ice operations, provided that this does not compromise the overall strength or watertight integrity of the ship. The selection of structural design criteria for plastic design is more difficult than in elastic design. In the latter, first onset of yield is relatively easy to predict, and thus offers a simple criterion for design. In plastic design, there are many possible limit states ranging from yield through to final rupture.

The IACS URs have selected a set of limit states for plating and framing design which allow substantial plastic stress but preclude the development of large plastic strains or structural deformation. The development process for these requirements has devoted considerable effort to the selection of suitable design criteria, as described by Kendrick and Daley (2000). These limit states are defined by analytical representations of mechanisms within the frame or plate, rather than by reserves against ultimate failure (locally, rupture) as might be determined by FEA or by testing, due to the needs of the ship design and classification process. The analytical solutions are based on energy methods, assuming the sets of mechanisms shown in Figure 3.22 and Figure 3.23, for loads at the centre and near the ends of framing, respectively.

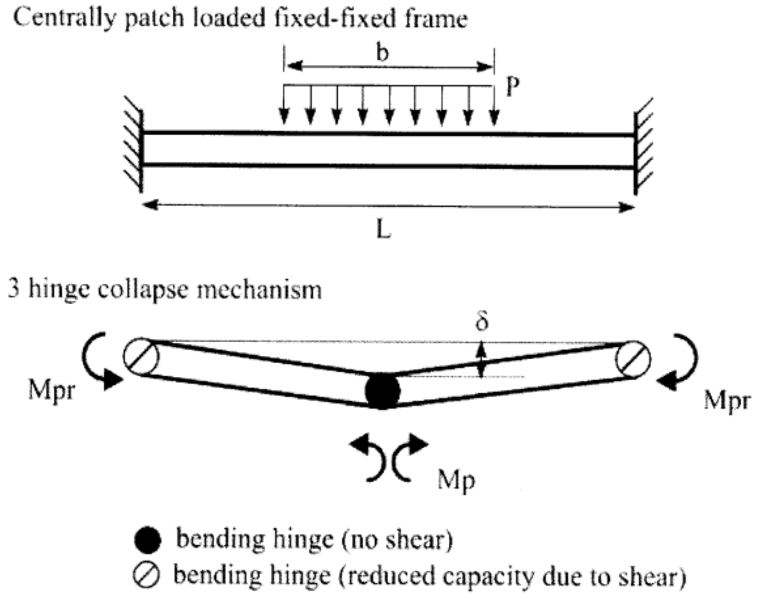


Figure 3.22: Symmetrical Loading: 3-Hinge Response

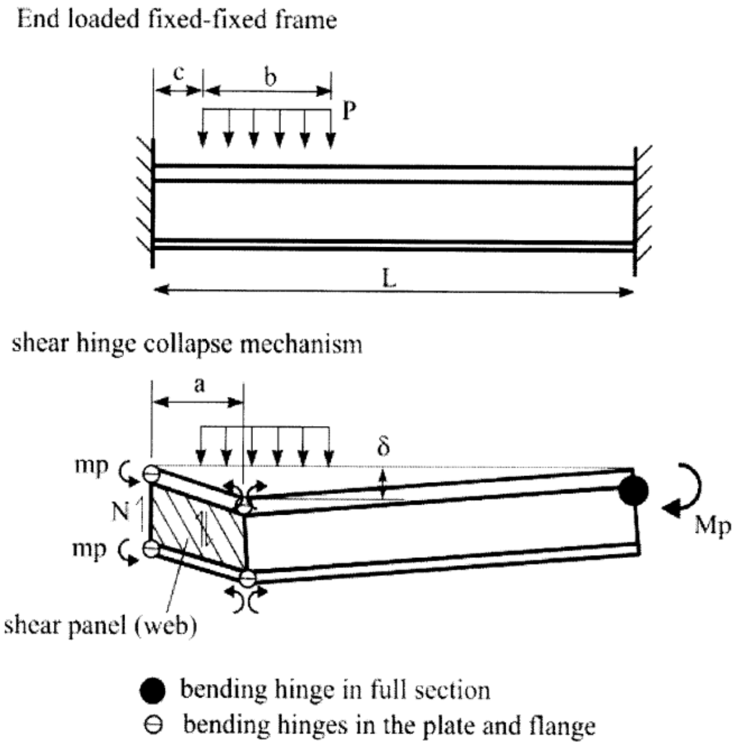


Figure 3.23: Asymmetrical Loading: Energy Absorption Mechanisms

Energy methods cannot provide deflection or strain predictions, and so it has been necessary to rely on finite element methods to ‘calibrate’ these aspects of the design criteria and procedures. At the design limit states the structures lose stiffness, but are still able to carry higher loads. Figure 3.24 illustrates the FE analysis of the behavior of a typical frame under the two possible design load locations (i.e., centred and close to one end), with first yield, and the points defined by the mechanisms underlying the relevant design equations also shown. The lower of the two pressure intensities defines the capability of this frame, and in this case, the symmetric case dominates.

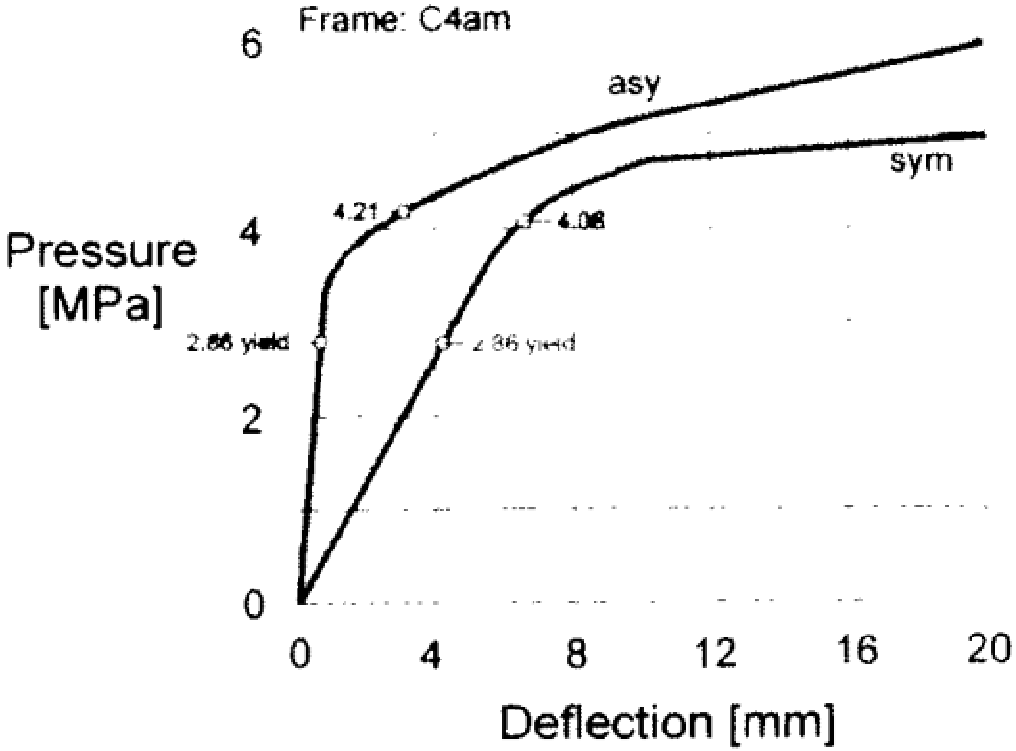


Figure 3.24: Illustration of Plastic Design Points

Figure 3.24 shows that there are various ways of describing the design limit states used in the UR rules. Nominally, the limit states are plastic collapse mechanisms. However, although they are relatively sophisticated, they still contain numerous simplifications. For several reasons the real structure will not collapse totally in the assumed manner or at the design load level. Two main reasons for this are that the assumed mechanisms ignore the effects of membrane stresses and strain hardening. As a result the real structure will have a substantial reserve capacity. More precisely then, the design limit states represent a condition of substantial plastic stress, prior to the development of large plastic strains and deformations, but where the structural elements are starting to show significant losses in stiffness. Permanent (residual) deflections under the design loads should not require repair, and should not be sufficient to cause damage to internal or external coatings.

The IACS (and other rule systems) are generally drawn from elastic analysis, and although some recent work is has been undertaken to confirm that these solutions are adequate (e.g., Bond and Kennedy 1998) more work is warranted to develop improved representation of stability in the elasto-plastic range.

In a comprehensive set of structural experiments (Daley and Hermanski 2008, Daley et. al. 2007, SSC Project 1442) the plastic limit state equations in the IACS Polar Rules were studied. Figure 3.25 illustrates the experimental arrangement for a large grillage subjected to transverse (i.e., external) loading in a very small load patch. Figure 3.26 shows the web deformations that were typical plastic responses.

The physical experiments reported in Daley and Hermanski (2008) showed generally good agreements with the capacity values in the IACS Polar Rules. There were differences in deformation patterns which may be significant for some cases. The physical experiments indicated that there is significant reserve plastic capacity, both in terms of load capacity and energy absorbing capacity, above the nominal plastic design point (which some would describe, incorrectly, as plastic ‘collapse). This may become increasingly important in the future, as more attention is paid to accidental and over overload cases. Two structures which display similar elastic capacity can easily have significantly different plastic capacities. Similarly, two structures with similar nominal plastic capacity can have significantly different extreme response reserve.

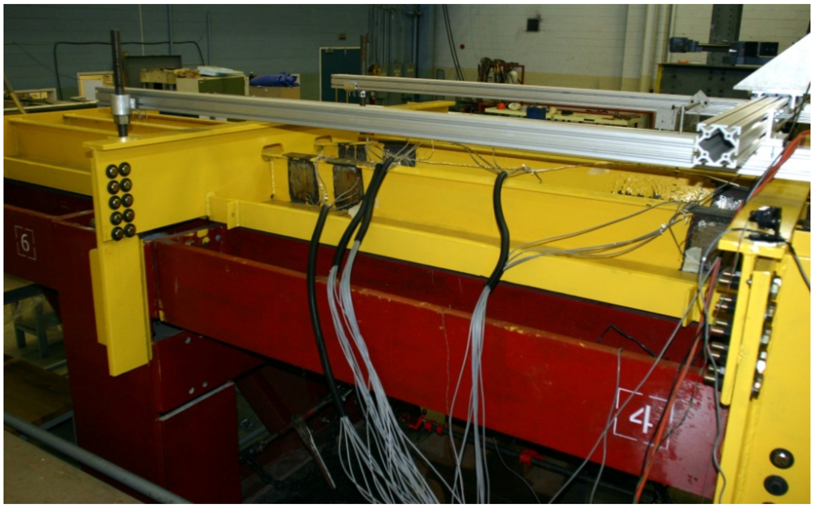


Figure 3.25: Large Grillage Test Arrangement (Daley et. al 2008)

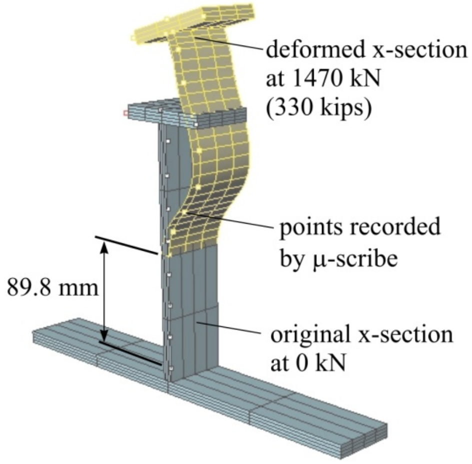


Figure 3.26: Microscribe Data for First and Last Load Step on Large Grillage Test LG2

3.3.5 Sandwich Plate System

3.3.5.1 Introduction

The *sandwich plate system*[4] (SPS) shown in Figure 3.27 is intended to replace standard steel stiffened panels in ship structures. The SPS is composed of unstiffened sandwich plates that consist of two thin steel plates bonded to a polyurethane elastomer core. The SPS was initially developed to provide impact resistant plating for offshore structures working in the Canadian Beaufort Sea (Brooking & Kennedy, 2004). SPS was developed in conjunction with Elastogran GmbH (a member of the BASF Group) and has approvals from the major Classification Societies (Lloyd's Register, 2006; Welch, 2007) and regulatory authorities (Brooking & Kennedy, 2004) for the use of SPS in newbuilds and the rehabilitation of ships.

Figure 3.27: Sandwich Plate System (SPS)

In flexure, the plates act as flanges and the core as the web. The flexural stiffness and strength are tailored as required by choosing appropriate thicknesses for the sandwich elements. The elastomer core provides continuous support to the steel plates, thus precluding local buckling (Kennedy, et al., 2006; Little, et al., 2007) and eliminating the need for closely spaced discrete stiffeners (see Figure 3.28), and transfers shear from one steel plate to the other (Brooking & Kennedy, 2004). Published literature suggests that SPS plates can be taken in to the fully plastic regime without local faceplate buckling or bond delamination between sandwich cores (Little et al., 2007).

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[4] Intelligent Engineering Ltd.

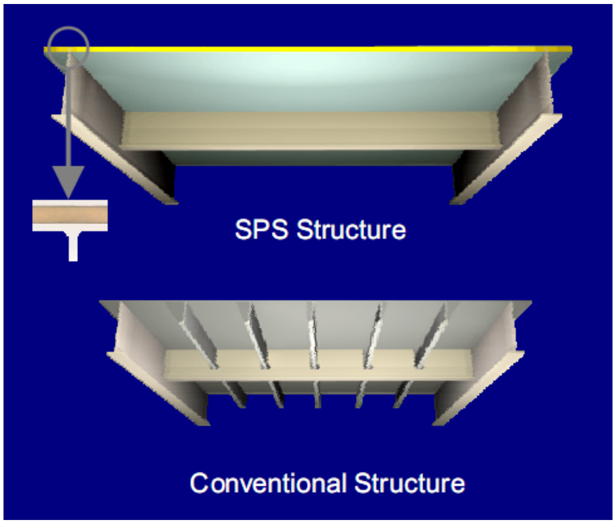

Figure 3.28: SPS (above) and Conventional (below) Structures

SPS plates were first used in the shipping industry in 1999 (Brooking & Kennedy, 2004). Since then, research and development has focused on material characterization, structural behavior and performance, design principles, fire resistance and engineering, energy absorption design philosophies and the development of connection specific details specific to sandwich plate structures.

3.3.5.2 SPS Benefits

Benefits of SPS construction over conventional steel structures (Brooking & Kennedy, 2004):

- Simplified structure
- Reduced weight
- Increased fatigue resistance
- Reduced susceptibility to corrosion
- A60 fire rating
- Enhanced puncture, impact, blast and ballistic resistance
- Inherent structural damping reducing vibration and noise transmission

3.3.5.3 Recent Applications of SPS

In total to date, Intelligent Engineering (the producers of SPS) have delivered over 150,000 m² of SPS plate to the marine industry for various applications including: deck reinstatements (Welch, 2007) (including RoRo, heli, and gun decks), funnel casings, newbuild and retrofit hulls, bulkhead and tanktop reinstatement (especially bulk carriers (Brooking, 2005; International Bulk Journal, 2007) anchor pad and superstructure strengthening[5]. Besides for marine applications, SPS is used in civil works such as road bridge decks, stadia terraces and flooring systems.

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[5] Calculated from "Project Portfolio" found at http://www.ie-sps.com/downloads/386.pdf including projects up to June, 2010.

3.3.5.4 Arctic Applications of SPS

As mentioned above, the original purpose for the SPS was impact resistant plating for offshore structures working in the Canadian Beaufort Sea (Brooking & Kennedy, 2004). To date, there has been no publically available literature published on arctic application or suitability for the SPS. A design study comparing a newbuild SPS hull with a traditional build of small products tanker (Brooking & Kennedy, 2004) has shown that at least in this case: the SPS design weighed slightly less than the traditional design, the elimination of secondary stiffening provided a 20% reduction in internal surface area, a reduction of weld volume of 50%, 6% increase in cargo capacity, and enhanced inspection and maintenance because of easier access and fewer locations with potential for coating breakdown and structural failure.

There is a definite need for research related to the suitability of the SPS to icebreak/strengthened hulls and superstructure. The simplified structure; reduced weight; increased fatigue resistance; reduced susceptibility to corrosion; enhanced puncture and impact resistance; and inherent structural damping reducing vibration and noise transmission exhibited by the SPS over standard stiffened plates promises beneficial application in arctic ship structures.

3.3.5.5 Sandwich Plate System – Fabrication

SPS plates require their internal surfaces to have a surface roughness of at least 60 microns and a surface cleanliness of SA 2½. The preparation uses standard steel fabrication practices. The internal cavities must be clean, dry and airtight. The SPS plates are restrained during elastomer injection and curing to ensure that the plates remain flat. The injection process usually takes around 8-12 minutes and must occur at a temperature no less than 20°C. The core is fully cured in about 15 minutes.

SPS structures may currently be produced using delivered pre-fabricated SPS panels, or by integration of SPS panel fabrication into a production line. As of 2004, SPS panels were being implemented into yards in Europe, Asia and North America (Brooking & Kennedy, 2004).

Other known issues to be explored:

- Large shipyards may not have the automated capability to construct ships with frame-spacings small enough for ice classed vessels.

3.4 Risk and Hazard Assessment

The term risk is defined as the combination of probability and consequences. Probability is the study of the degree of certainty in situations involving some uncertainty. Consequences mean outcomes or events that may happen as the result of the uncertain situation. In some cases of uncertain outcome the variability is precisely definable. For example, a fair six sided die has exactly equal probability (=1/6) of producing any of the six numbers on any single roll. This is a case in which we would say that all the uncertainty is 'statistical uncertainty'. Such cases permit the calculation of probabilities with high precision, even though the outcome in any one situation is unknown. There are other types of uncertainties which are more difficult to quantify. When some aspect of the system is unknown, the system behavior cannot be precisely quantified, until more is learned about the behavior. Take for example the case of a deck of cards with 'some' cards removed. The chance of drawing the nine of clubs from such a deck is not just a matter of statistical uncertainty, there is also the uncertainty about what the nature of the system is. This is called systematic uncertainty, or model uncertainty. With experimentation, the probabilities of drawing a nine of clubs can be estimated better and better. If it were known exactly how many cards were removed and how (were random cards removed or were clubs removed?) it would be possible to remove all model error and return to a case of pure statistical uncertainty.

In the case of arctic shipping, the dominating uncertainties are systemic or model uncertainties. This makes the problem of assessing risk much more challenging than if the problem was dominated by statistical uncertainty. The framework for risk assessment and risk based design does exist. The challenge is that many of the needed statistical parameters are poorly understood. Much work is still needed to understand the system, and its component probabilities. Remote sensing is being used to quantify the statistical models of the natural ice.

Shipboard and laboratory studies are focused at understanding the ice load mechanics and statistics. Vessel performance, transit and transportation models are needed to quantify the many operational uncertainties. Numerical simulations of ice interactions and structural response are examining the nature of these aspects. These various studies can be seen as attempts to reduce the model uncertainties.

Current ice class rules are not explicitly formulated using measures of risk (e.g., IACS URI2). While some specialists advocate that ice class rules should be formulated using a risk-based methodology, others advocate scenario-based design, where the focus is on the numerous possible ice interactions. Both approaches seek to deal with the many uncertainties in arctic vessel design and operation.

3.4.1 Risk Based Design Frameworks

There is literature that tackles the overall framework of risk to arctic ships. Jordaan et.al (1987) proposed a general framework for developing design criteria based on risk. The paper presents the general concept of risk based design and discusses the specific issues that relate to arctic ship design. Daley and Ferregut (1989) presented a model of structural risk for ice going ships, called ASPEN (Arctic Shipping Probability Evaluation Network). The ASPEN model used a cell grid map of the arctic, with ice statistics in each cell for each month. A user would specify a route in terms of cells (and month). The model calculated the encounter-detection-avoidance-impact-damage probabilities using a set of probability algorithms. The program could evaluate the sensitivities of aspects such as route selection, detection strategies, and structural capacity.

Buzuev and Fedyakov (1997) examined the reliability and risk of shipping in ice along the northern sea route (NSR) in Russia. The focus was more about transportation reliability than structural risks, though both rely on similar models of ice conditions.

Loughnane et.al (1995) examined the risks for an arctic oil tanker with a focus on oil spill risks and mitigation costs and strategies.

To some degree, both the Russian and Canadian operational control systems in the Arctic are risk-based, though this is not made explicit in the regulations. The Russian Northern Sea Route regulations (see also below) require:

- The use of ice strengthened ships, with class depending on area, season and general severity of the ice conditions;

- The use of icebreaker escort for certain operations;
- The development of an “ice passport” to give the operator an idea of the capabilities of the ship;
- Having a certified ice navigator/master aboard.

This system is described for example in translations of annexes to the relevant decrees of the Russian government.[6]

The Canadian Arctic Ice Regime Shipping System[7] (AIRSS) under the Arctic Shipping Pollution Prevention Regulations (see also below) matches actual ice conditions to ship capability with more precision than the Russian approach as regards the ice, but with rather less as regards the ship (only basic ice class is taken into account). Again, ice navigators must be certified in order to be permitted to operate. Considerable work has been undertaken to assess how well this system functions, see for example Timco et. al (2009).

3.4.2 Information Technology

Information technology plays three key roles in improving our ability to assess risk. Computer simulation technology has become an important research tool to study phenomena. Numerical simulations, if sufficiently advanced, can be the basis for experimentation as an alternative to either model scale laboratory studies or field studies. Remote sensing permits the collection of ice data, which is a key input for any risk assessment. And thirdly, database technology permits the assembly and study of data.

3.4.2.1 Computer Simulation

Computer simulations are advancing significantly. Computers are improving in capability and permitting more ambitious simulations. Structural analysis has employed computer since the 1950s, with large finite element packages being the primary tool. Recent advances in algorithms and software have greatly improved the assessment of non-linear structural behavior (Paik 2010).

Finite element models simulate structural behaviours at a level of sophistication that greatly exceeds any other aspect of arctic shipping. However, there are improvements in other areas such as the local ice loads, vessel ice going performance, and station keeping in ice.

Su et. al. (2010) present a numerical method for the prediction of ship performance in level ice based on a sequence of discreet breaking events.

3.4.2.2 Remote Sensing

Remote sensing as it relates to arctic shipping involves collecting data on the following arctic environmental factors: ice, waves, bathymetry, and weather phenomena such as wind, atmospheric pressure and temperature.

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[6] http://meeting.helcom.fi/c/document_library/get_file?folderId=76322&name=DLFE-30794.pdf

[7] http://www.tc.gc.ca/eng/marinesafety/tp-tp12259-menu-605.htm

Much literature is present regarding cold region remote sensing. Much of this literature is not relevant to ships operating in these regions and has not been included in this literature survey. Many of these remote sensing techniques however, may be adapted for uses applicable to arctic shipping. An overview of existing and adaptable remote sensing techniques is presented below

Submarine

There is a growing interest in the use of submersible for data collection in the arctic. Dowdeswell et. al. (2008) is a paper with 23 authors and 45 references. It gives a wide ranging overview of the use of autonomous underwater vehicles (AUVs) to investigate the ice-ocean interface in Antarctic and Arctic waters. Eichhorn (2009) discusses the use of the AUV "SLOCUM glider" under ice sensing operations.

Airborne

Ground Penetrating Radar (GPR) - a near-surface, non-invasive geophysical technique. Provides images of the dielectric properties of the top few tens of meters of the earth. Resolution is approximately metre scale. Radar data can be used to detect the presence of liquid organic contaminants, many of which have dielectric properties distinctly different from those of the other solid and fluid components in the subsurface. GPR images are interpreted to obtain models of the large-scale architecture of the subsurface and to assist in estimating hydrogeologic properties such as water content, porosity, and permeability (see Knight 2001, 229-255) Centre for Remote Sensing of Ice Sheets (CReSIS) Sensor Developments

- Multichannel Coherent Radar Depth Sounder (MCoRDS)
- Accumulation Radar
- Snow Radar
- Ku-band Radar Altimeter
- UAS Radar

Satellite

Available satellite technologies consist of optical imaging sensors, microwave imaging sensors and non-imaging sensors.

Optical imaging sensors detect either reflected or emitted radiation.

Sensors detecting visible light from the sun that is reflected off objects on earth are good for observing sea ice because sea ice has a high albedo compared with the surrounding ocean. Being dependent on visible light, these sensors are limited in arctic application during the winter months by a persistent lack of daylight. Further, cloud cover limits their use year round.

Sensors detecting infrared radiation emitted from objects on earth are also good for observing sea ice because the sea ice temperature is generally colder than that of the surrounding ocean. Limitations on the use of these sensors come from infrared radiation from clouds, and the near similar temperatures between melting ice and sea water during the warmer seasons.

The following satellites and sensors are commonly used to identify and map sea ice using both visible and infrared sensors[8]: the Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS), the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) and the National Aeronautics and Space Administration (NASA) Moderate Resolution Imaging Spectroradiometer (MODIS).

Passive microwave imaging sensors detect emitted microwave radiation from objects on earth. Microwaves emitted by ice can penetrate cloud cover, and are significantly different in magnitude than those emitted by the surrounding ocean. Because the microwave radiation emitted by ice is small in magnitude, it is difficult to detect unless the observation area is large; therefore, sea ice details (e.g., pack ice concentration) are generally unavailable. These sensors are valuable for detecting the presence of sea ice in a geographic area, and information availability is not limited by sunlight or clouds. These sensors have been used to monitor sea ice since 1972[9]. Ice observations from the following sensors are available from National Snow and Ice Data Centre (NSIDC): Electrically Scanning Microwave Radiometer (ESMR), NASA's Scanning Multichannel Microwave Radiometer (SMMR) DMSP Special Sensor Microwave/Imager (SSM/I) and the Advanced Microwave Scanning Radiometer–Earth Observing System (AMSR-E) sensor.

Active microwave imaging systems emit microwave radiation toward objects on the earth and detect the reflected microwaves. This provides them a much finer resolution than passive systems. One type of active system that is used for remote ice sensing is the Synthetic Aperture Radar (SAR). This system is a special type of imaging radar system from which sea ice characteristics may be determined. Since the amount of reflected energy depends on the characteristics of the ice, this type of sensor may be used to identify thick multi-year ice versus thin first year ice. The RADARSAT mission, managed by the Canadian Space Agency, is the primary SAR mission today[10]. In addition to identifying multi-year ice, SAR instruments can detect small leads in sea ice allowing them to help route ships through ice-covered regions. SAR images are currently used by the Canadian Ice Service and the National Ice Center.

Connor et.al.(2009) discuss the use of Envisat radar altimeter measurements for direct measurement of ice freeboards (and thus thickness) over Arctic sea ice. This technology addresses the issue of remote measurement of ice thickness which is a very important issue for arctic ships.

Quincey and Luckman (2009) provides a current state-of-the-art review of ice related satellite remote sensing technologies, methods and missions.

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[8] http://nsidc.org/seaice/study/visible_remote_sensing.html

[9] http:/sidc.org/seaice/study/passive_remote_sensing.html

[10] http://nsidc.org/seaice/study/active_remote_sensing.html

Ice remote sensing includes obtaining data regarding ice salinity (i.e. an analogue for ice age), thickness, snow cover, temperature, location, extent, and topography (e.g. pack ice concentration, as well as ice features such as ridges, hummocks, inclusions…). Harlow (2010) describes an analysis of airborne microwave data, where the emissivities were shown to relate to both ice and snow properties. Snow properties are particularly important for predictions of vessel performance.

3.4.2.3 Databases

Existing databases of ice related information include:

- Iceberg Databases
    - BMT Fleet Technology – Iceberg Sightings Database
    - NSIDC-IIP – Iceberg Sightings Database
    - NRC-IOT – Iceberg Collisions
    - NRC-CHC – Iceberg Management
- Marine Icing Databases
    - NRC-CHC
- Ice Charts Database
    - NRC-IOT – Ice Charts Database (1810-1958)
    - Canadian Ice Service
- Ice Pressures Database
    - NRC-IOT – Catalog on Local Ice Pressures (CLIP)

3.5 Regulatory and Other Issues

3.5.1 International and National Regulations and Standards

This section of the report does not include formal referencing for most of the regulations and standards, as these are subject to amendment from time to time and the latest versions are generally available at the organizations' websites. The commentary provided relates to the status as of the date of this report; i.e., mid-2010.

The main regulatory systems affecting Arctic operations include:

3.5.1.1 International

United Nations Convention on the Law of the Sea (UNCLOS 82)[11]

International Maritime Organization Guidelines for Ships Operating in Polar Waters[12]

Antarctic Treaty[13]

A number of countries also have national systems of regulation for their Arctic waters:

3.5.1.2 National

Canadian Arctic Shipping Pollution Prevention Regulations (ASPPR)[14]

Russian Northern Sea Route:

- Regulations for Navigation on the Seaways of the Northern Sea Route (NSR)[15]
- Regulations for Icebreaker-Assisted Pilotage of Vessels on the NSR
- Requirements for Design, Equipment and Supply of Vessels Navigating the NSR

Much of the current regulatory development for Arctic waters references Article 234 of UNCLOS, the so-called "Arctic clause", which is quoted in full below:

> *Article 234*
>
> *Ice-covered areas*
>
> *Coastal States have the right to adopt and enforce non-discriminatory laws and regulations for the prevention, reduction and control of marine pollution from vessels in ice-covered areas within the limits of the exclusive economic zone, where particularly severe climatic conditions and the presence of ice covering such areas for most of the year create obstructions or exceptional hazards to navigation, and pollution of the marine environment could cause major harm to or irreversible disturbance of the ecological balance. Such laws and regulations shall have due regard to navigation and the protection and preservation of the marine environment based on the best available scientific evidence.*

It is important to note that while the Arctic does have Coastal States (and recognized, though somewhat disputed exclusive economic zones (EEZ), the Antarctic does not. The Antarctic Treaty aims to preserve the Antarctic from development, while all of the Arctic Coastal States orient their Arctic policies to a greater or lesser extent towards sustainable development of resources and infrastructure.

Currently, the main regulatory thrust internationally is to reformulate the IMO recommendatory Guidelines into a mandatory Code for ships operating in Polar Waters. The schedule for this foresees ratification and implementation by 2012.

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[11] http://www.un.org/Depts/los/convention_agreements/convention_overview_convention.htm

[12] http://www.imo.org/

[13] http://www.ats.aq/documents/ats/treaty_original.pdf

[14] http://laws.justice.gc.ca/en/C.R.C.-c.353/

[15] www.morflot.ru/about/.../en/RULES%20OF%20**NAVIGATION**.doc

At a national level, Canada is moving to incorporate the IMO approach and the IACS Polar Classes into its Arctic regulations.

Mention also needs to be made of the Finnish-Swedish Ice Class Rules[16]. Although these have been developed for the Baltic, many Baltic-classed ships have also operated in the Arctic and other ice-covered waters. This rule system is still the most familiar to a majority of designers, builders and operators, and is fully incorporated into the classification society rules of most IACS member classification societies.

3.5.1.3 Classification Societies

A number of classification societies have in the past developed construction standards for Arctic class ships to supplement their Baltic classes. The most widely used by far have been those of the Russian Maritime Register of Shipping (RMRS), which are incorporated by reference into the Northern Sea Route regulations. In 2008 IACS adopted a set of Unified Requirements for Polar Class ships, which are now part of all IACS member rules (available at most societies' websites). As the URs do not incorporate all elements of member societies' previous (or more recent) approaches to ice class design, different societies still have somewhat different approaches to details of structural design, and a variety of "winterization" notations that can also affect structure and materials selection.

The structural approach taken by different ice class rule systems varies quite widely, as illustrated in Table 3.6 (Kendrick et. al., 2007). The Baltic rules are also essentially elastic, contain a strong displacement and a moderate power level dependency. Different ice load models underlie each system, with the URs being the most transparent in this regard.

Table 3.6: Structural Approach taken by Different Ice Class Rule Systems

Issue	Canadian		Russian		ABS	DNV	GL	LR
	ASPPR	CAC	Old	New				
No. of Classes	9	4	3 + 4 icebreaker	6	5 (8 if escort available	6 + 3 icebreaker	4	4
Displacement Dependency	Strong	Moderate	Strong	Strong	Strong	None	None	Moderate
Power Dependency	None	None	Weak	None	Weak	None	None	Moderate
Structural Design Basis	Elastic	Elasto-plastic	Elastic	Elasto-plastic	Elasto-plastic	Elastic	Elasto-plastic	Elastic

3.5.2 Human Resources

The Arctic represents a uniquely challenging operating environment. Traditionally, "Ice Masters" have learned on the job and experience remains the main qualifying requirement for most ice masters and ice navigators today under the various national standards. Efforts are under way to develop a more formal and portable ice navigator certification process, which will be required under any mandatory IMO Polar Code (see above).

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[16] www.sjofartsverket.se/pages/3265/b100_1.pdf

The lack of suitably qualified and experienced personnel is a major impediment to the development of Arctic shipping. At present, there is a fairly small pool partly composed of retired Coast Guard captains who support Arctic operations during the northern summer and Antarctic tourism in the northern winter. Many of the individuals are approaching final retirement and there are limited sources of new talent. It is generally considered to be very important that better ice simulators are developed as rapidly as possible to allow for accelerated training in future.

3.5.3 Escorted and Independent Operation

The Russian (and Soviet) administrations have always required most commercial operations in Arctic waters to proceed under escort by the national icebreaker fleet. This notionally persists today, although some new services with modern high ice class ships are effectively conducting independent operations for most of the time.

The Canadian approach does not require escort. During the Beaufort Sea operations in the 1980s the offshore companies invested in their own icebreaker fleets, which were used partly for escort and partly for ice management around offshore installations. On the other hand, the current all season operations into several northern Canadian nickel mines (Raglan and Voisey's Bay) use independently operating bulk carriers with no escorts available. The impending Baffinland iron ore project, which is orders of magnitude larger than the Canadian (or Russian) nickel projects will also use unescorted ships.

Escort modifies the loads on the escorted vessel, and can reduce them significantly. However, there are also risks involved. If the escorted ship is wider than the icebreaker, or turns more slowly, it can hit the edges of the channel. Also, ice pieces submerged by the escort can surface ahead of the escorted ship, or under it. Collision risk is obviously increased.

3.5.4 Search and Rescue

In an analysis by the Canadian Coast Guard (2007), it was seen that the SAR effectiveness in Arctic areas was less than 90%. The national benchmark assumed for the analysis of SAR system in Canada was 90%. The SAR effectiveness is defined as the percentage of lives saved out of the total number of lives at risk. This is to be achieved during conventional incidents. According to the Canadian Coast Guard, conventional units are defined as:

1. resources are able to respond within a short period of time;
2. the search object is located by the responding resource on scene in a timely manner;
3. environmental, geographic, and hydrographic conditions have little impact on the successful resolution of the incident; and,
4. the responding resource has the necessary capability and capacity to effectively resolve the incident.

SAR services for the Arctic maritime environment are very challenging. Incidents of Arctic SAR are not termed as "conventional incidents", but are termed as "difficult incidents", due to their harsh conditions. The level of system effectiveness typically accepted for SAR effectiveness in the Arctic is around 50+%. The 2007 SAR system effectiveness evaluation revealed higher-than-expected levels of service: 69.23% for the waters of the Northwest Territories Area; 86.67% for the James Bay Area; 81.48% for the eastern Arctic Area; and, 93.10% for the Nunavut Area.

For Northern Canada, there is a lack of SAR response units. The current SAR capacity in Northern Canada will not be able to meet the increased demands of the future. This would be partly due to year round commercial shipping in the future. Three Canadian Coast Guard Auxiliary (CCGA) units already exist in the Arctic at Rankin Inlet, Cambridge Bay and Iqaluit.

3.5.5 Environmental Protection

Both the Canadian and Russian Arctic are "zero discharge" areas for wastes dumped into the water under the applicable national regulations. Owing to the fact that the regulations predate most MARPOL agreements there are some anomalies in both systems; for example Canada permits the discharge of untreated sewage (though this is now being subsumed into other national regulations that follow MARPOL more closely).

Rather surprisingly the US and Canadian Arctic were not incorporated into the new North American Emission Control Area (ECA) for airborne emissions (particularly NOx and SOx). However, on the US side offshore projects (including vessel operations) have been subjected to annual caps on airborne emissions under Environmental Protection Agency (EPA) regulations.

Two areas of increasing concern in the Arctic are oil spill response and ballast water management. Many standard mitigation approaches to oil spills (booms, skimmers) do not work in the presence of ice. Cold temperatures limit the effectiveness of others and slow down natural remediation. The problems of response led to the incorporation of double-hulling requirements in the Canadian and Russian Arctic regulations well in advance of measures elsewhere, and spill prevention continues to be an important theme in Arctic regulations. More recently, the risks of invasive species becoming more able to tolerate Arctic conditions due to climate change has received increasing attention. Ice class ships tend to have relatively large ballast capacities due to the need to maintain propeller and rudder submergence and to reduce the range of waterlines exposed to ice and cold temperatures. This poses additional design challenges.

3.5.6 Vessel Repair

For any type of vessel repair facility in the Arctic, the location of the facility is of utmost importance. The location of the facility shall not impede the entry of vessels into the facilities. Most of the bays and inlets around the Canadian Arctic archipelago have fast ice and pack ice for most of the season and any facilities present in these areas have to make sure that they are accessible throughout the shipping season. Many of the northern ports have been built in natural harbours to provide protections from the environment.

The main challenge with a repair facility in the Arctic is that there would be a need for ships to be dry-docked for repairs as the damage would have been below the waterline. This would usually be the case since the most of the damage would occur due to interaction with ice floes.

A graving dock in the Arctic would be a dead load on the soil. The location of the facility must consider low-loadbearing soils and changes in soil conditions due to permafrost or possible modification of permafrost. During the 1980s, a floating dock was installed at Tuktoyaktuk in the Canadian Northwest Territories and saw considerable use for ship repair.

4. ISSUES MAP AND RESEARCH NEEDS

This concluding element of the study is intended to consolidate the current state and future challenges of arctic ship structural design, and to recommend future research directions – particularly those within the remit and capability of the SSC.

4.1 Issues Map

4.1.1 Preamble

The arctic is an environment experiencing rapid change. There are three separate but related vectors of change; technology, economy and climate.

Technology changes include:

- improved remote sensing and communication
- improved knowledge of ice loads and risk
- improved powering and vessel design
- improved simulation, training and operations

Developing trends in the economy are:

- driven by resources and global demand
- encouraging the adoption of new technology

The changes in climate include:

- reduction in mean ice cover area and thickness, and
- increase in variability

The changes in socio-political factors include:

- public concern for arctic environment, wildlife and indigenous peoples
- heightened boundary and security concerns

Within this overall pattern of change, the report addresses five areas affecting the future structural challenges for arctic vessels. In this study, the five main areas examined are; the environment, ice loads, material and structural behaviour, hazards and risk assessment and regulatory issues. Each of these presents a set of issues and research needs.

4.1.2 Environment

Issues and Knowledge Gaps: There are a range of unknowns regarding changing climate, including:

- speed of climate change
- potential increase in variability of extremes
- rate of growth of open water, and changes in wind/wave climate
- loss of multiyear ice
- possible release of ice hazards (MY ice and icebergs)

- sensitivity to environmental challenges (noise, pollution, invasive species)

These form part of the context in which ship design and operation must function. Some questions arising from this are raised below.

Questions:

- Should vessels being designed today try to anticipate climate change?
- Will ships need greater or lesser capability in coming years?

These are essentially economic and regulatory questions. While an owner may try to anticipate the effects of changing climate, it would be very difficult to embody any potential changes in climate into ice class rules. For the foreseeable future, ships in the Arctic will need to cope with (or avoid) all the ice types and properties that currently exist, which include multiyear ice and glacial ice. With climate change, the day may come when the complete absence of summer ice will naturally also mean the complete absence of multiyear ice. In such a case, one may anticipate a lowering in ice class structural requirements. However, arctic winter first year ice will remain very challenging and dangerous. The presence of glacial ice will likely still be present and may even become more common if more rapidly decaying glaciers flood the seas with icebergs (a trend that is already being seen). The current structural requirements may turn out to be approximately what is needed for vessels being operated more aggressively in somewhat lesser ice conditions. A new set of experiences will need to be examined and used to re-calibrate polar ice class rules.

It is difficult to propose clear research plans that can address these questions. Nevertheless, an obvious research need is:

- the improvement of ice load models, especially those concerned with glacial and heavy first year ice, will put us in a better position to adapt to an Arctic without multiyear ice.

4.1.3 Ice Loads

Issues and Knowledge Gaps: Understanding ice loads remains the primary structural challenge for arctic shipping. As outlined earlier, there are continuing uncertainties in such areas as:

- nature of extreme loads (especially for large ships)
- patterns of load (so design loads reflect the true patterns, not highly simplified ones)
- loads on deforming structures (to better understand risk of dangerous consequences)

Questions:

- What are the mechanics of ice loads below the ice belt?
- Will local ice pressures on much larger and faster ships will be similar to current vessels or much larger?

Necessary areas of research include:

- Field ice load data collection on large ships. This should include high spatial resolution of ice pressures and detailed ice edge shape, mass and property characterization.
- Testing and study (field, lab and or numerical) of mechanics of loads below the ice belt. This should include contact with single blocks, ridge keels, and ice trapped between the vessel and sea floor.
- Development of improved numerical models of ice crushing, for use in direct calculations of load and structural response.
- Study of the influence of speed on design loads. This will need to consider multiple scenarios and ice load models. Field data would be especially valuable.

4.1.4 Material and Structural Behaviour

Issues and Knowledge Gaps: Understanding the response of steel structure to ice loads, especially large overloads, is crucial to the prediction of risks for arctic shipping. Some areas of uncertainty include:

- The nature of real plastic collapse mechanisms in structure, especially larger members
- Conditions leading to tearing
- Influence of temperature, strain rates and slenderness (ice class ships differ from open water vessels in these three aspects, as well as in the load types)

Questions: The questions below relate both to the structural behavior and also to the nature of the loads – the two are generally not easily separable.

- Can plastic design methods give significant benefits to both safety and cost?
- What numerical methods (FE, FD, etc) are best suited to plastic and collapse analysis under ice loads?
- How can compatible principles be applied to the design of other features for ice loads (LNG containment systems, appendages, machinery)?

Necessary areas of research include:

- Study of dynamics in material (and structural) response to ice loads
- Study of full range of structural behaviour, including folding and tearing
- Development of practical numerical tools that include fracture in heavily deformed structures.

- The above might be addressed initially by empirical models that model response capacity in a simple aggregate manner with empirical model of tearing. These models would be something like the current pressure-area models that describe ice pressures empirically.

4.1.5 Hazard and Risk Assessment

Issues and Knowledge Gaps: There is an increasing consensus around the need to use risk-based methodologies to validate project and service safety levels. There is thus a perceived need to develop appropriate tools for risk-based design and assessment for arctic shipping. Some issues involved in this approach are:

- The need to develop a risk paradigm that reflects the reality of ships (rather than civil engineering structures) through realistic utilization of "standard" approaches (HAZID, HAZOP, etc)
- The need to account for the influence of 'learning' (operators are constantly testing capacity and both learn capacity and adjust operations – unlike the case with fixed installations)
- The recognition that dominant uncertainties are model uncertainties rather than statistical uncertainties.

Given these types of issue, the questions that result are summarized below.

Questions:

- How can vessel design be risk based when verification is so difficult?
- Should design be capacity based with risk assessment as a parallel activity?
- What will lower risks the most – risk models or ice load/strength models?
- How can additional data be collected in consistent ways to support future risk models?

Necessary areas of research include:

- Development of a risk modelling paradigm that includes the short and long term learning and risk optimization (feedback) that occurs on ships.
- Study of ways to assess costs and benefits in risk-based design. The costs and benefits should cover both commercial and societal measures (i.e., from the perspectives both of the vessel owner and for a much broader range of stakeholders).

4.1.6 Regulation/Other

Issues and Knowledge Gaps: Regulation in a rapidly changing situation is challenging. Normally, both prescriptive and performance-based regulations and standards will lag technological development, as the need to achieve consensus is time-consuming. Exceptions may occur when a major incident leads to political pressure to “do something”; however such regulations are rarely well thought-through. Some of the issues in this area include:

- The need to develop regulations that are both strong and flexible; and
- The need to avoid a ‘cabal’ of users, specialists and regulators (i.e., need for diverse input, transparency and debate).

The authors consider that performance-based – or “pure” risk-based standards and regulations can be quite dangerous when there is a limited knowledge base, as many practitioners may not know what they do not know, and regulators may not have the ability to assess submissions in any meaningful way.

Questions: The overarching question in this area is how to develop a ‘standard’ when there is so much debate and a rapid rate of change in the state of knowledge.

Necessary areas of research include:

- Development of a regulatory paradigm that includes consideration for change in engineering practice, technical theories and climate.

4.2 Research Directions

The issues and questions summarized above cover many areas. This subsection of the report focuses on potential research directions that are considered to be of particular relevance to the SSC. This has led to highlighting two of the thematic areas – ice loads, and material and structures response. The first of these is relatively unique to Arctic or more generally, to ice-classed ships. In the second area, some of the issues and knowledge gaps are more generally applicable to ships of all types and may offer leverage opportunities for research programs.

4.2.1 Ice Loads Research

The three most important areas of uncertainty in ice load modeling are considered to be:

i) the effect of ship size/kinetic energy on peak loads and pressures;

ii) changes in ice load patterns on a deflecting/deforming structure;

iii) load mechanisms for non-waterline areas of the hull.

The first of these is of great importance in selecting appropriate design points for larger ships and for other ship types that may need to maintain high operating speeds in ice-covered or infested waters.

The second is a major issue for risk assessment and for the treatment of accidental loads, such as impacts with icebergs and multi-year ice features and pressured ice conditions. It is known that the ice does not act as a rigid 'indenter' of the hull under these conditions, but there are not currently any proven modeling techniques for more sophisticated treatments.

The third area of uncertainty is a major driver of steel weight, particularly for larger vessels. To the degree that they are made explicit, rule ice load models are almost entirely impact models for the types of impact found at the bow and in turning (or backing) impacts. The worst case loads in these areas are quite different in nature from those experienced lower in the hull; empirical "hull area factors" are not necessarily valid for new designs or operating patterns.

The research approaches in all of these areas can involve a range of approaches. All will, in the end, require some level of validation against full scale data.

Size/energy effects can be explored systematically by experimentation below field scale, but preferably using relatively large apparatus. The types of technology and system discussed in Section 3.2.3 are expected to provide considerable new insights into these areas over the coming years. SSC may wish to undertake projects that explore aspects of loadings.

Improved insight into ice mechanics should allow for the development of better numerical modeling and simulation tools, which is also being facilitated by the development of massively parallel computer hardware and software designed for use in such systems. This applies to both structural loading and response mechanics, and also to aspects of the problem such as ice flow around the ship. Computation flow simulation, discrete element, finite difference and finite element methods may all need to be combined to develop a "unified theory" of ice loads on many areas of the ship. As with all grand theories, observation and real-world data are required to test the models. Ice trials are extremely expensive, but SSC may be able to play a role in catalyzing collaborative trials programs, particularly given the interests of the USN, USCG, Canadian Navy and CCG in a new generation of Arctic ships.

4.2.2 Research into Materials and Structural Response

The three most important areas of uncertainty in this field are considered to be:

i) steel grade requirements for thicker low temperature steels;

ii) improved methods for plastic analysis of structures;

iii) coating performance on deformed structures.

The first of these is important to material cost, fabrication and repair. Higher grades of steel need increasingly specialized equipment to weld, and are generally less available than lower steel grades. Unfamiliarity is a major cost driver for shipyards, and results in additional premiums for cost. It also gives rise to problems of quality control and inspection.

Plastic design approaches remain relatively poorly understood by most naval architects and structural engineers. The analytical methods in the URs for polar class ships do not provide solutions for all structural elements. The use of finite element methods to extend (or substitute for) analytical solutions requires experience or training, both of which are in short supply. Certain issues, such as the "true" nature of instability in the plastic regime, and the ability of FE techniques to model strain in detail, require further exploration.

The advent of requirements for coating longevity under IMO and IACS increases the challenge to develop a better understanding of coating performance on structures with visible levels of deformation. Almost all ice class ships, whether Baltic (notionally elastic), Russian (elasto-plastic) or Polar Class (elasto-plastic) do suffer local deformation in service. In some cases coatings fail, with major economic consequences for recoating, repair, or loss of life expectancy.

Exploration of the steel grade question will require some lateral thinking regarding appropriate testing techniques. Exploring failure mechanisms in thick specimens at low temperatures directly is not simple, but the use of simplistic methods such as Charpy tests of small samples is simply inadequate.

Typical non-linear finite element analysis is now readily capable of modeling large strain and large deformation behavior for ductile behavior of steel. However, the inclusion of material fracture is very difficult and normally not even attempted. Material grades relate strongly to cold temperature fracture resistance. In order to improve the rational assessment of issues related to steel grades and fracture, there is a need to significantly improve finite element modeling tools. It may well be that new modeling paradigms will be needed in order to allow for the development of models that can readily include stress, thermal, welding, ductility and fracture effects in a practical engineering analysis.

As noted in section 3.3.3, there is very little published data on the strain limits of coatings, but considerable empirical evidence of in-service failure. This is an area where testing can be relatively simple and where the development of guidelines or standards that match coating performance to structural design philosophy would be very useful. This type of work would also be of considerable value to the broader marine community. “Acceptable” levels of deformation before repair are by no means consistently applied between classification societies or administrations, and this is one aspect of continued fitness for service that it would be useful to explore.

4.3 Summary

To conclude this study, the authors have revisited the questions raised at Section 1 of the report, and summarized the (complex) answers to these as follows:

Changes to the arctic climate are not likely to lead directly to changes in ice loads (either increased or decreased loads) in the foreseeable future. Loads will be more dependent on the types of operation envisaged, which may well encompass a wider range as ice cover changes.

Similarly, as arctic ice retreats and shipping seasons are extended, cold embrittlement, and other material degradation issues (such as corrosion and fatigue) will not become more (or less) significant. There is, however, a continuing need for a better understanding of some of these issues.

It is quite likely that future oil and gas projects will develop their own infrastructure in the Arctic, as is already happening in Russia. Bulk mineral operations will also require shore-side facilities such as docks and loading systems. There are also moves to enhance governmental capabilities to address emergency response capabilities. Based on past experience most other types of development and the shipping operations associated with these will attempt to continue with any significant infrastructure investments.

Improvements in material grades, welding standards and overall design may have some positive impact on arctic ship structural risks.

However, it is more important to develop better methods that can inform the operator of the actual capability of the vessel; and to ensure that regulations and standards mitigate the risk of catastrophic failures.

In the same vein, changes in design methods, standards and corporate policies may contribute to improved safety levels, but the greatest potential influence is in creating an enhanced safety culture. This requires a better appreciation of the nature of the risks involved in Arctic operations.

Currently, there are not sufficient numbers of adequately trained people to perform the design, operation, research and regulation activities that are already under way in the Arctic. This will be aggravated (certainly) by the retirement of the generation with experience from the previous “Ice Age” of the 1980s and (probably) by a continuing increase in Arctic activity. The SSC may be able to assist in developing a future generation by sponsoring research, symposia and workshops.

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PROJECT TECHNICAL COMMITTEE MEMBERS

The following persons were members of the committee that represented the Ship Structure Committee to the Contractor as resident subject matter experts. As such they performed technical review of the initial proposals to select the contractor, advised the contractor in cognizant matters pertaining to the contract of which the agencies were aware, performed technical review of the work in progress and edited the final report.

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