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A METHOD FOR HULL SCANTLINGS CALCULATIONS FOR SHIPS SAILING IN LOW SALINITY WATERS

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Abstract

In IACS UR I "Polar Class Requirements", which has been introduced in the Rules of all Classification Societies participating in IACS, there is no special consideration for the navigation in low salinity waters where the strength of ice is increased.

In general the salinity of the sea is (31-39‰) but there are areas with lower salinity, like the Caspian Sea (salinity 0-14 ‰) and rivers (around 0‰). The Caspian Sea is an area rich in oil and Bureau Veritas has recently classified several Offshore Service Vessels for operation in this area.

In this paper we investigate the influence of low salinity sea water on ice strength and consequently on the hull scantlings of icebreaking ships. We consider that the sea water salinity in low-salinity areas, which we call brackish waters, is the ¼ of the normal salinity of the sea. The ice which is formed in low salinity areas is a low salinity ice. This makes the ice stronger and affects the force applied on icebreaking ships and consequently their hull scantlings.

In IACS UR I, two ways of ice failure are adopted: flexural failure and crushing failure. The low salinity of the ice increases its flexural strength while the crushing strength is almost not affected. The influence of the low salinity on the flexural strength of the ice is calculated by the introduction of a new flexural failure coefficient C_f. The new increased values of this coefficient affect the hull scantlings, but only at the bow area, since according to IACS URI, only at bow we have flexural failure of the ice, while in non-bow areas we have crushing failure.

This new coefficient C_f has been introduced in Bureau Veritas Rules and can be used for the hull scantlings calculations of ships sailing in low salinity waters.

1. Introduction

In recent years, at least 7 offshore service vessels for use in the Caspian Sea have been built under the supervision of Bureau Veritas. The Caspian Sea is an area rich in hydrocarbons, representing reserves estimated at 3.5% of world oil reserves and 5% of world gas reserves. One example is the Kashagan field operated by Total. Bureau Veritas is also involved in the certification of fixed platforms and drilling platform projects in the Caspian Sea. Exploration and production in this area are steadily increasing, especially in the north. Figure 1 shows a map of the Caspian Sea with the main areas of hydrocarbon fields.

Figure 1. Hydrocarbons in the Caspian Sea

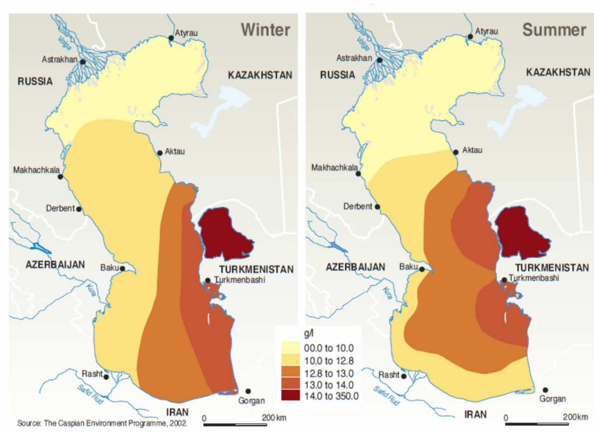

Figure 2. Salinity of the Caspian Sea

The main features of the Caspian Sea are as follows [1]:
- Average depth: 5.0 m
- Swell: 3.0 m (5% probability)
- Salinity: 10 ‰
- Air temperature: - 30 °C / - 10 °C
- Seawater temperature: 0 °C / 0.5 °C
- Typical wind speed: 12 knots
- Strong wind speed > 30 knots
- Annual ice thickness <1.0 m

The Caspian Sea is characterized by a particularly low salinity. In fact, while the average salinity of seas and oceans is around 35 ‰, the salinity of the Caspian Sea is of the order of quarter of the average salinity of the oceans and seas. This low salinity leads to increased strength of the ice.

Figure 2 provides the salinity in the Caspian Sea, which ranges from a value close to zero in the north at a value of 14 ‰ in the southeast.

In this paper, we will initially examine the influence of salinity on the strength of ice, before seeing how to change the Bureau Veritas Rules formulae to reflect this change in ice strength taking into account that the low salinity of the sea water gives us low salinity ice.

We will explain the changes made in the rules of Bureau Veritas for classification of ice reinforced ships, to meet the fact that regulations for ice strengthening are based on average values of the ice strength and do not take into account the peculiarity of the ice in areas of low salinity, like the Caspian Sea.

Figure 3. Vessel operating in Caspian Sea

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

Table 1. Definition of ice Classes (IACS URI)

2. Ship type

Figure 2 shows one of the vessels operating in ice in the Caspian Sea. This type of vessels, specially designed for use in the Caspian Sea, have the following features:

- Independent operations throughout the year in the Northern Caspian Sea
- Icebreaking capabilities: 0.6 m
- Length: 66.0 m
- Width: 16.4 m
- Depth: 4.4 m
- Draft: 2.5 - 3.0 m
- Engine: 3 azimuth thrusters
- Total power 4.8 MW

Ships of this type are in service in the Caspian Sea for 4 to 5 years to the satisfaction of their operators.

3. Rules "Polar Class"

In 2007, IACS published the UR (Unified Requirements) I1, I2 and I3 [2] defining Polar Classes of ice reinforced ships. These requirements have been taken by Bureau Veritas and introduced in a regulatory note, the NR527 [3] published in 2007. The ice classes are 7 and range from PC7 (lowest, for annual ice) to PC1 (highest for multi-year ice). Table 1 provides an overall view of the Polar classes, providing for each one, the ice type suitable for operation.

In the Caspian Sea, Polar Classes PC6 or PC7 are largely sufficient.

4. Ice Strength

In IACS URI [2] the ice loads are described through flexural strength and crushing strength in connection with the class factors. From the documents [1], [4] and [7] we can get the following formulae for the class factors.

$$C_F = \sigma_f \cdot h_{ice}^2 \qquad (1) \qquad \text{(flexural failure)}$$

$$C_C = P_0^{0.36} \cdot V_{ship}^{1.28} \qquad (2) \qquad \text{(crushing failure)}$$

We are going to investigate the influence of ice salinity on the above factors. From the documents above we have for flexural / crushing strength:

Flexural Strength: $$\sigma_f = 1.76 \cdot e^{-5.88 \cdot \sqrt{\nu_b}} \qquad (3) \qquad (\text{MPa})$$

Crushing Strength: $$\sigma_c = 49 \cdot \varepsilon^{0.22} \cdot \left[1 - \left(\frac{\nu_T}{280}\right)^{0.5}\right] \qquad (4) \qquad (\text{MPa})$$

Brine volume ratio: $$\nu_b = S_i \cdot \left(0.532 + \frac{49.185}{|T|}\right) \qquad (5) \qquad \text{(parts per thousand ‰)}$$

S_i : Salinity of the ice (‰)
T : Temperature of the ice (^{o}C)
P_0 : Ice pressure at 1m^2 (MPa)
h_{ice} : Ice thickness (m)
ν_τ : total porosity in the ice (brine and air) in parts per thousand (‰)
ε : strain rate in s^{-1}

From Eq. 1,3,5 we can have:

$$C_F = \sigma_f \cdot h_{ice}^2 = 1.76 \cdot e^{-5.88 \cdot \sqrt{\nu_b}} \cdot h_{ice}^2 = 1.76 \cdot e^{-5.88 \cdot \sqrt{S_i \cdot \left(0.532 + \frac{49.185}{|T|}\right)}} \cdot h_{ice}^2 \qquad (6)$$

P_0 is the pressure applied on the ship from the ice as the ice fails because its crushing strength or flexural strength is reached. (P_0 is the σ_c in crushing failure or the σ_f in flexural failure)

5. Ice Temperature

The ice encountered by the ship during the ice breaking operation is in contact with the water. So since the temperature of water is not below -2 ^{o}C we can assume that the temperature of the ice at the area in contact with the ship will not be less than -10 ^{o}C.

6. Crushing failure

Assuming that $v_b = v_\tau$, (0 air porosity) from Eq. 4,5 we have for the compression strength:

$$\sigma_c = 49 \cdot \varepsilon^{0.22} \cdot \left[1 - \left(\frac{v_T}{280}\right)^{0.5}\right] = 49 \cdot \varepsilon^{0.22} \cdot \left[1 - \left(\frac{S_i \cdot \left(0.532 + \frac{49.185}{|T|}\right)}{280}\right)^{0.5}\right] \qquad (7)$$

From [6] we have that the range of ε is 10^{-7} to 10^{-4}. For $\varepsilon = 10^{-7}$ and $\varepsilon = 10^{-4}$, T = -10 ^{o}C we calculate the $\sigma_c = f(S_i)$ and as we can see in Figures 4,5 that σ_c is almost independent of S_i. For $S_i = 0$ the σ_c takes its maximum values, which are respectively 1.41 for $\varepsilon = 10^{-7}$ and 6.46 for $\varepsilon = 10^{-4}$.

So we can also say that since P_0 is σ_c, the P_0 and consequently the factor $C_C = P_0^{0.36} \cdot V_{ship}^{1.28}$ are independent of ice salinity in the case of crushing failure. This means that crushing failure of the ice is independent of the ice salinity.

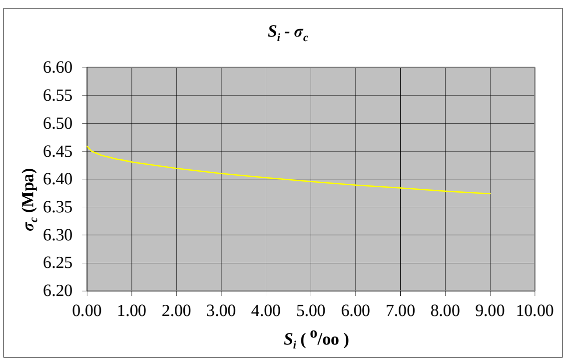

Figure 4. $S_i - \sigma_c$ ($\varepsilon = 10^{-4}$)

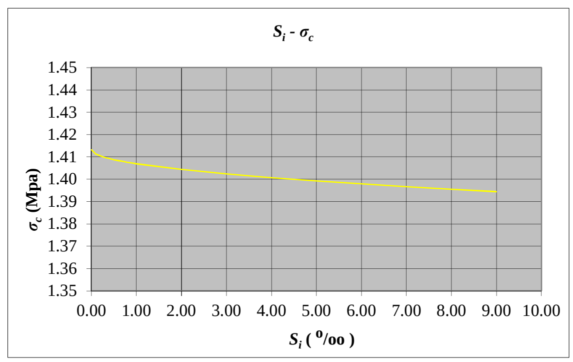

Figure 5. $S_i - \sigma_c$ ($\varepsilon = 10^{-7}$)

Figure 4,5. Influence of low salinity S_i on ice crushing failure σ_c

7. Flexural failure

As we can see in Figure 6 for T = -10 ^{o}C the flexural strength $\sigma_f = 1.76 \cdot e^{-5.88 \cdot \sqrt{v_b}}$ is much more dependent on ice salinity S_i and the maximum value that σ_f can take (for $S_i = 0 \rightarrow e^{-5.88 \cdot \sqrt{v_b}} = 1$) is 1.76, independent of the temperature T and ice thickness h_{ice}.
So the factor $C_F = \sigma_f \cdot h_{ice}^2$ and consequently the flexural failure of the ice depend on the ice salinity.

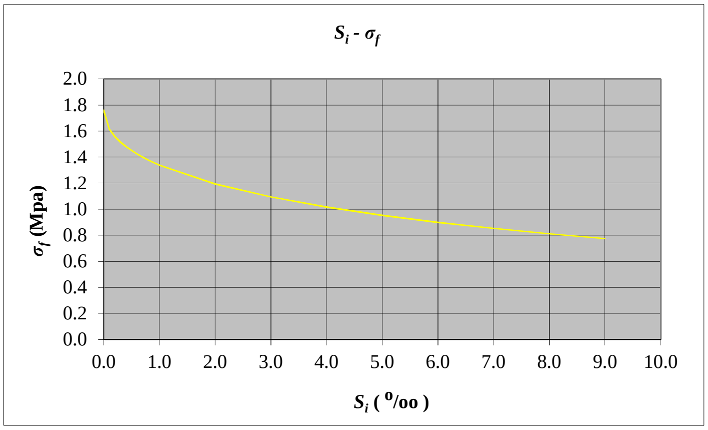

Figure 6. Influence of low salinity S_i on ice flexural failure σ_f

Also According to [2] the force applied on hull areas other than the bow has a crushing nature, as it depends only on C_c, C_Δ and Δ. So since low salinity influences the flexural failure of the ice, we can say that influences the ship's scantlings only at the bow area.

8. Definition of Salinity associated with each Polar class

The relationship between flexural strength σ_f and ice salinity S_i for a certain temperature T as we have seen in §4 is given by the formula below

$$\sigma_f = 1.76 \cdot e^{-5.88 \cdot \sqrt{v_b}} = 1.76 \cdot e^{-5.88 \cdot \sqrt{S_i \cdot \left(0.532 + \frac{49.185}{|T|}\right)}} \qquad (8)$$

Solving with Mathematica this equation for S_i we take:

$$S_i = \frac{28.9231 \cdot |T| \cdot \left(\ln\left(0.568182 \cdot \sigma_f\right)\right)^2}{49.185 + 0.532 \cdot |T|} \qquad (9)$$

In the Table 2 below we see the values of open sea ice salinity S_i corresponding to Polar Classes for temperature T = -10, -20, -30 °C.

POLAR CLASS or ICEBREAKER	σ_f (MPa) Table 2	Open Sea Ice Salinity S_i (°/oo)		
		-10 °C.	-20 °C.	-30 °C.
1	1.40	0.28	0.51	0.70
2	1.30	0.49	0.89	1.22
3	1.20	0.78	1.42	1.95
4	1.10	1.17	2.14	2.94
5	1.00	1.70	3.09	4.26
6	0.70	4.51	8.22	11.32
7	0.65	5.27	9.59	13.22

Table 2. Ice salinity S_i versus Polar Class for various temperatures T

9. Calculation of Class factor C_F

For ice temperature of T = -10 °C the salinity S_i of the open sea ice for the various ice classes is according to Table 2. We assume that the low salinity sea water gives ice of the same low salinity.

Since only the flexural strength of the ice is influenced from the low salinity, we can calculate the Class factor C_F, which is used for the calculation of flexural ice strength, for ice salinity of 0, 1/3 and 1/4 of the salinity of the open sea ice as this is given in Table 2 for T = -10 °C.

We can apply these values of Class factor C_F for scantling calculations for sea areas of low salinity, like the Caspian Sea, which we will call brackish waters.

The Class factors C_F for ice Salinity of 1/3 and 1/4 of the Salinity of the open sea is calculated, as we have seen in §4, from the formula below.

$$C_F = \sigma_f \cdot h_{ice}^2 = 1.76 \cdot e^{-5.88 \cdot \sqrt{\nu_b}} \cdot h_{ice}^2 = 1.76 \cdot e^{-5.88 \cdot \sqrt{S_i \cdot \left(0.532 + \frac{49.185}{|T|}\right)}} \cdot h_{ice}^2$$

In the case of zero ice salinity S_i the above formula is simplified to:

$$C_f = 1.76 \cdot h_{ice}^2$$

In Table 3 and in Figure 7 we can see the values of Class factor C_F for ice salinity of 0, 1/3 and 1/4 of the ice salinity of the open sea ice.

POLAR CLASS or ICEBREAKER	C_F (Sea Ice Salinity)	C_F (0 Ice Salinity)	C_F variation	C_F (1/3 of open Sea Ice Salinity)	C_F variation	C_F (1/4 of open Sea Ice Salinity)	C_F variation
PC 1	68.60	86.24	1.26	75.53	1.10	76.92	1.12
PC 2	46.80	63.36	1.35	53.17	1.14	54.45	1.16
PC 3	21.17	31.05	1.47	24.88	1.18	25.64	1.21
PC 4	13.48	21.56	1.60	16.44	1.22	17.05	1.26
PC 5	9.00	15.84	1.76	11.42	1.27	11.94	1.33
PC 6	5.49	13.80	2.51	8.10	1.48	8.70	1.59
PC 7	4.06	11.00	2.71	6.19	1.52	6.69	1.65

Table 3. Influence of low ice salinity S_i on factor C_F

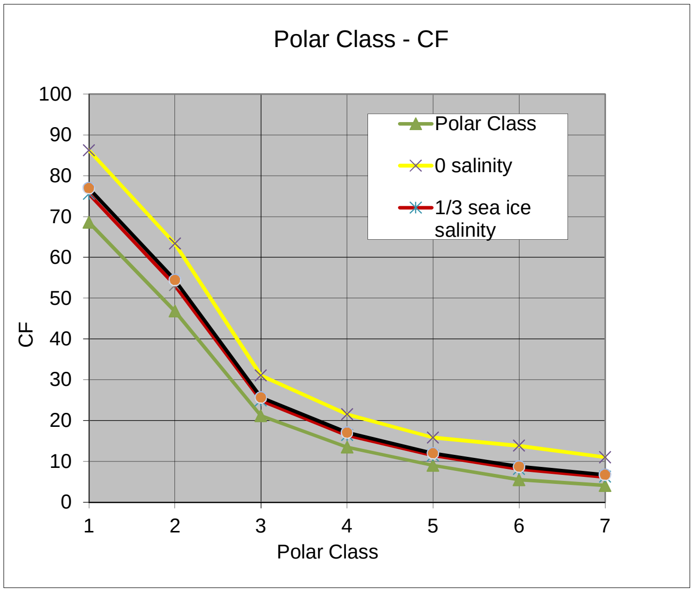

Figure 7. Influence of low ice salinity S_i on Polar Classes

10. Comparison

We investigate the influence of low ice salinity on bow scantling requirements. We will apply this approach on a test ship (Polar class 6) with the characteristics shown in Table 4. The bow of this ship is constructed with transverse construction system. In order to check the influence of the reduced values of C_F also on the longitudinal construction system we are going to apply the same calculation on a hypothetical longitudinal construction system with scantlings (*s* and *l*) as defined in Table 4.

D	2450	tn
s (T)	0.3	m
l (T)	1.8	m
s (L)	0.3	m
l (L)	1.8	m
L	63	m
B	16.4	m
T	3.0	m
C_w, C_b	0.8	
P_0 (ice)	1.5	Mpa
V_{ship}	4.5	knots

Table 4. Characteristics of a test Ship (Polar Class 6)

s (T): spacing of transverse ordinary stiffeners at bow.
l (T): span of transverse ordinary stiffeners at bow.
s (L): spacing of longitudinal ordinary stiffeners at bow. (Hypothetical)
l (L): span of longitudinal ordinary stiffeners at bow. (Hypothetical)

In Tables 5,6 below we can see a comparison for the scantling requirements between IACS URI [2] and our calculations with a reduced ice salinity (0, 1/3, 1/4 of open sea ice salinity). The coefficients we see in the Tables 5,6 express the increase/decrease of the IACS URI [2] bow scantling requirements due to the application of the low salinity requirements as these are expressed in this paper.

In the Tables 5 and 6 below we see the influence of the new factor C_F (ice salinity = 0, 1/3 and 1/4 of open sea ice salinity) in plate thickness, in shear area and stiffener section modulus requirement, (**net**) for the ship mentioned in Table 4, assuming that we have flexural failure of the ice.

POLAR CLASS or ICEBREAKER	Plate (mm)			Shear area (cm^2)			*SM* (cm^3)		
	(0)	**(1/4)**	**(1/3)**	**(0)**	**(1/4)**	**(1/3)**	**(0)**	**(1/4)**	**(1/3)**
PC 1	1.04	1.02	1.02	1.15	1.07	1.06	1.13	1.06	1.05
PC 2	1.05	1.03	1.02	1.20	1.10	1.08	1.17	1.08	1.07
PC 3	1.07	1.03	1.03	1.26	1.12	1.10	1.22	1.10	1.09
PC 4	1.09	1.04	1.04	1.33	1.15	1.13	1.27	1.13	1.11
PC 5	1.11	1.05	1.05	1.41	1.19	1.16	1.34	1.16	1.13
PC 6	1.18	1.09	1.08	1.75	1.32	1.27	1.62	1.28	1.23
PC 7	1.20	1.10	1.08	1.84	1.36	1.29	1.69	1.31	1.25

Table 5. Increase/decrease of IACS URI [2] bow scantling requirements, due to application of the low salinity requirements for all Polar classes. (Transverse system, Ice salinity = 0, 1/3 and 1/4 of open sea ice salinity)

POLAR CLASS or ICEBREAKER	Plate (mm)			Shear area (cm^2)			*SM* (cm^3)		
	(0)	**(1/3)**	**(1/4)**	**(0)**	**(1/3)**	**(1/4)**	**(0)**	**(1/3)**	**(1/4)**
PC 1	1.03	1.01	1.01	1.10	1.04	1.05	1.22	1.08	1.10
PC 2	1.03	1.01	1.02	1.14	1.06	1.07	1.18	1.07	1.09
PC 3	1.04	1.02	1.02	1.21	1.08	1.10	1.22	1.09	1.11
PC 4	1.05	1.02	1.03	1.28	1.12	1.14	1.29	1.12	1.14
PC 5	1.06	1.03	1.03	1.37	1.15	1.18	1.38	1.15	1.18
PC 6	1.11	1.04	1.05	1.69	1.28	1.33	1.70	1.28	1.34
PC 7	1.12	1.05	1.06	1.73	1.26	1.32	1.73	1.27	1.33

Table 6. Increase/decrease of IACS URI [2] bow scantling requirements, due to application of the low salinity requirements for all Polar classes. (Longitudinal system, Ice salinity = 0, 1/3 and 1/4 of open sea ice salinity)

11. New Rule requirement

We concider as brackish waters areas with salinity lowear than the open sea salinity. We are going to use for these areas sea water salinity equal to 1/4 of the water salinity of the open sea. Consequently the ice salinity in brackish waters will be the 1/4 of the ice salinity of open sea waters.
In Bureau Veritas Rules [3] we introduce, for this value of ice salinity, new values of Class factor C_F of ice flexural failure for brackish waters according to the Table 7 below.

Brackish waters cover also the Caspian Sea.

POLAR CLASS or ICEBREAKER	C_C (crushing failure)	C_F (flexural failure)		C_D (load patch dimensions)	C_Δ (displacement)	C_L (longitudinal strength)
		Brackish water	Open sea			
1	17,69	76,92	68,60	2,01	250000	7,46
2	9,89	54,45	46,80	1,75	210000	5,46
3	6,06	25,64	21,17	1,53	180000	4,17
4	4,50	17,05	13,48	1,42	130000	3,15
5	3,10	11,94	9,00	1,31	70000	2,50
6	2,40	8,70	5,49	1,17	40000	2,37
7	1,80	6,69	4,06	1,11	22000	1,81

Table 7. Class factors

12. Conclusion

In this paper we have firstly checked the influence of water salinity and consequently the influence of ice salinity on ice strength. (flexural or crushing)

We have come to the conclusion that the low ice salinity influences only the flexural failure of the ice which according to IACS URI [2] is restricted only at the bow area of the ship.

We have also defined the values of ice salinity which are connected with the Polar Classes for various temperatures and we have decided to work with T = -10 ^{o}C.

Furthermore we have proposed a way to evaluate the influence of the low ice salinity to scantling requirements for Polar Class Ships and Icebreakers, through the calculation of the Class factor C_F , for a certain value of ice salinity.

Finally we have decided to use as salinity of brackish water the value of 1/4 of open sea salinity which covers also the area of the Caspian Sea. We have introduced a new Class factor C_F of flexural failure of the ice for brackish waters. This factor will influence the bow scantlings in the case of flexural failure of the ice.

13. References

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