Application of Polar Class Rules for Fatigue to an Existing Arctic Class Icebreaker Propeller

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ABSTRACT

This paper presents a benchmark evaluation of an existing propeller design in accordance with the requirements in the current ABS rules for Polar Class vessels. The propeller is from the existing Canadian R-Class icebreaker, which was originally designed and built to the Canadian Arctic Class construction standard. The Canadian Arctic Class rules required very highly strengthened vessels. The hull structural aspects of the Polar rules have been well explored in relation to existing high ice class requirements; the present work explores the machinery requirements. The propeller is found to meet the Polar Class 6 (PC6) requirements, based on fatigue assessment. The blade strength assessment is found to meet the requirements of PC1.

KEYWORDS

Polar Class rules, R-Class propeller, Blade force, Fatigue strength.

1 INTRODUCTION

Early ice class rules were relatively crude and typically were simple percentage increases over open water requirements. Today through the IMO (International Maritime Organization) and IACS (International Association of Classification Societies), high ice class requirements are being standardized in the form of the Polar Class rules. These rules represent the latest guidance available for ice going vessels, so they have a relatively short history.

In the 1970s and 1980s, there was an increase in activities in Polar waters. In response, several administrations took initiatives to establish a framework for detailed ice-class requirements for the construction and operation of vessels. This led to the development of the Polar Code, which came into force in 2017.

Fatigue failure of a structural component is the combination of two stages of failure: crack initiation and crack propagation. Fatigue life is the combined loading cycles over the two stages causing the structure to fail. In analyzing fatigue strength of a propeller, both dynamic loading and fatigue strength properties of the material must be considered. Most of the failures regarding marine propeller blades are reported as the consequence of the initiation of a fatigue crack at the blade root. Tokuda et al. (1978) and Helle (1981) reported that the fatigue life of marine propellers can be calculated based on the fatigue crack initiation period and crack propagation rate to cause failure. Wenschot et al. (1983) investigated the corrosion fatigue strength of a marine propeller of Ni-Al-Bronze and established a relationship between the tensile strength and the corrosion fatigue properties of the alloy. Bose et al. (1998) investigated the design analysis approach of propeller blades under different limit states and proposed two additional limit states for considering ice loading for ice class propellers, besides elastic limit state and fatigue limit state. Bose et al. (1998) also suggested designers perform detailed stress analysis using suitable finite element methods to get an accurate picture of stress distribution in blades under ice loading.

Some investigations have been done in recent years regarding the fatigue damage of ice class vessels, but mostly limited to the ship hull. Suyuthi et al. (2013) developed a systematic procedure for assessing fatigue damage of ship hulls navigating in ice covered waters. Liu et al. (2015) performed design and optimization analysis of an existing R-Class marine propeller, based on IACS (International Association of Classification Society) URI3 rules using a panel method code. Although Liu et al. (2015) included direct stress and bending moments in the analysis, no calculation was performed to assess the fatigue strength of propeller. The present investigation demonstrates the fatigue assessment of the same R-Class marine propeller blade considered by Liu, applying ABS Polar Class machinery rules.

2 APPROXIMATE CORRESPONDENCE AMONG ICE CLASS RULES

The development of new harmonized IACS Polar Class rules aimed to reduce the number of types of high ice class rules. For example, ABS removed their high ice class rules and replaced them with the Polar Class rules in 2012. The new machinery rules are the product of long term research and development efforts, which include full-scale trials, laboratory investigations, numerical simulations of propeller-ice interaction, and analysis of ice class propeller damage history.

An approximate correspondence among ice-classes is shown in Table 1.

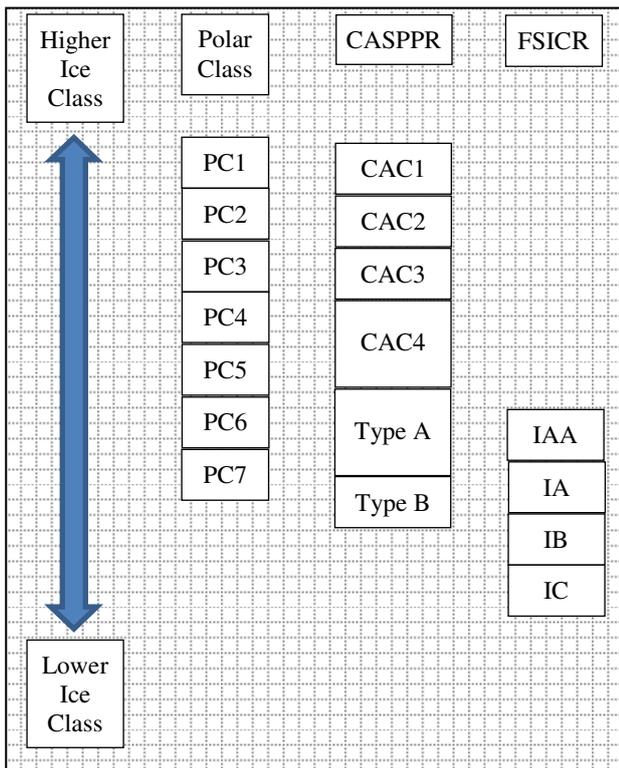**Table 1. Approximate correspondence among ice-classes:**

Table 1 is prepared based on the information given in Ship Safety Bulletin (Bulletin no. 04/2009) of Transport Canada, CASPPR (Canadian Arctic Shipping Pollution Prevention Rule), and Maritime Safety Regulation (TraFi 31299/2010) of Transport Safety Agency, Finland.

The R-Class propeller considered for the present fatigue study has been used by 3 similar CCGS (Canadian Coast Guard Ship) ice-breakers: *Sir John Franklin* (renamed as *CCGS Amundsen*), *Pierre Radisson*, and *Des Groseilliers*. These ice-breakers were designed and built to Canadian Arctic Class 3 (CAC3). With reference to the above table regarding the approximate correspondence among ice classes, it is noted that CAC3 approximately corresponds to PC3 (Polar Class 3). In the present study, the R-Class propeller is assessed by applying the criteria of ABS Polar Class rules for all 7 Polar Classes.

Table 2. Description of different Polar Classes under IMO and IACS UR (Unified Requirements) are given below:

Polar Class	H_{ice} (m)	S_{ice}	Description
PC1	4.00	1.2	Year-round operations in all polar waters
PC2	3.50	1.1	Year-round operations in moderate multi-year ice conditions
PC3	3.00	1.1	Year-round operations in second-year ice, which may include multi-year ice
PC4	2.50	1.1	Year-round operations in thick first-year ice, which may include old ice
PC5	2.00	1.1	Year-round operations in medium first-year ice, which may include old ice
PC6	1.75	1.0	Summer / autumn operations in medium first-year ice, which may include old ice
PC7	1.50	1.0	Summer / autumn operations in thin first-year ice, which may include old ice

Table 2 is extracted from IACS Machinery Requirements for Polar Class Ships (IACS-UR-I3), 2006

Table 2 contains values of ice thicknesses specified by Polar Class rules (H_{ice}) and ice strength index (S_{ice}) for PC3 and other Polar Classes. These values are used for calculating propeller blade forces.

3 ASSESSMENT METHOD AND RESULTS

ABS Polar Class rules for machinery are applied here to determine and apply the blade forces, in order to check the blade strength. The R-Class propellers are open, so the rules for open propellers are used. After assessing the blade strength, the stress results are used to assess blade fatigue strength. As there is no guideline to perform fatigue strength assessment in IACS URI3 (2007), guidelines from ABS Steel Vessel rules are used to carry out the fatigue assessment. CAD software is used to do solid modeling of the propeller blade. FEA (Finite Element Analysis) software ANSYS Workbench is used to perform the simulation, meshing, and analysis of the propeller blade.

3.1 Blade Force Calculation

Basically there are two (2) types of force on a propeller blade when it encounters ice. The first is contact load due to the penetration of the propeller blade into ice. The other force originates from non-contact hydrodynamic loads due to the presence of ice in the water. The contact loads can be described as due to milling of an ice block by a propeller blade, and as due to impact when ice blocks hit the blade at the back or face side.

In ABS Polar Class machinery rules two (2) types of loads are considered: maximum backward blade force (F_b) and maximum forward blade force (F_f).

As per ABS rules, maximum backward blade force 'F_b' can be calculated using the following:

$$F_b \text{ (kN)} = 27 \, S_{ice} \, [nD]^{0.7} \left[\frac{EAR}{Z}\right]^{0.3} D^2 \qquad (1)$$

$$F_b \text{ (kN)} = 23 \, S_{ice} \, [nD]^{0.7} \left[\frac{EAR}{Z}\right]^{0.3} [H_{ice}]^{1.4} \, D \qquad (2)$$

Equation (1) is applicable when $D < D_{limit\_b}$ and equation (2) is applicable when $D \geq D_{limit\_b}$, where $D_{limit\_b} = 0.85 \, [H_{ice}]^{1.4}$.

For maximum forward blade force 'F_f':

$$F_f \text{ (kN)} = 250 \left[\frac{EAR}{Z}\right] D^2 \qquad (3)$$

$$F_f \text{ (kN)} = 500 \left[\frac{1}{1-\frac{d}{D}}\right] H_{ice} \left[\frac{EAR}{Z}\right] D \qquad (4)$$

Equation (3) is applicable when $D < D_{limit\_f}$ and equation (4) is applicable when $D \geq D_{limit\_f}$, where $D_{limit\_f} = \left[\frac{2}{1-\frac{d}{D}}\right] H_{ice}$.

In equations (1) to (4), D, EAR, Z, n and d are propeller diameter (m), expanded area ratio, number of blades, nominal rotational speed in rps, and propeller hub diameter (m), respectively.

There are 5 loading scenarios and 7 Polar Classes in the ABS Polar machinery rules. Load cases are described explicitly in the ABS Polar rules and hence they are not reported here. In determining the loads to be applied under different cases, particulars of the propeller for the CCGS R-class icebreaker were obtained from Liu et al. (2015) and official website of CCGS.

Table 3. Particulars of ice breaker(s) and R-Class propeller used in the calculation:

Draft	7.00 m
Power (Max. Continuous Rating)	10,142 kW
Propeller diameter	4.115 m
Rotational speed at MCR	3.0 rps
No. of Propellers	2
No. of blades (Z)	4
EAR	0.7085
Blade root thickness	280 mm
Hub diameter (d)	1.2806 m

Using equations (1) to (4), and particulars of the ice class propeller mentioned in Table 3, blade forces are calculated for the 7 Polar Classes (PC1 to PC7) and 5 Load Cases (LC1 to LC5) described in the Polar rules.

Table 4. Calculated blade forces on the R-Class propeller:

PC	F_b_LC1 (kN)	F_b_LC2 (kN)	F_f_LC3 (kN)	F_f_LC4 (kN)	F_b,F_f_LC5 (kN)
1	1896	948	750	375	1138
2	1738	869	750	375	1043
3	1675	837	750	375	1005
4	1298	649	750	375	779
5	949	475	750	375	570
6	716	358	750	375	450
7	577	288	750	375	450

The loads are applied as uniform pressure over a specified area, as per the guidelines provided in ABS Polar Class machinery rules *(ABS Rules for Building and Classing Steel Vessels, 2016; Part-6, Chapter-1, Section-3 (6-1-3)/9.5)*.
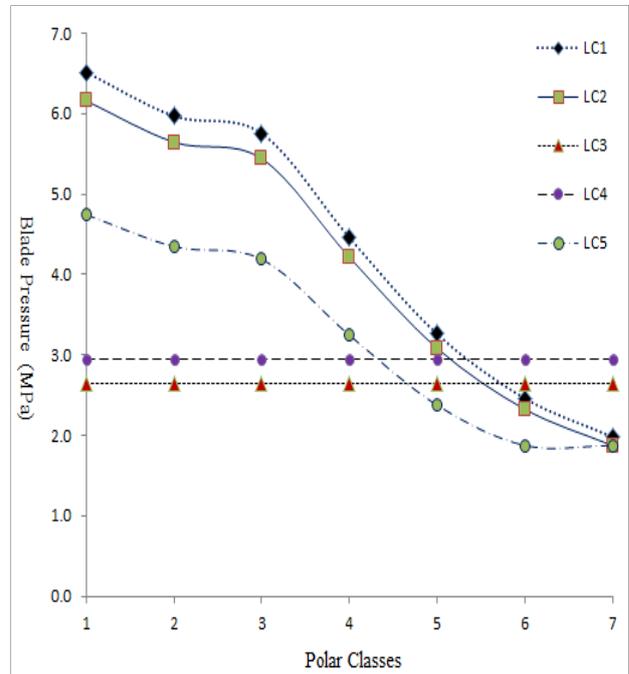

Figure 1: Variation of blade pressure for 5 load cases under 7 Polar Classes

As per the formula, S_{ice} is not considered in calculating 'F_f'. Propeller diameter (D) is less than D_{limit_f} for all 7 Polar Classes and thus H_{ice} is also not considered in calculating F_f. Thus equation (3) is used to calculate F_f, and there is no variation in loading with ice classes for load cases 3 and 4, as illustrated in Table 4 and Figure 1.

Liu et al. (2015) assessed the strength of the same R-Class propeller. They concluded that the propeller blades were over-designed for PC3 (CAC3) and suggested optimization could save 1.4 tons of blade material. No fatigue assessment was performed by Liu et al. (2015).

3.2 Strength Assessment Criteria

In ABS Polar Class machinery rules at section 6-1-3/11.5, the criteria to assess maximum blade stress and blade fatigue design are described. In checking blade stresses *(von Mises or equivalent)*, the criterion is: blade stresses obtained through applying backward or forward blade force shall not be greater than allowable stress for the blade material. Allowable stress, $\sigma_{all} = \sigma_{ref} / S$, where S is the safety margin (usually 1.5) and σ_{ref} is the reference stress. From the rules: $\sigma_{ref} = 0.7\sigma_u$ or $0.6\sigma_{0.2} + 0.4\sigma_u$, whichever is less. σ_u is specified as the maximum ultimate tensile strength and $\sigma_{0.2}$ is specified as maximum yield or 0.2% proof strength, if yield is not available. The R-class propeller blade is marine grade Ni-Al-Bronze (NAB) alloy, having $\sigma_u = 620.5$ MPa and $\sigma_{0.2} = 268.9$ MPa. Therefore $\sigma_{ref} = 410$ MPa and $\sigma_{all} = 273.3$ MPa. So the maximum von Mises (or equivalent) stress pertaining to the blade under any load case and polar class shall not be greater than 273.3 MPa. The tensile strength and yield strength of the propeller blade material considered are the tested values for the R-Class propeller blade material, where minimum specified values are used, as per ABS rules.

3.3 Blade Stress Assessment: Modeling, Meshing and Simulation

A finite element analysis (FEA) technique or equivalent is required by the Polar Rules. One of the inputs to an FEA is a geometry that represents the propeller blade to be analyzed. For this work, a process was developed to produce a working 3D model using a simple table of offsets. The table of offsets was used to develop the geometry of 3D model of propeller blade incorporating pitch, skew and rake. From the geometry, a surface model and then a solid model of the propeller blade were generated to use for analysis in the FEA software. For the convenience of calculation, only 1 blade was analyzed and fillet at blade root was not modelled.

As the NAB alloy used for the propeller blade is not available in the material library of the FEA software (ANSYS Workbench) used, the material was modeled using the properties of typical NAB material. Properties of material were obtained from Liu et al. (2015).

Table 5. Properties of NAB material used in calculation:

Yield strength	268.9 MPa
Ultimate tensile strength	620.5 MPa
Proof stress	193.0 MPa
Corrosion Fatigue strength (air)	158.6 MPa
Corrosion Fatigue strength (salt water)	120.0 MPa
Density	7556 Kg/m^3

After modeling the 3D solid model of the propeller blade and material, the hub of the propeller was also modeled and integrated with the blade. Boundary constraints were applied at the internal surface of hub. Then meshing was performed using the meshing tool of FEA software.
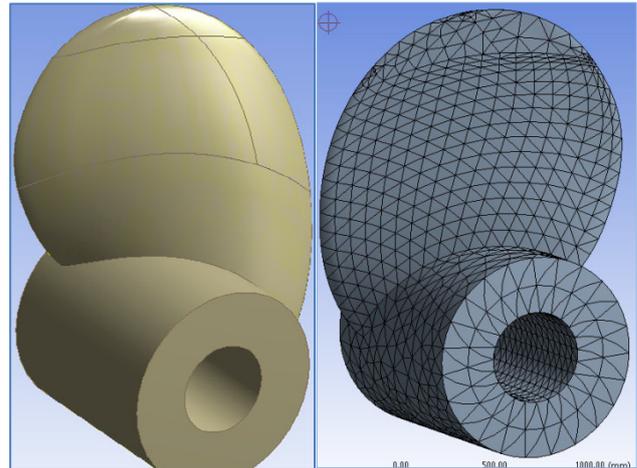

Figure 2: diagrams showing unmeshed and meshed 3D models of propeller blade integrated with hub (fillet at the blade root was not modelled)

Analysis of the meshed model was done using the loads calculated according to the ABS rules. The stress results obtained through the analysis are shown in Table 6.

Table 6. Stress (σ) results of the R-Class propeller blade:

PC	σ_b_LC1 (MPa)	σ_b_LC2 (MPa)	σ_f_LC3 (MPa)	σ_f_LC4 (MPa)	σ_b, σ_f_LC5 (MPa)
1	241	204	109	93	224
2	220	187	109	93	205
3	212	180	109	93	197
4	164	139	109	93	153
5	120	102	109	93	112
6	91	76	109	93	88
7	73	62	109	93	88

3.4 Blade Fatigue Assessment

Fatigue is due to the cyclic loading acting on the structure over a period of time on a more or less regular basis. In the presence of cyclic loading, the structure may fail even at a stress below the allowable limit. Thus a fatigue assessment of the structure is important, even though the structure complies with the requirements of a stress assessment. The structure will fail when the cumulative load cycles becomes large enough to deteriorate the restoration capacity of structure. The duration over which such failure phenomenon occurs is called the fatigue life (Meese 2013 and Almar-Naess 1985).

A fatigue assessment is typically based on an S-N curve, which shows the relation between stress intensity ($\Delta\sigma$) and the number of cycles before failure (N) encountered or likely to be encountered by the structure. For the case of propeller blades, fatigue is assessed based on the stresses as a result of the forward and backward bending forces.

Figure 3 is a graphical demonstration of mean stress (σ_m), stress intensity ($\Delta\sigma$), and stress amplitude (σ_a), which can be calculated as follows:

$\sigma_m = (\sigma_{high} + \sigma_{low}) / 2$
$\sigma_a = (\sigma_{high} - \sigma_{low}) / 2$
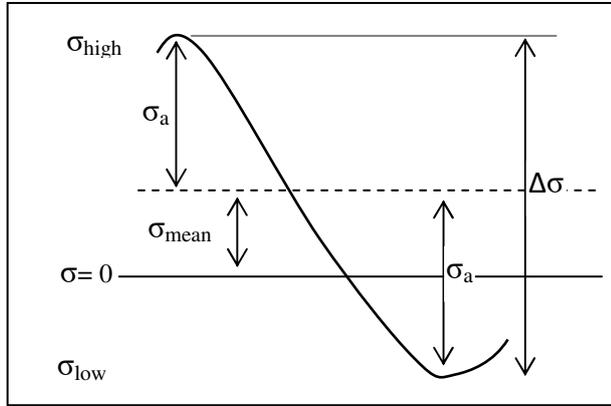$\Delta\sigma = 2 \cdot \sigma_a$

Figure 3: Showing fatigue stress terms

The stress values σ_{high} and σ_{low} are derived from FEA simulation. These values represent the highest change of stress in an element in the analysis between compatible load cases.

Guidelines to do fatigue assessment for ice class propeller blade are not included in IACS URI3. ABS has included their requirements and guidelines for fatigue assessment in Polar rules (section 6-1-3/11). By following ABS rules, Table 7 was developed, illustrating stress intensity ($\Delta\sigma$), stress amplitude (σ_a), and cumulative number of load cycles (N_{ice}) likely to be experienced by the R-Class propeller blade.

Table 7: Stress (principal) intensity and cumulative load cycles (N_{ice}) for the R-Class propeller

PC	$\Delta\sigma$ (MPa)	σ_a (MPa)	k_2	N_{class}	N_{ice}
1	424	212	1.31	21.0E+6	165.56E+6
2	398	199	1.07	17.0E+6	109.24E+6
3	388	194	0.83	15.0E+6	74.52E+6
4	327	164	0.71	13.0E+6	55.69E+6
5	271	135	0.62	11.0E+6	40.72E+6
6	233	116	0.57	9.0E+6	30.67E+6
7	210	105	0.52	6.0E+6	18.72E+6

In Table 7, 'N_{class}' is the reference number of impacts per propeller rotation speed for each ice class, as given in ABS Polar rules (6-1-3/Table 6). 'N_{ice}' was calculated based on N_{class} using the formula given in ABS rules:

$$N_{ice} = k_1 \cdot k_2 \cdot N_{class} \cdot n \qquad (5)$$

In equation (5), $k_1 = 2$ for wing propeller, values for k_2 were calculated using the formulas given in ABS rules for

different scenarios and they are shown in Table 7, 'n' is the shaft rotational speed in rps at MCR.

In calculating N_{ice}, it was assumed that the propeller center line was at a depth of 5.0 meter from the minimum ballast waterline in ice (LIWL) of the ship. The value of 'N_{ice}' will vary with the variation of depth of submergence of propeller, as the value of 'k_2' will also change accordingly: the higher the depth of submergence, the lower the number of load cycles encountered by the propeller blade (N_{ice}).

Next a Miner Summarize Table (MST) was developed in order to plot the limiting and actual S-N curve for blade material for all 7 Polar Classes. In developing the MST, the guidelines in ABS rules at 6-1-3/11.5.2 were followed. The loading frequency spectrum was divided into 10 blocks and each block incorporated 10% of the load. Table 8 was developed to show distribution of stress amplitude (σ_a) for all the Polar Classes. Similarly, Table 9 was also generated to give load cycles for each ice class and load block. The cumulative load cycles in Table 9 *(last row of table)*, must be the same as N_{ice} in Table 7.

Table 8. Stress amplitude (σ_a) in MPa for all 7 Polar Classes:

Load-ing	PC1	PC2	PC3	PC4	PC5	PC6	PC7
100%	212	199	194	163	135	116	105
90%	190	179	174	147	121	104	94
80%	169	159	155	131	108	93	84
70%	148	139	135	114	95	81	74
60%	127	119	116	98	81	70	63
50%	106	99	97	81	68	58	53
40%	85	80	78	65	54	47	42
30%	63	59	58	49	41	35	32
20%	42	40	39	33	27	23	21
10%	21	20	19	16	13	12	11

Table 9 was developed by calculating the number of load cycles under each block (n_i).

The formula used to determine the number of cycles in each block is:

$$n_i = N_{ice}^{\left\{1 - (1 - \frac{i}{z})^k\right\}} - \sum_{i=1}^{i} n_{i-1} \qquad (6)$$

In equation (6), 'i' is the single load block (1 to 10), 'z' is the total number of load blocks (10), and 'k' is the Weibull exponent (typically 0.75 for open and 1.0 for ducted propeller).

The complete MST for the R-class propeller blade is the combination of Table 8 and Table 9; due to space constraints they are shown separately. After developing the MST for all 7 Polar Classes, the S-N curves of the propeller of NAB were developed.

Table 9. Number of load cycles (n_i) for all 7 Polar Classes:

Loading	PC1	PC2	PC3	PC4	PC5	PC6	PC7
100%	7	6	6	6	6	6	5
90%	37	34	31	29	27	26	23
80%	248	217	192	175	159	145	123
70%	1.65E+3	1.38E+3	1.18E+3	1.04E+3	915	812	659
60%	10.93E+3	8.81E+3	7.22E+3	6.21E+3	5.27E+3	4.55E+3	3.51E+3
50%	72.52E+3	56.08E+3	44.26E+3	36.95E+3	30.42E+3	25.51E+3	18.75E+3
40%	48.12E+4	35.70E+4	27.11E+4	21.98E+4	17.55E+4	14.30E+4	10.00E+4
30%	31.93E+5	22.72E+5	16.61E+5	13.08E+5	10.12E+5	80.18E+4	53.38E+4
20%	21.19E+6	14.46E+6	10.18E+6	77.85E+5	58.36E+5	44.95E+5	28.48E+5
10%	140.61E+6	92.08E+6	62.35E+6	46.33E+6	33.66E+6	25.20E+6	15.20E+6
Total	165.56E+6	109.24E+6	74.52E+6	55.69E+6	40.72E+6	30.67E+6	18.72E+6

In Table 9, the number of cycles under each block (n_i) is calculated based on the formula provided in ABS rules, 6-1-3/11.1. As a prerequisite to apply the Miner Summarize method, the overall load spectrum must be divided into a minimum number of 10 load blocks, as described in ABS rules at 6-1-3/11.1.1. If a higher number of blocks is used, there will be a fewer cycles in each block, which will cause less fatigue damage to the structure and hence the cumulative fatigue damage of structure will be smaller. In that case, the calculation is less conservative. Similarly, if the number of blocks used is less than 10, the calculation is more conservative. The load distribution pattern follows the Weibull distribution, where cumulative distribution function of the probability distribution is an exponential function.

S-N curves of the propeller blade are plotted in Figure 4 for the Ni-Al-Br (NAB) alloy. The limiting S-N curve (sloped straight line) for NAB material is plotted, as well as the S-N curves for all 7 Polar Classes. Guidelines described in ABS rules at section 6-1-3/11.5.2 were followed in generating the curves. The left hand side portion of S-N curve of the NAB material is a straight line having slope 4.5 and passing through the point (σ_{E7}, 10^7), where $\sigma_{E7} = \{(\sigma_{FAT-E7} / S) \cdot K_{size} \cdot K_{mean}\}$. Here mean fatigue strength, $\sigma_{FAT-E7} = 120$ MPa for Ni-Al-Bronze (CU3) alloy and safety factor, S = 1.5. ABS rules include formulas for geometric size factor, K_{size}, and mean stress effect, K_{mean}, to calculate σ_{E7}. After plotting the first portion of limiting S-N curve up to 10^8 cycles, the second portion of the curve is plotted, which is also a sloped straight line starting at the end point of first portion of S-N curve at 10^8 cycles and having a slope of 10.

The effect of mean stress on the fatigue properties of blade material is taken into account by incorporating K_{mean} in the equation to determine fatigue limit stress (σ_{E7}). The σ_{E7} formulation in the ABS Rules has a term σ_{FAT-E7}, which is a Mean Fatigue Strength term based on R = -1 and a 50% survivability. The K_{mean} factor in the equation reduces σ_{E7} as the change in stress moves away from R = -1. Hence the limiting S-N curve will shift with the variation of mean stress, which will directly affect the fatigue properties of the blade material and the results of fatigue assessment.

The ABS rules for Polar Class ships require the fatigue to be evaluated using a Miner's Summation rule, described in ABS (Steel Vessels) Polar Class machinery rules at 6-1-3/11.1. As per the rule, the accumulated fatigue failure using linear elastic Miner's rule must be less than 1.0.

From the S-N curve (Figure 4) it is seen that for PC3 and above Polar Classes, fatigue failure or damage (**D**) is more than 1.0, as for these Polar Classes some portion of the actual S-N curves crosses the limiting S-N curve. Also for PC4, the S-N curve is overtaking the limiting S-N curve, and hence '**D**' for PC4 will also be more than 1.0. Thus '**D**' was calculated only for PC5 and lower Polar Classes to assess the fatigue failure of the R-Class propeller blade using Miner's Summation rule.

Fatigue damages calculated are as follows:

$$\mathbf{D_5}(PC5) = \sum_{i=1}^{i=9} \frac{n_i}{N_i}$$

$= (0.0005 + 0.002 + 0.006 + 0.019 + 0.061 + 0.150 + 0.277 + 0.4285 + 0.4188) = 1.363 > 1.0$

Here 'n_i' is the number of actual load cycles obtained from MST and 'N_i' is the allowable or limiting load cycles obtained by extending the S-N curve up to the limiting S-N curve.

A similar calculation was done to check PC6. Thus for PC6 fatigue damage:

$\mathbf{D_6}$ (PC6) = (0.0002 + 0.0009 + 0.003 + 0.009 + 0.022 + 0.052 + 0.099 + 0.172 + 0.111) = 0.469 < 1.0.

With $\mathbf{D_6} <$ 1.0, the propeller design for the R-Class ice breaker meets the fatigue requirements of PC6.

From the analysis it is noted that the fatigue damage of the R-Class propeller is proportionate to the cumulative number of load cycles (N_{ice}) encountered by the propeller.
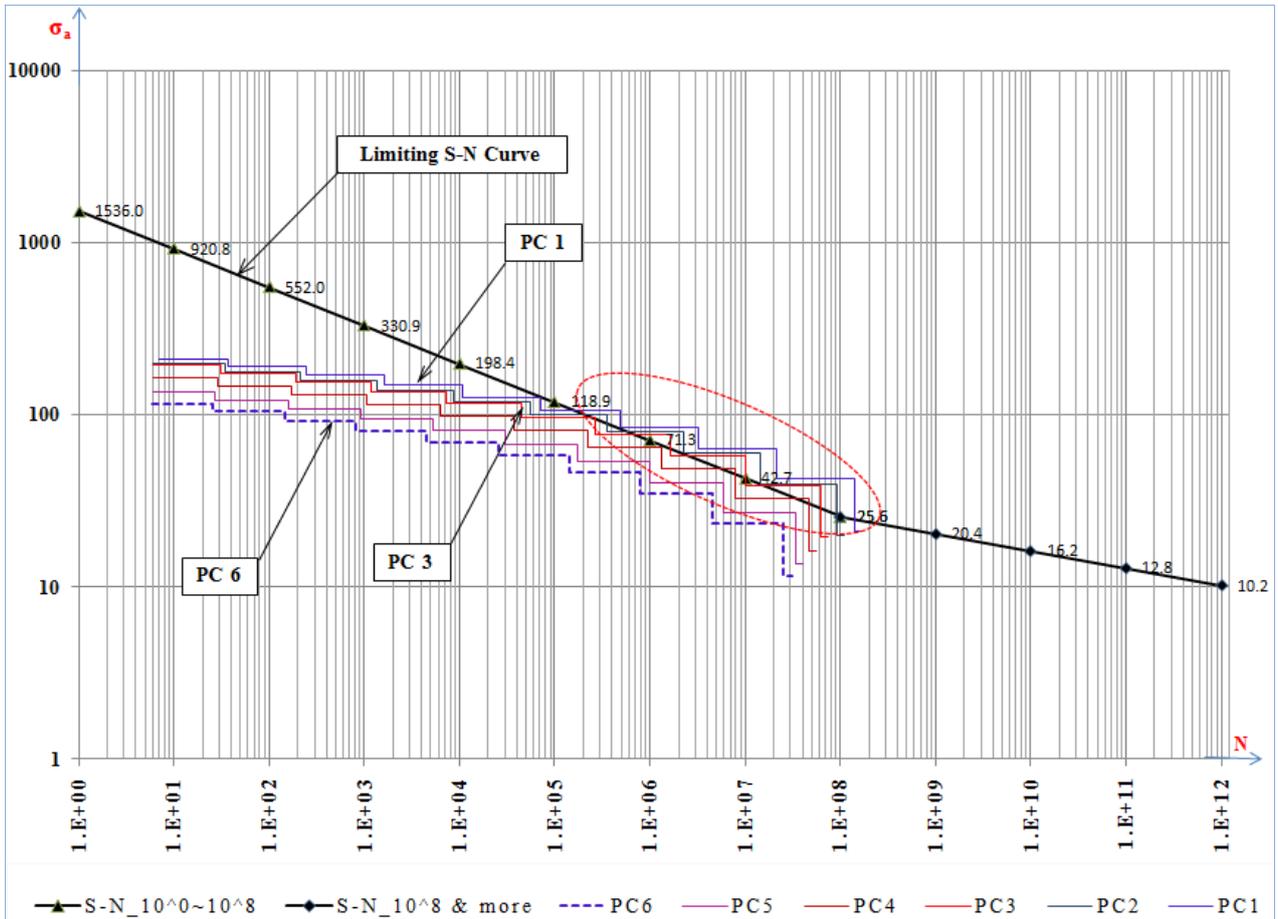
Figure 4: Showing limiting S-N curve (sloped straight lines) and actual S-N curves for PC6 and above Polar Classes

4 DISCUSSION ON RESULTS

The following conclusions and remarks can be made on the basis of the strength calculations and analysis done for the R-Class propeller blade:

- Allowable von Mises stress determined in section 3.2 is 273.3 MPa and the maximum stress obtained for all 7 Polar Classes is 241 MPa (Table 6) for PC1. The maximum stress obtained for PC3 is almost 212 MPa. Hence the propeller blade design is adequate to meet the requirements of the highest Polar Class (PC1) based on blade stress assessment.

- The R-Class propeller is found to meet PC6 (and lower Polar Classes) requirements based on the fatigue strength assessment, as the S-N curve for PC6 of the R-Class propeller design is below the limiting S-N curve and the Miner's Sum (0.469) is less than 1.0. The S-N curve of R-Class propeller for PC5 is also below the limiting S-N curve, but the Miner's Sum (1.363) is more than 1.0 and thus the R-Class propeller design does not comply with the requirements for PC5.

- The depth of the propeller center line of the vessel from LIWL (Minimum Ballast Water Line in Ice) is assumed 5.0 meter, which is more than the propeller diameter. The number of load cycles in the load spectrum per blade (N_{ice}) will change considerably with the change of the depth of submergence of the propeller.

- Modeling of fillet radius at blade root was not done, which affects the results of the calculations due to the stress concentration.

5 CONCLUSIONS

This paper describes fatigue assessment based on ABS Polar Class rules for an existing ice-class propeller. The R-Class propeller was expected to meet PC3 or equivalent requirements, but based on the current fatigue assessment the propeller blade design meets PC6 conditions.

6 ACKNOWLEDGEMENT

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