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Ice Class Requirements on Side Shell Structures

A comparison of local strength class requirements regarding plastic design of ice-reinforced side shell structures

Master of Science Thesis

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Gothenburg, Sweden, 2012

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A THESIS FOR THE DEGREE OF MASTER OF SCIENCE

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Abstract

The demand for shipping in Arctic regions is increasing, and with this comes an increased interest in ice-strengthened ships. Today there exist several class rules satisfying additional requirements for operation in geographical areas with ice-infested waters. Hence, it is crucial for classification societies, designers and ship-owners to understand how formulations of each rule-set impact on structural members to be able to design a ship that suits a certain operational purpose.

The aim of this thesis is to perform a comparison study on structural properties and steel grades on mid-bodies with a constant cross section, regarding ice-strengthening requirements relevant in the ice-reinforced region. To provide an overview of fundamental differences of ice class rule-sets, a comparison is conducted through case studies in which three different fictitious ships are used. The rule formulations of Det Norske Veritas (DNV), Finnish-Swedish Ice Class Rules (FSICR), IACS Polar Class and the Russian Maritime Register of Shipping (RS) are compared with an emphasis on the local structure and material requirements. Since the comparison is focused on rule-sets, no numerical analysis on the strength is considered.

To enable comparisons between class rules, a computer code is developed where the rule-sets are adopted. The computer code uses ship particulars together with rule formulations to calculate the outcome on the actual local strength of each rule-set. Main parameters, i.e. frame spacing, direction of frames, displacement and yield strength in the rule formulation are varied in order to find their influence on the weight and structural properties. In addition to this, issues in the results are identified together with recommendations of areas that need to be further looked into with a numerical analysis on the actual structure.

The comparison shows that the direction of framing plays a major role in the reinforcements needed and the total weight outcome on mid-bodies with a constant cross section. Due to the shape of the ice load, transverse framing has favourable requirements on local design in the perspective of weight. The result has been validated with the DNV software Nauticus Hull.

It is found that when designing a ship according to notations with higher requirements, "tailormade" beam profiles may result in a better distribution of structural safety margins and a lighter structure. The study also shows that requirements on steel grade depending on structural member and thickness vary between rule-sets. It is concluded that using steel with higher yield strength can be economical since it may result in a lower requirement on the grade and less material in the structure. The study shows a case with a weight-saving of 9% and a cost-saving of 5% when upgrading the yield strength. To be aware of these behaviours one can benefit from this and design an approved structure that fulfils the requirements with reduced weight and cost.

Keywords: framing, ice class rule-sets, local strength, material grades, mid-body, side shell structure, plastic section modulus.

Preface

This thesis is a part of the requirements for the master's degree in Naval Architecture at Chalmers University of Technology, Gothenburg, and has been carried out at the Division of Marine Design, Department of Shipping and Marine Technology, Chalmers University of Technology in cooperation with Det Norske Veritas, Division of Tanker and Dry Cargo, in Høvik, Norway.

We would like to acknowledge and thank our examiner and supervisor, Professor Jonas Ringsberg at the Department of Shipping and Marine Technology, for the time and supervision he has given us. We would also like to thank our co-supervisors Jens-Petter Fossedal Olsen at Tanker and Dry Cargo and Marcus Larsson at Special ships, OSV and Conversion at Det Norske Veritas for the time and supervision they have given us. Moreover, we would like to thank Ivar Håberg, Head of Section on Tanker and Dry Cargo, for giving us the opportunity to perform this thesis.

Figures with references used in this thesis are printed with the permission of the copyright owners. We would like to thank you all for this permission.

Finally, we would like to clarify that without any of above-mentioned persons this thesis would not have materialized.

Gothenburg, June, 2012
Filip Bergbom Wallin and Carl-Johan Åkerström

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Abbrevations

CSR	Common Structural Rules
DAT	Design-ambient air temperature for structural material
DNV	Det Norske Veritas
FSICR	Finnish-Swedish Ice Class Rules
HT	High Tensile Steel
IACS	International Association of Classification Societies Ltd.
IACS PC	International Association of Classification Societies Ltd. Polar Class
IACS UR	IACS Unified Requirements,where UR I denotes Polar Class
IMO	International Maritime Organization
LIWL	Lower Ice Waterline
L_{OA}	Length over all
MS	Mild Steel
NSR	Northern Sea Route
RS	Russian Maritime Register of Shipping
UIWL	Upper Ice Waterline

1. Introduction

1.1. Background

The demand for shipping in Arctic regions is increasing [1], not only the increased volumes of transported gas and oil from Russia but also the use of the Northern Sea Route (NSR). With this comes an increased interest in ice-strengthened ships that satisfies additional requirements of the structural integrity when navigating in geographical areas with ice-infested waters.

According to Liu and Kronbak [2] the route via the NSR could save about 40% of the sailing distance from Asia to Europe compared with shipping through the Suez Canal. A 40% saving of the distance will consequently not mean 40% of cost saving due to factors including increased costs of building ice-classed ships, fees, navigation difficulties, etc. Still, the economic competiveness of the NSR remains unstudied.

Requirements are developed to ensure ship safety and ship traffic without interferences in regions with ice infested waters. Ice-classed ships are designed to resist the loads from ice, which generally results in a heavier ship. In shipping, “weight is money” and ships are often built with low tolerances towards requirements from rule-sets. Still, displacement is of paramount importance when breaking ice. Designing a ship with a high ratio between the deadweight and lightship improves the ships’ profitability while reducing emissions. This is a step for continued sustainable development within the shipping industry.

Today, there are several rule-sets in existence regarding ice-strengthening. Rule-sets are developed from numerical analyses and experience of navigation in ice to ensure safety when operating under different conditions. In addition, to own developed ice notations, most classification societies, for example Det Norske Veritas (DNV), have adopted the Finnish-Swedish Ice Class Rules (FSICR) or developed their own from them [3].

In addition to class rules, ships have to fulfil requirements set by maritime authorities entering their jurisdiction. TraFi [4] have published recommendations for accepting notations from class societies that differ from the FSICR for operation in the Baltic Sea during winter. According to Liu and Kronbak [2], the Russian marine operations headquarters accept ships with ice-strengthening according to or at least the equivalent of FSICR 1B to operate in the NSR if they fulfil additional requirements on crewing and icebreaker assistance, etc.

In 2006, The International Association of Classification Societies (IACS) published Unified Requirements (IACS UR) for Polar Ship construction (IACS PC) to replace the member societies’ current rule-sets. The major differences between rule-sets of ice-strengthening requirements are based on different theories, constraints and approaches [3].

Riska [3] presented extensive calculations and comparisons of IACS members’ ice notations where results were presented as differences in dimensions and properties between the rule-sets and the direction of framing. In the study, a fixed-shape factor was used converting elastic properties to plastic properties.

1.2. Objectives with the investigation

The main objective is to compare local strength class requirements regarding the plastic design of ice-reinforced side shell structures and the material requirements in the mid-body region. The aim is to illustrate similarities in structural and material requirements between ice class rules IACS PC [5], DNV [5], FSICR [5], DAT (-X˚C) [5] and RS [6, 7] regarding the ships' purpose of operation.

In order to understand and enable prediction of the structural outcome, it is of interest to study the main particular influence on the weight and strength. Hence, a parameter study is to be performed where the main parameters in the rule formulations [5, 7] are altered. As a result, information of the important influence of parameters on the weight and structural properties can be outlined. Additionally, the aim is to identify issues and areas for further study, for example conservative/non-conservative areas of the structures under consideration that need to be investigated in more detail by numerical analysis.

1.3. Methodology and limitations

To compare class requirements, a set of three fictitious ships have been created; a large, a medium and a small ship with different purposes, see Appendix A for ship particulars. Each ship represents a typical ship intended for operation in ice-infested waters. The ship particulars are used as input in a computer code based on a selection of classification rules [5, 6, 7]. The actual structural properties are compared to enable fair comparisons between rules. A structure that fulfils the requirements is created with use of a beam database of standard profiles and standard steel plate thicknesses. Since there are differences in the rule formulations, all data are presented with plastic design calculated according to IACS PC [5]. The comparison is outlined in three separate cases, as presented in Table 1. Each case is associated with three notations together with a representative ship.

Table 1. Outline of comparison.

Case:	Notation 1:	Notation 2:	Notation 3:	Ship:
I	ICE-1A + DAT (-20°C)	PC-7	RS Arc4	Ship I
II	DNV ICE-15 + DAT (-30°C)	PC-4	RS Arc6	Ship II
III	POLAR-10 + DAT (-30°C)	PC-2	RS Arc7	Ship III

A series of parameters is varied to study each parameter's influence on the results. The focus has been on rule-set requirements [5, 7] depending on local structure of the mid-body. Hence, no numerical analysis on global strength has been taken in consideration.

The analysis is horizontally limited to the mid-body and vertical limited to the main reinforced region of the ice-belt presented as the upper and lower boundary in Fig. 1. The boundaries depend on class rule-set and particulars. Moreover, additional assumptions necessary for the analysis are stated in Section 3.3.

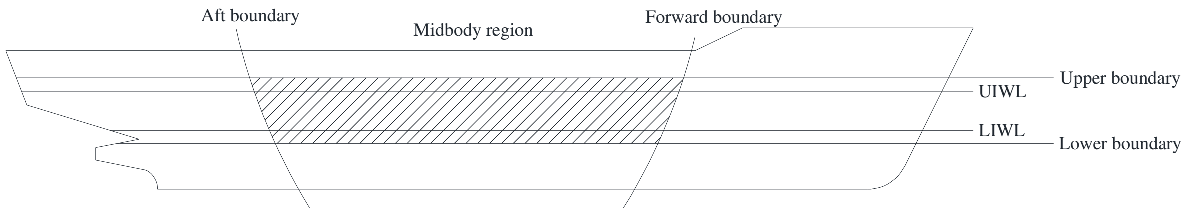


Fig. 1. Area limitations of analysis.

The computer code used for weight analysis, calculations and parameters studies was created in MATLAB® R2010b [8]. Calculations with rule-sets of the FSICR, DNV and IACS PC are validated with calculation sheets integrated in the DNV software Nauticus Hull [9]. No validation is performed for RS rule-sets. Figure 2 presents the schematic workflow.

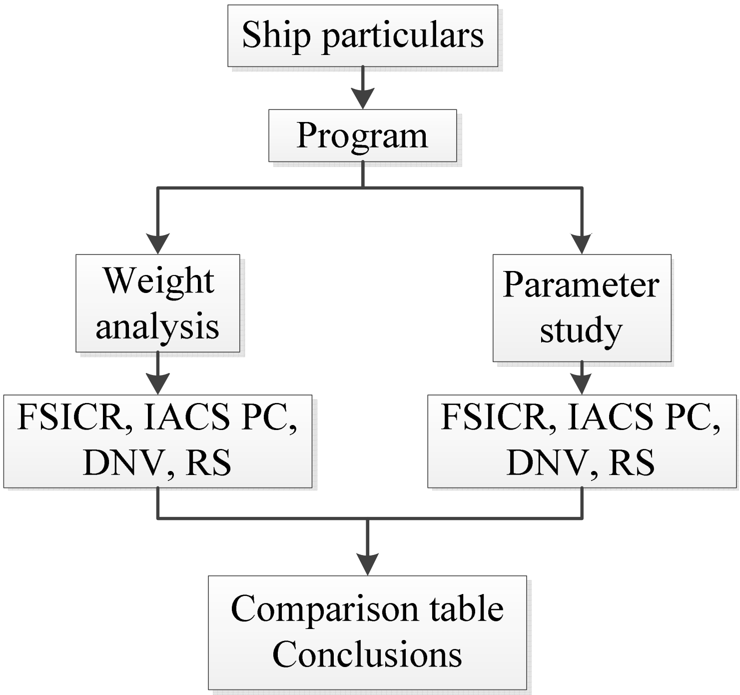


Fig. 2. Schematic workflow.

2. Ice-strengthening

This section covers the basics of ice-strengthening of ship structures. In Section 2.1 a general description of the rule-sets considered in the study and their characteristics is presented. It continues with presenting the differences in the hull extent of ice-strengthening in Section 2.2 and characteristics of local strength on side shell structures in Section 2.3. Material requirements are presented for the considered rule-sets in Section 2.4. In the report, when rule-sets of the FSCIR, DNV, IACS PC and DAT (-X˚C) are stated, they refer to [5] and the rule-set of RS refers to [6, 7] unless otherwise mentioned.

2.1. Ice classes and its notations

Class societies have rule-sets covering requirements on ships intended for operation in ice-infested waters. Rule-sets consist of several ice notations. Notations are generally dependent on the geographical area of operation and differ with respect to operational capability and structural strength. Depending on the ship's purpose and area of operation, it puts a responsibility on the owner to select an appropriate ice-class notation on the ship.

The FSICR is based upon an elastic approach in the definition of structural capacity and was originally established to ensure safe operation in the Baltic Sea during winter. The notations set minimum requirements for engine power and ice-strengthening for ships assuming that icebreaker assistance is available when required. The rules are intended for the design of merchant ships operating in first-year ice conditions during part of the year.

In 2006, the International Association of Classification Societies (IACS) published a document named *Unified Requirements for Polar Class Ships* as a complement to IMO *Guidelines for Ships Operating in Arctic Ice Covered Waters*. The unified common rules and regulations are referred to the IACS UR sub-section Polar Class (PC). The IACS PC is intended to replace the member societies' current rule-sets regarding ice-strengthening requirements. The structural requirements are developed by a plastic-based limit state analysis with experience from Arctic operations. The plastic approach in the definition of structural capacity is further described in Section 2.3.2.

DNV have a set of rules in Pt5. Ch.1 Sec.4 regarding vessels for arctic and icebreaking service. The notations in this set are called ICE-05 (or -10 or -15) and POLAR-10 (or -20 or -30). These rules apply to icebreakers and to passenger and cargo vessels intended to operate independently in the ice-infested waters of Arctic regions.

The Russian Maritime Register of Shipping (RS) includes intact and damage stability requirements into their rules and stands out from most IACS members who have adopted the FSICR. At the ship owner's discretion, the IACS polar class notations and the RS ice rules may be applied simultaneously to acquire double notations, provided such ships comply with the requirements for both the IACS PC and the RS rules regarding ice-strengthened ships. The categories of ice class ships in RS are: Ice1-3, which refers to ships intended for navigation in freezing non-arctic seas. The second category, Arc4-9, refers to ships intended for navigation in Arctic seas.

In Table 2, the general description and ice thickness are presented for each notation treated in the investigation. Information about operational description is found in each rule-set specified

in the left-most column. The WMO ice nomenclature [10] was used to find comparable values of ice thicknesses for IACS PC. Two ice thicknesses are defined for each RS notation.
The right-most column defines allowed ice thickness during summer and autumn, and the left column defines allowed ice thickness during winter and spring. The difference is due to the yield strength of the ice, which varies with the ice temperature.

Table 2. General description of considered class societies' ice notations.

Class	Ice notation	General description	Ice thickness	
FSICR/ DNV *Pt.5 Ch.1 Sec.3*	IA Super/ ICE-1A*	Normally capable of navigating in difficult ice conditions without assistance of icebreakers	1.0m	
	IA/ ICE-1A	Capable of navigating in difficult ice conditions, with assistance of icebreakers when necessary	0.8m	
	IB/ ICE-1B	Capable of navigating in moderate ice conditions, with assistance of icebreakers when necessary	0.6m	
	IC/ICE-1C	Capable of navigating in light ice conditions, with assistance of icebreakers when necessary	0.4m	
DNV *Pt.5 Ch.1 Sec.4*	POLAR-30	Winter ice with pressure ridges and multi-year ice-floes and glacial ice inclusions	3.0m	
	POLAR-20		2.0m	
	POLAR-10		1.0m	
	ICE-15	Ice encountering in winter ice with pressure ridges. No ramming anticipated	1.5m	
	ICE-10		1.0m	
	ICE-05		0.5m	
IACS *Pt.5 Ch.1 Sec.8*	PC-1	Year-round operation in all Polar waters	3.0m	
	PC-2	Year-round operation in moderate multi-year ice conditions	3.0m	
	PC-3	Year-round operation in second- year ice which may contain old ice inclusions	2.5m	
	PC-4	Year round operation in thick first-year ice, which may include old ice inclusions	1.2m	
	PC-5	Year-round operation in medium first-year ice, which may contain old ice inclusions	0.7 - 1.2m	
	PC-6	Summer/autumn operation in medium first-year ice, which may include old ice inclusions	0.7 - 1.2m	
	PC-7	Summer/autumn operation in thin first-year ice, which may include old ice inclusions	0.7m	
RS *Pt.1 2.2.3.1*	Arc9	Multi-year ice	3.5m	4.0m
	Arc8	Multi-year ice	2.1m	3.0m
	Arc7	Second year ice	1.4m	1.7m
	Arc6	Thick first-year ice	1.1m	1.3m
	Arc5	Medium first-year ice	0.8m	1.0m
	Arc4	Thin first-year ice	0.6m	0.8m
	Ice3	Non-arctic ships. Independent navigation in open pack ice at a speed of 5 knots	0.7m	
	Ice2		0.55m	
	Ice1		0.4m	

Finnish and Swedish authorities have developed requirements for ships operating in the Northern Baltic in winter: the FSICR. The FSICR have become the de-facto standard for first-year ice, and, hence, many classification societies have adopted the rule-set as their Baltic rules, the number of rule-sets is decreased [3]. In IACS PC, PC-6 and PC-7 have been developed to give equivalence to IA Super and IA, respectively [11]. RS is another exception whose lower classes are intended for the Baltic Sea. Table 3 presents an extract from a report by TraFi [4] with FSICR acceptance of other class notations.

Table 3. FSICR acceptance of other notations according to TraFi.

FSICR	DNV	IACS	RS
IA Super	ICE-1A*	PC-6	RS Arc5
IA	ICE-1A	PC-7	RS Arc4

The FSICR rules have requirements on the propulsive power of the ship; this is to reduce the need for icebreaking assistance. The equivalence of the FSICR and IACS PC may be granted if the required engine output of the ship complies with requirements in the rule-set of the FSICR. The same requirements apply for the equivalence of the FSICR and RS.

2.2. Hull area extent

In general, the hull area extent of ice class rule-sets is limited in the vertical direction to an ice-belt. In the notations, limits are defined by the upper ice waterline (UIWL) and the lower ice waterline (LIWL) at which the ships are intended to operate. This means that all loading conditions including trim, independent of the water salinity, shall be within the draught enveloped by the UIWL and the LIWL. In this section, the hull-area extent of investigated rule-sets is defined.

The ice-strengthened regions of the FSICR, as presented in Fig. 3, are divided into three regions; the forward, mid-body, and aft regions. The area of interest for the analysis is the mid-body region, which is defined from the aft boundary of the bow region to a line parallel to and 0.04L aft of the aft borderline of the hull where the waterlines run parallel to the centre line, CL.

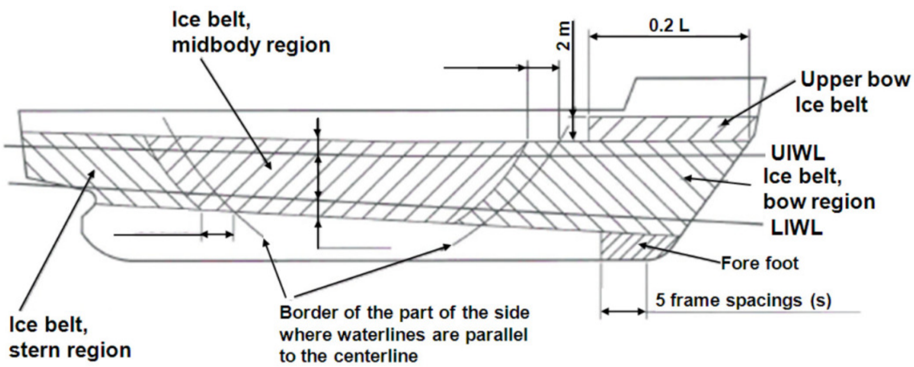


Fig. 3. Hull area extent of the FSICR [5].

The required vertical hull extension of the ice-strengthening according to the FSICR differs between the shell plating and frames, which is particular for the ice notations of the FSICR. Compared to the other investigated rules, which also consider a larger area under the LIWL, the rule-set of the FSICR focus the ice-strengthening to the ice-belt region. The vertical extension of the shell plating shall not be less than shown in Table 4. The vertical extension of the ice frames shall not be less than shown in Table 5.

Table 4. Vertical extension of shell plating in the FSICR.

Notation	Region	Above UIWL (m)	Below LIWL (m)
ICE-1A*	Mid-body ice-belt	0,60	1,20
ICE-1A		0,50	0,75
ICE-1B		0,40	0,70
ICE-1C		0,40	0,60

Table 5. Vertical extension of the frames FSICR.

Notation	Region	Above UIWL (m)	Below LIWL (m)
ICE-1A*	Mid-body ice-belt	1,20	2,00
ICE-1A		1,00	1,30
ICE-1B			
ICE-1C			

For the DNV rule-set of vessels for arctic and icebreaking service, DNV ICE & DNV POLAR, the ice-reinforced hull is divided into seven areas. The areas included are bow, stem, stern, mid-body, bottom, lower bow area and lower transition area. The side view of the ice-reinforced areas is presented in Fig. 4.

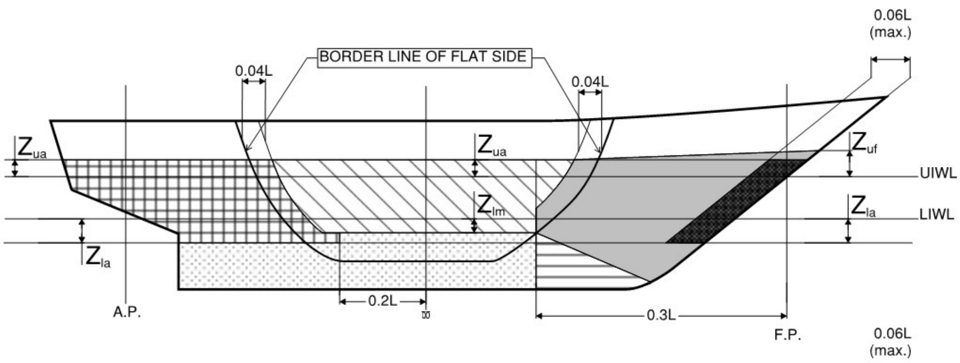


Fig. 4. Hull area extent of DNV ICE and DNV POLAR [5].

The mid-body reaches from the stern area to the bow area in the longitudinal direction. In the vertical, it shall not be less than defined in Table 6.

Table 6. Vertical extension of ice-strengthening for DNV ICE & POLAR.

Notation	Region	Above UIWL (m)	Below LIWL (m)
ICE-05	Midbody ice-belt	0,80	1,10
ICE-10		1,00	1,60
ICE-15		1,90	3,70
POLAR-10		1,40	2,30
POLAR-20		2,80	4,60
POLAR-30		4,20	9,20

In IACS PC, the hull is divided into several areas depending on the magnitude of the expected load, as seen in Fig. 5. There are four regions in the longitudinal direction: Bow, Bow intermediate, Mid-body and Stern. The regions, except for the bow are divided into sub- areas in the vertical direction such as Bottom, Lower and Ice-belt regions. Hence, IACS PC requires a greater area of reinforcement compared to the FSICR. According to Bridges et al. [11], the hull area extent and pressure distribution are similar in IACS PC and RS rule formulations.

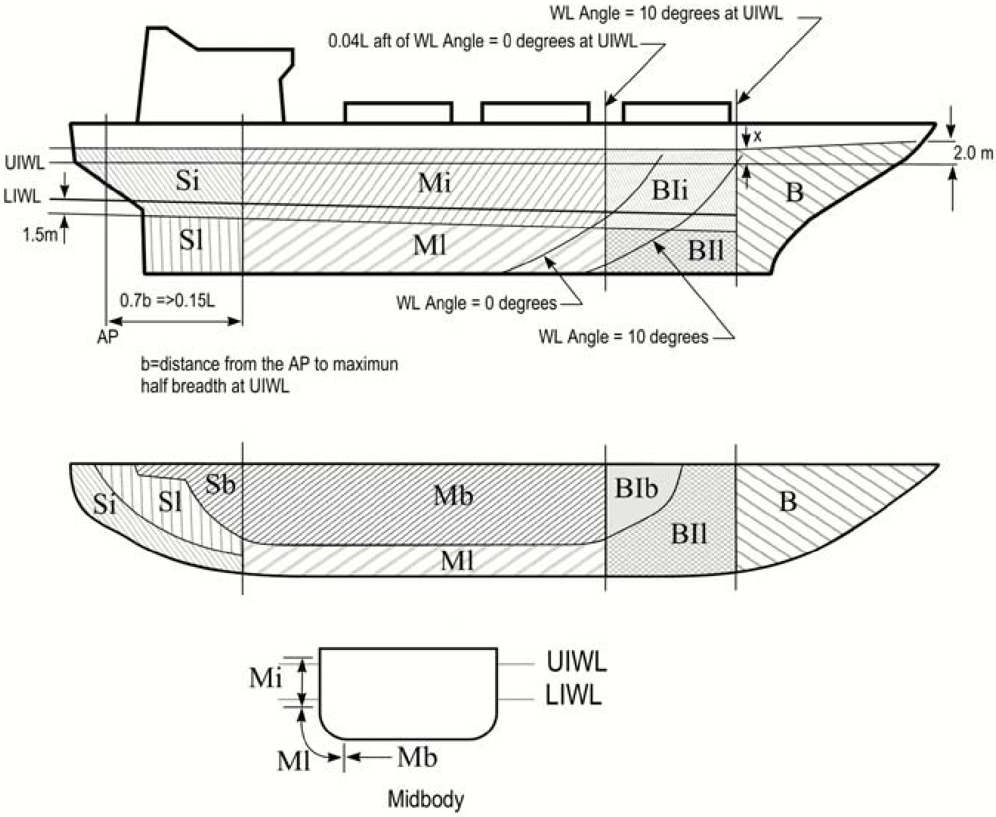


Fig. 5. Hull area extent of IACS PC [5].

The vertical extension of the ice-strengthening of the mid-body ice-belt shall not be less than given in Table 7. The extent of the mid-body ice-belt, Mi does not change as much as other rule-sets. Instead, the IACS PC has requirements on the mid-body lower area, Ml below the ice-belt. Only the limit above UIWL is increased for the higher notations due to tougher operational conditions

Table 7. Vertical extension of ice-strengthening for the IACS PC.

Notation	Region	Above UIWL (m)	Below LIWL (m)
PC-1 – PC-4	Midbody ice-belt, Mi	1,50	1,50
PC-5 – PC-7		1,00	

For the RS rule-set, the hull area lengthwise is divided into a forward region (A), intermediate region (B), mid-body region (B) and aft region (C). The ice-strengthening regions in the vertical direction are divided into four regions as presented in Fig. 6.

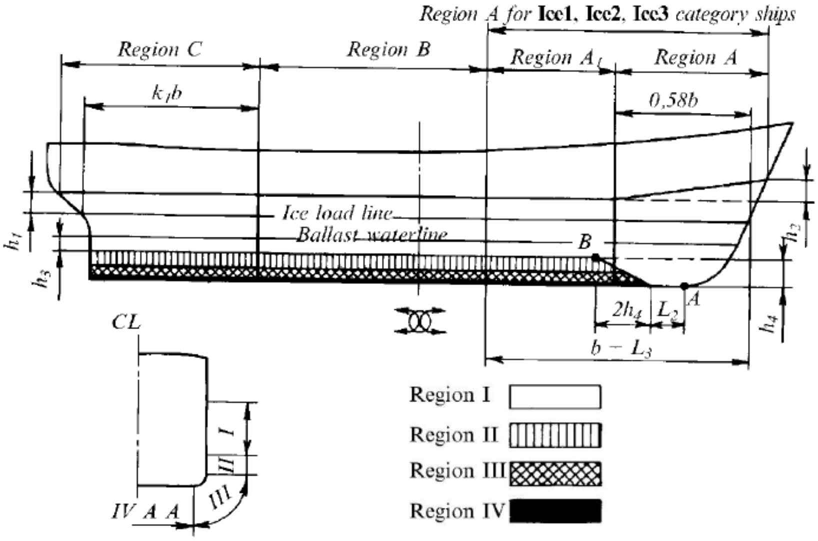


Fig. 6. Hull-area extent of RS rules set [7].

In the RS rules, the vertical extent (*h_1, h_3*) over the Ice load line (corresponding to UIWL) and below the Ballast water line (corresponding to LIWL) varies with the ship beam when the beam, *B* is larger than 20m. This is a different approach compared to the FSICR, DNV and IACS PC notations, whose vertical limits are defined only by fixed limits. The vertical extent is, for the RS-rules, that they shall not be less than defined in Table 8.

Table 8. Vertical extension of ice-strengthening for RS.

Notation	Region	Above UIWL (m)	Below LIWL (m)
Arc 7-9	Mid-body, region BI	$h_1 = 0{,}75$, if $B \le 20m$ $h_1 = \frac{0{,}5 \cdot B + 8}{24}$, if $B \succ 20m$	$h_3 = 1{,}6 \cdot h_1$
Arc 5-6			$h_3 = 1{,}35 \cdot h_1$
Arc 4		$h_1 = 0{,}60$, if $B \le 20m$ $h_1 = \frac{0{,}5 \cdot B + 8}{36}$, if $B \succ 20m$	$h_3 = 1{,}20 \cdot h_1$
Ice 3		$h_1 = 0{,}50$, if $B \le 20m$ $h_1 = \frac{0{,}5 \cdot B + 8}{30}$, if $B \succ 20m$	$h_3 = 1{,}10 \cdot h_1$
Ice2			$h_3 = h_1$
Ice1		$h_1 = 0{,}50$	

2.3. Local strength

Rule-set requirements of local strength apply to properties of structural members that are directly or indirectly exposed to ice pressure. Generally, the rule-sets cover same region of reinforcement, but equations and the influence of boundary conditions differ between rules. A common approach of determining and calculating the local strength of rule-sets is to calculate the design pressure or ice load, which the side shell structure in the ice-belt must resist. The load is defined in rule formulations and depends on the thickness of ice and the local structure. When the load is established, the structural requirements thickness on the shell plating, shear area and section modulus on the frames can be calculated depending on the direction of the frames. Depending on the rule-set of choice there are additional requirements and regulations on other structural members affected by the ice load. Rule equations can be found in Appendix C. The section modulus requirements in the rules considered in the project are based on two different calculation theories, further described in Section 2.3.2.

2.3.1. Characteristics of local structure

To meet the requirements of ice class rule-sets on a level of local strength, additional requirements on plate thickness and local strength on structural members are set. The plate thickness required depends on the characteristics of the added frames, i.e. structural members, the direction of the framing and frame spacing. By changing these parameters the required plate thickness differs.

The direction of framing generally depends on the purpose and size of the ship. For large ships with a closed cross-section it may be advantageous to use longitudinal framing, while for ships with open cross-sections, transverse framing is commonly applied.

Figure 7 shows a part of the mid-body with transverse framing in the ice-belt region. In the figure the frame spacing, web frame spacing and stringer distance are presented as well as the definition of height above BL.

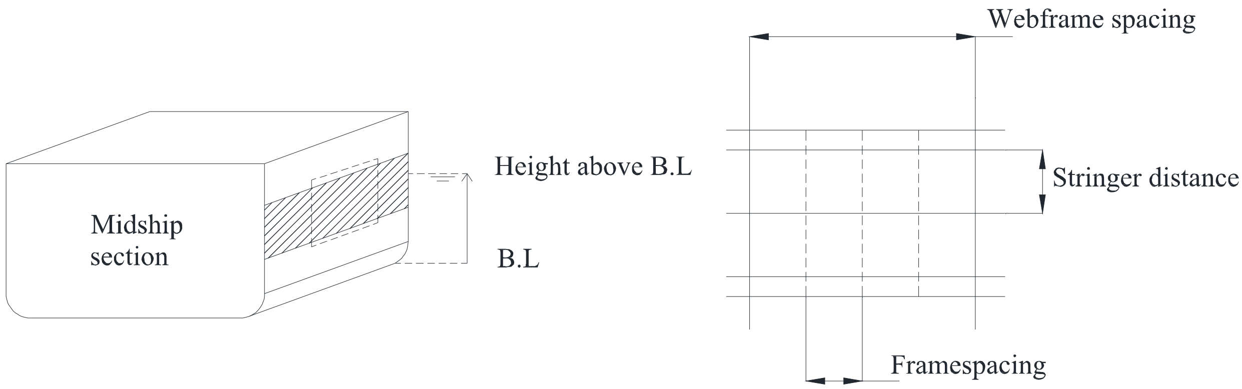


Fig. 7. Side shell structure of a transversely framed mid-body.

In Fig. 8, an inside view of a side shell is presented. The shell plating is longitudinally stiffened with flat bulb profiles between the web frames.

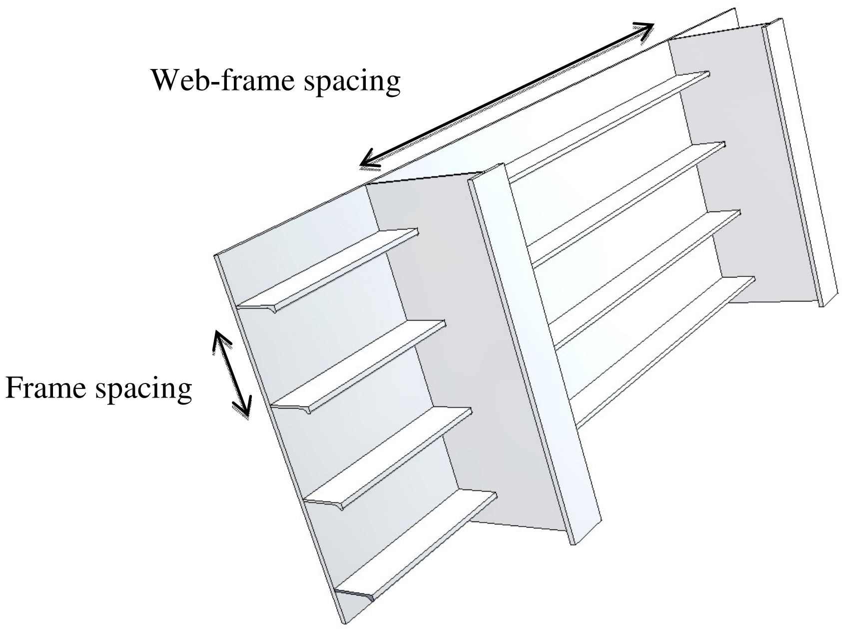


Fig. 8. Side shell structure with longitudinal framing.

Areas between web frames are stiffened by introducing steel profiles. Frame spacing between structural members generally becomes smaller, when ice-classing a ship for notations with higher requirements. This has to be taken in consideration; otherwise issues might arise regarding installation, inspection and maintenance of the structure. Flat bulb steel profiles are commonly used for this purpose.

The characteristics of flat bulb steels are similar to flat bar steels, but with improved structural stability. The rule-sets [5, 7] consider requirements of the structural stability, each presented in Appendix C. As an example, the rule formulation of the structural stability in the IACS PC is presented in Eq. (2.1) and Eq. (2.2). In the rule-set [5], the ratio of web height, h_w to net web thickness, t_{wn} of any framing member of a flat bar section shall not exceed:

$$h_w / t_{wn} \leq 282 / (\sigma_F)^{0,5} \tag{2.1}$$

while for a bulb, tee and angle sections the ration shall not exceed:

$$h_w / t_{wn} \leq 805 / (\sigma_F)^{0,5} \tag{2.2}$$

The rule formulation in Eq. (2.2) provides more freedom of choice when selecting profiles and their structural properties than for flat bar steels, which reach their limits earlier, seen in Eq. (2.1).

2.3.2. Principles of plastic and elastic design

This section aims to briefly explain the differences between the elastic and plastic method and how framing requirements have been developed in the IACS PC. More detailed information of application and extensive derivation of plastic framing requirements for polar ships are found in articles by Daley [12, 13]. Unless otherwise mentioned, this section refers to these references.

As mentioned, rule formulations of the FSICR and DNV are developed upon elastic methods, while in the IACS PC it is derived from analysis of plastic frame collapse. In the RS rule-set, the section modulus is taken as the plastic one, as it is termed the ultimate section modulus [3].

In Daley and Kendrick [14], it is stated that a plastic design can help ensure a better balance of material distribution to resist design and extreme loads. This is important since actual loads affecting the structure can be greater than the design values. With a plastic design, a better balance of strength is allowed, which ensures safety margins against ultimate collapse under accidental overloads. Plastic design does allow minor local deformations as long as it does not compromise the overall strength or the watertight integrity. Moreover, one can benefit from using plastic methods since it ensures a considerable strength reserve. This may or may not be the case with elastic design.

In Fig. 9, presented by Daley and Kendrick [14], an example shows a centrally loaded fixed beam. Assuming elastic design, the yield strength (σ_y) is easy to predict, due to its linear behaviour, while in the plastic design there are several states of yield until collapse. In the example, the typical yield appears earlier than the designed limit state.

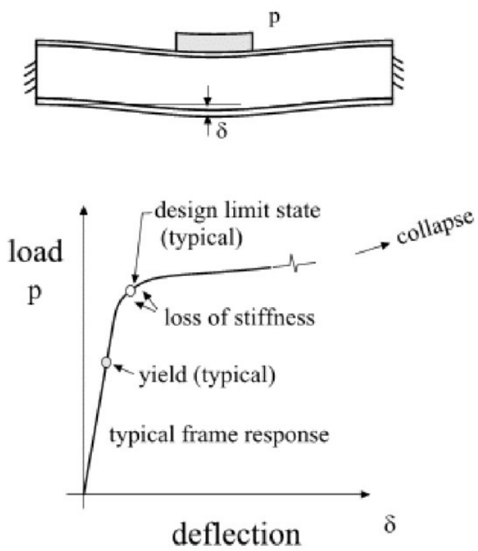


Fig. 9. Load-deflection curve of a frame showing design points [14].

While calculating the response for a structural member with an applied load it is important to use correct boundary conditions. According to Daley and Kendrick [14], the frames within the ice-strengthened region provide full fixity. This means that intersections between frames and the hull girder provide this constraint. In the rule-set of DNV exceptions are presented when they are set to simple supported, or a combination of fixed and simple supported. When fixed, there is no rotation of the ends, while the moment is transferred to the surrounding structure, free ends are allowed to rotate and hence no moment is transferred.

The equations of plastic approach are based on energy balance and can be solved by equating the external work with the internal work. The external work is carried out by the ice load that depends on the load-patch pressure, length of load along the frame and the frame spacing. The internal work is done by the hinges and shear panels; normally referred to the limit state equations. There are three limit states used in the IACS PC, which all results in the formation of different collapse mechanisms, boundary conditions and load formulations. The three limit states considered for frames are defined by Daley and Kendrick [14] and presented in Fig. 10, Fig. 11 and Fig. 12.

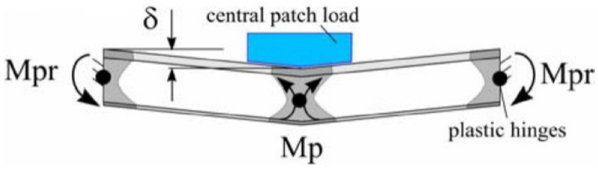


Fig. 10. 3-Hinge collapse (centrally loaded fixed-fixed frame) [14].

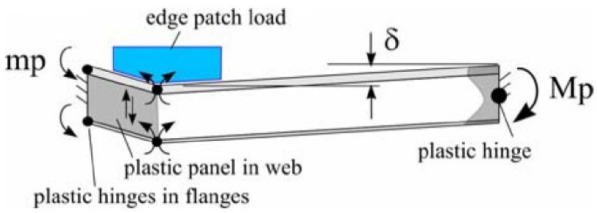


Fig. 11. Asymmetric shear collapse (end-loaded fixed-fixed frame) [14].

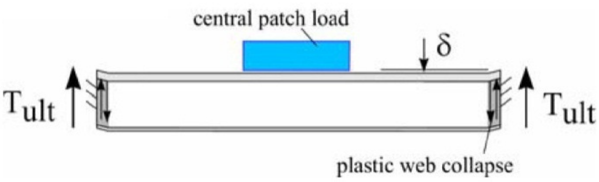


Fig. 12. Web collapse [14].

Depending on the characteristics of the structure, the energy balance will differ. In the IACS PC this is integrated when selecting the boundary condition, j and geometry of structural members affecting the value of A_1 and A_4. Factor A_1 is included in Eq. (C29) (see Appendix C) calculating the plastic section modulus requirements for transversely framed structures considering the limit states in Fig. 10 and Fig. 11. Factor A_4 is included in Eq. (C37) for longitudinally framed structures, where the increase requirement of the shear area leads to a limit state of web collapse as seen in Fig. 12. The higher requirement of shear area is necessary due to the behaviour of the actual load. The rule formulation of the plastic section modulus is found in Appendix C.

The rule formulation of calculating the plastic section modulus in the IACS PC and RS has a factor included that is taken into account if the actual shear area is larger than the one required. In this case, the requirements on the plastic section modulus will be reduced. This leads to an iterative process when selecting frames and may result in other characteristics of the structural member than those favourable in elastic design. According to Daley [12] this formulation will contribute to the structural safety without the cost of extra weight.

There are two equations for calculating the plastic section modulus in the IACS PC. When the cross-sectional area of the attached plate flange exceeds the cross-sectional area of the local frame, the plastic section modulus is calculated according to Eq. (C30), in Appendix C. When the cross-sectional area of the local frame exceeds the cross-sectional area of the attached plate flange, the plastic neutral axis is located in the frame instead of in the intersection between the frame and attached plate flange. The actual net-effective plastic section modulus, Z_p is then calculated according to Eq. (C31). Daley states that the calculation procedure with a fixed plastic neutral axis located in the intersection of the frame and attached plate flange is a more physically realistic and far simpler model for calculating the plastic section capacity in ship framing.

2.3.3. Variance between elastic section modulus and plastic section modulus

To enable comparisons between elastic and plastic rule formulations, Riska [3] presented an approach using a fixed ratio ($Z_p/Z_e = 1.35$) in order to achieve a rough basis for comparison. The ratio is based on elastic and plastic calculations of bulb profiles attached to a plate with a thickness of 15mm and a frame spacing of 600mm. The ratio is termed as the shape factor and may be interpreted as the plastic capacity reserve. In order to validate the applicability of Riska's shape factor in the comparisons, the actual shape factor was calculated and plotted for each ship used in the analysis of the investigation. In Fig. 13, Z_p/Z_e is plotted for Ship I depending on the web height of the attached frame. The properties of frames are imported from a beam database. The frame is attached to a plate with a thickness of 26mm and a frame spacing of 600mm. The adequate region for delimiting the outcome of the result is a web height from 200 to 700mm. An average value of the shape factor to be used for this case is found to be 1.5. Figures showing the shape factor for Ship II and Ship III are presented in Appendix E. A calculation approach with a fixed shape factor is not suitable for a fair comparison between different rule formulations and ship design. Instead, this report has taken an approach of calculating the actual properties and dimension of the structural members; further explained in Section 3.2.

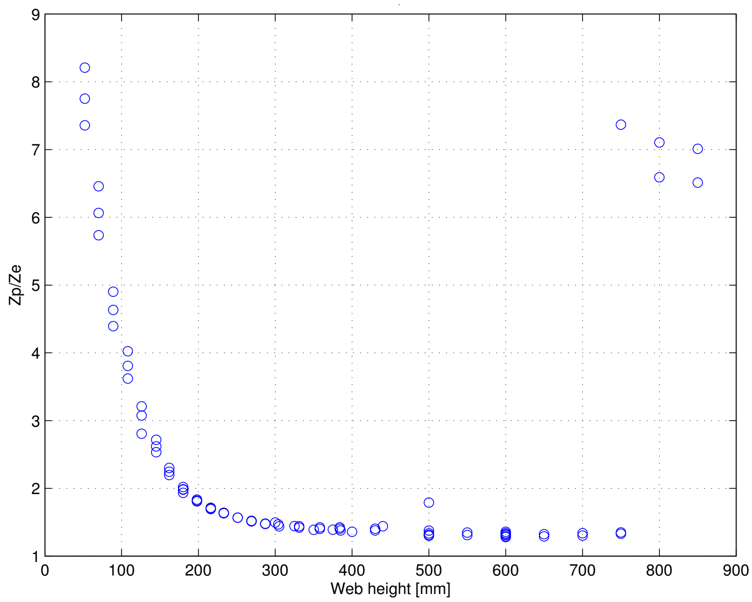


Fig. 13. The plastic/elastic section modulus ratio (Z_p/Z_e) for Ship I.

2.4. Material requirements

In addition to structural requirements, ice notations have requirements regarding steel grades stated in the rule-sets, which consider the choice of steel grades due to material thickness and the location of the exposed plating. There are three material rule-sets to be looked into. DNV have adopted the DAT (-X°C) in Pt.5 Ch.1 Sec.7 [5], which apply to materials in ships of any type intended to operate for longer periods in areas with a low air temperature. The DAT notation shows the design-ambient air temperature for structural material properties where (-X°C) designates temperature in Celsius (°C).

In the ARCOP report [11], it is stated that requirements for materials in the IACS PC are defined for each notation to ensure acceptable toughness of the structure. In the RS rule-set a similar approach is used by defining a minimum temperature, which provides a certain set of material requirements. The RS and IACS PC are compatible with the IACS UR S6 "Use of steel grades for various hull members - ships of 90m length and above". Hence, differences occur based on experience of each rule-set.

In ship drawings, the steel grades (A, B, D, E, F) of structural members are stated and if the material is manufactured of high tensile steel (HT) the letter is followed by an (H). The first letter in the steel name refers to which substance it is hardened with. A high-performance material such as HT-steel is more expensive than mild steel (MS). In the comparisons in Section 4, material tables show the required steel grade both the MS and HT.

Transition from ductile to brittle behaviour is the main reason for having material requirements. Operating a ship in temperatures below the material transition temperature will result in a structure with changed structural properties. A cooled structural member may become stronger because of decreased interatomic spacing, which increases attraction between the atoms. It may also become more brittle depending on the characteristics of the material.

In Fig. 14 the required steel grade according to DAT (-X°C) is presented. The figure shows that the requirement on material grade depends on three things:

- Design temperature.
- Structural category.
- Thickness of the structural member.

If the structural category is known, the material grade can be selected based on the design temperature and plate thickness. To illustrate an example; if a 30mm plate on a ship were to be applied for structural category III with a design temperature of –30°C, grade E or EH would be acquired.

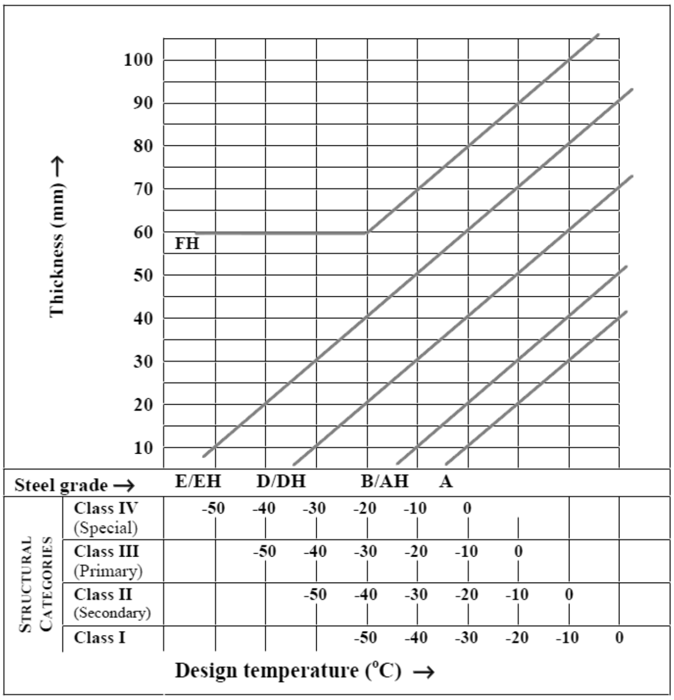


Fig. 14. Required steel grades according to DAT (-X°C) [5].

The design temperature defines the minimum temperature of the ambient air in which the ship is supposed to operate in. The structural member category depends on the location of the structural member and its load case. Material requirements depending on the thickness of structural member are influenced by the boundary conditions, where the distance between the plate surface and mid-plane is considered. Generally, for thin plates the boundary condition of a free surface leads to zero lateral stress throughout the plate thickness. With increased plate thickness the distance from the surface as well as the stress will increase. As an example of this, Zia-Ebrahimi [15] performed Charpy V-notch tests, which showed that an increase of the specimen thickness from 12.7mm to 25.4mm resulted in an upward shift of 25°C in the ductile to brittle transition temperature. In Fig. 15 this can be explained by a shift of the energy curve 25°C to the right where the fracture appearance will occur at a 25°C higher temperature and a lower absorbed energy level, Cv.

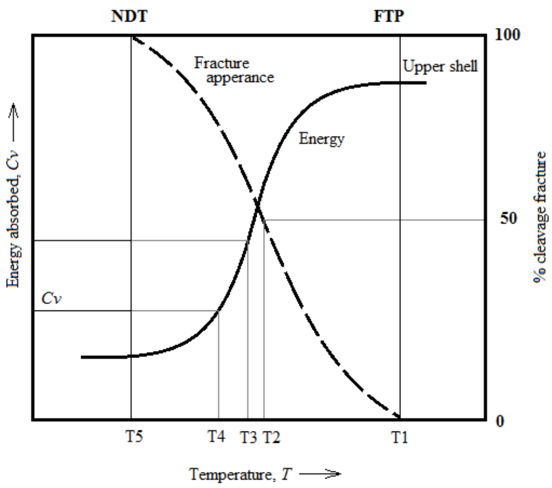


Fig. 15. Typical transition temperatures from Charpy V-notch tests.

In Fig. 15 five different transition temperatures defined. A material that is subjected to a temperature below T1 in Fig. 15 is in a state where less energy can be absorbed than in an ideal state. At temperature T5, minor plastic deformation may occur. This means that the load-carrying capacity is significantly reduced and therefore the risk of structural collapse is increased. Temperature T4 is normally named the transition temperature. This point is defined where a standard specimen absorbs an impact energy of 20J.

Increasing the carbon content normally hardens steel. This treatment will results in higher yield strength and a less ductile behaviour of the material. Increasing the carbon content energy curve in Fig. 15 is shifted downwards and the transition will then occur at a higher temperature.

In addition to the steel grade requirement, ice notations require corrosion and abrasion protection in terms of additional thickness (t_s, t_c, t_k, A_k, Δs_{sp0}). Protection from corrosion and abrasion i.e. effective protection is recommended for surfaces and shell plating of ice-classed ships. Besides steel grade and material requirements of structural members, ice notations add thickness for abrasion and corrosion in scantling calculations. In the FSICR and DNV, who have adopted the DAT-notations [16], corrosion allowance is to be taken as 2mm. If an abrasion-resistant coating is applied, a 1mm reduction in corrosion may be allowed.

The IACS PC requirements include a minimum corrosion/abrasion addition applied to the structure within the mid-body ice-strengthened area. The minimum addition depends on the class notation. Assuming effective protection, the minimum addition, t_s, is set to 2.0mm for PC 4 -7 and 2.5mm for PC-1 to PC-3. Calculating the required shell plating with the RS rule-set the corrosion addition, Δs_{sp0}, is added to the calculations. The corrosion addition required depends on the annual reduction in mm and the planned ship life, T, see Eq. (C13).

3. Basis of the analysis

In this section the basis of the analysis is presented. It starts by defining the area of investigation and the outline of the comparisons in Section 3.1. It continues with a presentation of the calculation procedure in Section 3.2 followed by assumptions necessary for the analysis in Section 3.3. Finally, the background for the investigated areas is stated in Sections 3.1 to 3.6.

3.1. Area of investigation

The area of interest is the mid-body side shell structure in the horizontal direction and to the ice-belt in the vertical direction. To enable comparisons of rule-sets three cases are outlined. Each case considers three different notations and a fictitious ship intended for operation in ice-infested waters. The outline of the comparison presented in Table 9 was created together with DNV. The particulars of the fictitious ships presented in Appendix A are representative for existing ships with "Notation 1" stated in Table 9.

Table 9. Outline of comparisons.

Case:	Notation 1:	Notation 2:	Notation 3:	Ship:
I	ICE 1A + DAT (-20°C)	PC-7	RS Arc4	Ship I
II	DNV ICE-15 + DAT (-30°C)	PC-4	RS Arc6	Ship II
III	POLAR-10 + DAT (-30°C)	PC-2	RS Arc7	Ship III

3.2. Calculation procedure

A computer code was created in MATLAB® 2010b [8] where the ice-notations in the rule-sets of DNV, FSCIR, IACS PC and RS were transferred into a code. Validation of results, except RS, was carried out with calculation sheets integrated in the DNV software Nauticus Hull [9]. Ship particulars and notations of investigation were used identically in both programs and the structural requirements were equal. An additional validation was made with existing drawing of ships with approved ice notations.

The flowchart in Fig. 16 shows a basic workflow of the code.

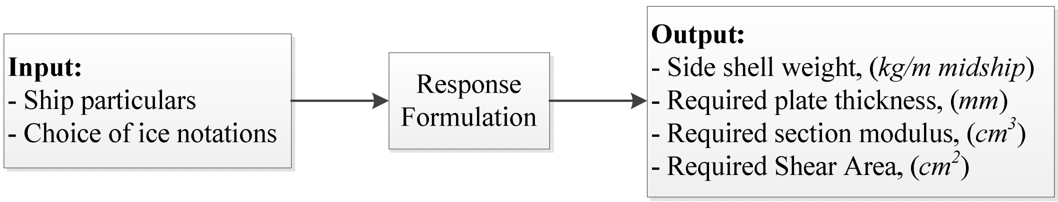


Fig. 16. Schematic of calculation procedure.

The computer code is based on the fourth approach suggested in Daley [12] where a table of standard profiles is adopted. This approach is in practice trial and error and is stated as the most appropriate one in an economic aspect. This provides information of the smallest frame that falls within the safe region while satisfying rule-set requirements.

For rule-sets based on elastic design, the interpretation to plastic design is performed according to Eq. (30) and Eq. (C31).

The response formulation provides an output in graphs with information of weight (*kg/m midships section*), plate thickness (*mm*) and information on required structural members, i.e. section modulus (cm^3) and shear area (cm^2) depending on frame spacing or height above baseline. Rule equations of required plate thickness and structural members for each class society are presented in Appendix C.

3.3. Assumptions

In order to carry out the analysis, the following assumptions are made:

- Available thickness of the shell plating is assumed to be even 0.5mm, since plates are normally manufactured with these set thicknesses.
- To enable a comparable presentation of actual structural properties of the rule-sets it is necessary to present the data without corrosion allowance. The structural requirements are calculated in accordance with the rule formulation and therefore corrosion requirements are fulfilled. Since corrosion allowance of the RS notation depends on planned ship life, an assumed life is set at 25 years. The corrosion allowance for the FSICR, DNV and IACS PC is the same as stated in Section 2.4, while for the RS-notations RS Ice1 to RS Arc6 are assumed as being the same for PC4-7 and for RS Arc7 to RS Arc9 the corrosion allowance is the same as in PC1-3.
- Brackets on frames are not considered in calculations. Calculating with brackets reduces the span length and differs between rule formulations.
- Properties of framing members in Eq. (C30) and Eq. (C31) used for plastic section modulus are not applicable for flat-bulb profiles because of their geometric shape. To be able to use flat-bulb profiles, DNV recommended a conversion of the profiles to L-profiles with equivalent properties of elastic section modulus, height and web thickness. Where the beam database of existing flat-bulb steel was insufficient T-profiles were added to the beam database in order to carry out analyses of higher notations.
- In the RS rule-set, the requirements regarding stringer distance have not been taken into account in the calculations. These requirements have been disregarded since the stringer distance and web-frame spacing has already been defined in ship particulars.
- Calculating the actual shear area and section modulus for the structural members the angle between shell plate and frame, $\rho_{w,}$ is set at 90°. This provides an ideal case where the beam properties are fully utilized.
- The rule-sets use different load formulations on the mid-body - the FSICR and DNV are dependent on the bow shape. In the FSICR, the bow shape influences the power requirements and therefore indirectly affects the load formulation. In DNV rules, it is possible to use a bow that is wider than the mid-body region and with this achieves a reduction factor from 0.6 to 0.5. The ships considered in the study are not using this feature.
- The frames within the ice-strengthened region provide full fixity, according to the design case described by Daley and Kendrick [14]. This means that intersections between frames and the hull girder provide this constraint.
- It is implied that the basic design equations of the computer code assumes uniform cross-sections and properties along their length.

3.4. Parameter study

Performing parameter studies with scantling requirements provides a better understanding of the influence of parameters on the weight outcome of each notation. To be able to compare the results, the study has been carried out on each case stated in Table 9.

The results will not be linear, since some equations are in the power of 1/6 and others in the power of 3. Hence, tendencies in the result may be useful for finding a favourable design.

A typical cost formulation with dependent variables may be written as:

$$price = f\left(weight, \sigma_F, material \cdot grade\right) = f\left(displacement, s, l, \sigma_F, P_s, ice \cdot notation\right)$$

where, the right-most parameters are varied one at a time in the study in order to present their influence on the result.

3.5. Material grade

Since the fictitious ships are intended to operate in a certain area independent of class, an appropriate DAT notation is added to the the FSICR and DNV notations in order to enable comparison. For Ship I the DAT (-20°C) notation is added as an appropriate material grade to the comparison and for Ships II and III the DAT (-30°C) notation is added. The three material requirements considered are dependent on the location of structural member and its thickness. In addition to this, the DAT-notation also considers the lowest mean daily average air temperature.

Comparisons of material requirements are treated individually in each case comparison. Finally, all material requirements treated in the study are presented in Table 19 in Section 4.4.4.

3.6. Weight comparison

The weight calculations in this study only consider the plate and frames, since the larger structural members (stringers and web frames) are designed due to the ships' purpose of operation and global strength requirements [11]. The calculation is established to estimate the weight, kg/m midships section, of the ice-belt with the stated hull extent limits. The weight analysis will provide information about the influence of local designs of the weight with varying frame spacing. The distance between frames is generally a design parameter that is easy to change and it has a great impact on the rule formulations and therefore also on the weight outcome. With this analysis, it may be possible to predict which design that will be used for each notation and ship setup.

4. Results of analysis

Results presented in this section are based on calculations of rule-set requirements defined in Case I, Case II and Case III, which are outlined in Table 1. Each comparison is divided into four parts. First, a comparison of the requirements of the structural members is presented. The results are presented as plots where the required structural outcome for the fictitious ships is presented, respectively, depending on frame spacing and the height above BL with fixed frame spacing according to ship particulars in Appendix A. The results reflect how frame spacing impacts on structural requirements stated in each rule-set of interest. It also presents the structural requirements on the members depending on the vertical extension of the side-shell structure. This enables information for a comparison of structural similarities of rule outcome.

Secondly, a study of each parameter's influence on the weight and structural requirements is presented. This is followed by a material comparison outlined for each case where the steel grade required for the rule-set is presented depending on the structural component and its thickness. Finally, a weight and cost comparison is presented where the weight of the ice-belt region, in the kg/m midships section, is plotted depending on the frame spacing of the mid-body. This plot clarifies how the change of frame spacing impacts on the weight outcome.

In rule formulations, longitudinal framing has higher requirements on local strength compared to transverse framing. This is seen in Appendix G (G2 to G9) where both directions of framing are compared for Case I. For Case II and Case III, requirements are too high with longitudinal framing and therefore calculations are performed only with transverse framing.

A brief summary of the results from Cases I, II and III is presented in Section 4.4. In Appendix G, results from extensive comparisons of notations are outlined.

4.1. Comparison for Case I

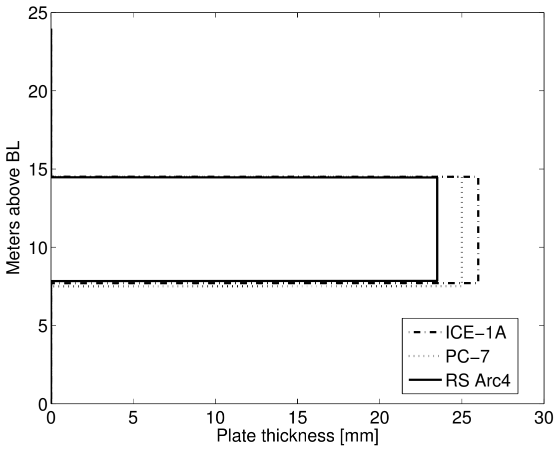
The ship used in Case I is designed for trade in areas with light ice conditions. Notations considered in comparison of Case I is presented in Table 10. The ship particulars are found in Appendix A.

Table 10. Notations in Case I.

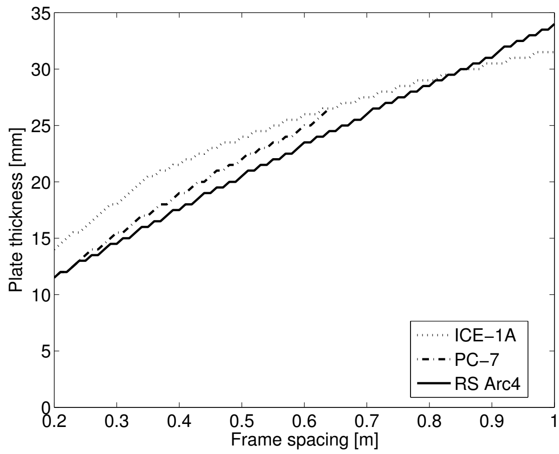
Case:	Notation 1:	Notation 2:	Notation 3:	Ship:
I	ICE 1A + DAT (-20°C)	PC-7	RS Arc4	Ship I

4.1.1. Structural members

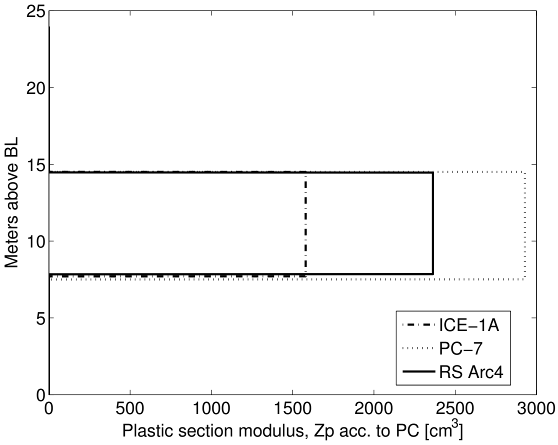
The requirements on structural members for Case I are presented in Fig. 17: (a), (c) and (e) show requirements on structural members depending on the height above baseline, longitudinally framed with a frame spacing of 600mm. UIWL is located at 13.5m and LIWL is located at 9.0m. Figures 17: (b), (d) and (f) show requirements on structural members depending on the frame spacing. When calculating the required structural members of ice-strengthening, the requirements on local design of the Common Structural Rules CSR are also included in the result. The requirements of the CSR must still be fulfilled.



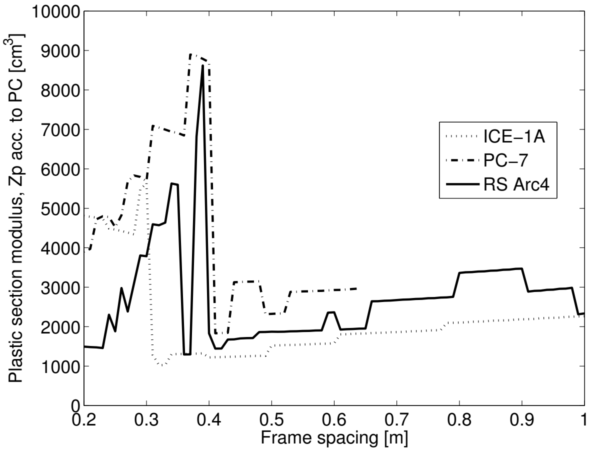
(a). Height over BL versus plate thickness.



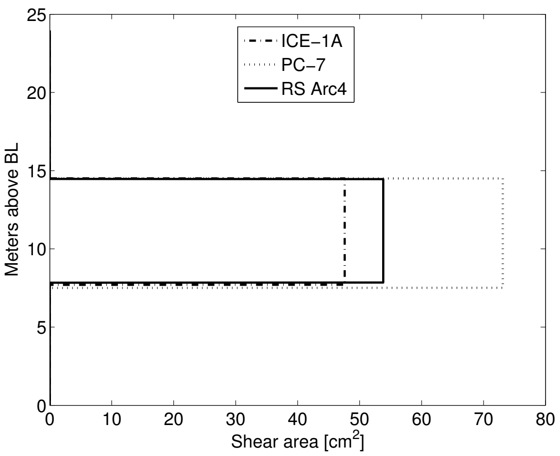
(b). Plate thickness depending on frame spacing.



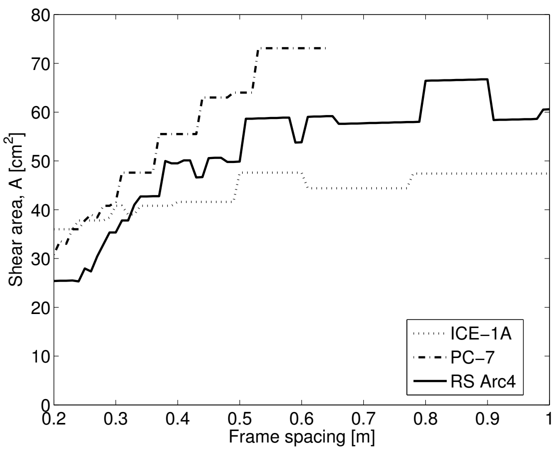
(c). Height over BL versus section modulus.



(d). Section modulus depending on frame spacing.



(e). Height over BL versus shear area.



(f). Shear area depending on frame spacing.

Fig. 17. Structural outcome of Case I: (a), (c) and (e) show the height over baseline versus requirements on structural members, (b), (d) and (f) show the requirements for structural members depending on the frame spacing.

4.1.2. Comparison of material grade

In Table 11, an overview of the material grade requirements of the shell plating and structural members depending on notations are presented for Case I. The MS and HT-steel grade is presented in the table. Section 2.4 describes the differences of steel grades.

Table 11. Comparison of DAT (-20°C) with PC-7 and RS Arc4.

<table>
<tr><th rowspan="2">Thickness (mm)</th><th>DAT
(-20°C)</th><th>PC-7</th><th>RS Arc4</th></tr>
<tr><th>Shell plating & structural members</th><th>Shell plating & structural members</th><th>Shell plating & structural members</th></tr>
<tr><td>45<t<50</td><td rowspan="2">E/EH</td><td rowspan="3">D/DH</td><td rowspan="2">D/DH</td></tr>
<tr><td>40<t<45</td></tr>
<tr><td>35<t<40</td><td rowspan="4">D/DH</td><td rowspan="2">B/AH</td></tr>
<tr><td>30<t<35</td><td rowspan="7">B/AH</td></tr>
<tr><td>25<t<30</td><td rowspan="6">A/AH</td></tr>
<tr><td>20<t<25</td></tr>
<tr><td>15<t<20</td><td rowspan="2">B/AH</td></tr>
<tr><td>10<t<15</td></tr>
<tr><td>5<t<10</td><td rowspan="2">A</td></tr>
<tr><td>t<5</td></tr>
</table>

Figure 18 presents the required corrosion addition for the structural members in Case I. In the figure, +C denotes the notation with effective protection coatings and –C without these. Note that, ICE-1A and PC-7+C are both 2mm.

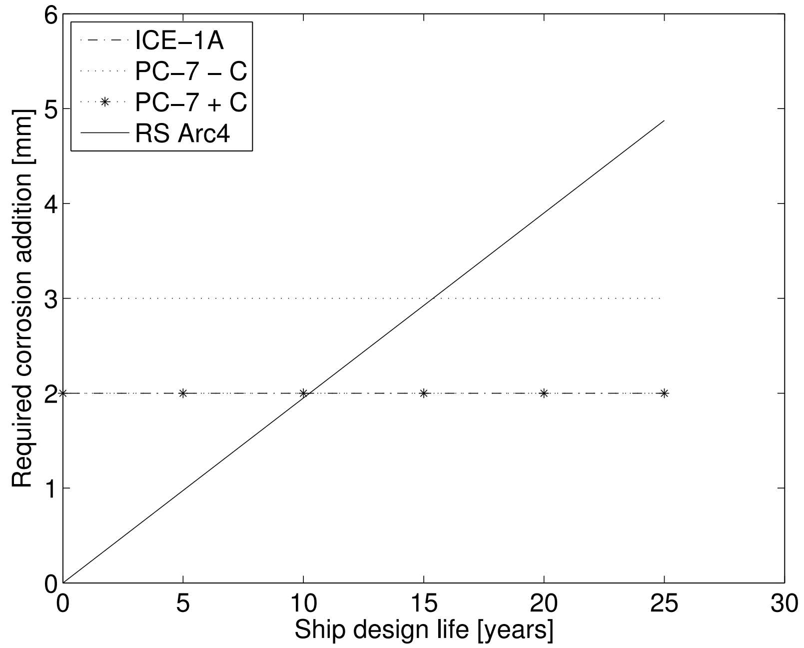


Fig. 18. Required corrosion and abrasion addition for notations in Case I.

4.1.3. Parameter study

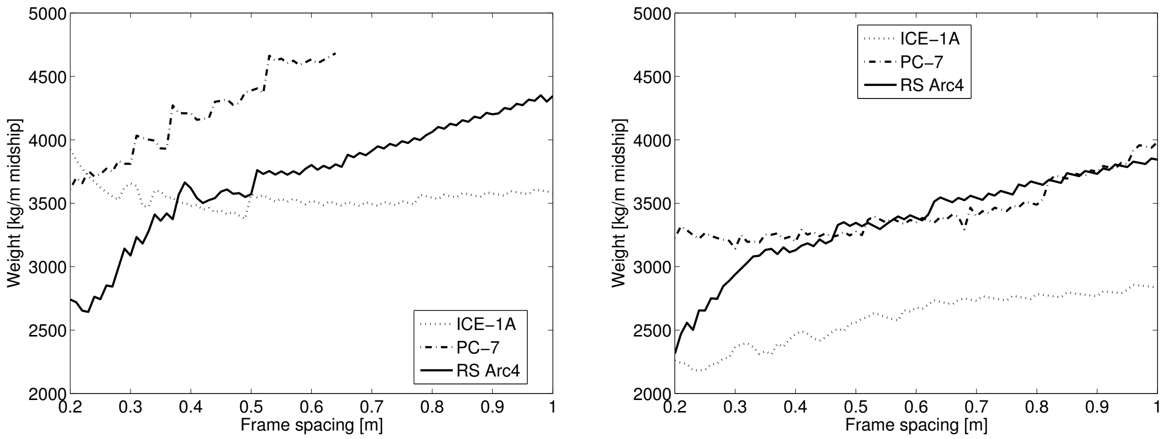
Each parameter's influence on the weight is presented in Table 12. In Appendix F, the complete outcome of the parameter study is presented. The influence uses a four-point scale noted None, Low, Moderate and High.

Table 12. Parameter influence on weight for Ship I.

	ICE-IA	PC-7	RS Arc4
Frame spacing	Low	High	Moderate
Web frame spacing	High	High	Moderate
Displacement, Δ	Low	Low	Low
Yield strength	High	High	High
Installed power	Low	None	None

4.1.4. Weight comparison

In Fig. 19 the weight, in kg/m midships, of Ship I is presented for ICE-1A, PC-7 and RS Arc4. The outcome with longitudinal framing depending on frame spacing is presented in (a). The same setup is run with transverse framing and is presented in (b). The stringer distance had to be set for transverse calculation and it is assumed to be the same as the web frame spacing for the longitudinal calculation. Analysing the outcome of these two figures shows that it might be beneficial to apply transverse framing depending on the overall design of Ship I.



(a) with longitudinal framing **(b)** with transverse framing

Fig. 19. Weight comparison of Case I: (a) shows the weight with longitudinal framing while (b) shows the weight with transverse framing.

4.2. Comparison of Case II

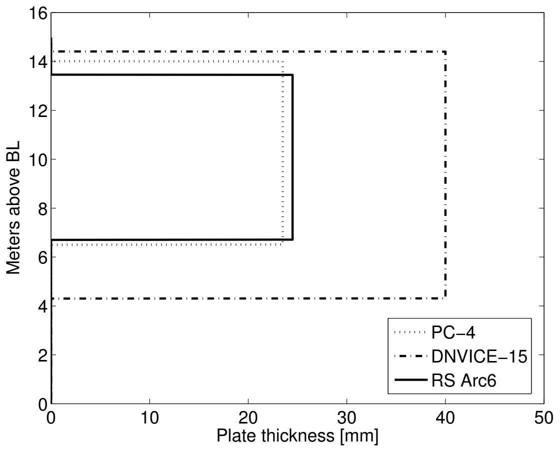
The ship used in Case II is Ship II, which is a ship designed for trade in areas with harsh ice conditions. Notations considered in comparison with Case II are presented in Table 13. Ship particulars are found in Appendix A.

Table 13. Notations in Case II.

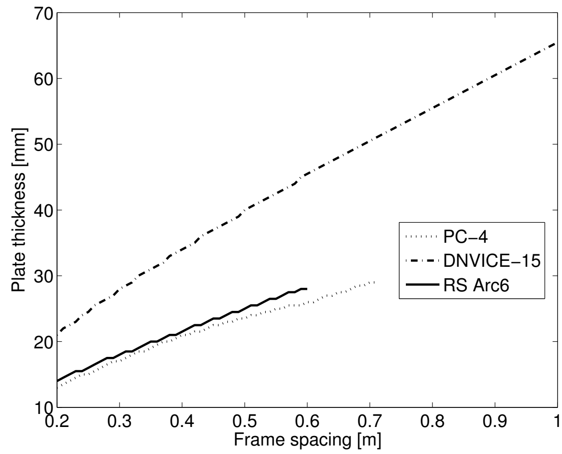
Case:	Notation 1:	Notation 2:	Notation 3:	Ship:
II	DNV ICE-15 + DAT (-30°C)	PC-4	RS Arc6	Ship II

4.2.1. Structural members

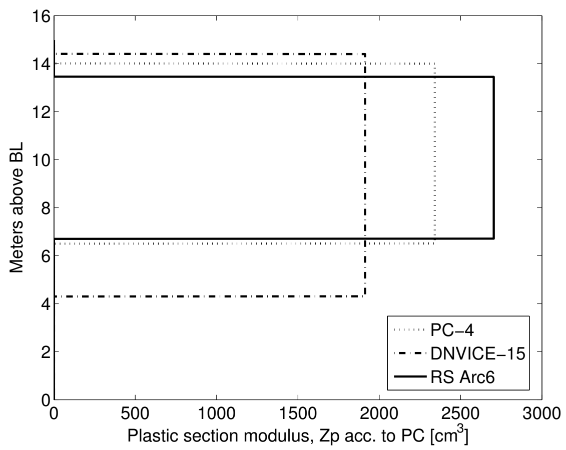
The requirements on structural members for Case II are presented in Fig. 20: (a), (c) and (e) show the requirements for structural members depending on the height above baseline, transversally framed with frame spacing of 500mm. UIWL is located at 12.5m and LIWL is located at 8.0m. Figures 20 (b), (d) and (f) show the requirements for structural members depending on the frame spacing.



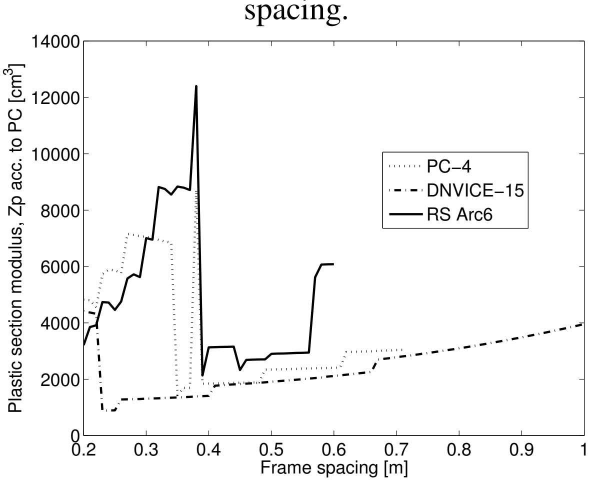
(a). Height over BL versus plate thickness.



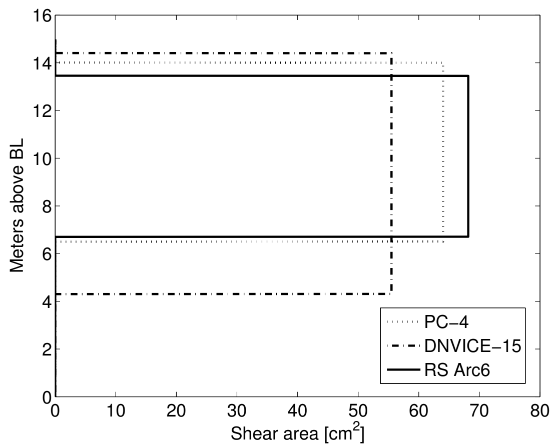
(b). Plate thickness depending on frame spacing.



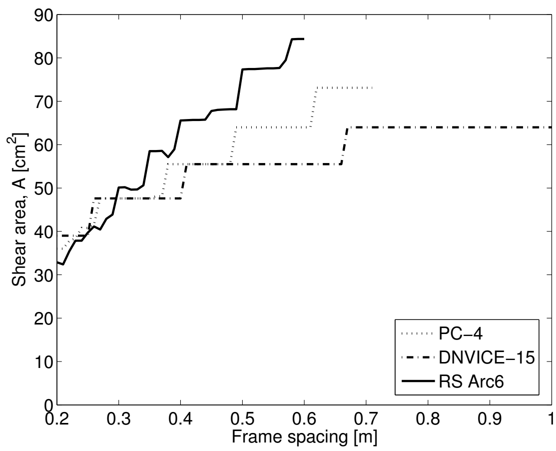
(c). Height over BL versus section modulus.



(d). Section modulus depending on frame spacing.



(e). Height over BL versus shear area.



(f). Shear area depending on frame spacing.

Fig. 20. Structural outcome of Case II: (a), (c) and (e) show the height over baseline versus requirements on structural members; (b), (d) and (f) show the requirements for structural members depending on the frame spacing.

4.2.2. Comparison of material grade

In Table 14, an overview of the material grade requirements of the shell plating and structural members depending on notations is presented for Case II. The MS and HT-steel grade is presented in the table. Section 2.4 describes the differences of steel grades.

Table 14. Comparison of DAT (-30°C) with PC-4 and RS Arc6.

<table>
<tr><th rowspan="2">Thickness (mm)</th><th>DAT
(-30°C)</th><th colspan="2">PC-4</th><th>Arc6</th></tr>
<tr><th>Shell plating & structural members</th><th>Shell plating</th><th>Structural members</th><th>Shell plating & structural members</th></tr>
<tr><td>45<t<50</td><td rowspan="4">E/EH</td><td rowspan="2">E/EH</td><td>E/EH</td><td rowspan="2">E/EH</td></tr>
<tr><td>40<t<45</td><td rowspan="5">D/DH</td></tr>
<tr><td>35<t<40</td><td rowspan="5">D/DH</td><td rowspan="3">D/DH</td></tr>
<tr><td>30<t<35</td></tr>
<tr><td>25<t<30</td><td rowspan="4">D/DH</td></tr>
<tr><td>20<t<25</td><td>B/AH</td></tr>
<tr><td>15<t<20</td><td rowspan="4">B/AH</td><td rowspan="4">A/AH</td></tr>
<tr><td>10<t<15</td><td rowspan="3">B/AH</td></tr>
<tr><td>5<t<10</td><td rowspan="2">B/AH</td></tr>
<tr><td>t<5</td></tr>
</table>

Figure 21 presents the required corrosion addition for the structural members in Case II. In the figure, +C denotes the notation with effective protection coatings and –C without these.

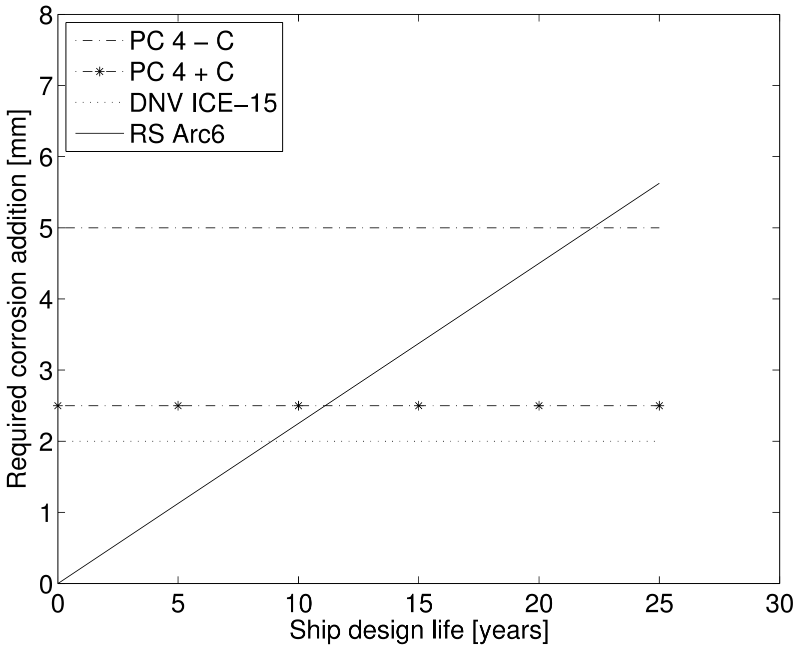


Fig. 21. Required corrosion and abrasion addition for notations in Case II.

4.2.3. Parameter study

Each parameter's influence on the weight is presented in Table 15. In Appendix F, the complete outcome of the parameter study is presented. The influence uses a four-point scale noted None, Low, Moderate and High.

Table 15. Parameter influence on weight for Ship II.

	DNV	IACS PC	RS
Frame spacing	High	Low	High
Stringer distance	None	None	Moderate
Displacement, Δ	None	Moderate	Moderate
Yield strength	High	High	High

4.2.4. Weight comparison

In Fig. 22, the weight, in kg/m midships, of Ship II is presented for PC-4, DNV ICE-15 and RS Arc6 with transverse framing depending on frame spacing.

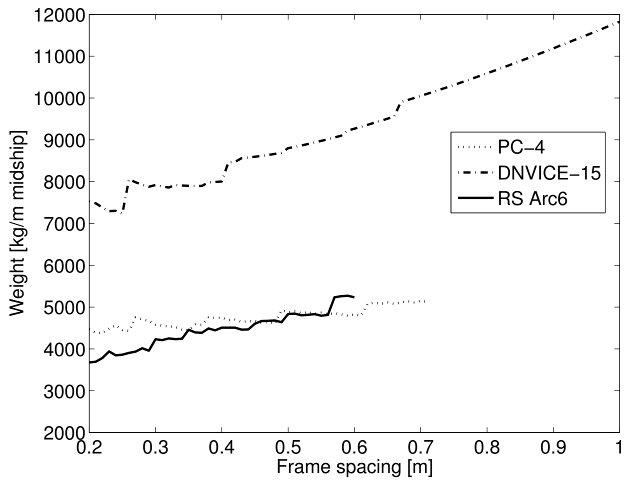


Fig. 22. Weight comparison of Case II with transverse framing.

4.3. Comparison with Case III

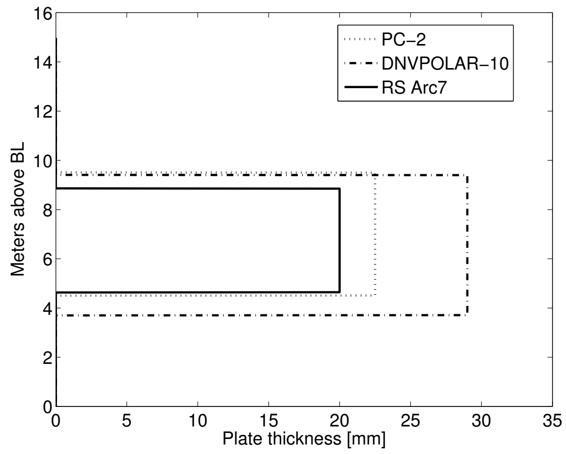
The ship used in Case III is Ship III, which is designed for icebreaking service. Notations considered in comparison with Case III are presented in Table 16. Ship particulars are found in Appendix A.

Table 16. Notations in Case III.

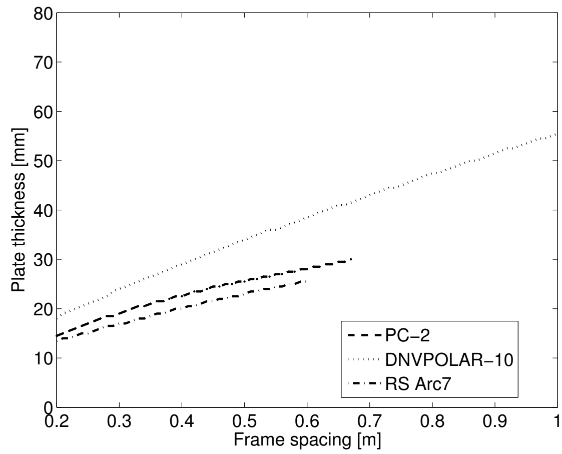
Case:	Notation 1:	Notation 2:	Notation 3:	Ship:
III	POLAR-10 + DAT (-30°C)	PC-2	RS Arc7	Ship III

4.3.1. Structural members

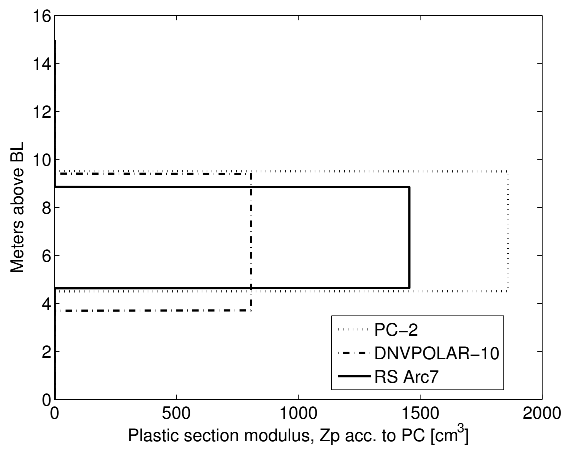
The requirements for structural members for Case III are presented in Fig. 23: (a), (c) and (e) show the requirements for structural members depending on the height above baseline, transversally framed with a frame spacing of 400mm. UIWL is located at 8.0m and LIWL is located at 6.0m Figures 23 (b), (d) and (f) show the requirements for structural members depending on the frame spacing.



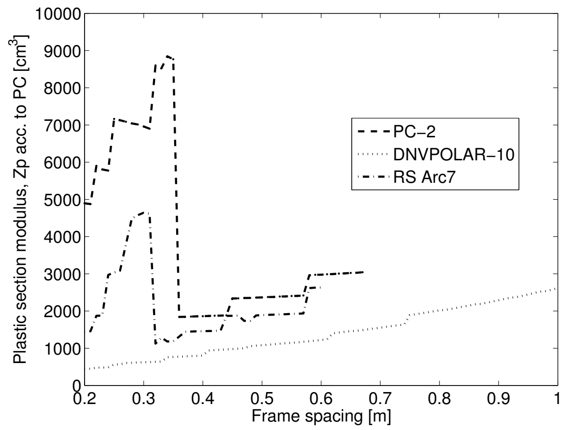
(a). Height over BL versus plate thickness.



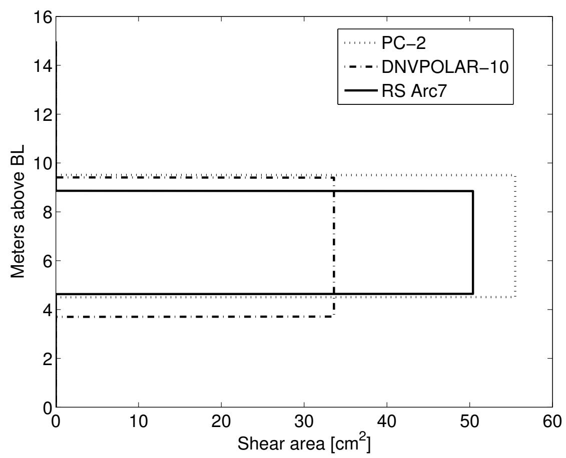
(b). Plate thickness depending on frame spacing.



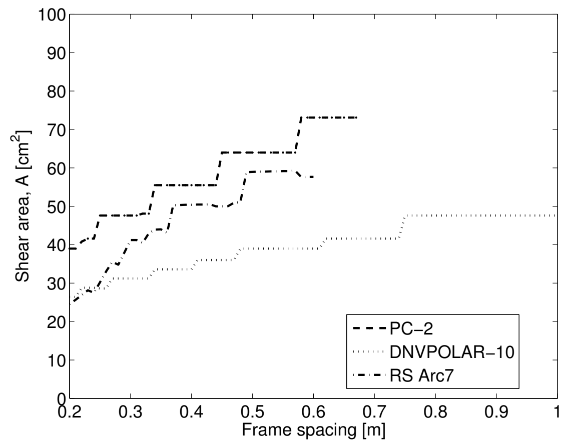
(c). Height over BL versus section modulus.



(d). Section modulus depending on frame spacing.



(e). Height over BL versus shear area.



(f). Shear area depending on frame spacing.

Fig. 23. Structural outcome of Case III: (a), (c) and (e) show the height over baseline versus the requirements for structural members; (b), (d) and (f) show the requirements for structural members depending on the frame spacing.

4.3.2. Comparison of material grade

In Table 17, an overview of the material grade requirements for the shell plating and structural members depending on notations is presented for Case III. The MS and HT-steel grade is presented in the table. Section 2.4 describes differences of steel grades.

Table 17. Comparison of DAT (-30°C) with PC-2 and RS Arc7.

<table>
<tr><th rowspan="2">Thickness (mm)</th><th>DAT (-30°C)</th><th colspan="2">PC-2</th><th>RS Arc7</th></tr>
<tr><th>Shell plating & structural members</th><th>Shell plating</th><th>Structural members</th><th>Shell plating & structural members</th></tr>
<tr><td>45<t<50</td><td rowspan="4">E/EH</td><td rowspan="2">E/EH</td><td>E/EH</td><td rowspan="2">E/EH</td></tr>
<tr><td>40<t<45</td><td rowspan="5">D/DH</td></tr>
<tr><td>35<t<40</td><td rowspan="5">D/DH</td><td rowspan="3">D/DH</td></tr>
<tr><td>30<t<35</td></tr>
<tr><td>25<t<30</td><td rowspan="4">D/DH</td></tr>
<tr><td>20<t<25</td><td>B/AH</td></tr>
<tr><td>15<t<20</td><td rowspan="4">B/AH</td><td rowspan="4">A/AH</td></tr>
<tr><td>10<t<15</td><td rowspan="3">B/AH</td></tr>
<tr><td>5<t<10</td><td rowspan="2">B/AH</td></tr>
<tr><td>t<5</td></tr>
</table>

Figure 24 presents the required corrosion addition for the structural members in Case III. In the figure, +C denotes notation with effective protection coatings and –C without these.

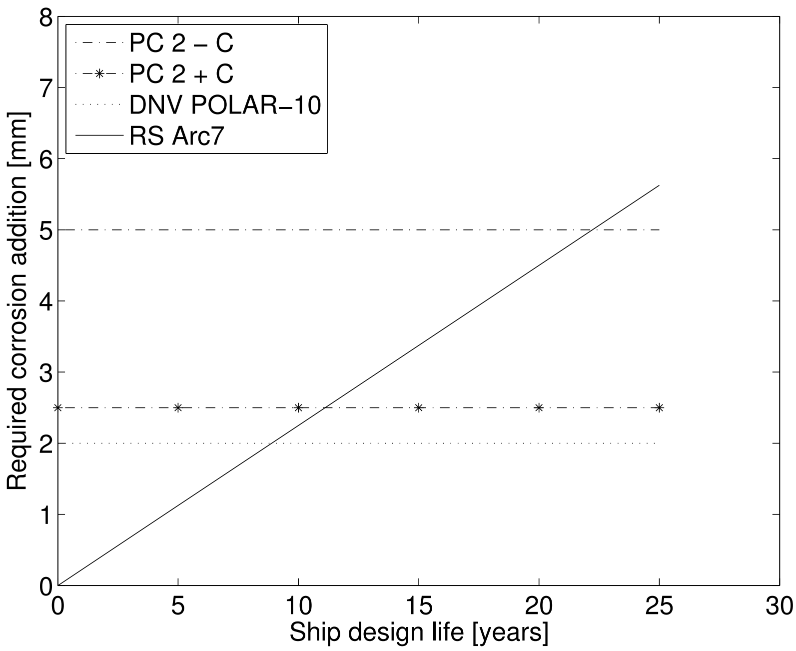


Fig. 24. Required corrosion and abrasion addition for notations in Case III.

4.3.3. Parameter study

Each parameter's influence on the weight is presented in Table 18. In Appendix F, the complete outcome of the parameter study is presented. The influence uses a four-point scale noted None, Low, Moderate and High.

Table 18. Parameter influence on weight for Ship III.

	DNV	IACS PC	RS
Frame spacing	High	Low	Moderate
Stringer distance	Low	Low	Moderate
Displacement, Δ	None	Low	Moderate

Table 18 should be used while noting that the beam database is insufficient for Ship III, which has a great impact on the results.

4.3.4. Weight comparison

In Fig. 25, the weight, in kg/m midships, of Ship III is presented for PC-2, POLAR-10 and RS Arc7 with transverse framing depending on frame spacing.

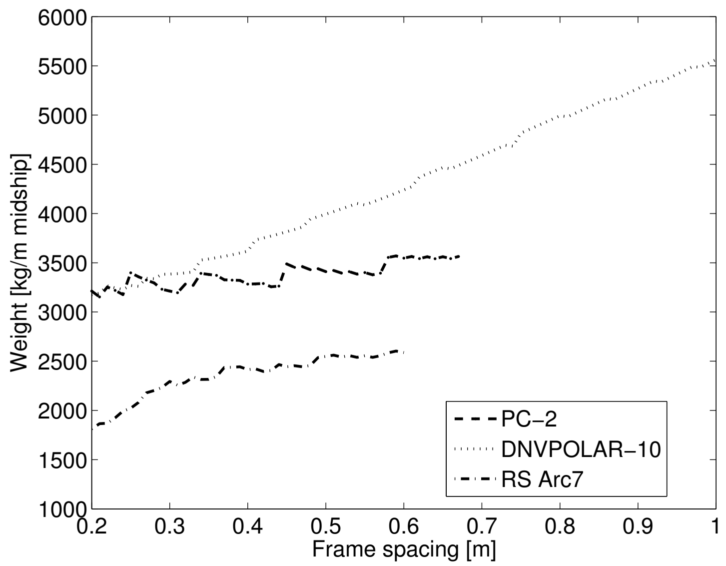


Fig. 25. Weight calculation for Case III depending on frame spacing.

4.4. Summary of results

This section summarises the results from the three cases in Sections 4.1, 4.2 and 4.3. In Appendix G an extensive comparison of notations is presented.

4.4.1. Structural members

In Fig. 17, Fig. 20 and Fig. 23 the rapid increase in structural properties is caused by change of beam. The difference in structural properties, i.e. the section modulus between beams, increases with growing dimensions. Comparing this with the weight outcome in Fig. 19, Fig. 22 and Fig. 25, it is seen that the most weight-effective structure is immediately before a change of beam. The differences of hull extent between the considered notations are presented in the left-most figures. Observe that this is only the main ice-belt region - some notations have sub-regions below the main ice-belt region, as seen in Section 2.2.

4.4.2. Parameter study

Increasing yield strength of the local structure results in lower structural requirements and less weight. The length of the local beam has a small impact in transverse framing while it has a large impact in longitudinal framing. Differences may occur between comparisons due to gaps in the beam database. The complete parameter study for each case is presented in Appendix F.

4.4.3. Weight comparison

The result shows that differences in the extent of the hull area have a major impact on the weight outcome. In Fig. 19, it is seen that transverse framing fulfils requirements with less weight and has its low weight region when using small-frame spacing, while a longitudinal framing has different low-weight regions depending on the rule-set. A local structure with transverse framing requires less weight than longitudinal framing.

4.4.4. Differences in material grade needed

In Table 19, an overview of the material grade requirements for the shell plating and structural members depending on notations is presented based on material requirements for each notation.

Table 19. Material grade requirements for structural members.

<table>
<tr><th rowspan="2">Thickness (mm)</th><th>DAT (-20°C)</th><th>DAT (-30°C)</th><th>PC-1 – PC-5</th><th>PC-1 – PC-5</th><th>PC-6 & PC-7</th><th>Ice1 Ice2 Ice3 Arc4</th><th>Arc5-9</th></tr>
<tr><th>Shell plating & structural members</th><th>Shell plating & structural members</th><th>Shell plating</th><th>Structural members</th><th>Shell plating & structural members</th><th>Shell plating & structural members</th><th>Shell plating & structural members</th></tr>
<tr><td>45<t<50</td><td rowspan="2">E/EH</td><td rowspan="4">E/EH</td><td rowspan="2">E/EH</td><td>E/EH</td><td rowspan="3">D/DH</td><td rowspan="2">D/DH</td><td rowspan="2">E/EH</td></tr>
<tr><td>40<t<45</td><td rowspan="5">D/DH</td></tr>
<tr><td>35<t<40</td><td rowspan="4">D/DH</td><td rowspan="5">D/DH</td><td rowspan="2">B/AH</td><td rowspan="3">D/DH</td></tr>
<tr><td>30<t<35</td><td rowspan="7">B/AH</td></tr>
<tr><td>25<t<30</td><td rowspan="4">D/DH</td><td rowspan="6">A/AH</td></tr>
<tr><td>20<t<25</td><td>B/AH</td></tr>
<tr><td>15<t<20</td><td rowspan="2">B/AH</td><td rowspan="4">B/AH</td><td rowspan="4">A/AH</td></tr>
<tr><td>10<t<15</td><td rowspan="3">B/AH</td></tr>
<tr><td>5<t<10</td><td rowspan="2">A</td><td rowspan="2">B/AH</td></tr>
<tr><td>t<5</td></tr>
</table>

The use of DAT provides a larger freedom compared to IACS PC and RS since the design temperature is independent of notation.

Table 20 presents the price for different steel grades. Combining the table with the parameter studies in Appendix F and Table 19, it is seen that it is possible to design an approved structure that is about 8% lighter and 5% cheaper just by choosing a stronger steel.

Table 20. Steel plate price per tonne acquired by Norsk Stål, 2012-04-18 [17].

			/H	/H	/H
	Yield strength	235 MPa	315 MPa	355 MPa	390 MPa
Steel grade	A	€ 840	€ 868	€ 884	€ 919
	B	€ 854	-	-	-
	D	€ 859	€ 873	€ 889	€ 924
	E	€ 890	€ 904	€ 921	€ 955

The corrosion and abrasion additions added to the plate structure for each rule-set in this study is presented in Fig. 26. In the figure +C denotes notation with effective protection coatings and –C without these. The FSICR and PC 6-7+C (with effective protection) are both 2mm.

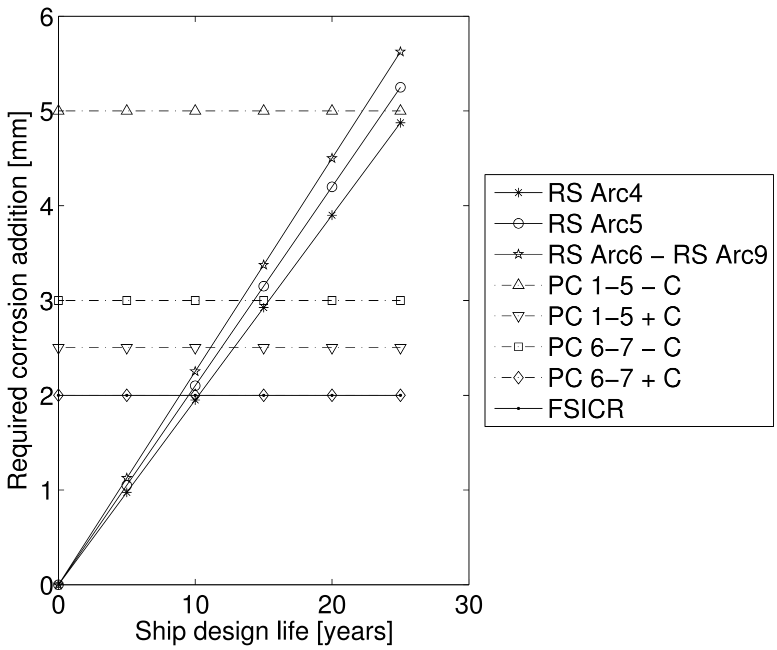


Fig. 26. Required corrosion and abrasion addition on structural members of each rule-set.

5. Discussion

The discussion is made based on the analysis of each case. The application of this work is limited since each rule-set in the investigation has more requirements and criteria that have to be fulfilled; hence the present analysis only considers local strength. Moreover, it can be used as guidance.

Throughout the analysis, the rule-set shows advantages of having transverse frames in the ice-belt region. For example, on a ship ice-classed according to the FSICR with a longitudinal main girder it can be an advantageous and weight-effective way to locally apply transverse framing in the ice-belt region. However, it should be considered that transverse framing is not applicable on all ship types. The analysis only considers the locally additional strength required in the ice-belt region. Moreover, the weight advantages may diminish when global requirements are considered with regard to the CSR.

Calculating the actual structural properties regarding plastic design, the location of the plastic neutral axis, z_{NA}, is considered, as seen in Eq. (C30) and Eq. (C31) in Appendix C. In the rule formulation of IACS PC, calculating the actual net effective plastic section modulus, the cross-sectional area of the frame and plate is considered. If the cross-sectional area of the local frame exceeds the cross-sectional area of the attached plate flange, the plastic-neutral axis will be located within the local frame, which requires another rule formulation. The impact of this is seen in comparisons of the plastic section modulus with low frame spacing. It is important to be aware of this behaviour.

Applying the trial and error approach together with requirements for the structural stability of frames sets high demands on the beam database being used. It is seen that the current beam database is insufficient for higher notations and this should be considered when studying results. Calculating the actual plastic section modulus was preferable compared to interpreting a fixed shape factor since the study considered three different ships with varying frame spacing.

If the design of the structural integrity of the ship differs, the computer code may not be applicable on the whole mid-body region at once. Then, it is recommended to divide the hull into partitions where the weight and the structural properties are calculated for each part.

Changing the yield strength in the parameter study for Ships I and II shows a major impact on the structural properties and weight outcome. A higher yield strength together with a carefully designed frame spacing may result in thinner shell plating, which reduces the structural weight.

When studying the RS rule-set, it shows differences compared to the other rule-sets and rule formulations. It considers many factors and takes more aspects into consideration. An example of this is the vertical extent of ice-strengthening which is dependent on the ship beam. The corrosion addition in the RS rule-set is dependent on the planned ship life. This is a thoughtful way of applying a useful design on each ship. This can be compared to fixed values of corrosion addition in other rule-sets that are dependent on the level of notation.

6. Conclusions

An analysis of the mid-body, regarding requirements on ice-strengthening provides information on the influence of important parameters on the weight, structural properties and fundamental differences in ice class rule-sets.

Choosing either transverse or longitudinal framing plays a major role in the reinforcements needed and affects the total weight outcome of the mid-body, as seen in Fig. 19 and Appendix G. It is found that due to the shape of the ice load, transverse framing has favourable requirements on local design. Rule-sets generally show the advantage of having transverse frames in the ice-belt region. However, it is important to keep in mind that, depending on ship type and a ship's purpose of operation, there might be other requirements that restrict the use of transverse- or longitudinal frames.

It is found that the IACS PC and RS includes a formulation that if the shear area is larger than required, the required plastic section modulus will be reduced compared to if the shear area is sufficient. This provides a greater freedom to adjust characteristics and properties of the structure in the design phase.

The weight outcome between the different rule-sets should not be compared since the extent of the main ice-belt varies depending on each formulation, as seen in Table 4 to Table 8. Then, a more appropriate comparison could be calculated as kg/m^2 of reinforced hull area rather than kg/m in the midships section.

Being aware of the influence of applying a higher yield strength and the impact of a change in frame spacing affecting the thickness of the shell plating may result in an improved structural strength and a lighter structure. Hence, this awareness may also lead to a favourable steel-grade requirement of choice. This may save weight, money and provide an improved structural integrity. In addition to this, the combinations of the FSICR and DNV with DAT demand more awareness of the operational use compared to the IACS PC and RS, which have minimum requirements.

The figures in Appendix G present the structural response depending on the frame spacing for several comparisons. The influence of higher yield strength is presented in the extensive parameter study in Appendix F and the price list of steel grades is shown in Table 20.

Finally, the study indicates the importance of careful consideration regarding the intended purpose of the vessel when selecting the appropriate ice notation.

7. Future work

The objective was to analyse the requirements for local strength on the mid-body regarding the reinforced ice-belt region. If needed, the computer code developed in the current study is prepared for future extension covering requirements for bow and stern as well as the global strength of a ship.

The outcome of rule formulation when calculating the actual section modulus according to the IACS PC is encouraged to be looked into further with numerical FEA. An overestimation may occur when using the present formulation of the structural strength to find a corresponding PC notation for an existing ship. Moreover, to find a frame spacing resulting in less weight, kg/m midships and an improved structural response of ice loads, the hollows in the weight comparison figures should be further investigated with a numerical FE-analysis.

The plastic section modulus rule formulation is encouraged to be revised. Developing an equation for flat-bulb steels or stating in rule-sets is an appropriate way of converting their properties to L-profiles. This would enable direct calculations with flat-bulb steel profiles.

Finally, in rule-sets of DNV and the FSICR, the bow shape shows an impact on the mid-body load formulation. A life-cycle analysis of a ship should be investigated with respect to the bow shape. Some unconventional bow shapes result in a lower structural requirement and a higher cargo capacity. This has to be analysed with respect to a higher fuel consumption that may be a result of unconventional bow shapes.

8. References

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Appendix A. Ships used in the analysis

Particulars of the fictitious ships used in the analysis are presented in Table A1. Ship I is designed for trade in areas with light ice conditions, Ship II is designed for trade in areas with harsh ice conditions and Ship III is designed for icebreaking service.

Table A1. Ship particulars.

	Ship I	**Ship II**	**Ship III**
Case:	I	II	III
Applied ice notation:	ICE-IA PC-7 RS Arc4	DNV ICE-15 PC-4 RS Arc6	POLAR-10 PC-2 RS Arc7
L (*m*)	300	200	100
B (*m*)	42	30	25
D (*m*)	24	15	15
UIWL (*m*)	13 500	12 500	8 000
LIWL (*m*)	9 000	8 000	6 000
Displacement (*t*)	150 000	50 000	14 000
Direction of frames	Longitudinal	Transverse	Transverse
Propulsive power (*kW*)	30 000	20 000	16 000
Web frame spacing (*mm*)	3 200	NA	NA
Stringer spacing (*mm*)	NA	2 500	2 400
Frame spacing (*mm*)	600	500	400
Yield strength plate (*MPa*)	315	355	500
Yield strength structural members (*MPa*)	315	355	500

Appendix B. Nomenclature

Symbol	Unit	Class	Definition
A	cm^2	DNV	Rule cross-sectional area
a	m	PC	Frame span/ Design span of longitudinal
a	m	RS	Frame spacing of main direction girders
A_1	-	PC	Maximum of A_{1A} and A_{1B}
A_{1A}	-	PC	Shear factor in rule modulus equation for 3-hinge mechanism
A_{1B}	-	PC	Shear factor in rule modulus equation for shear mechanism
A_4	-	PC	Factor which takes to account boundary conditions
A_f	cm^2	RS	Required web area for a conventional frame
AF	-	PC	Hull Area Factor
A_K	cm^2	DNV	Corrosion addition area
A_L	cm^2	PC	Required effective shear area of longitudinal framing members
a_o	-	RS	$= \dfrac{a}{1+0,5\cdot\dfrac{a}{c}}$
A_{pn}	cm^2	PC	Net cross-sectional area of local frame
A_t	cm^2	PC	Required effective shear area of transverse framing members
A_w	cm^2	PC	The actual net effective shear area
A_w	cm^2	DNV	Rule web area
b	m	PC	Height of design ice load patch
b	m	RS	Vertical distribution of ice pressure
B	m	-	Rule breadth of ship
b_1	m	PC	$= k_o \cdot b_2$ where k_o and b_2 factors depending of b and s
b_1	m	RS	$= k_o \cdot b_2$ where k_o and b_2 factors depending of a and b
b_w	mm	PC	Distance from mid thickness of plane of local frame web to the centre of the flange area
c	-	DNV	Factor depending on the type of stiffener/bracket connection
c	m	RS	Equals b or l depending on the grillage direction
C	-	FSCIR	$C = 805$ for profiles and $C = 282$ for flat bars
D	m		Rule depth of ship
E	-	RS	Factor depending on span length (l)
f_1	-	FSICR	Factor which takes into account the height of load area (h) and the frame spacing (s)
f_2	-	FSICR	Factor which takes into account the height of load area (h) and the frame spacing (s)
f_3	-	FSICR	Factor which takes into account the maximum shear force versus the load location and the shear stress distribution
f_4	-	FSICR	Factor which takes into account the load distribution to adjacent frames
f_5	-	FSICR	Factor which takes into account the maximum shear force versus load location and the shear stress distribution

Symbol	Unit	Class	Definition
h	cm^3	PC	Height of web
h	m	FSICR	Height of load area
h_f	cm	RS	Frame web height
h_{fc}	cm	PC	Height of local frame measured to the centre of the flange area
h_l	cm	RS	Web height of a longitudinal
h_o	m	DNV	Lesser of the effective height of contact area (h) and frame spacing (s)
h_o	m	DNV	Height/length of load area depending on boundary conditions and frame direction (h, s, k, S, l)
h_w	mm	PC	Height of local frame web
k_1	-	RS	Factor adopted as the greater of $\frac{1}{1+0{,}76\cdot\left(a_o/l\right)}$ and $0{,}8$
k_2	-	RS	$=\frac{4}{k}$
k_3	-	RS	Factor greater of $=\frac{1}{1+z+\sqrt{z}\cdot\beta^{2{,}5}}$ and $=0{,}7$
k_4	-	RS	Factor depending on presence of side stringers
k_a	-	DNV	Aspect ratio for plate field
k_c	-	RS	=0,90 for rolled profiles =0,85 for welded profiles
k_f	-	RS	Factor used when calculating W_f
k_k	-	RS	Factor equal to 0,9 or 1,0 depending on boundary conditions
k_l	-	RS	=0,63 for the purpose of simplified calculation
k_s	-	DNV	Factor which takes into account arm length of bracket (C1), direction of frames, h0 (lesser of h, l)
k_w	-	DNV	Influence factor for narrow strip of load (perpendicular to s)
l	m	FSICR	Frame span
l	m	RS	Distance between adjacent transverse members alt. design frame span
l	m	DNV	Effective span of frame
l	m	PC	Distance between frame supports
L	m		Rule length of ship
LL	m	PC	Length of loaded portion of span, lesser of a and b
m_1	-	FSICR	Boundary condition factor, if continuous beam or frames without brackets
m_e	-	DNV	Bending moment factor
m_o	-	FSICR	Factor based on boundary condition for main and intermediate frames
m_p	-	DNV	Bending moment factor
m_t	-	FSICR	Factor which takes into account boundary condition (m_o), height of load area (h) and frame span (l)
p	kN/m^2	FSICR RS	Ice pressure in region under consideration

Symbol	Unit	Class	Definition
P_{avg}	*MPa*	PC	Average patch pressure depending on bow, load area and force
p_o	*kN/m²*	DNV	Basic ice pressure
PPF	-	PC	Peak Pressure Factor
p_{PL}	*kN/m²*	FSICR	Equal to $0{,}75p$
R_{eH}	*MPa*	RS	Upper yield strength of material used
s	*m*	FSICR DNV PC	Framer spacing measured along the plating between ordinary and/or intermediate frames
s_{af}	*mm*	RS	Actual frame web thickness of a transversal
s_{al}	*mm*	RS	Actual frame web thickness of a longitudinal
s_{sp}	*mm*	RS	Shell plating thickness
s_{sp0}	*mm*	RS	Shell plating thickness without corrosion addition
T	*years*	RS	Planned service life of an s structure
t	*mm*	FSICR	Plate thickness in the ice-belt
T	*m*	-	Rule draught of ship
t_c	*mm*	FSICR	Increment for abrasion and corrosion
t_k	*mm*	DNV	Corrosion addition
t_{net}	*mm*	PC	Plate thickness required to resist ice loads
t_{pn}	*mm*	PC	Fitted net shell plate thickness
t_s	*mm*	PC	Corrosion and abrasion allowance/Corrosion addition
t_{wn}	*mm*	PC	Net web thickness
u	*mm/year*	RS	Annual reduction of shell plating thickness
w	-	PC	Length of design ice load patch
W_f	-	RS	The ultimate section modulus
W_{f0}	-	RS	Section modulus
w_k	-	DNV	Section modulus corrosion factor
Y	-	PC	Factor which takes into account the length of the loaded portion of span (LL) and the frame span (a)
Y	-	RS	$=1-0{,}5\beta$
z	-	RS	$=\frac{1}{2\beta}(a/l)^2$
Z	*cm³*	FSICR DNV	Rule section modulus
z_{na}	*mm*	PC	Distance from the attached shell plate to the plastic neutral axis $=(100\cdot A_{fn}+h_w\cdot t_{wn}-1000\cdot t_{pn}\cdot s)/(2\cdot t_{wn})$
Z_p	*cm³*	PC	Actual net effective plastic section modulus
Z_{pL}	*cm³*	PC	Required section modulus for longitudinal
Z_{pt}	*cm³*	PC	Required section modulus for transverse framing
α	-	DNV	Factor depending on the load patch and ice-load ratio
α	*deg*	DNV	Bow shape angle

Symbol	Unit	Class	Definition
β	*deg*	DNV	Angle of web with shell plating
β	-	RS	$=\frac{b}{l}$ but not greater than $\beta = 1$
Δ_f	*tons*	-	Displacement in fresh water at ice class draught
Δs	*mm*	RS	Corrosion allowance $= u(T-12)$
Δs_{sp0}	*mm*	RS	Corrosion addition on shell plating $= 0{,}75 \cdot T \cdot u$
σ	N/mm^2	DNV	Equal to $0{,}9\sigma_F$
σ_F	N/mm^2	FSICR	Minimum upper yield stress of material
σ_f	N/mm^2	DNV	Yield stress of material
τ	N/mm^2	DNV	Equal to $0{,}45\sigma_F$
φ_w	*deg*	PC	Angle between shell plate and web frames
ω_f	-	RS	$=1+k_c\frac{\Delta s}{s_{af}}$
ω_l	-	RS	$=1+k_c\frac{\Delta s}{s_{al}}$

Appendix C. Rule equations

The rule equations stated are based on the following sources:

Rule-set:	Reference:
FSICR	Sec 3 in [5]
DNV ICE & POLAR	Sec 4 in [5]
IACS PC	Sec 8 in [5]
RS	Sec 4 in [7]

Plate thickness with transversal framing

FSICR

$$t_p = 21{,}1 \cdot s \cdot \sqrt{\frac{f_1 \cdot p_{PL}}{\sigma_F}} + t_c [mm] \tag{C1}$$

DNV ICE & POLAR

$$t = 23 \cdot k_a \cdot \frac{s^{0,75}}{h_o^{0,25}} \cdot \sqrt{\frac{k_w \cdot p_o}{m_p \cdot \sigma_f}} + t_k [mm] \tag{C2}$$

IACS PC

$$t_{net} = 500 \cdot s \cdot \sqrt{\frac{AF \cdot PPF_p \cdot P_{avg}}{\sigma_F}} \cdot \frac{1}{1 + s/(2 \cdot b)} + t_s [mm] \tag{C3}$$

RS

$$s_{sp} = s_{sp0} + \Delta s_{sp0} [mm] \tag{C4}$$

where:

$$s_{sp0} = 15{,}8 \cdot a_0 \cdot \sqrt{\frac{p}{R_{eH}}} [mm] \tag{C5}$$

$$\Delta s_{sp0} = 0{,}75 \cdot T \cdot u [mm] \tag{C6}$$

Plate thickness with longitudinal framing

FSICR

$$t_p = 21{,}1 \cdot s \cdot \sqrt{\frac{p}{f_2 \cdot \sigma_F}} + t_c\,[mm] \tag{C7}$$

DNV ICE & POLAR

$$t = 23 \cdot k_a \cdot \frac{s^{0,75}}{h_o^{0,25}} \cdot \sqrt{\frac{k_w \cdot p_o}{m_p \cdot \sigma_f}} + t_k\,[mm] \tag{C8}$$

IACS PC

$$t_{net} = 500 \cdot s \cdot \sqrt{\frac{AF \cdot PPF_p \cdot P_{avg}}{\sigma_F}} \cdot \frac{1}{1 + s/(2 \cdot l)} + t_s\,[mm] \text{ when } b \geq s \tag{C9}$$

$$t_{net} = 500 \cdot s \cdot \sqrt{\frac{AF \cdot PPF_p \cdot P_{avg}}{\sigma_F}} \cdot \sqrt{2 \cdot \frac{b}{s} - \left(\frac{b}{s}\right)^2} \cdot \frac{1}{1 + s/(2 \cdot l)} + t_s\,[mm] \text{ when } b < s \tag{C10}$$

RS

$$s_{sp} = s_{sp0} + \Delta s_{sp0}\,[mm] \tag{C11}$$

where:

$$s_{sp0} = 15{,}8 \cdot a_0 \cdot \sqrt{\frac{p}{R_{eH}}}\,[mm] \tag{C12}$$

$$\Delta s_{sp0} = 0{,}75 \cdot T \cdot u\,[mm] \tag{C13}$$

Shear area with transversal framing

FSICR

$$A = \frac{8{,}7 \cdot f_3 \cdot p \cdot h \cdot s}{\sigma_F} \left[cm^2\right] \qquad \text{(C14)}$$

DNV ICE & POLAR

$$A_w = \frac{5{,}8 \cdot k_s \cdot (h_o \cdot s)^{1-\alpha} \cdot (1 - 0{,}5 \cdot s) \cdot p_o}{\tau \cdot l \cdot \sin\beta} \left[cm^2\right] \qquad \text{(C15)}$$

IACS PC

The actual net effective shear area, A_w of a framing member is given by:

$$A_w = h \cdot t_{wn} \cdot \sin\varphi_w / 100 \left[cm^2\right] \qquad \text{(C16)}$$

The actual net-effective shear area of the frame, A_w is to comply with the following condition:

$$A_w \geq A_t \qquad \text{(C17)}$$

where:

$$A_t = 100^2 \cdot 0{,}5 \cdot LL \cdot s \cdot \left(AF \cdot PPF_t \cdot P_{avg}\right) / 0{,}577 \cdot \sigma_F \left[cm^2\right] \qquad \text{(C18)}$$

RS

$$A_f = \frac{8{,}7 \cdot p \cdot a \cdot b}{R_{eH}} \cdot k_2 \cdot k_3 \cdot k_4 + 0{,}1 \cdot h_f \cdot \Delta s \left[cm^2\right] \qquad \text{(C19)}$$

Shear area with longitudinal framing

FSICR

$$A = \frac{8{,}7 \cdot f_4 \cdot f_5 \cdot p \cdot h \cdot l}{\sigma_F} \left[cm^2\right] \qquad \text{(C20)}$$

DNV ICE & POLAR

$$A_w = \frac{3{,}7 \cdot (l - 0{,}5 \cdot s) \cdot h_o^{1-\alpha} \cdot p_o}{\tau \cdot \sin\beta \cdot l^{\alpha}} + A_k \left[cm^2\right] \qquad \text{(C21)}$$

IACS UR PC

The actual net-effective shear area, A_w of a framing member is given by:

$$A_w = h \cdot t_{wn} \cdot \sin\varphi_w / 100 \left[cm^2\right] \qquad \text{(C22)}$$

The actual net-effective shear area of the frame, A_w is to comply with the following condition:

$$A_w \geq A_L \qquad \text{(C23)}$$

where:

$$A_L = 100^2 \cdot \left(AF \cdot PPF_t \cdot P_{avg}\right) \cdot 0{,}5 \cdot b_1 \cdot a / 0{,}577 \cdot \sigma_F \left[cm^2\right] \qquad \text{(C24)}$$

RS

$$A_l = \frac{8{,}7}{R_{eH}} \cdot p \cdot b_1 \cdot l \cdot c \cdot k_1 + 0{,}1 \cdot h_l \cdot \Delta s \left[cm^2\right] \qquad \text{(C25)}$$

Section modulus with transversal framing
FSICR

$$Z = \frac{p \cdot s \cdot h \cdot l}{m_t \cdot \sigma_F} \cdot 10^3 \left[cm^3\right] \qquad (C26)$$

DNV ICE & POLAR

$$Z = \frac{520 \cdot c \cdot s^{1-\alpha} \cdot \left(1 - 0{,}1 \cdot \frac{h_1^{\ 2}}{l^2}\right) \cdot (l - 0{,}5 \cdot s) \cdot h_o^{1-\alpha} \cdot p_o}{\tau \cdot l \cdot \sin\beta} \left[cm^3\right] \qquad (C27)$$

IACS PC

The actual net-effective plastic section modulus of the plate/frame combination is to comply with the following condition:

$$Z_p \geq Z_{pt} \qquad (C28)$$

where:

$$Z_{pt} = 100^3 \cdot LL \cdot Y \cdot s \cdot \left(AF \cdot PPF_t \cdot P_{avg}\right) \cdot a \cdot A_1 / (4 \cdot \sigma_F) \left[cm^3\right] \qquad (C29)$$

The actual net-effective plastic section modulus, Z_p is calculated with following formula if the cross-sectional area of the attached plate flange exceeds the cross-sectional area of the local frame:

$$Z_p = A_{pn} \cdot \frac{t_{pn}}{20} + \frac{h_w \cdot t_{wn} \cdot \sin\varphi_w}{2000} + A_{fn} \cdot \frac{h_{fc} \cdot \sin\varphi_w - b_w \cdot \cos\varphi_w}{10} \left[cm^3\right] \qquad (C30)$$

When the cross-sectional area of the local frame exceeds the cross-sectional area of the attached plate flange, the actual net-effective plastic section modulus, Z_p is calculated as:

$$Z_p = t_{pn} \cdot s \cdot \left(z_{na} + \frac{t_{pn}}{2}\right) \cdot \sin\varphi_w + \frac{\left((h_w - z_{na})^2 + z_{na}^{\ 2}\right) \cdot t_{twn} \cdot \sin\varphi_w}{2000} + \ldots$$
$$\ldots + \frac{A_{fn} \cdot \left((h_{fc} - z_{na}) \cdot \sin\varphi_w - b_w \cdot \cos\varphi_w\right)}{10} \qquad (C31)$$

RS

$$W_f = k_f \cdot W_{f0} \left[cm^3\right] \qquad (C32)$$

where:

$$W_{f0} = \frac{250}{R_{eH}} \cdot p \cdot b \cdot a \cdot l \cdot Y \cdot k_k \cdot E \cdot \omega_f \left[cm^3\right] \qquad (C33)$$

Section modulus with longitudinal framing

FSICR

$$Z = \frac{f_4 \cdot p \cdot h \cdot l^2}{m_1 \cdot \sigma_F} \cdot 10^3 \left[cm^3\right] \tag{C34}$$

DNV ICE & POLAR

$$Z = \frac{41 \cdot h_o^{1-\alpha} \cdot l^{2-\alpha} \cdot p_o \cdot w_k}{\sigma \cdot \sin\beta} \left[cm^3\right] \tag{C35}$$

IACS PC

The actual net-effective plastic section modulus of the plate/frame combination is to comply with the following condition:

$$Z_p \geq Z_{pL} \tag{C36}$$

where:

$$Z_{pL} = 100^3 \cdot \left(AF \cdot PPF_t \cdot P_{avg}\right) \cdot b_1 \cdot a^2 \cdot A_4 / \left(8 \cdot \sigma_F\right) \left[cm^3\right] \tag{C37}$$

The actual net-effective plastic section modulus, Z_p is calculated with following formula if the cross-sectional area of the attached plate flange exceeds the cross-sectional area of the local frame:

$$Z_p = A_{pn} \cdot \frac{t_{pn}}{20} + \frac{h_w \cdot t_{wn} \cdot \sin\varphi_w}{2000} + A_{fn} \cdot \frac{h_{fc} \cdot \sin\varphi_w - b_w \cdot \cos\varphi_w}{10} \left[cm^3\right] \tag{C38}$$

When the cross-sectional area of the local frame exceeds the cross-sectional area of the attached plate flange, the actual net-effective plastic section modulus, Z_p is calculated as:

$$\begin{aligned} Z_p &= t_{pn} \cdot s \cdot \left(z_{na} + \frac{t_{pn}}{2} \right) \cdot \sin\varphi_w + \ldots \\ \ldots &+ \frac{\left((h_w - z_{na})^2 + z_{na}{}^2\right) \cdot t_{twn} \cdot \sin\varphi_w}{2000} + \frac{A_{fn} \cdot \left(\left(h_{fc} - z_{na}\right) \cdot \sin\varphi_w - b_w \cdot \cos\varphi_w\right)}{10} \end{aligned} \tag{C39}$$

RS

$$W_l = W_{l0} \cdot k_l \left[cm^3\right] \tag{C40}$$

where:

$$W_{l0} = \frac{125}{R_{eH}} \cdot p \cdot b_1 \cdot l \cdot (l - 0{,}5 \cdot a) \cdot c^2 \cdot \omega_i'' \left[cm^3\right] \tag{C41}$$

Structural stability of framing

FSICR

The web thickness of the frames is to be at least the maximum of the followings:

$$t_w = 9mm \tag{C42}$$

$$t_w = \frac{1}{2} \cdot t_p \,[mm] \tag{C43}$$

For flat bars:

$$t_w = \frac{h_w \sqrt{\sigma_F}}{282} \,[mm] \tag{C44}$$

For profiles:

$$t_w = \frac{h_w \sqrt{\sigma_F}}{805} \,[mm] \tag{C45}$$

DNV ICE & POLAR – Transversal frames

The web thickness of a flanged profile is not to be less than:

$$t_w = 1.5 \cdot \left(\frac{p_o}{\sigma_f \cdot \sin \beta} \right)^{0.67} \left(\frac{h_w \cdot s}{t_s} \right)^{0.33} + t_k \,[mm] \tag{C46}$$

DNV ICE & POLAR – Longitudinal frames

The web thickness of a flanged profile is not to be less than:

$$t_w = 1.5 \cdot \left(\frac{p_o}{\sigma_f \cdot \sin \beta} \right)^{0.67} \left(\frac{h_w \cdot h_o}{t_s} \right)^{0.33} + t_k \,[mm] \tag{C47}$$

IACS PC

For flat bar sections:

$$h_w / t_{wn} \le 282 / (\sigma_F)^{0.5} \tag{C48}$$

For bulb, tee and angle sections

$$h_w / t_{wn} \le 805 / (\sigma_F)^{0.5} \tag{C49}$$

Appendix D. Beam database

Flat bulb steel profiles 1(2):

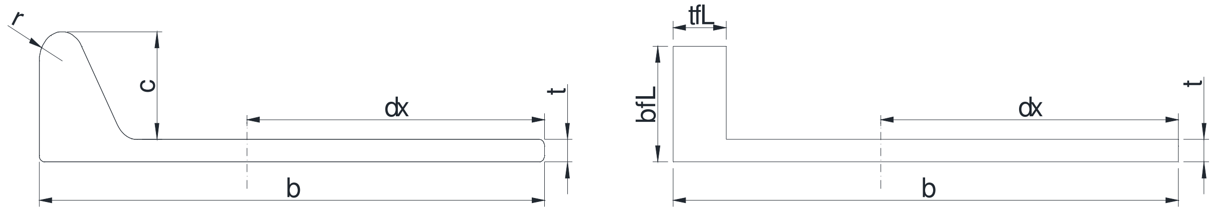


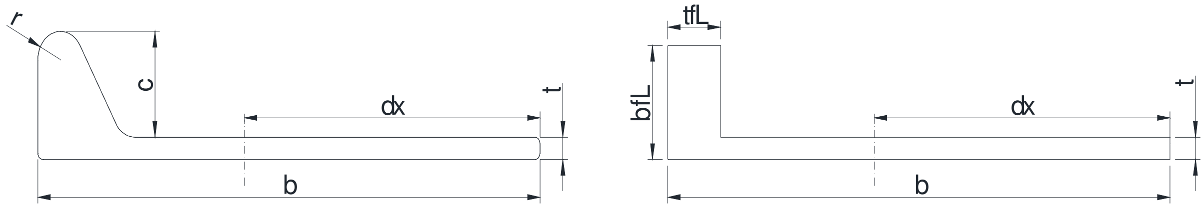
Fig. D1. A flat bulb steel and an L-profile with dimensions.

Table D1. Beam database of the flat bulb steel profiles.

ID	b	t	c	r	b_{fL}	t_{fL}	A	G	U	d_x	I_x	W_x
#	*mm*	*mm*	*mm*	*mm*	*mm*	*mm*	cm^2	*kg/m*	m^2/m	*cm*	cm^4	cm^3
HP 1	60	4,0	12,5	3,5	16,5	8	3,5	2,8	0,1	3,8	12	3,2
HP 2	60	5,0	12,5	3,5	17,5	8	4,1	3,2	0,1	3,7	14	3,8
HP 3	60	6,0	12,5	3,5	18,5	8	4,7	3,7	0,1	3,6	16	4,5
HP 4	80	5,0	14,0	4,0	19,0	10	5,4	4,3	0,2	4,9	34	6,9
HP 5	80	6,0	14,0	4,0	20,0	10	6,2	4,9	0,2	4,8	39	8,2
HP 6	80	7,0	14,0	4,0	21,0	10	7,0	5,5	0,2	4,7	43	9,2
HP 7	100	6,0	15,5	4,5	21,5	11	7,8	6,1	0,2	6,0	76	12,7
HP 8	100	7,0	15,5	4,5	22,5	11	8,7	6,9	0,2	5,9	85	14,5
HP 9	100	8,0	15,5	4,5	23,5	11	9,7	7,7	0,2	5,8	94	16,3
HP 10	120	6,0	17,0	5,0	23,0	12	9,3	7,3	0,3	7,2	133	18,4
HP 11	120	7,0	17,0	5,0	24,0	12	10,5	8,3	0,3	7,1	149	21,1
HP 12	120	8,0	17,0	5,0	25,0	12	11,7	9,2	0,3	7,0	165	23,7
HP 13	140	7,0	19,0	5,5	26,0	14	12,4	9,8	0,3	8,3	241	29,0
HP 14	140	8,0	19,0	5,5	27,0	14	13,8	10,9	0,3	8,2	266	32,5
HP 15	140	9,0	19,0	5,5	28,0	14	16,6	13,5	0,3	8,0	291	36,4
HP 16	160	7,0	22,0	6,0	29,0	15	14,6	11,5	0,4	9,7	373	38,6
HP 17	160	8,0	22,0	6,0	30,0	15	16,2	12,7	0,4	9,5	411	43,3
HP 18	160	9,0	22,0	6,0	31,0	15	17,8	14,0	0,4	9,4	449	47,9
HP 19	180	8,0	25,0	7,0	33,0	18	18,9	14,8	0,4	10,9	609	55,9
HP 20	180	9,0	25,0	7,0	34,0	18	20,7	16,2	0,4	10,7	663	61,8
HP 21	180	10,0	25,0	7,0	35,0	18	22,5	17,6	0,4	10,6	717	67,7
HP 22	200	9,0	28,0	8,0	37,0	20	23,7	18,6	0,5	12,1	942	77,7
HP 23	200	10,0	28,0	8,0	38,0	20	25,7	20,1	0,5	12,0	1017	85,0
HP 24	200	11,5	28,0	8,0	39,5	20	27,7	21,7	0,5	11,8	1127	95,3
HP 25	200	12,0	28,0	8,0	40,0	20	29,7	23,3	0,5	11,7	1164	99,6

Beam database of the flat bulb steel profiles continues on following page.

Flat bulb steel profiles 2(2):



ID	b	t	c	r	b_{fL}	t_{fL}	A	G	U	d_x	I_x	W_x
#	*mm*	*mm*	*mm*	*mm*	*mm*	*mm*	cm^2	*kg/m*	m^2/m	*cm*	cm^4	cm^3
HP 26	220	10,0	31,0	9,0	41,0	22	29,1	22,8	0,5	13,4	1396	104,2
HP 27	220	11,5	31,0	9,0	42,5	22	31,2	24,5	0,5	13,2	1545	117,0
HP 28	220	12,0	31,0	9,0	43,0	22	33,4	26,2	0,5	13,0	1595	122,7
HP 29	240	10,0	34,0	10,0	44,0	24	32,5	25,5	0,5	14,8	1864	126,2
HP 30	240	11,0	34,0	10,0	45,0	24	34,9	27,4	0,5	14,6	1997	137,0
HP 31	240	12,0	34,0	10,0	46,0	24	37,3	29,3	0,6	14,4	2127	147,5
HP 32	260	10,0	37,0	11,0	47,0	27	36,1	28,4	0,6	16,2	2433	150,0
HP 33	260	11,0	37,0	11,0	48,0	27	38,7	30,4	0,6	16,0	2605	162,8
HP 34	260	12,0	37,0	11,0	49,0	27	41,3	32,4	0,6	15,8	2773	175,4
HP 35	280	11,0	40,0	12,0	51,0	29	42,7	33,5	0,6	17,4	3332	191,1
HP 36	280	12,0	40,0	12,0	52,0	29	45,5	35,7	0,6	17,2	3546	205,8
HP 37	300	11,0	43,0	13,0	54,0	31	46,8	36,7	0,7	18,9	4191	221,7
HP 38	300	12,0	43,0	13,0	55,0	31	49,8	39,1	0,7	18,7	4459	239,0
HP 39	300	13,0	43,0	13,0	56,0	31	52,8	41,4	0,7	18,5	4722	255,9
HP 40	320	12,0	46,0	14,0	58,0	33	54,3	42,6	0,7	20,1	5524	274,7
HP 41	320	13,0	46,0	14,0	59,0	33	57,5	45,1	0,7	19,9	5848	294,0
HP 42	340	12,0	49,0	15,0	61,0	35	58,8	46,2	0,8	21,6	6756	312,9
HP 43	340	14,0	49,0	15,0	63,0	36	65,6	51,5	0,8	21,1	7539	357,1
HP 44	370	13,0	53,5	16,5	66,5	39	69,7	54,7	0,8	23,5	9467	402,2
HP 45	370	15,0	53,5	16,5	68,5	39	77,1	60,5	0,8	23,1	10481	454,7
HP 46	400	14,0	58,0	18,0	72,0	42	81,5	64,0	0,9	25,5	12922	506,9
HP 47	400	16,0	58,0	18,0	74,0	42	89,5	70,2	0,9	25,0	14209	568,4
HP 48	430	14,0	62,5	19,5	76,5	45	89,9	70,6	1,0	27,7	16425	592,3
HP 49	430	15,0	62,5	19,5	77,5	46	94,2	73,9	1,0	27,4	17246	628,5
HP 50	430	17,0	62,5	19,5	79,5	46	102,8	80,7	1,0	27,0	18850	699,4

T-profiles:

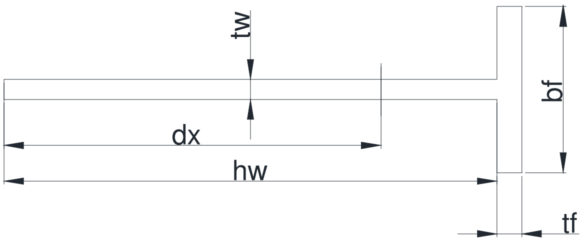


Fig. D2. T-profile with dimensions.

Table D2. Beam database of the T-profiles.

ID	h_w	t_w	b_f	t_f	A	G	U	d_x	I_x	W_x
#	*mm*	*mm*	*mm*	*mm*	cm^2	*kg/m*	m^2/m	*cm*	cm^4	cm^3
T 1	315	12	100	15	51	40	0,82	19,63	5329	271
T 2	340	12	120	15	57	45	0,91	21,62	6995	324
T 3	370	12	120	20	66	52	0,97	24,23	9523	393
T 4	395	12	120	20	69	54	1,02	25,62	11387	444
T 5	425	12	120	25	78	61	1,08	28,17	14752	524
T 6	455	12	120	25	81	64	1,13	29,58	17255	583
T 7	460	12	120	30	87	68	1,14	30,66	18626	608
T 8	475	12	120	35	93	73	1,15	31,64	19904	629
T 9	525	12	120	25	84	66	1,18	30,98	20006	646
T 10	525	12	120	25	90	71	1,28	33,75	26297	779
T 11	525	12	150	25	98	77	1,34	35,10	28421	810
T 12	530	12	150	30	105	82	1,35	36,36	30592	841
T 13	535	12	150	35	113	88	1,36	37,48	32589	870
T 14	575	12	150	25	104	81	1,44	37,92	36423	961
T 15	585	12	150	35	119	93	1,46	40,46	41708	1031
T 16	625	12	150	25	110	86	1,54	40,70	45699	1123
T 17	630	12	150	30	117	92	1,55	42,12	49111	1166
T 18	635	12	150	35	125	98	1,56	43,39	52260	1204
T 19	625	12	200	25	122	96	1,64	42,81	50443	1178
T 20	630	12	200	30	132	104	1,65	44,32	54119	1221
T 21	635	12	200	35	142	111	1,66	45,65	57451	1259
T 22	675	12	200	25	128	100	1,74	45,68	62194	1362
T 23	685	12	200	35	148	116	1,76	48,70	70810	1454
T 24	725	12	200	25	134	105	1,84	48,53	75513	1556
T 25	735	12	200	35	154	121	1,86	51,70	85939	1662
T 26	775	12	200	25	140	110	1,94	51,34	90478	1762
T 27	780	12	200	30	150	118	1,95	53,10	96989	1827
T 28	785	12	200	35	160	126	1,96	54,67	102919	1883
T 29	830	14	200	30	172	135	2,05	54,48	127066	2332
T 30	835	14	200	35	182	143	2,06	56,06	134891	2406
T 31	880	14	200	30	179	141	2,15	57,25	147917	2584
T 32	885	14	200	35	189	148	2,16	58,89	158019	2683

Appendix E. Shape factor calculations for Ship I, II and III

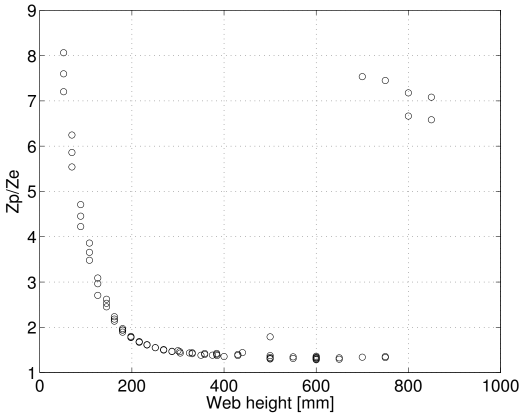


Fig. E1. The plastic/elastic section modulus ratio (Z_p/Z_e) for profiles in beam database attached to plate with thickness 25mm and a frame spacing of 600mm corresponding to Ship I.

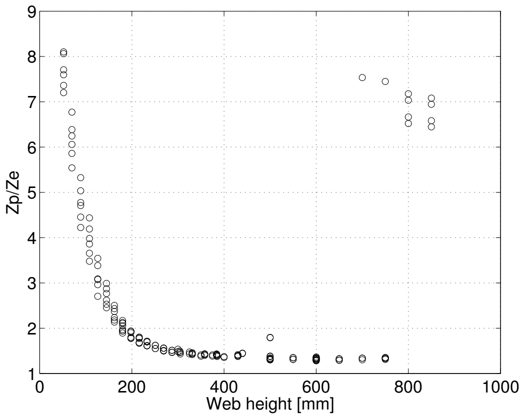


Fig. E2. The plastic/elastic section modulus ratio (Z_p/Z_e) for profiles in beam database attached to plate with thickness 32mm and a frame spacing of 500mm corresponding to Ship II.

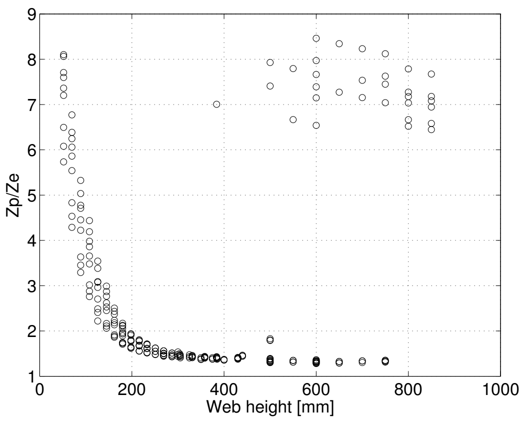


Fig. E3. The plastic/elastic section modulus ratio (Z_p/Z_e) for profiles in beam database attached to plate with thickness 25mm and a frame spacing of 400mm corresponding to Ship III.

Appendix F. Results of parameter study for Ship I, II and III

In the appendix, the complete parameter study is presented in tables for each ship and case with one parameter changing at a time. The upper table of each page represents each parameter's actual values with regard to the rule formulation. This table is followed by the corresponding percentage change. The parameters considered in the study are the frame spacing, web frame spacing/stringer distance, displacement and yield strength.

For Ship I, the propulsive power is added to the parameter study for ICE-IA since the FSICR is the only rule-set in this study with power requirements in the formulations. In tables where values are set to N/A, the rule formulation requires a larger beam database. For Ship III, the parameter study with yield strength could not be performed due to high requirements for the structural members. The outline of the parameter study is presented below:

Case:	**Direction of framing:**	**Page:**
Case I	Longitudinal	F2–F6
Case I	Transverse	F7–F11
Case II	Transverse	F12–F15
Case III	Transverse	F16–F18

Case I with longitudinal framing

		Ship I (Frame spacing [m])				
		0,48	*0,54*	*0,6*	*0,66*	*0,72*
		80%	90%	100%	110%	120%
Plate thickness [mm]	ICE-IA	23,5	24,5	26	27	28
	PC-7	21,5	23	25	N/A	N/A
	RS Arc4	20	21,5	23,5	25	26,5
Shear area [cm^2]	ICE-IA	42	48	48	44	44
	PC-7	63	73	73	N/A	N/A
	RS Arc4	50	59	54	58	58
Plastic section modulus [cm^3]	ICE-IA	1259	1539	1580	1840	1881
	PC-7	3148	2885	2929	N/A	N/A
	RS Arc4	1864	1883	2363	2643	2690
Weight [kg/m midship section]	ICE-IA	3403	3514	3520	3510	3511
	PC-7	4290	4624	4635	N/A	N/A
	RS Arc4	3580	3726	3801	3882	3932

		Ship I (Frame spacing [m])				
		0,48	*0,54*	*0,6*	*0,66*	*0,72*
		80%	90%	100%	110%	120%
Plate thickness [mm]	ICE-IA	90%	94%	100%	104%	108%
	PC-7	86%	92%	100%	N/A	N/A
	RS Arc4	85%	91%	100%	106%	113%
Shear area [cm^2]	ICE-IA	88%	100%	100%	92%	92%
	PC-7	86%	100%	100%	N/A	N/A
	RS Arc4	93%	109%	100%	107%	107%
Plastic section modulus [cm^3]	ICE-IA	80%	97%	100%	116%	119%
	PC-7	107%	98%	100%	N/A	N/A
	RS Arc4	79%	80%	100%	112%	114%
Weight [kg/m midships section]	ICE-IA	97%	100%	100%	100%	100%
	PC-7	93%	100%	100%	N/A	N/A
	RS Arc4	94%	98%	100%	102%	103%

Case I with longitudinal framing

		Ship I (Web frame spacing [m])				
		2,56	*2,88*	*3,2*	*3,52*	*3,84*
		80%	90%	100%	110%	120%
Plate thickness [mm]	ICE-IA	26	26	26	26	26
	PC-7	24,5	24,5	25	N/A	N/A
	RS Arc4	23	23	23,5	23,5	23,5
Shear area [cm^2]	ICE-IA	36	41	48	48	55
	PC-7	63	64	73	N/A	N/A
	RS Arc4	45	51	54	66	66
Plastic section modulus [cm^3]	ICE-IA	1122	1435	1580	1824	2640
	PC-7	3218	2383	2929	N/A	N/A
	RS Arc4	1285	1536	2363	3203	3203
Weight [kg/m midships section]	ICE-IA	3238	3366	3520	3592	3793
	PC-7	4236	4336	4635	N/A	N/A
	RS Arc4	3393	3535	3801	3905	3905

		Ship I (Web frame spacing [m])				
		2,56	*2,88*	*3,2*	*3,52*	*3,84*
		80%	90%	100%	110%	120%
Plate thickness [mm]	ICE-IA	100%	100%	100%	100%	100%
	PC-7	98%	98%	100%	N/A	N/A
	RS Arc4	98%	98%	100%	100%	100%
Shear area [cm^2]	ICE-IA	75%	85%	100%	100%	115%
	PC-7	86%	88%	100%	N/A	N/A
	RS Arc4	83%	94%	100%	122%	122%
Plastic section modulus [cm^3]	ICE-IA	71%	91%	100%	115%	167%
	PC-7	110%	81%	100%	N/A	N/A
	RS Arc4	54%	65%	100%	136%	136%
Weight [kg/m midships section]	ICE-IA	92%	96%	100%	102%	108%
	PC-7	91%	94%	100%	N/A	N/A
	RS Arc4	89%	93%	100%	103%	103%

Case I with longitudinal framing

		Ship I (Δ [dwt])				
		120000	*135000*	*150000*	*165000*	*180000*
		80%	90%	100%	110%	120%
Plate thickness [mm]	ICE-IA	25,5	26	26	26	26
	PC-7	24,5	24,5	25	25	N/A
	RS Arc4	23	23	23,5	23,5	23,5
Shear area [cm^2]	ICE-IA	42	48	48	44	47
	PC-7	73	73	73	73	N/A
	RS Arc4	59	59	54	59	59
Plastic section modulus [cm^3]	ICE-IA	1321	1572	1580	1802	1971
	PC-7	2966	2922	2929	2929	N/A
	RS Arc4	1917	1917	2363	1924	1924
Weight [kg/m midships section]	ICE-IA	3329	3474	3520	3526	3579
	PC-7	4580	4580	4635	4635	N/A
	RS Arc4	3734	3734	3801	3786	3786

		Ship I (Δ [dwt])				
		120000	*135000*	*150000*	*165000*	*180000*
		80%	90%	100%	110%	120%
Plate thickness [mm]	ICE-IA	98%	100%	100%	100%	100%
	PC-7	98%	98%	100%	100%	N/A
	RS Arc4	98%	98%	100%	100%	100%
Shear area [cm^2]	ICE-IA	88%	100%	100%	92%	98%
	PC-7	100%	100%	100%	100%	N/A
	RS Arc4	109%	109%	100%	109%	109%
Plastic section modulus [cm^3]	ICE-IA	84%	99%	100%	114%	125%
	PC-7	101%	100%	100%	100%	N/A
	RS Arc4	81%	81%	100%	81%	81%
Weight [kg/m midships section]	ICE-IA	95%	99%	100%	100%	102%
	PC-7	99%	99%	100%	100%	N/A
	RS Arc4	98%	98%	100%	100%	100%

Case I with longitudinal framing

		Ship I (σF [MPa])				
		235	*275*	*315*	*355*	*390*
		75%	87%	100%	112%	123%
Plate thickness [mm]	ICE-IA	30	27,5	26	24,5	23,5
	PC-7	N/A	N/A	25	23,5	22,5
	RS Arc4	26	24,5	23,5	22	21,5
Shear area [cm^2]	ICE-IA	63	56	48	41	36
	PC-7	N/A	N/A	73	64	64
	RS Arc4	78	68	54	50	47
Plastic section modulus [cm^3]	ICE-IA	3299	1985	1580	1412	1085
	PC-7	N/A	N/A	2929	2369	2355
	RS Arc4	2945	2383	2363	1913	1738
Weight [kg/m midships section]	ICE-IA	4163	3859	3520	3230	3012
	PC-7	N/A	N/A	4635	4226	4116
	RS Arc4	4492	4105	3801	3489	3385

		Ship I (σF [MPa])				
		235	*275*	*315*	*355*	*390*
		75%	87%	100%	112%	123%
Plate thickness [mm]	ICE-IA	115%	106%	100%	94%	90%
	PC-7	N/A	N/A	100%	94%	90%
	RS Arc4	111%	104%	100%	94%	91%
Shear area [cm^2]	ICE-IA	131%	117%	100%	85%	75%
	PC-7	N/A	N/A	100%	88%	88%
	RS Arc4	144%	126%	100%	93%	87%
Plastic section modulus [cm^3]	ICE-IA	209%	126%	100%	89%	69%
	PC-7	N/A	N/A	100%	81%	80%
	RS Arc4	125%	101%	100%	81%	74%
Weight [kg/m midships section]	ICE-IA	118%	110%	100%	92%	86%
	PC-7	N/A	N/A	100%	91%	89%
	RS Arc4	118%	108%	100%	92%	89%

Case I with longitudinal framing

		Ship I (propulsive power [kW])				
		24000	*27000*	*30000*	*33000*	*36000*
		80%	90%	100%	110%	120%
Plate thickness [mm]	ICE-IA	25,5	25,5	26	26	26
Shear area [cm^2]		42	48	48	44	47
Plastic section modulus [cm^3]		1321	1572	1580	1802	1971
Weight [kg/m midships section]		3329	3474	3520	3526	3579

		Ship I (propulsive power [kW])				
		24000	*27000*	*30000*	*33000*	*36000*
		80%	90%	100%	110%	120%
Plate thickness [mm]	ICE-IA	98%	98%	100%	100%	100%
Shear area [cm^2]		88%	100%	100%	92%	98%
Plastic section modulus [cm^3]		84%	99%	100%	114%	125%
Weight [kg/m midships section]		95%	99%	100%	100%	102%

Case I with transverse framing

		Ship I (Frame spacing [m])				
		0,48	*0,54*	*0,6*	*0,66*	*0,72*
		80%	90%	100%	110%	120%
Plate thickness [mm]	ICE-IA	19	20,5	22	22,5	23,5
	PC-7	17,5	18,5	19,5	21	22
	RS Arc4	18,5	19,5	21	22	23,5
Shear area [cm^2]	ICE-IA	26	29	29	31	31
	PC-7	41	48	48	45	48
	RS Arc4	50	50	50	59	54
Plastic section modulus [cm^3]	ICE-IA	590	732	763	819	938
	PC-7	1320	1470	1491	1745	1551
	RS Arc4	1459	1480	1900	1918	2396
Weight [kg/m midships section]	ICE-IA	2495	2620	2679	2703	2758
	PC-7	3274	3372	3349	3411	3424
	RS Arc4	3351	3297	3385	3508	3576

		Ship I (Frame spacing [m])				
		0,48	*0,54*	*0,6*	*0,66*	*0,72*
		80%	90%	100%	110%	120%
Plate thickness [mm]	ICE-IA	86%	93%	100%	102%	107%
	PC-7	90%	95%	100%	108%	113%
	RS Arc4	88%	93%	100%	105%	112%
Shear area [cm^2]	ICE-IA	90%	100%	100%	107%	107%
	PC-7	85%	100%	100%	94%	100%
	RS Arc4	100%	100%	100%	118%	108%
Plastic section modulus [cm^3]	ICE-IA	77%	96%	100%	107%	123%
	PC-7	89%	99%	100%	117%	104%
	RS Arc4	77%	78%	100%	101%	126%
Weight [kg/m midships section]	ICE-IA	93%	98%	100%	101%	103%
	PC-7	98%	101%	100%	102%	102%
	RS Arc4	99%	97%	100%	104%	106%

Case I with transverse framing

		Ship I (Stringer distance [m])				
		2,56	*2,88*	*3,2*	*3,52*	*3,84*
		80%	90%	100%	110%	120%
Plate thickness [mm]	ICE-IA	22	22	22	22	22
	PC-7	19,5	19,5	19,5	19,5	19,5
	RS Arc4	21	21	21	21	21
Shear area [cm^2]	ICE-IA	24	29	29	31	34
	PC-7	38	38	48	44	48
	RS Arc4	43	51	50	59	54
Plastic section modulus [cm^3]	ICE-IA	619	763	763	884	924
	PC-7	1115	1115	1491	1713	1882
	RS Arc4	1379	1510	1900	1890	2330
Weight [kg/m midships section]	ICE-IA	2568	2679	2679	2749	2799
	PC-7	3081	3081	3349	3355	3411
	RS Arc4	3209	3327	3385	3525	3541

		Ship I (Stringer distance [m])				
		2,56	*2,88*	*3,2*	*3,52*	*3,84*
		80%	90%	100%	110%	120%
Plate thickness [mm]	ICE-IA	100%	100%	100%	100%	100%
	PC-7	100%	100%	100%	100%	100%
	RS Arc4	100%	100%	100%	100%	100%
Shear area [cm^2]	ICE-IA	83%	100%	100%	107%	117%
	PC-7	79%	79%	100%	92%	100%
	RS Arc4	86%	102%	100%	118%	108%
Plastic section modulus [cm^3]	ICE-IA	81%	100%	100%	116%	121%
	PC-7	75%	75%	100%	115%	126%
	RS Arc4	73%	79%	100%	99%	123%
Weight [kg/m midships section]	ICE-IA	96%	100%	100%	103%	104%
	PC-7	92%	92%	100%	100%	102%
	RS Arc4	95%	98%	100%	104%	105%

Case I with transverse framing

		Ship I (Δ [dwt])				
		120000	*135000*	*150000*	*165000*	*180000*
		80%	90%	100%	110%	120%
Plate thickness [mm]	ICE-IA	21,5	21,5	22	22	22
	PC-7	19	19,5	19,5	20	20
	RS Arc4	20,5	21	21	21	21
Shear area [cm^2]	ICE-IA	29	29	29	31	31
	PC-7	41	48	48	48	44
	RS Arc4	50	50	50	50	51
Plastic section modulus [cm^3]	ICE-IA	757	757	763	797	797
	PC-7	1355	1491	1491	1497	1719
	RS Arc4	1894	1900	1900	1900	1753
Weight [kg/m midships section]	ICE-IA	2633	2633	2679	2725	2725
	PC-7	3169	3349	3349	3404	3411
	RS Arc4	3333	3385	3385	3385	3397

		Ship I (Δ [dwt])				
		120000	*135000*	*150000*	*165000*	*180000*
		80%	90%	100%	110%	120%
Plate thickness [mm]	ICE-IA	98%	98%	100%	100%	100%
	PC-7	97%	100%	100%	103%	103%
	RS Arc4	98%	100%	100%	100%	100%
Shear area [cm^2]	ICE-IA	100%	100%	100%	107%	107%
	PC-7	85%	100%	100%	100%	92%
	RS Arc4	100%	100%	100%	100%	102%
Plastic section modulus [cm^3]	ICE-IA	99%	99%	100%	104%	104%
	PC-7	91%	100%	100%	100%	115%
	RS Arc4	100%	100%	100%	100%	92%
Weight [kg/m midships section]	ICE-IA	98%	98%	100%	102%	102%
	PC-7	95%	100%	100%	102%	102%
	RS Arc4	98%	100%	100%	100%	100%

Case I with transverse framing

		Ship I (σF [MPa])				
		235	*275*	*315*	*355*	*390*
		75%	87%	100%	112%	123%
Plate thickness [mm]	ICE-IA	25	23,5	22	21	20
	PC-7	22,5	21	19,5	18,5	18
	RS Arc4	23,5	22	21	20	19,5
Shear area [cm^2]	ICE-IA	33	31	29	29	26
	PC-7	51	47	48	41	38
	RS Arc4	57	59	50	50	50
Plastic section modulus [cm^3]	ICE-IA	1062	904	763	750	623
	PC-7	2349	1900	1491	1349	1172
	RS Arc4	2603	1903	1900	1497	1491
Weight [kg/m midships section]	ICE-IA	3094	2885	2679	2588	2430
	PC-7	3906	3576	3349	3114	2975
	RS Arc4	3854	3630	3385	3222	3170

		Ship I (σF [MPa])				
		235	*275*	*315*	*355*	*390*
		75%	87%	100%	112%	123%
Plate thickness [mm]	ICE-IA	114%	107%	100%	95%	91%
	PC-7	115%	108%	100%	95%	92%
	RS Arc4	112%	105%	100%	95%	93%
Shear area [cm^2]	ICE-IA	114%	107%	100%	100%	90%
	PC-7	106%	98%	100%	85%	79%
	RS Arc4	114%	118%	100%	100%	100%
Plastic section modulus [cm^3]	ICE-IA	139%	118%	100%	98%	82%
	PC-7	158%	127%	100%	90%	79%
	RS Arc4	137%	100%	100%	79%	78%
Weight [kg/m midships section]	ICE-IA	115%	108%	100%	97%	91%
	PC-7	117%	107%	100%	93%	89%
	RS Arc4	114%	107%	100%	95%	94%

Case I with transverse framing

		Ship I (propulsive power [kW])				
		24000	*27000*	*30000*	*33000*	*36000*
		80%	90%	100%	110%	120%
Plate thickness [mm]	ICE-IA	21,5	21,5	22	22	22
Shear area [cm^2]		29	29	29	31	31
Plastic section modulus [cm^3]		757	757	763	797	797
Weight [kg/m midships section]		2633	2633	2679	2725	2725

		Ship I (propulsive power [kW])				
		24000	*27000*	*30000*	*33000*	*36000*
		80%	90%	100%	110%	120%
Plate thickness [mm]	ICE-IA	98%	98%	100%	100%	100%
Shear area [cm^2]		100%	100%	100%	107%	107%
Plastic section modulus [cm^3]		99%	99%	100%	104%	104%
Weight [kg/m midships section]		98%	98%	100%	102%	102%

Case II with transverse framing

		Ship II (Frame spacing [m])				
		0,40	*0,45*	*0,50*	*0,55*	*0,60*
		80%	90%	100%	110%	120%
Plate thickness [mm]	ICE-15	34	37	40	42,5	45,5
	PC-4	21	22,5	23,5	25	26
	RS Arc6	21,5	23,5	25	26,5	28
Shear area [cm^2]	ICE-15	48	56	56	56	56
	PC-4	56	56	64	64	64
	RS Arc6	66	68	77	77	84
Plastic section modulus [cm^3]	ICE-15	1409	1829	1913	2001	2116
	PC-4	1846	1872	2341	2375	2406
	RS Arc6	3130	2328	2898	2935	6083
Weight [kg/m midships section]	ICE-15	8004	8595	8800	8975	9267
	PC-4	4747	4671	4879	4864	4823
	RS Arc6	4509	4603	4834	4795	5235

		Ship II (Frame spacing [m])				
		0,40	*0,45*	*0,50*	*0,55*	*0,60*
		80%	90%	100%	110%	120%
Plate thickness [mm]	ICE-15	85%	93%	100%	106%	114%
	PC-4	89%	96%	100%	106%	111%
	RS Arc6	86%	94%	100%	106%	112%
Shear area [cm^2]	ICE-15	86%	100%	100%	100%	100%
	PC-4	88%	88%	100%	100%	100%
	RS Arc6	86%	88%	100%	100%	109%
Plastic section modulus [cm^3]	ICE-15	74%	96%	100%	105%	111%
	PC-4	79%	80%	100%	101%	103%
	RS Arc6	108%	80%	100%	101%	210%
Weight [kg/m midships section]	ICE-15	91%	98%	100%	102%	105%
	PC-4	97%	96%	100%	100%	99%
	RS Arc6	93%	95%	100%	99%	108%

Case II with transverse framing

		Ship II (Stringer distance [m])				
		2	*2,25*	*2,5*	*2,75*	*3*
		80%	90%	100%	110%	120%
Plate thickness [mm]	ICE-15	40	40	40	40	40
	PC-4	23,5	23,5	23,5	23,5	23,5
	RS Arc6	25	25	25	25	25
Shear area [cm^2]	ICE-15	56	56	56	56	56
	PC-4	64	64	64	64	64
	RS Arc6	66	68	77	77	78
Plastic section modulus [cm^3]	ICE-15	1913	1913	1913	1913	1913
	PC-4	2341	2341	2341	2341	2341
	RS Arc6	3194	2359	2898	2898	4613
Weight [kg/m midships section]	ICE-15	8800	8800	8800	8800	8800
	PC-4	4879	4879	4879	4879	4879
	RS Arc6	4436	4552	4834	4834	4976

		Ship II (Stringer distance [m])				
		2	*2,25*	*2,5*	*2,75*	*3*
		80%	90%	100%	110%	120%
Plate thickness [mm]	ICE-15	100%	100%	100%	100%	100%
	PC-4	100%	100%	100%	100%	100%
	RS Arc6	100%	100%	100%	100%	100%
Shear area [cm^2]	ICE-15	100%	100%	100%	100%	100%
	PC-4	100%	100%	100%	100%	100%
	RS Arc6	86%	88%	100%	100%	101%
Plastic section modulus [cm^3]	ICE-15	100%	100%	100%	100%	100%
	PC-4	100%	100%	100%	100%	100%
	RS Arc6	110%	81%	100%	100%	159%
Weight [kg/m midships section]	ICE-15	100%	100%	100%	100%	100%
	PC-4	100%	100%	100%	100%	100%
	RS Arc6	92%	94%	100%	100%	103%

Case II with transverse framing

		Ship II (Δ [dwt])				
		40000	*45000*	*50000*	*55000*	*60000*
		80%	90%	100%	110%	120%
Plate thickness [mm]	ICE-15	40	40	40	40	40
	PC-4	23	23	23,5	24	24
	RS Arc6	24,5	25	25	25	25,5
Shear area [cm^2]	ICE-15	56	56	56	56	56
	PC-4	56	56	64	64	64
	RS Arc6	68	68	77	77	74
Plastic section modulus [cm^3]	ICE-15	1913	1913	1913	1913	1913
	PC-4	1890	1896	2341	2347	2347
	RS Arc6	2707	2713	2898	2898	2904
Weight [kg/m midships section]	ICE-15	8800	8800	8800	8800	8800
	PC-4	4529	4588	4879	4938	4938
	RS Arc6	4598	4651	4834	4834	4887

		Ship II (Δ [dwt])				
		40000	*45000*	*50000*	*55000*	*60000*
		80%	90%	100%	110%	120%
Plate thickness [mm]	ICE-15	100%	100%	100%	100%	100%
	PC-4	98%	98%	100%	102%	102%
	RS Arc6	98%	100%	100%	100%	102%
Shear area [cm^2]	ICE-15	100%	100%	100%	100%	100%
	PC-4	88%	88%	100%	100%	100%
	RS Arc6	88%	88%	100%	100%	96%
Plastic section modulus [cm^3]	ICE-15	100%	100%	100%	100%	100%
	PC-4	81%	81%	100%	100%	100%
	RS Arc6	93%	94%	100%	100%	100%
Weight [kg/m midships section]	ICE-15	100%	100%	100%	100%	100%
	PC-4	93%	94%	100%	101%	101%
	RS Arc6	95%	96%	100%	100%	101%

Case II with transverse framing

		Ship II (σF [MPa])				
		275	*315*	*355*	*390*	*420*
		77%	89%	100%	110%	118%
Plate thickness [mm]	ICE-15	N/A	N/A	40	38	37
	PC-4	N/A	N/A	23,5	22,5	22
	RS Arc6	N/A	N/A	25	24	23,5
Shear area [cm^2]	ICE-15	N/A	N/A	56	48	48
	PC-4	N/A	N/A	64	56	56
	RS Arc6	N/A	N/A	77	66	66
Plastic section modulus [cm^3]	ICE-15	N/A	N/A	1913	1526	1509
	PC-4	N/A	N/A	2341	1885	1879
	RS Arc6	N/A	N/A	2898	3182	3176
Weight [kg/m midships section]	ICE-15	N/A	N/A	8800	8119	7960
	PC-4	N/A	N/A	4879	4470	4411
	RS Arc6	N/A	N/A	4834	4329	4276

		Ship II (σF [MPa])				
		275	*315*	*355*	*390*	*420*
		77%	89%	100%	110%	118%
Plate thickness [mm]	ICE-15	N/A	N/A	100%	95%	93%
	PC-4	N/A	N/A	100%	96%	94%
	RS Arc6	N/A	N/A	100%	96%	94%
Shear area [cm^2]	ICE-15	N/A	N/A	100%	86%	86%
	PC-4	N/A	N/A	100%	88%	88%
	RS Arc6	N/A	N/A	100%	86%	86%
Plastic section modulus [cm^3]	ICE-15	N/A	N/A	100%	80%	79%
	PC-4	N/A	N/A	100%	81%	80%
	RS Arc6	N/A	N/A	100%	110%	110%
Weight [kg/m midships section]	ICE-15	N/A	N/A	100%	92%	90%
	PC-4	N/A	N/A	100%	92%	90%
	RS Arc6	N/A	N/A	100%	90%	88%

Case III with transverse framing

		Ship III (Frame spacing [m])				
		0,32	*0,36*	*0,40*	*0,44*	*0,48*
		80%	90%	100%	110%	120%
Plate thickness [mm]	POLAR-10	25	27	29	31	33
	PC-2	20	21,5	22,5	24	25
	RS Arc7	17,5	19	20	21,5	22,5
Shear area [cm^2]	POLAR-10	31	34	34	36	39
	PC-2	48	55	55	55	64
	RS Arc7	41	43	50	50	51
Plastic section modulus [cm^3]	POLAR-10	635	773	806	968	1057
	PC-2	8601	1841	1859	1885	2353
	RS Arc7	1124	1312	1457	1869	1743
Weight [kg/m midships section]	POLAR-10	3397	3551	3618	3792	3943
	PC-2	3283	3372	3282	3263	3429
	RS Arc7	2285	2344	2415	2466	2456

		Ship III (Frame spacing [m])				
		0,32	*0,36*	*0,40*	*0,44*	*0,48*
		80%	90%	100%	110%	120%
Plate thickness [mm]	POLAR-10	86%	93%	100%	107%	114%
	PC-2	89%	96%	100%	107%	111%
	RS Arc7	88%	95%	100%	108%	113%
Shear area [cm^2]	POLAR-10	91%	100%	100%	106%	115%
	PC-2	87%	100%	100%	100%	116%
	RS Arc7	82%	86%	100%	100%	102%
Plastic section modulus [cm^3]	POLAR-10	79%	96%	100%	120%	131%
	PC-2	463%	99%	100%	101%	127%
	RS Arc7	77%	90%	100%	128%	120%
Weight [kg/m midships section]	POLAR-10	94%	98%	100%	105%	109%
	PC-2	100%	103%	100%	99%	104%
	RS Arc7	95%	97%	100%	102%	102%

Case III with transverse framing

		Ship III (Stringer distance [m])				
		1,92	*2,16*	*2,4*	*2,64*	*2,88*
		80%	90%	100%	110%	120%
Plate thickness [mm]	POLAR-10	29	29	29	29	29
	PC-2	22,5	22,5	22,5	22,5	22,5
	RS Arc7	20	20	20	20	20
Shear area [cm^2]	POLAR-10	34	34	34	36	36
	PC-2	55	55	55	56	64
	RS Arc7	41	43	50	50	51
Plastic section modulus [cm^3]	POLAR-10	806	806	806	930	930
	PC-2	1859	1859	1859	1859	2304
	RS Arc7	1155	1327	1457	1848	1701
Weight [kg/m midships section]	POLAR-10	3618	3618	3618	3714	3714
	PC-2	3282	3282	3282	3282	3525
	RS Arc7	2226	2302	2415	2471	2482

		Ship III (Stringer distance [m])				
		1,92	*2,16*	*2,4*	*2,64*	*2,88*
		80%	90%	100%	110%	120%
Plate thickness [mm]	POLAR-10	100%	100%	100%	100%	100%
	PC-2	100%	100%	100%	100%	100%
	RS Arc7	100%	100%	100%	100%	100%
Shear area [cm^2]	POLAR-10	100%	100%	100%	106%	106%
	PC-2	100%	100%	100%	102%	116%
	RS Arc7	82%	86%	100%	100%	102%
Plastic section modulus [cm^3]	POLAR-10	100%	100%	100%	115%	115%
	PC-2	100%	100%	100%	100%	124%
	RS Arc7	79%	91%	100%	127%	117%
Weight [kg/m midships section]	POLAR-10	100%	100%	100%	103%	103%
	PC-2	100%	100%	100%	100%	107%
	RS Arc7	92%	95%	100%	102%	103%

Case III with transverse framing

		Ship III (Δ [dwt])				
		11200	*12600*	*14000*	*15400*	*16800*
		80%	90%	100%	110%	120%
Plate thickness [mm]	POLAR-10	29	29	29	29	29
	PC-2	22	22,5	22,5	23	23
	RS Arc7	19,5	20	20	20	20,5
Shear area [cm^2]	POLAR-10	34	34	34	34	34
	PC-2	56	56	55	56	56
	RS Arc7	43	50	50	50	50
Plastic section modulus [cm^3]	POLAR-10	806	806	806	806	806
	PC-2	1855	1859	1859	1864	1864
	RS Arc7	1323	1457	1457	1457	1461
Weight [kg/m midships section]	POLAR-10	3618	3618	3618	3618	3618
	PC-2	3243	3282	3282	3322	3322
	RS Arc7	2269	2415	2415	2415	2448

		Ship III (Δ [dwt])				
		11200	*12600*	*14 000*	*15400*	*16800*
		80%	90%	100%	110%	120%
Plate thickness [mm]	POLAR-10	100%	100%	100%	100%	100%
	PC-2	98%	100%	100%	102%	102%
	RS Arc7	98%	100%	100%	100%	103%
Shear area [cm^2]	POLAR-10	100%	100%	100%	100%	100%
	PC-2	102%	102%	100%	102%	102%
	RS Arc7	86%	100%	100%	100%	100%
Plastic section modulus [cm^3]	POLAR-10	100%	100%	100%	100%	100%
	PC-2	100%	100%	100%	100%	100%
	RS Arc7	91%	100%	100%	100%	100%
Weight [kg/m midships section]	POLAR-10	100%	100%	100%	100%	100%
	PC-2	99%	100%	100%	101%	101%
	RS Arc7	94%	100%	100%	100%	101%

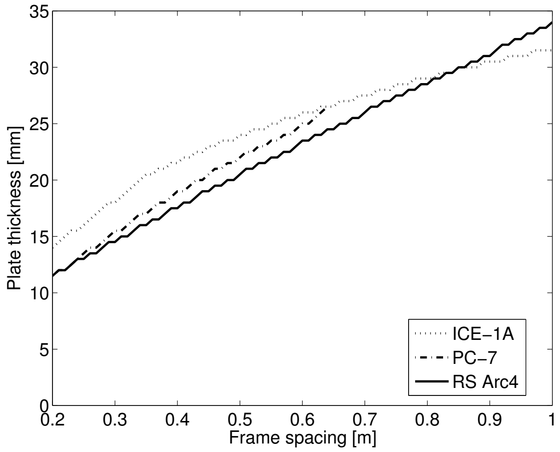
Appendix G. Comparison of notations

Figures in this appendix present the structural and weight differences depending on notation and the direction of framing.

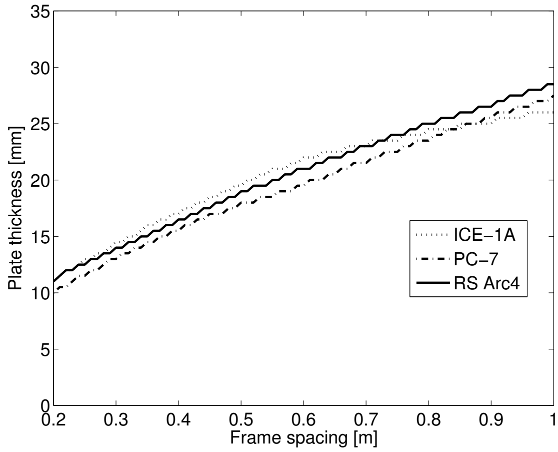
Each comparison presents differences in plate thickness, section modulus, shear area and weight. The outline of the comparisons is presented below.

Comparison of longitudinal and transverse framing for Case I 1(2)

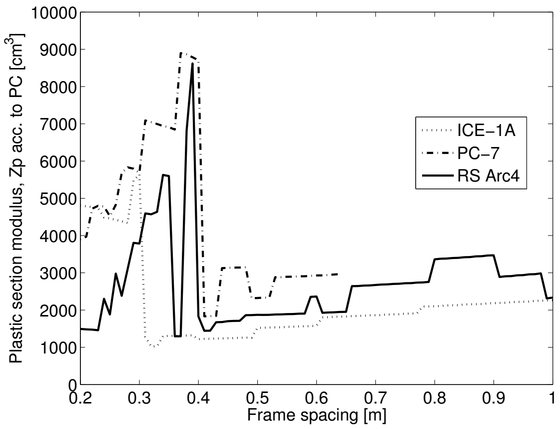
Longitudinal framing **Transverse framing**



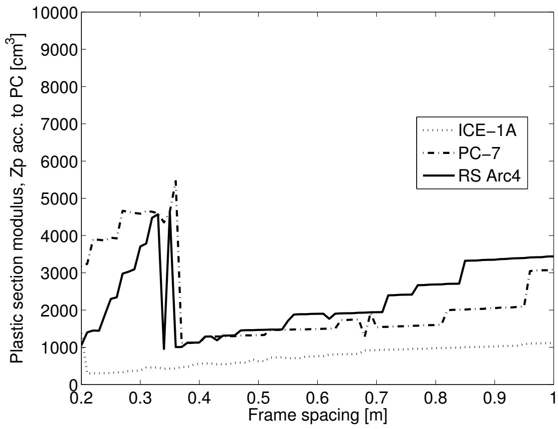
(a). Plate thickness.



(b). Plate thickness.



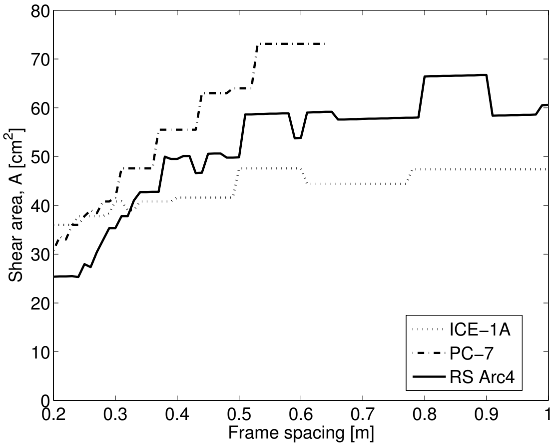
(c). Section modulus.



(d). Section modulus.

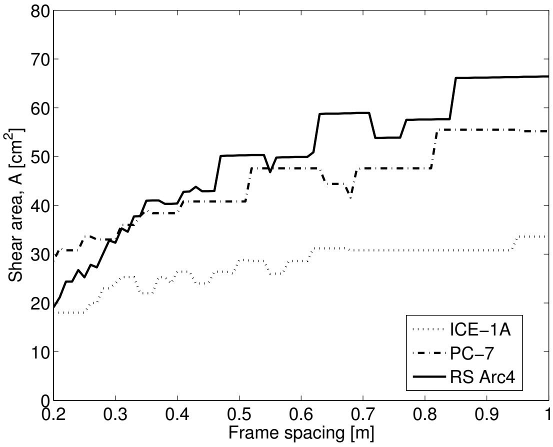
Comparison of longitudinal and transverse framing for Case I

Longitudinal framing

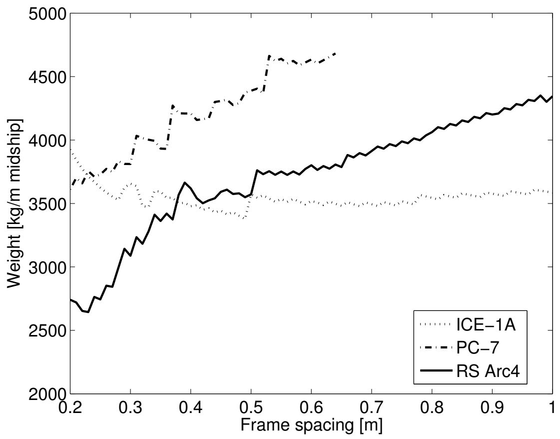


(e). Shear area.

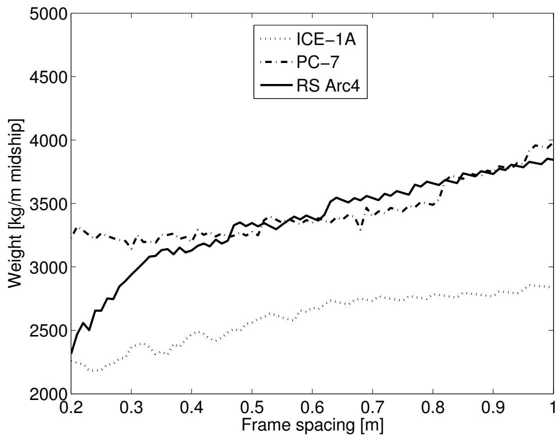
Transverse framing



(f). Shear area.



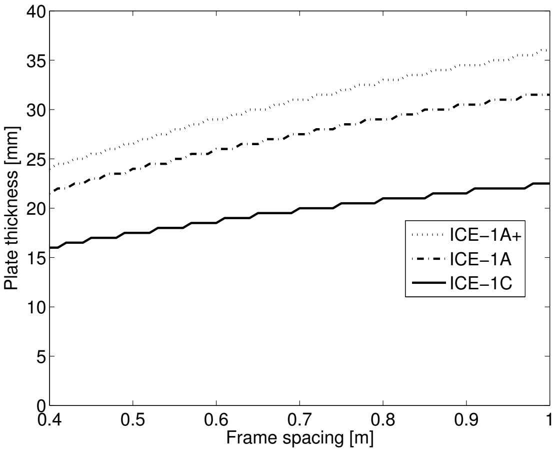
(g). Weight.



(h). Weight.

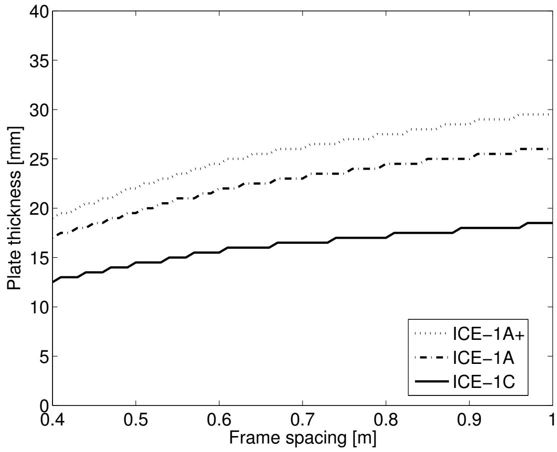
Comparison of longitudinal and transverse framing for FSICR on Ship I 1(2)

Longitudinal framing

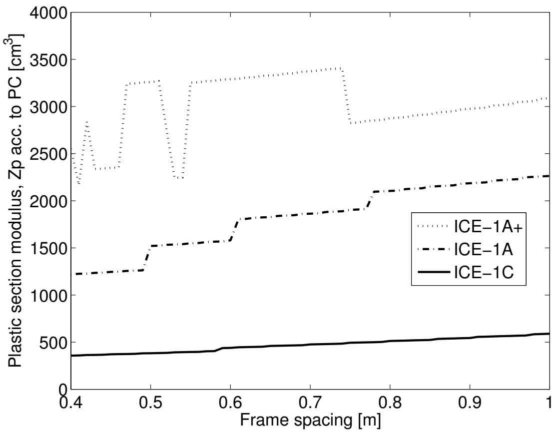


(a). Plate thickness.

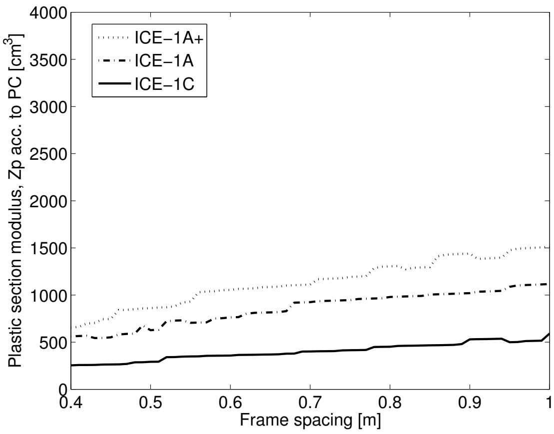
Transverse framing



(b). Plate thickness.



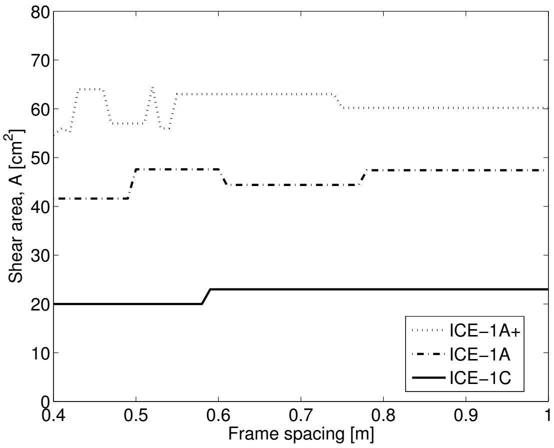
(c). Section modulus.



(d). Section modulus.

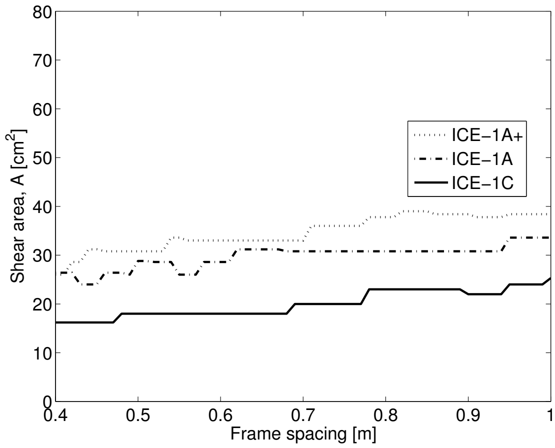
Comparison of longitudinal and transverse framing for FSICR on Ship I 2(2)

Longitudinal framing

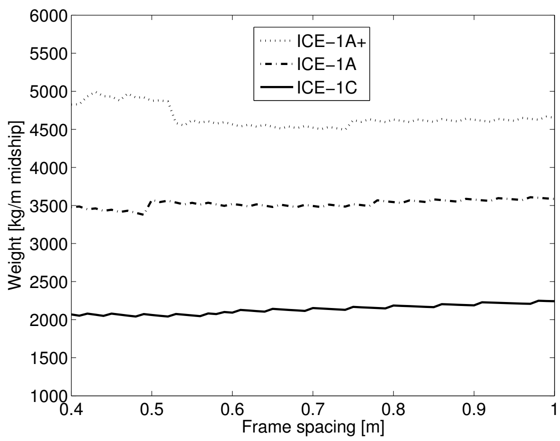


(e). Shear area.

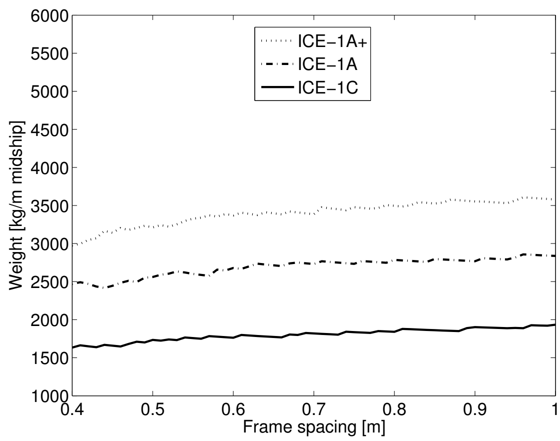
Transverse framing



(f). Shear area.



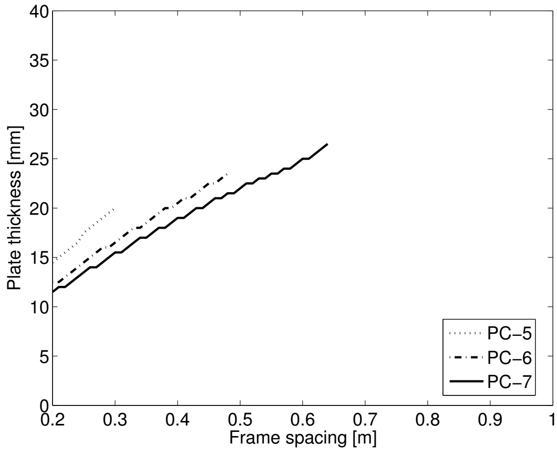
(g). Weight.



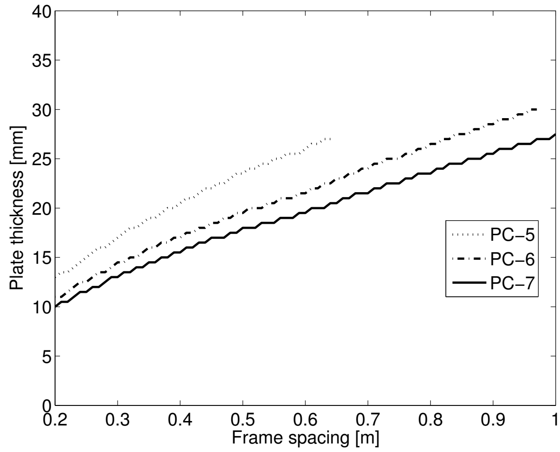
(h). Weight.

Comparison of longitudinal and transverse framing of lower PC notations for Ship I
1(2)

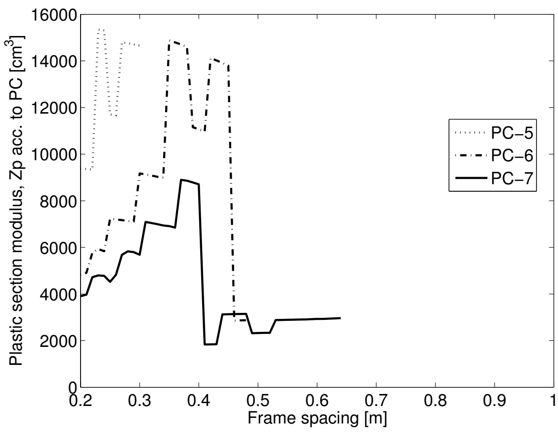
Longitudinal framing | **Transverse framing**



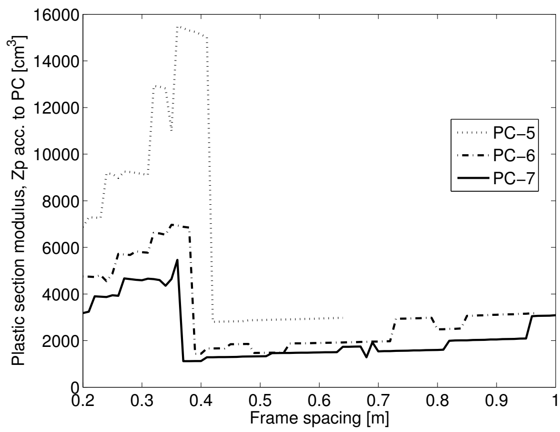
(a). Plate thickness.



(b). Plate thickness.



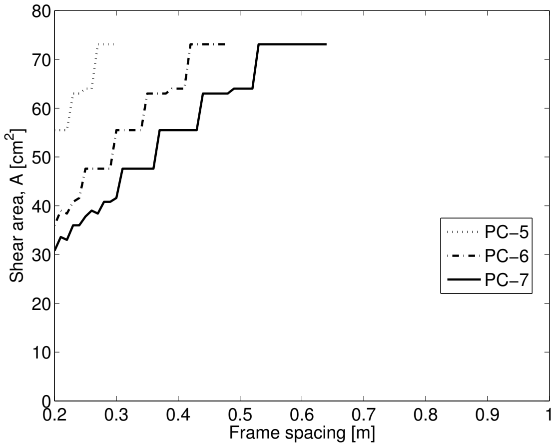
(c). Section modulus.



(d). Section modulus.

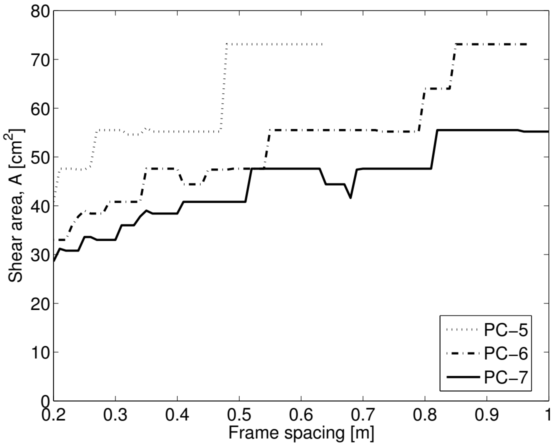
Comparison of longitudinal and transverse framing of lower PC notations for Ship I
2(2)

Longitudinal framing

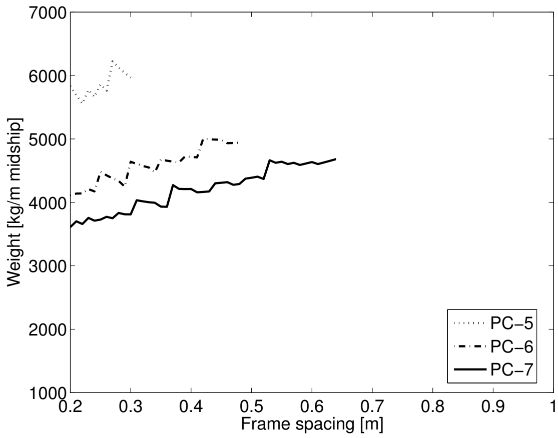


(e). Shear area.

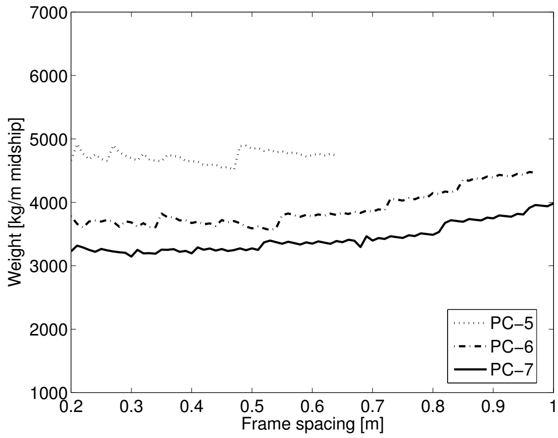
Transverse framing



(f). Shear area.



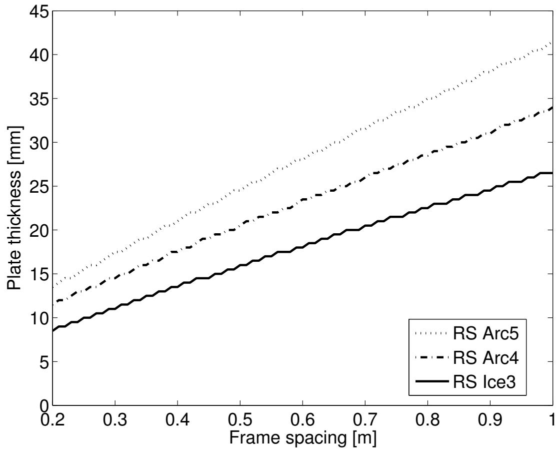
(g). Weight.



(h). Weight.

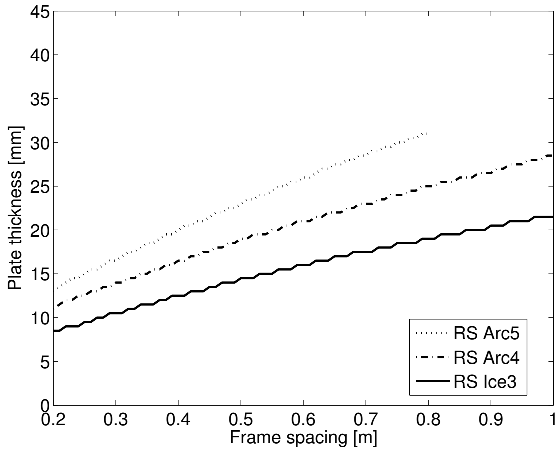
Comparison of longitudinal and transverse framing of lower RS notations for Ship I
1(2)

Longitudinal framing

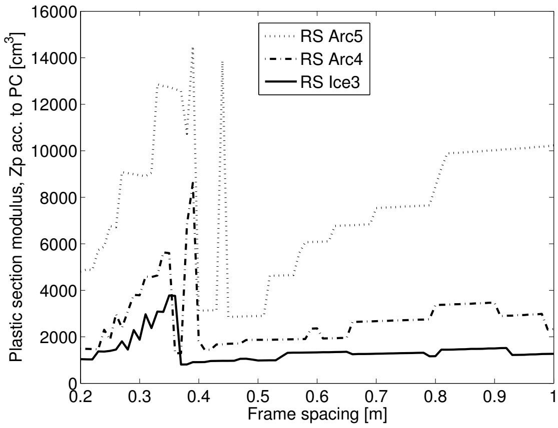


(a). Plate thickness.

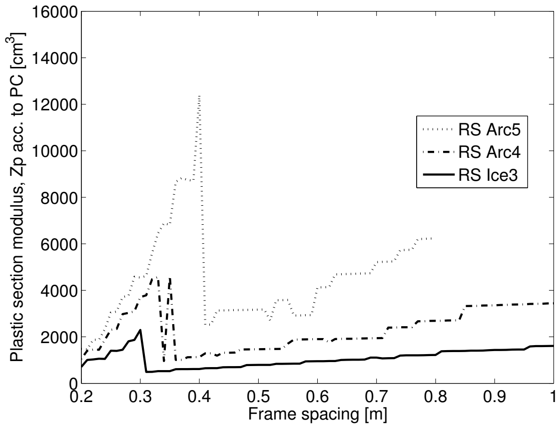
Transverse framing



(b). Plate thickness.



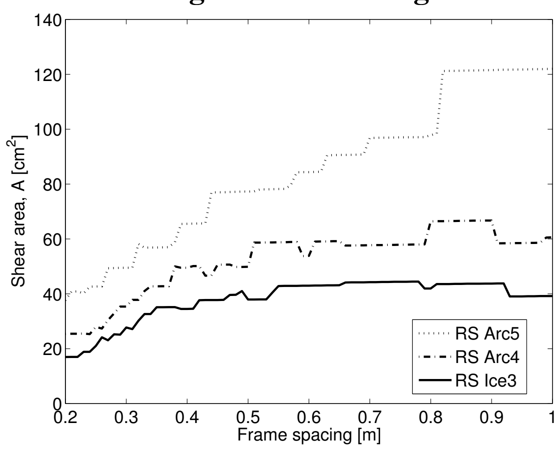
(c). Section modulus.



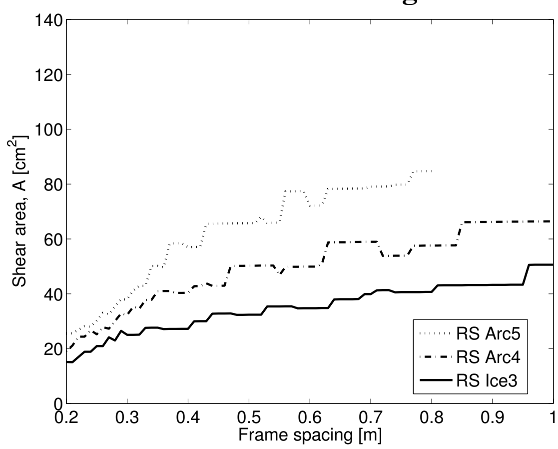
(d). Section modulus.

Comparison of longitudinal and transverse framing of lower RS notations for Ship I
2(2)

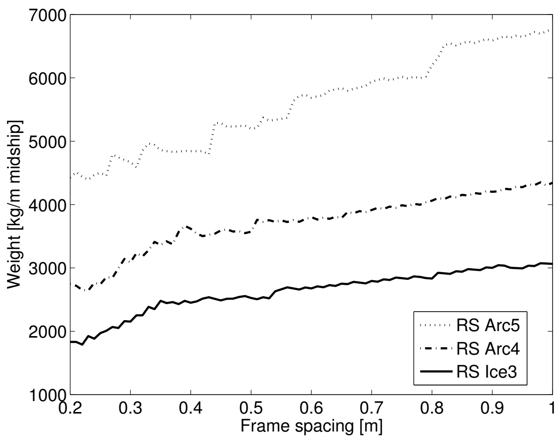
Longitudinal framing **Transverse framing**



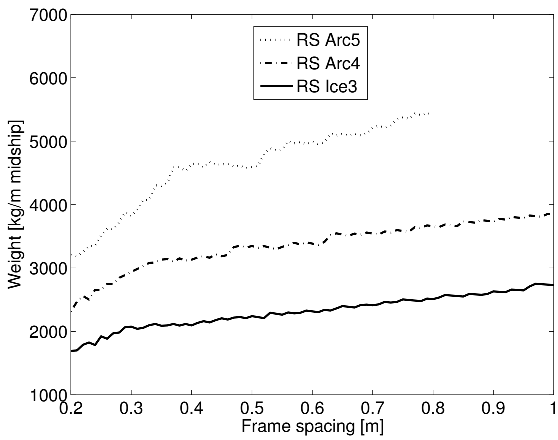
(e). Shear area.



(f). Shear area.



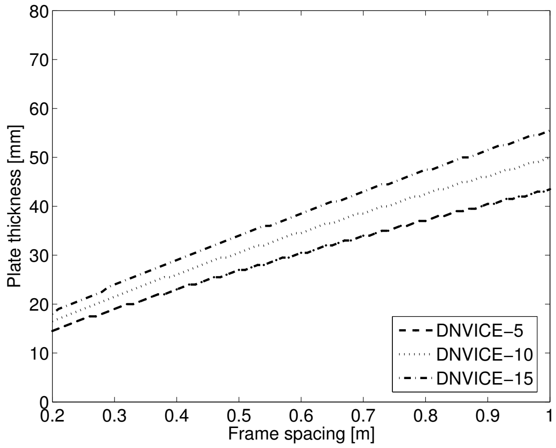
(g). Weight.



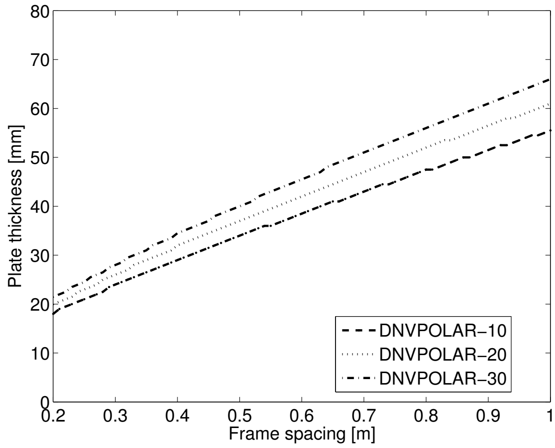
(h). Weight.

Comparison of DNV ICE and DNV POLAR with transverse framing for Ship III
1(2)

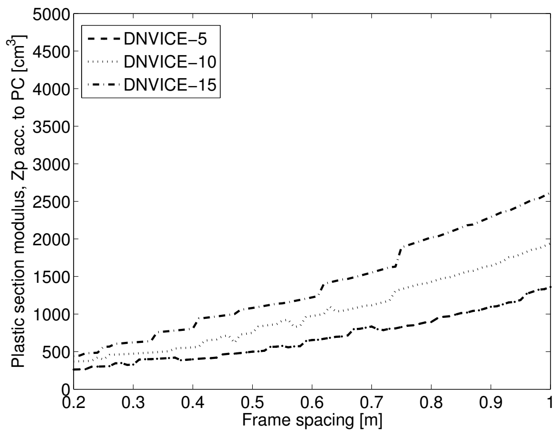
DNV ICE | **DNV POLAR:**



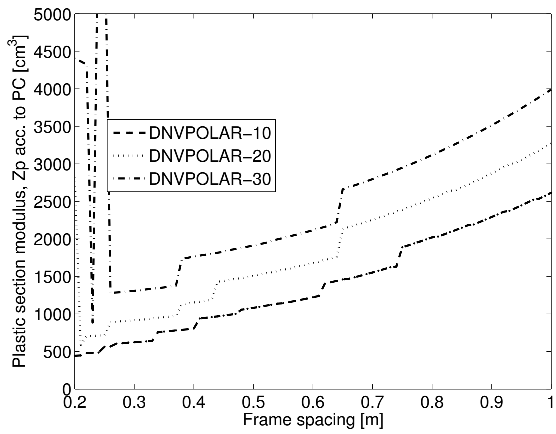
(a). Plate thickness.



(b). Plate thickness.



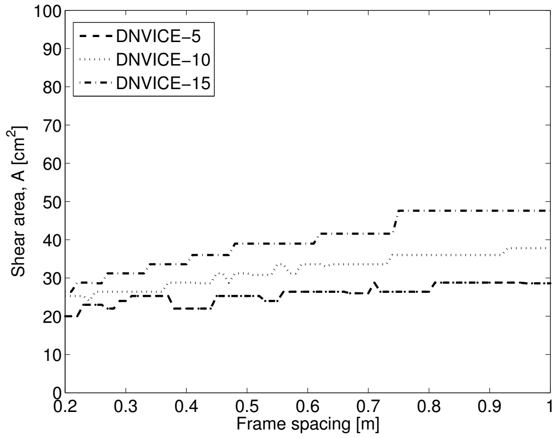
(c). Section modulus.



(d). Section modulus.

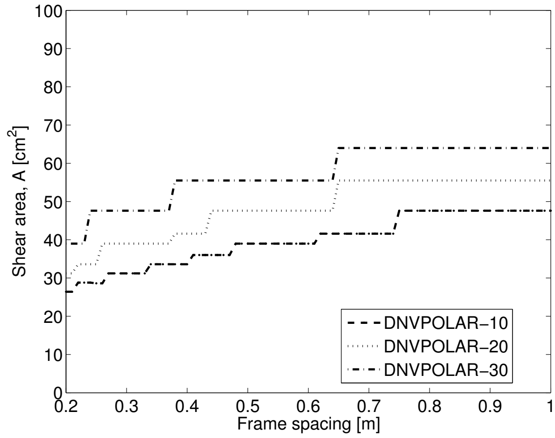
Comparison of DNV ICE and DNV POLAR with transverse framing for Ship III
2(2)

DNV ICE

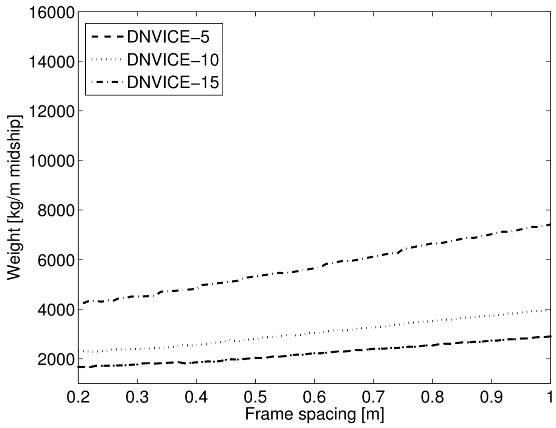


(e). Shear area.

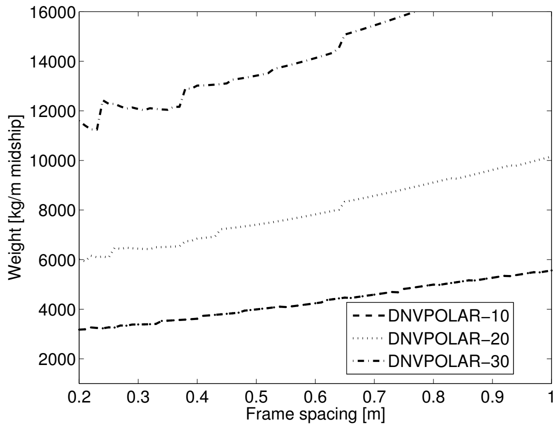
DNV POLAR



(f). Shear area.



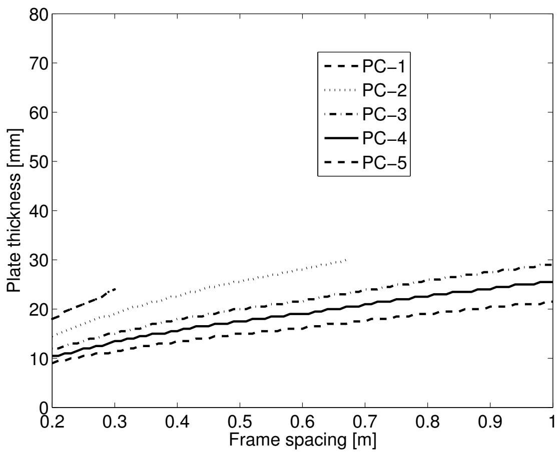
(g). Weight.



(h). Weight.

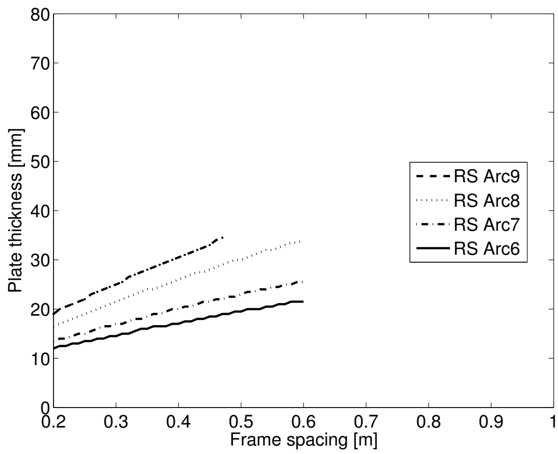
Comparison of higher notations of PC and RS with transverse framing for Ship III
1(2)

IACS PC

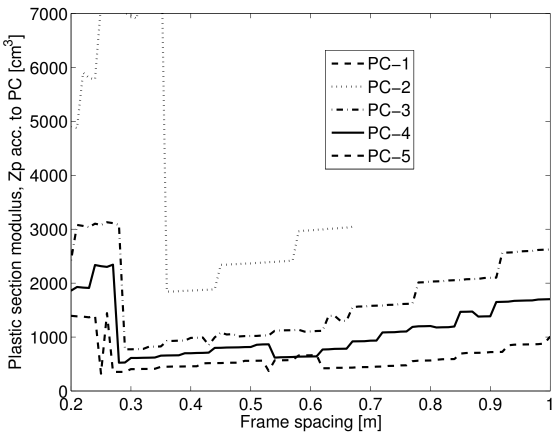


(a). Plate thickness.

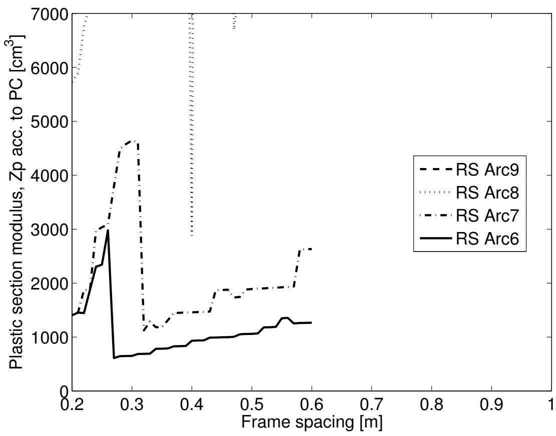
RS



(b). Plate thickness.



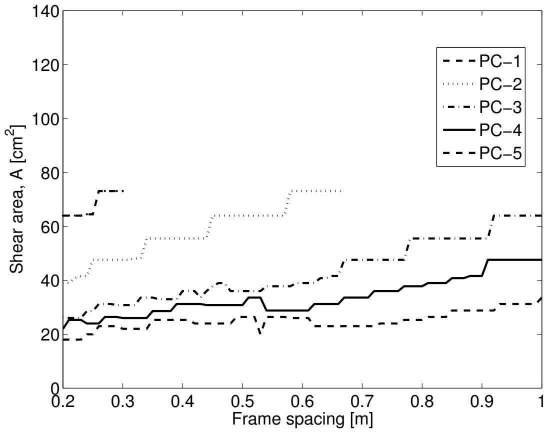
(c). Section modulus.



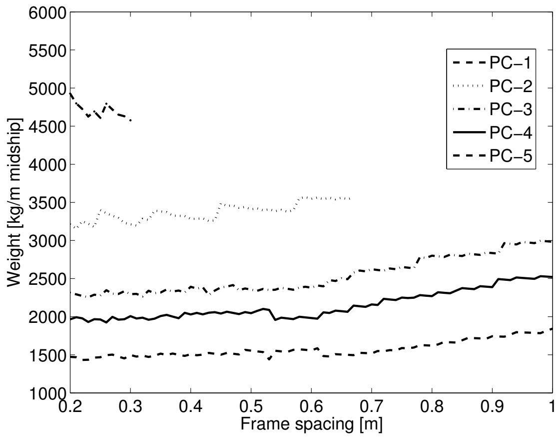
(d). Section modulus.

Comparison of higher notations of PC and RS with transverse framing for Ship III
2(2)

IACS PC

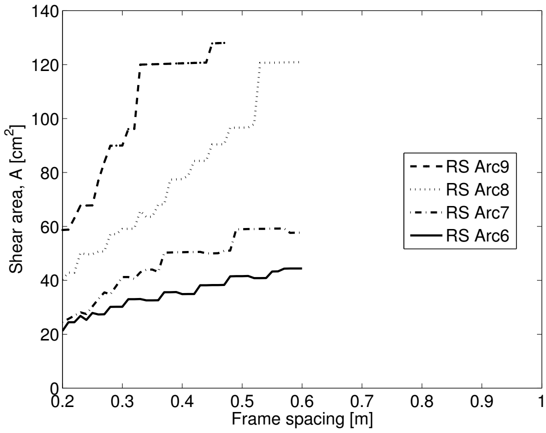


(e). Shear area.

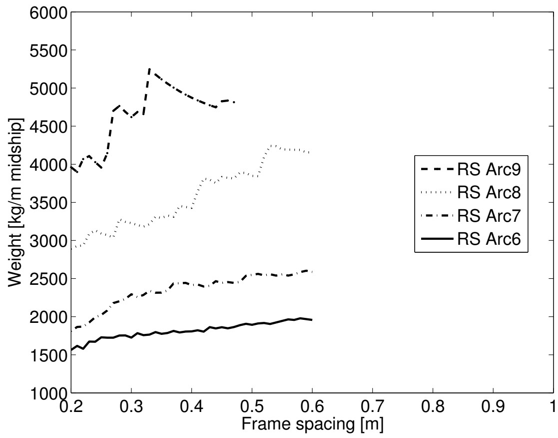


(g). Weight.

RS



(f). Shear area.



(h). Weight.