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REVISION OF BLADE FATIGUE DESIGN CRITERIA FOR FINNISH-SWEDISH ICE CLASS RULES

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Report's title

Revision of blade fatigue design criteria for Finnish-Swedish ice class rules

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Summary

In this report the ”fatigue avoidance criterion”, used in latest Finnish-Swedish Ice Class Rules (FSICR), was investigated. It was found out that there has been an error in the calculation procedure of the latests 2017 rules, and the parameters stated in the rules are incorrect. New parameters were calculated according to revised equations and the ”fatigue avoidance criterion” is shown to work properly with these new parameters. In one calculated example case, the error with the incorrect current parameters is almost 50%.

Using publicly available DNVGL material data, simple comparison calculations were carried out. It would seem that with the new corrected parameters the fatigue calculation is probably the defining blade design criteria, at least in the higher ice classes.

There is a possibility that some of the ships that have been ice classed according to latest 2017 FSICR have a propeller design which does not fulfil the full fatigue calculation procedure.

Corrections to the current rules, as suggested in Chapter 6 of this report, are relatively straightforward. However, fatigue calculation procedure might require more thorough investigation if, for example, the manufacturers consider that the rules are too conservative. One possibility might be to lower the safety factor from 1.5 to 1.3.

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1. Background

The propeller blade fatigue design principle for Finnish Swedish Ice Class Rules (FSICR) was first developed in VTT by Gary Marquis. The methodology proposed to use two slope SN curves. Information from classification societies proposed that especially for steel propellers a one slope SN-curve (slope 8-10) would fit better to test results. This methodology was then developed and included to the FSICR.

The methodology was obtained with regression analysis so that in the application area (Stress and number of revolutions) the error should be less than 5%. During industry hearing this methodology was criticized to be too complex and therefore a simple methodology was developed that would indicate if the fatigue calculation could be neglected in the design process. This methodology is denoted as ”fatigue avoidance criterion” in this report. The background for the fatigue design methodology is shown in reference *[1]*.

After the ”fatigue avoidance criterion” was developed two modification to the ice class rules have been made that affected the parameter values of the methodology. Both of these changes were incorporated in the latest 2017 FSICR.

1. The safety factor for static design methodology was decreased from 1.5 to 1.3. This was agreed in the IACS machinery group (DnV,GL,Lloyds,VTT).

2. In order to be conservative in fatigue design it was agreed to increase the fatigue stress level calculated in the FSICR method by 5%. This was agreed in the IACS machinery group as well.

During 2020 when VTT was reviewing a propeller blade fatigue design calculations, it was found out that there is something wrong with the ”fatigue avoidance criterion”. Calculations of the propeller blade showed inconsistence regarding the fatigue design procedure. According to the ”fatigue avoidance criterion” the design would fulfil the fatigue requirements but when calculating the full fatigue procedure the design would fail. In order to find the reason for this inconsistence the study reported here was initiated.

It was found out that when the FSICR were updated in 2017 *[2]* an error was included in the parameters which are used for calculating the ”fatigue avoidance criterion”. Also it was found that there was a typing error in one of the equations in the original blade fatigue design report which could contribute to errors [1]

2. Parameters for calculating the fatigue avoidance criteria

To calculate the simplified ”fatigue avoidance criterion” in FSICR chapter 6.6.2.3, equation 6.40 is used. This is shown below in equation 1. If the mean fatigue strength σ_{exp} is higher than the criterion, the full fatigue calculation can be skipped.

$$\sigma_{exp} \geq B_1 \sigma_{ref2}^{B_2} \log(N_{ice})^{B_3} \tag{1}$$

For calculation, parameters B_1, B_2 and B_3 are given in the rules. Below in Table 1 the parameters of the current rules are shown.

Table 1, B parameters as stated in the 2017 FSICR

	Open propeller	***Ducted propeller***
B_1	*0.00246*	*0.00167*
B_2	*0.947*	*0.956*
B_3	*2.101*	*2.470*

These B parameters are dependent on C parameters which are used in full fatigue calculation procedure. Current C parameters are listed in Table 2.

Table 2, C parameters as stated in the 2017 FSICR

	Open propeller	***Ducted propeller***
C_1	*0.000747*	*0.000534*
C_2	*0.0645*	*0.0533*
C_3	*-0.0565*	*-0.0459*
C_4	2.22	2.584

These same parameters are found in the original blade fatigue design report [1]. However, as stated earlier, a 5% increase to C_1 parameter was done in order to increase safety. Thus, the original value of C_1 in the blade fatigue design report [1] is lower, 0.000711. Other C parameters were unchanged. As stated, the B parameters are dependent on the C parameters and this relationship is found in the original blade fatigue design report [1]. These equations are shown below.

$$B_1 = (\frac{1}{\gamma})(C_1 1.5^{-C_2})^{\frac{1}{(1-C_3)}} \tag{2}$$

$$B_2 = \frac{1}{(1-C_3)} \tag{3}$$

$$B_3 = \frac{C_4}{(1-C_3)} \tag{4}$$

It was found out that equation (3) has an typing error and equation (2) has to be modified because of the change in static stress safety factor from 1.5 to 1.3.

The new correct equations are listed below.

$$B_1 = \left(\frac{SF_F}{SF_S}\right)^{\frac{1}{(1-C_2)}} (\frac{1}{\gamma})(C_1 {SF_S}^{-C_2})^{\frac{1}{(1-C_3)}} \tag{5}$$

$$B_2 = \frac{(C_2+1)}{(1-C_3)} \tag{6}$$

$$B_3 = \frac{C_4}{(1-C_3)} \tag{7}$$

SF_F = 1.5 (Safety Factor Fatigue) and SF_S = 1.3 (Safety Factor Static). By using the new correct equations 5 - 7 and C values from Table 2, correct B values can be calculated. These are shown below in table Table 3.

Table 3. New corrected B parameter values

	Open propeller	***Ducted propeller***
B_1	*0.00328*	*0.00223*
B_2	*1.0076*	*1.0071*
B_3	*2.101*	*2.471*

When comparing values in Table 1. and Table 3. it can be seen that there is a large difference in B_1 parameters and smaller difference in B_2 parameter. B_3 parameter is unchanged.

3. Example calculation of ”fatigue avoidance criterion”

Example calculation of the ”fatigue avoidance criterion” was carried out for an example ship. New corrected B values are used in these calculations. In the end of the chapter there is a comparison calculation with old incorrect B values. The resulting ”fatigue avoidance criterion” was compared with the full two-slope fatigue calculation. When in full fatigue calculation the maximum stress of load distribution is taken as σ_{ref} / 1.3 we should end up with same safety margin as with the ”fatigue avoidance criterion”.

The ship has a bronze propeller and ice class IA. Below in Table 4. and Table 5 are listed the calculation parameters and material values.

Table 4. Parameters for ”fatigue avoidance criterion” calculation

C1	0.000747	
C2	0.0645	
C3	-0.0565	
C4	2.22	
B1	0.00328	
B2	1.00757	
B3	2.10128	
σ u	630	MPa
σ 0.2	235	MPa
σ ref2	393	MPa
k1	1.3	
k2	1	
k3	1	
Nclass	6000000	
n	6.3	1/s
Nice	49140000	
σ exp E8	110	Mpa
Fatigue Avoidance Criteria	98.17	Mpa
Safety Factor	**1.681**	

Table 5. Parameters for full two-slope fatigue calculation

σ ice max (σ ref2 / 1.3)	302	Mpa
γ e1 γ e2	0.67	
γ v	0.75	
γ m	0.75	
σ exp E8	110	MPa
σ fl	41.46	Mpa
roo	0.08106	
σ fat	24.48	Mpa
Safety Factor	**1.693**	

It can be seen that the safety factor for ”fatigue avoidance criterion” is 0,7% less than the safety factor for the full two-slope fatigue calculation. Thus, the ”fatigue avoidance criterion” seems to work correctly in this case.

If the same example calculation is carried out with the current B parameters, as stated in Table 1., the calculated ”fatigue avoidance criterion” is **51.21** MPa, almost 50% lower value. The safety factor in that case would be **3.22**.

4. Comparison calculations with different materials

To better understand how the fatigue calculation limits the design of propeller for different materials, some example calculations were carried out. Because there are no material values listed in FSICR, material values given in DNVGL rules were used. Ultimate and yield strength values were taken from DNVGL rules for classification Pt.4 Ch.5 Sec.1 table 4. and fatigue strength values were taken from DNVGL rules for classification Pt.6 Ch.6 Sec.6 table 23. These are listed below.

Table 6. Material mechanical properties as given in DNV rules for classification Pt.4 Ch.5 Sec.1 and Pt.6 Ch.5 Sec.6. The extrapolated fatigue strength is extrapolated with SN-curve slope of 4.5.

Material	Minimum yield strength [MPa]	Minimum tensile strength [MPa]	Fatigue strength σFat-E7, [MPa]	Extrapolated fatigue strength σFat-E8, [MPa]
Mn-Bronze, CU1 (High tensile brass)	175	440	80	48.0
Mn-Ni-Bronze, CU2 (High tensile brass)	175	520	80	48.0
Ni-Al-Bronze, CU3	245	590	120	71.9
Mn-Al-Bronze, CU4	275	630	105	62.9
Martensitic stainless steel (12Cr 1Ni)	440	590	120	71.9
Martensitic stainless steel (13Cr 4Ni/13Cr 6Ni)	550	750	150	89.9
Martensitic stainless steel (16Cr 5Ni)	540	760	165	98.9
Austenitic stainless steel (19Cr 10Ni)	180	440	130	77.9

It should be noted that the fatigue strength values in Table 6 are given for 10 million cycles. In FSICR the calculation is carried out with intention of 100 million cycles and thus the Table 6. values should be extrapolated to 100 million cycles. For correct values this requires knowledge on the SN-curve of the material. However, complete S-N curves are not available and thus the fatigue strength at 100 million cycles is estimated by using SN-curve slope value of 4.5. This value should give a conservative estimation, as slope values from 4.5 to 10 are given in FSICR (figure 6-7). These extrapolated values are given in the last column of Table 6.

Next, the ”fatigue avoidance criterion” is calculated with equation 1 for different materials in Table 6. In equation 1 the N_{ice} parameter requires knowledge of some parameters from the propulsion system as well as ice class (see rule equation 6-14). For simplification, parameters for N_{ice} are taken as follows: $k_1 = 1$, $k_2 = 0.8$, $k_3 = 1$, $n = 3$. This would mean a conventional shaftline propulsion and a centreline propeller. Otherwise, values are average values for some known ice classed ships. Criterion is calculated for different ice classes in Table 7.

Table 7. ”fatigue avoidance criterion” and comparison fatigue strength for different materials

	ice class IC		*ice class IB*		*ice class IA*		*ice class IAS*	
Material	**criterion**	**σFat-E8 / Criterion**	**criterion**	**σFat-E8 / Criterion**	**criterion**	**σFat-E8 / Criterion**	**criterion**	**σFat-E8 / Criterion**
CU1	52.43	*0.91*	55.93	0.86	60.21	0.80	63.36	0.76
CU2	58.45	*0.82*	62.35	0.77	67.12	0.71	70.64	0.68
CU3	71.63	*1.00*	76.41	0.94	82.25	0.87	86.56	0.83
CU4	78.04	*0.81*	83.25	0.76	89.61	0.70	94.31	0.67
12Cr 1Ni	77.29	*0.93*	82.44	0.87	88.75	0.81	93.40	0.77
13Cr 4Ni/13Cr 6Ni	98.42	*0.91*	104.99	0.86	113.02	0.80	118.94	0.76
16Cr 5Ni	99.75	*0.99*	106.40	0.93	114.54	0.86	120.54	0.82
19Cr 10Ni	53.00	*1.47*	56.53	1.38	60.86	1.28	64.04	1.22

From Table 7. it can be seen that all the materials, excluding the Austenitic stainless steel (19Cr 10Ni), fail the criterion (σFat-E8 / Criterion < 1) in all but the lowest ice class. In simple terms, this can be understood so that if the blade is designed to just barely meet the static strength criterion, it would most likely not meet the the fatigue calculation criteria. This then makes the fatigue calculation the defining case for blade design.

However, beyond this simple example there are matters to consider in real calculation. In reality the principal stresses should be used in fatigue calculation where as in static calculation von mises stress is usually used. In the above example it is assumed that the stress for fatigue calculation is taken from the static calculation and in essence it would then be the von mises stress. Another consideration is that the stress used in fatigue calculation should be taken as an average of max forward and max backward load at the *same point*. This would usually be lower than the max stress used for static calculation.

As stated earlier, another major contributing factor for results seen in Table 7., is the used slope for extrapolating the fatigue strength values. With real material data, the fatigue strength would probably be higher. However, it should be noted that whether the fatigue calculation is the limiting criteria, is very much dependent on the ratio of ultimate strength and fatigue strength. This can be seen with Austenitic stainless steel (19Cr 10Ni) which has relatively low yield and ultimate strength when compared to fatigue strength.

5. Discussion

The ”fatigue avoidance criterion” is found to be erroneous in the latest 2017 version of FSICR. The criterion gives too good results, and if no other fatigue calculation is carried out, might show incorrectly that the propeller blade fulfils the rules, even if it does not pass the full fatigue calculation. The result of this is that after 2017 some propellers might have been classed incorrectly and might not fulfil the fatigue criteria of the rules.

The correction to the erroneous parameters and equations is presented in chapter 2 of this document. Corrections are relatively straightforward. However, it should be further investigated if the fatigue calculation should be revised more thoroughly. One aspect would be that the fatigue stress safety factor could be lowered from 1.5 to 1.3, as has been done with the static stress criteria.

As stated, some propellers might have been incorrectly classed due to the errors in the current rules. It remains an open question how these should be treated. If these are re-evaluated it might be necessary to check these more accurately to avoid unnecessary modifications to propellers. For example if the ship in question is not frequently operating in ice infested waters, the amount of ice induced impacts on the propeller can probably be reduced.

6. Proposal for rule change

Based on findings on this report, it is proposed that the current FSICR blade fatigue calculation procedures are updated with the new B parameter values as listed in Table 3. This will ensure that the blade ”fatigue avoidance criterion”, as calculated in equation 6.40 in the 2017 FSICR, will be conservative as intended originally.

Further changes require more investigations on how to proceed. All classification societies should be informed on the matter.

7. Summary

In this report the ”fatigue avoidance criterion” used in latest FSICR was investigated. It was found out that there has been an error in the calculation procedure of the latests 2017 rules and the parameters stated in the rules are incorrect. New parameters were calculated according to revised equations and the ”fatigue avoidance criterion” is shown to work properly with these new parameters. In one calculated example case, the error with the incorrect current parameters is almost 50%.

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References

[1] Marquis, G., Koski, K., Koskinen, P., 2008. Fatigue Design Methodology for Propellers Operating in Ice (Rev2). VTT Research Report VTT-R-00717-08.

[2] Trafi, 2017. Ice class regulations 2017 “Finnish-Swedish Ice Class Rules 2017”, Trafi/494131/03.04.01.00/2016

[3] DNV-GL. DNVGL rules for classification Pt.6 Ch.6 Sec.6, Additional class notations - Cold climate, July 2020

[4] DNV-GL. DNVGL rules for classification Pt.4 Ch.5 Sec.1, Systems and components - Rotating machinery - driven units, October 2020