Fatigue

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Consequence and uncertainty-informed fatigue life prediction of ships

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ABSTRACT: Currently, fatigue life prediction of steel welded joints in ships is carried out using class rules and guidance, e.g. DNV-CG-0129. Such methods use a lower bound of the S-N curve. A Design Fatigue Factor (DFF) is suggested in DNV-RP-C203 as a safety factor to the fatigue life for locations that require a higher reliability level. It does not include model and modelling uncertainties. Therefore, this paper provides a framework to select an effective fatigue (FAT) class based on a probabilistic approach at a reliability level appropriate to the uncertainty in design and consequence of failure of the detail. This is offered as a more transparent alternative to the application of a DFF. The designer can perform the fatigue analysis with limited additional effort, whilst obtaining a reliable fatigue life prediction that can ultimately result in improved designs and fewer premature repairs.

1 INTRODUCTION

1.1 *Problem introduction*

Currently, DNV-CG-0129 (2021a) gives a description of the fatigue assessment for ship structures. Amongst the many parameters to be determined, the Class Guideline prescribes to use a conservative lower bound of the S-N curves to account for uncertainties in the fatigue capacity calculation. Deterministic values are used for the Stress Concentration Factor (SCF), cumulative damage used in Miner's rule, and far field nominal loads based on an idealized structure. The margins are therefore implicitly modelled with the selection of the design S-N curve, and not influenced by the severity of the consequences of a failure for the ship or extent of knowledge regarding actual uncertainties for the considered loads, structure and detail. Although information for a probabilistic approach is offered by DNV-CG-0129 (2021a), this approach tends to be time-consuming and does not fit in current design practice for commercial shipping.

1.2 *Literature context*

Besides the deterministic fatigue life prediction based on the 2.3% Probability of Failure (PoF) curve, both DNV-RP-C203 (2019) and DNV-CG-0129 (2021a) suggest uncertainty factors to apply in a probabilistic fatigue life prediction. The class guideline for ship structures, DNV-CG-0129, includes information for a probabilistic approach in the appendix whereas the recommend practice for offshore steel structures, DNV-RP-C203, includes the same in the main text.

The DNV-RP-C203 also introduces the Design Fatigue Factor (DFF). This DFF is typically applied as a safety factor to decrease the PoF for structural details where inspection and repair is more challenging. It is a factor by which the resulting fatigue life N is divided. Under the assumption of an ergodic load the DFF is, using the Linear Damage Accumulation Model (LDAM) by Palmgren (1924) and Miner (1945), equal to one over the critical damage (η). The recommended DFF can be obtained from e.g. DNV-RP-C203 (2021e) and DNV-OS-C101 (2021b) and deviations can be made in correspondence with the client of the ship. However, the linear scale of the DFF in relation to the fatigue life does not accurately reflect the non-linear nature of the probability density function of the fatigue life and is therefore considered as an abstract figure.

In scientific literature a probabilistic approach to fatigue, using the S-N curve approach, is applied to steel welded structures by, amongst others, Chryssanthopoulos & Righiniotis (2006), Kepka & Kepka (2018), Feng et al. (2021), Gao et al. (2021) and Zhao (2021). A detailed overview of uncertainties in the fatigue life prediction is given by ISSC (2018) and Dong et al. (2022). Chryssanthopoulos & Righiniotis (2006) applies the S-N curve approach, using probabilistic distributions, to improve the estimate of the probability and size of the initial crack for the fracture mechanics approach. Kepka & Kepka (2018) applies a rainflow-counting algorithm to

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a time trace to obtain a load histogram and samples the corresponding fatigue life using the probabilistic description of the S-N curve, which corresponds to the probabilistic approach in DNV-CG-0129. Feng et al. (2021) calculates a stochastic SCF with FEM based on variations in production temperature and workmanship and applies this in the fatigue life prediction. The variations in the geometry and material parameters are obtained from measurements. Both Ogeman et al. (2014), Nussbaumer & Grigoriou (2016) and Fricke & Karl (2005) report the variations in local modelling of the weld. Gao et al. (2021) applies only the S-N curve scatter (as was done by Kepka & Kepka, 2018) and compares in addition different damage accumulation models as alternatives to the LDAM. Zhao (2021) focusses on offshore structures and considers a single slope S-N curve formulation based on small-scale experimental data, as well as the probabilistic distributions of the uncertainties similar to the ones used in this paper, to calibrate the DFF's that are reported in DNV-ST-0126 (2021c). Zhao concludes that the reported DFF's can be substantially lower than what is reported by DNV to achieve the intended annual probability of failure. The work by Leonetti et al. (2020) accounts for the uncertainties in the S-N curve and damage accumulation model on the structural detail scale by inferring constant and variable amplitude fatigue test data to a novel generalized random fatigue-limit formulation of the S-N curve and damage accumulation. Velarde et al. (2019) presents a fatigue reliability analysis for a concrete offshore wind structure based on the mean S-N curve and uncertainties in the model input parameters (structural, soil, metocean and fatigue damage). The result is expressed in terms of the reliability index β.

1.3 *Novelty*

In order to incorporate probabilistic information in a deterministic framework, the authors propose to introduce a risk assessment based method. The acceptable PoF depends on the consequence of such a failure. A required fatigue (FAT) class is selected to achieve this required reliability, allowing for a deterministic calculation to complete the fatigue analyses. In this way, the current design practice is adhered to and, in addition, it provides the designer with the flexibility to select a PoF level suited for the location. Our approach differs from the DFF since it explicitly enables a selection of a PoF level corresponding to location-specific uncertainties and reliability demands whereas the DFF is a linear safety factor that is applied to the fatigue life N.

1.4 *Goal*

The goal of this paper is to provide a framework to translate the probabilistic analysis of fatigue life, based on distributions and parameters suggested in DNV-CG-0129 and the Joint Committee on Structural Safety (JCSS), to effective FAT classes at certain probabilities of failure. The result enables structural engineers and ship designers to select a FAT class which adequately reflects the consequence of failure of the detail and the location specific uncertainty distributions. The implementation is low effort and poses a method that is closely related to the current design practice.

1.5 *Scope*

This paper focuses on the determination of the influence of uncertainties in both the loading effects and response, under the assumption of a deterministic input of the Weibull distribution of the loading amplitudes. All reported probabilities of failure are thereby conditional to the load input and assumed uncertainties. The approach closely resembles the probabilistic approach as suggested by DNV and is supplied with probabilistic a priori input from DNV as well as JCSS. Monte Carlo analyses are used to assess the variations. It is noted that the distributions from DNV and JCSS are generic and subject to uncertainty in itself (Dong et al., 2022). The analysis is performed for the Hot Spot Structural Stress Concept (HSSSC) and is based on the DNV-CG-0129 (2021a) closed form damage estimate for two-slope S-N curve and a Weibull distributed load. This formulation is based on the LDAM.

2 METHOD

A probabilistic network is created to cover the fatigue analysis from global loads to fatigue damage. A Monte-Carlo analysis of the spectral fatigue approach is performed to determine the probabilistic predicted fatigue life. The spectral approach is used to limit computational efforts. This analysis results in a probabilistic formulation of the predicted fatigue life which is conditional to the load input and assumed uncertainties. The probabilistic formulation is used to derive the effective FAT class that corresponds to a user-defined and location-specific reliability level.

2.1 *Probabilistic network*

The probabilistic model, as shown in Figure 1, is based on the probabilistic approach in DNV-CG -0129 (2021a) and DNV-RP-C203 (2021e). The blue blocks in Figure 1 represent the calculation nodes that are also part of the current deterministic analysis. The orange blocks represent the uncertainties that affect the distribution of the resulting probabilistic fatigue life. The dotted line between the nominal load and critical damage indicates the potential relation between both

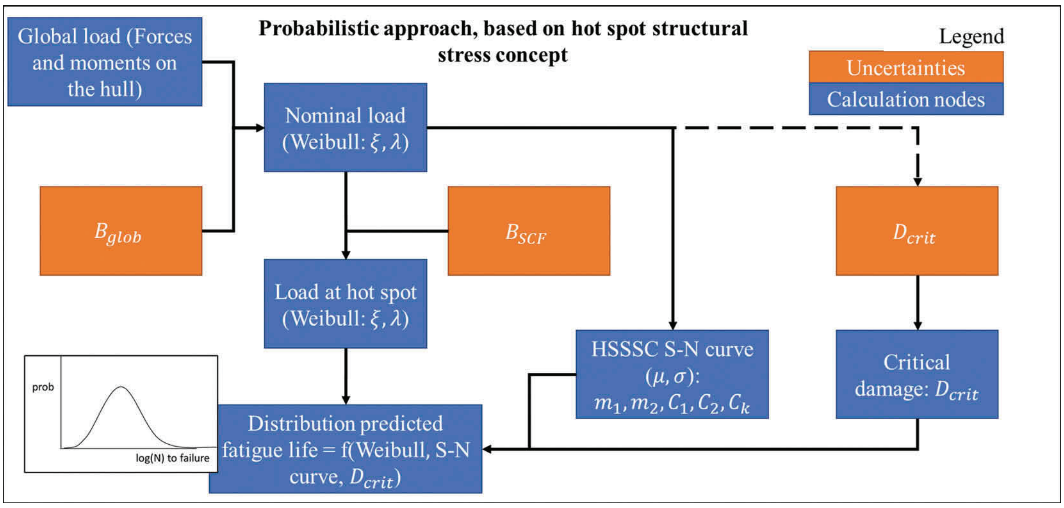

Figure 1. Diagram indicating the probabilistic approach.

blocks due to load interaction and sequence effects. This relation is not incorporated in the current model. The probabilistic analysis results in a probabilistic distribution of the number of cycles to failure. A certain PoF corresponds to a number of cycles to failure N.

The following uncertainties from DNV-CG-0129 (2021a) and JCSS (2013) are taken into account:

1. B_{glob}: global model uncertainty, accounting for uncertainties in the loading and loading effects
2. B_{SCF}: local model uncertainty, accounting for the uncertainty in the determination of the Stress Concentration Factor (SCF)
3. B_{η}: damage accumulation uncertainty, accounting for the simplifications made in the LDAM.

It is assumed that all sources of uncertainty are independent. This assumption is also made in literature (e.g. Nikolaidis and Kaplan, 1991). DNV (both in DNV-CG-1029 and DNC-RP-C203) implicitly recommends to multiply B_{glob} and B_{SCF}, resulting in the combined uncertainty B_{Stress}. This is combined to B_{Stress} in Equation 1.

$$B_{stress} = B_{glob} \cdot B_{SCF} \tag{1}$$

B_{Stress} is multiplied with the scale parameter of the Weibull distribution (q) to modify all considered stress levels accordingly, see Equation 2. The Weibull shape parameter remains constant, as is also assumed in DNV-RP-C210 (2021d). The critical damage, η, is multiplied with the obtained fatigue life N.

$$q = B_{stress} \cdot SCF \cdot q_{design} \tag{2}$$

The scatter in the S-N curve is explicitly accounted for by taking samples of the full S-N curve formulation with a standard deviation of $\delta = 0.2$ that effectively alters the location of the S-N curve knuckle. For each Monte Carlo sample, the intercepts $\log_{10}(K_1)$ and $\log_{10}(K_2)$ are calculated based on the modified location of the knuckle of the S-N curve. The slope remains unchanged in the calculation for both parts of the S-N curve, which in turn introduces a source of uncertainty.

2.2 *Input parameters*

The probabilistic model is applied to an example case based on generic parameters. The Weibull shape parameter ξ is estimated from the vertical wave bending moment (VWBM) for a rule length of 150 m. Only considering the VWBM is a simplification of the total load, which is used in most studies on the uncertainty of the fatigue loads (Dong et al., 2022). For the VWBM, DNV recommends the following formulation of ξ (Hovem, 1993):

$$\xi = 2.21 - 0.54\log_{10}(L) \tag{3}$$

in which L is the vessel rule length in m. For a rule length of 150 m this yields $\xi = 1.035$. The stress level is assumed proportional to the VWBM. This assumption neglects any non-linearities in the loading and response, as well as the effect of pressure variations on the hull. DNV-CG-0129 proposes a Weibull distribution for both the VWBM and the stress level in the fatigue life prediction. The assumption of proportionality is used to apply the same Weibull shape parameter to the VWBM and stress level distribution.

The Weibull scale parameter q is, for this example, set to 86 MPa, corresponding to an equivalent stress level, based on the constant amplitude S-N curve, of 150 MPa. The derivation for these relations is reported below. The two-parameter Weibull distribution is given by:

$$ {}_i = \left(\frac{\xi}{q}\right)\left(\frac{S_i}{q}\right)^{\xi-1} e^{-\left(\frac{S_i}{q}\right)^{\xi}} \tag{4}$$

in which S_i and n_i are the stress bins and number of cycles (normalized) at each stress bin level, respectively. The fatigue life N_i of each stress bin S_i equals:

$$N_i = \begin{cases} \frac{K_1}{S_i^{m_1}} = \frac{10^{6.301+3\log_{10}(FAT)}}{S_i^{m_1}}, \text{for } S_i \geq S_k \\ \frac{K_2}{S_i^{m_2}} = \frac{10^{7+5\log_{10}(0.585FAT)}}{S_i^{m_2}}, \text{for } S_i \leq S_k \end{cases} \tag{5}$$

in which $m_1$and m_2 are the inverse slope and K_1 and K_2 are the intercept of the S-N curve on respectively the left and right side of the knuckle, located at S_k in MPa and FAT is the applied FAT class, in this example FAT90. The results from Equation 5 accumulate to a total life N of $N = \eta \Big/ \sum_{i=1}^{k} \frac{n_i}{N_i}$.

The probabilistic input of the model uncertainties (Table 1) are obtained from the design guidelines DNV-CG-0129 (2021a) and JCSS (2013). JCSS provides one estimate of the probabilistic input for each stochastic variable whereas DNV indicates a range. DNV-1 and DNV-2 give the largest (and thereby conservative) and smallest variability of the indicated ranges, respectively. DNV-3 is the reference distribution that is used in DNV-RP-C203 and by Lotsberg (2016) to illustrate the mechanism of the DFF.

Table 1. Probabilistic input of the model uncertainties (mean, coefficient of variation).

	Probabilistic distributions		
Source	B_{glob}	B_{SCF}	η
DNV-1	N(1, 0.20)	N(1, 0.10)	LN(1, 0.30)
DNV-2	N(1, 0.15)	N(1, 0.05)	LN(1, 0.30)
DNV-3	combined: N(1, 0.25)	LN(1, 0.30)	
JCSS	LN(1, 0.10)	LN(1, 0.20)	LN(1, 0.30)

The number of samples for the Monte Carlo analysis is determined by ensuring that the resulting effective FAT class with two significant digits does not change with additional samples. This is, for the example case, accomplished by using a million samples.

2.3 *Fatigue life prediction*

The prediction of the fatigue life is based on the closed form damage estimate from DNV-CG-0129, based on a bi-linear S-N curve and Weibull distribution. The damage formulation is (DNV 2021a):

$$D = N_D \left[\frac{q^{m_1}}{K_1} \Gamma\left(1 + \frac{m_1}{\xi}; \left(\frac{\mathrm{S_k}}{q}\right)^{\xi}\right) + \frac{q^{m_2}}{K_2} \gamma\left(1 + \frac{m_2}{\xi}; \left(\frac{\mathrm{S_k}}{q}\right)^{\xi}\right) \right] \tag{6}$$

in which D is the dimensionless fatigue damage, N_D is the design fatigue life in number of cycles, q is the Weibull scale parameter in MPa, ξ is the dimensionless Weibull shape parameter and γ and Γ are the incomplete (lower) and complementary incomplete (upper) Gamma functions, respectively. The damage at the design fatigue life can be translated to the number of cycles at failure using:

$$N_{max} = \frac{\eta}{\left[\frac{q^{m_1}}{K_1} \Gamma\left(1 + \frac{m_1}{\xi}; \left(\frac{\mathrm{S_k}}{q}\right)^{\xi}\right) + \frac{q^{m_2}}{K_2} \gamma\left(1 + \frac{m_2}{\xi}; \left(\frac{\mathrm{S_k}}{q}\right)^{\xi}\right) \right]} \tag{7}$$

in which N_{max} is the predicted fatigue life and η is the critical damage in the LDAM.

2.4 *Effective FAT class*

The applied initial FAT class for all structural details is a FAT 90. This is the same curve as the D curve that DNV-CG-0129 recommends for the hot spot structural stress concept. It is assumed that all effective FAT classes, based on the original FAT 90, follow the bi-linear Basquin formulation and have an inverse slope m = 3 and m = 5 on the left and right side of the knuckle. This assumed Basquin-type formulation corresponds to the DNV-CG-0129 D curve. Thereby, the effective FAT class is selected on the abscissa (log(N)), by means of the S-N curve sampling.

Part of the goal of this paper is to make the implementation of reliability based fatigue analysis low-effort and closely related to the current yard practice. The current yard practice comprises a deterministic approach with a lower-bound design level of the S-N curve of the applicable FAT class. In the novel approach, the FAT class is selected to reflect the required location-specific reliability level, without requiring a probabilistic analysis by the designer. Hence, a standard deterministic fatigue analyses is performed, where only the applicable FAT class is adjusted. The selected equivalent FAT class is derived in such manner that the PoF is similar for the probabilistic analysis and the effective deterministic analysis.

3 RESULTS

The results of the probabilistic model and resulting effective FAT classes are presented for an example case with an SCF of 1.5, ship length L of 150 m and Weibull scale parameter q of 86 MPa. In all analyses performed, the S-N curve scatter is accounted for. This means that at the 2.3% PoF, the reference deterministic analysis corresponds to the currently applied FAT 90.

3.1 *Effective FAT classes*

The resulting effective FAT classes of the example case are given in Table 2 together with the PoF that corresponds to the fatigue life that is predicted with the deterministic approach (assuming no uncertainties apart from the reported scatter in the S-N curve). It is observed that this PoF is higher for the wider distributions (DNV-1 vs. DNV-2).

Table 2. Effective FAT classes at PoF levels for each of the reported sets of uncertainty distributions.

	Deterministic	Probabilistic		
PoF	-	DNV-1	DNV-2	JCSS
1%	87	64	71	62
2.5%	90	69	76	68
5%	93	74	80	73
10%	96	80	85	80
20%	101	89	92	89
PoF at FAT 90	2.3%	21.6%	16.3%	20.7%

In the DNV documents, a design S-N curve is drawn for a 97.7% probability of survival (DNV-RP-C203). FAT 90 of the deterministic analysis results indeed in a 2.3% PoF, which corresponds with 97.7% probability of survival. Table 2 shows that the effective FAT classes based on the JCSS distributions are lower than based on the DNV distributions for same PoF. This can be attributed to the relatively high coefficient of variation (CoV) on the local model uncertainty (Stress Concentration Factor) B_{SCF} that is proposed in the JCSS. DNV proposes a range of 0.1 to 0.15, where JCSS proposes a value of 0.2.

3.2 *Comparison with the DFF*

In DNV-RP-C203, the DFF is used to add a certain amount of conservatism to the design of a specific welded detail in a structure or zone within the floating offshore structure. The DFF is a linear factor that is applied to the inverse of the fatigue life N. A higher DFF yields a higher level of conservatism and a lower predicted fatigue life. The maximum listed DFF in DNV-RP-C203 is 10. This DFF is given for the splash zone of an offshore structure (essential, non-inspectable). For a 5-year inspection interval for non-accessible areas, not planned for inspection and repairs during operation, DNV-OS C101 (2021b) recommends a DFF equal to 3. The results in this section are thereby reported for a DFF equal to 1, 3, 5 and 10. Although these values are relatable to the daily practice, they do not bear a relation with the uncertainty in fatigue damage accumulation. In daily practice, a fatigue life of 100 years gives reassurance to the operator. However, the uncertainty is related to both the fatigue life and the stress level. The latter has a 3th, or even 5th order effect on the fatigue life. The Monte Carlo sample size is increased for this analysis to 10 million samples considering that the analysis of higher DFF values yields a prediction further in the tail of the probability distribution of the fatigue life. The PoFs for each of the considered DFF values and each of the considered sets of uncertainty distributions are included in Table 3. Table 3 indicates a reduction of the conditional PoF for higher DFF values.

Table 3. Comparison of the PoF for the DFF value for each of the reported sets of uncertainty distributions.

	Det	Probabilistic		
DFF	-	DNV-1	DNV-2	JCSS
DFF = 1	2.3%	21.6%	16.3%	20.7%
DFF = 3	7e-4%	3.7%	1.2%	4.3%
DFF = 5	*	1.2%	0.2%	1.7%
DFF = 10	*	0.2%	1e-2%	0.4%

* Output too small to obtain with the current number of Monte Carlo samples.

3.3 *Verification with Lotsberg and DNV-RP-C203*

The deterministic approach in the DNV documents is explained in detail, whereas the probabilistic approach is documented to a limited extent. Two publications related to the DNV documents (Lotsberg 2016, DNV-RP-C203 2021e) have been identified that provide an example of the output of the probabilistic analysis by indicating the PoF as a function of the DFF. However, the underlying assumptions are not provided. Both Lotsberg (2016) and DNV-RP-C203 (2021e) report a graph that indicates the relation between the conditional PoF and the DFF. The results of these graphs are used for verification of the novel method presented in this paper. To extract a continuous formulation, a least squares estimate cubic fit is applied to the datapoints in the graphs by Lotsberg (2016) and in DNV-RP-C203 (2021e). For the data by Lotsberg this yields:

$$\log(\mathrm{PoF}) = -0.0033\mathrm{DFF}^3 + 0.0785\mathrm{DFF}^2 - 0.8711\mathrm{DFF} - 0.0768 \tag{8}$$

For the data DNV-RP-C203 this yields:

$$\log(\mathrm{PoF}) = -0.0025\mathrm{DFF}^3 + 0.0617\mathrm{DFF}^2 - 0.6923\mathrm{DFF} - 0.2646 \tag{9}$$

It should be noted that these fits are valid for DFFs in the range from 1 to 10.

There is a lack of information on the background of the curves of the DFF as a function of the PoF by Lotsberg and in DNV-RP-C203. The formulation of the S-N curve (single or dual slope) is not defined, the fixed or flexible nature of the S-N curve knuckle is not discussed, nor is the probabilistic method. The verification of the probabilistic model is performed under the assumption that the S-N curve has a flexible knuckle location and that the same probabilistic method as used in the novel model is applied. Considering that no further information on spectrum shape and S-N curve formulations is included in the explanation by Lotsberg, it is also possible that a single slope closed form formulation of the damage was used. The verification is performed for both a single and dual slope S-N curve formulation. In DNV-CG-0129, the single slope based formulation is given by:

$$D = N_D\left[\frac{q^{m_1}}{K_1}\Gamma\left(1 + \frac{m_1}{\xi}\right)\right] \tag{10}$$

The comparison between the PoF at a DFF value for each of the models (Lotsberg, DNV-RP-C203 and the present paper with a single and dual slope) is included in Table 4.

It is observed that the PoF values of the models by Lotsberg and in DNV-RP-C203 are not identical while the reported input is. Besides that, the single slope formulation in the model of this paper provides a closer resemblance to the models by Lotsberg and in DNV-RP-C203, it is deemed plausible that Lotsberg and DNV-RP-C203 have applied the single slope formulation. Due to the relatively close resemblance of the results to the present paper with a single slope formulation, it is concluded that the novel model is verified for further use.

Table 4. Comparison of the PoF for a DFF value as reported by Lotsberg (2016), in DNV-RP-C203 (2021e) and with the method as presented in this paper – for both a single and dual slope S-N curve model.

PoF	Lotsberg	DNV-RP -C203	Present paper	
n slopes	unknown	unknown	1 (m =3)	2 (m =3,m= 5)
DFF = 1	13.40%	12.70%	15.2%	23.85%
DFF = 3	0.85%	1.40%	0.82%	4.56%
DFF = 5	0.13%	0.32%	0.11%	1.46%
DFF = 10	8e-3%	3e-2%	2e-3%	0.19%

4 DISCUSSION

It is observed that the found effective FAT class, based on the probabilistic analysis, is lower than assumed in the deterministic approach. If the same PoF were to be obtained, the acceptable stress level for a structural detail must be reduced. This arguably makes the resulting design more conservative. However, it should be noted that this PoF is conditional to the assumed load input and the assumed uncertainties. The conditionality to the assumed load input does not deviate from the current deterministic approach. The conditionality to the assumed uncertainties is specific to the probabilistic approach. In reality, only the phenomenological parameters affect the scatter, which can be the actual variations in the modelling of the detail (B_{SCF}), the scatter in the S-N curve (B_{SN}) and the global loading effects (in part in B_{glob}). The actual PoF of a structural detail is likely to differ from the obtained conditional PoF, which is discussed in the section below.

4.1 *Conditional PoF*

In the presented results, the PoF is conditional to the assumed distributions of the uncertainties related to the global model, local model and critical damage. The present analysis is based on a priori estimates of the distributions of the uncertainty factors. These are general factors that are not specific to a ship type and are thereby hypothesized to contain much variability. Adding to that, the widely used statistical parameters "often originate from outdated literature, limited experimental data and assumptions" (Dong et al., 2022).

The global model uncertainty comprises both the loading uncertainty, which is, amongst others, considered in Hageman et al. (2022), and the transfer from global loads to far field stresses at the detail of interest. The uncertainty in the transfer is affected by the production quality of the vessel and influences the load path throughout the structure, as well as the level of detail used to calculate it. If the actual loading coincides with the currently assumed load input (based on the North-Atlantic scatter diagram) and uncertainties, the actual PoF, when accounting for the model uncertainties, is higher than the intended 2.3% with the deterministic approach (up to 20.7%, see Table 3). However, any deviations from the assumed operational profile due to e.g. different operational areas, weather avoidance and reduced percentage of time at sea all may reduce the actual PoF to lower levels. To obtain 2.3% PoF, the effective time spent in North Atlantic has to be reduced to approximately 30%. At first sight, this may be reasonable for a majority of the fleet, which may be acceptable for a deterministic approach. When a probabilistic method is foreseen, a more realistic sailing history is appropriate. The influence of the time in seagoing operations can be studied with the assumption of an ergodic load distribution with the presented model. Next to that, changes in the operational area can be studied provided representative time traces or load histograms can be obtained. It is recommended to study the influence of the scatter diagram (i.e. North Atlantic, World Wide Operation, or a specific dominant trade route) on the fatigue life prediction. This scatter diagram should be reflected in the formulation of the Weibull shape and scale parameter or in a realistic histogram to reflect the load.

The uncertainty of the SCF is in the same order of magnitude as that of the global model, depending on the chosen set of distributions. Round-robin results (Nussbaumer & Grigoriou 2016, Fricke & Karl 2005, Ogeman et al. 2014) indicate typical CoVs of the local model uncertainty in the order of 5% for a variety in assumed extrapolation methods and elements, making the global model uncertainty governing over the local model uncertainty.

The uncertainty in the damage criterion can be reduced when the LDAM by Palmgren and Miner is replaced by a non-linear damage criterion that can account for load interaction effects. This would however complicate the analysis.

4.2 *Implementation in practice*

The presented approach with effective FAT classes enables a designer or customer to select the appropriate (conditional) PoF for a structural detail. This choice can be made based on the expected consequence and an acceptable risk level as well as on the uncertainties that are specific to the considered location. This is not possible with the DFF, considering that the DFF is applied to the deterministic analysis as a safety factor on the fatigue life. The uncertainties are not a variable input. Furthermore, it is noted that the DFF provides a margin to the number of cycles, other than a margin to the stress ranges at the hot spot.

To determine an adequate PoF for a welded detail, a so-called risk matrix can be adopted. The risk-matrix indicates a risk as a function of the consequence and the probability of occurrence. The resulting risk level is expressed in terms of “low”, “medium” and “high”. This approach is getting more traction in the maritime industry to weigh the risk of alternative designs. No references were found that apply the approach of the risk matrix to the fatigue life prediction of ships.

By way of illustration, one can select a welded detail in the bottom of the ship and on the longitudinal deck girder. A failure in the first location is unacceptable, as it comprises longitudinal strength and watertightness, while the latter only gives a manageable effect on the longitudinal strength. To keep an equal risk for both details, this means that the required PoF is lower for the bottom detail than for the girder detail.

4.3 *Damage criterion based on small scale specimens*

Both the currently applied deterministic and the proposed probabilistic model, based on DNV-CG-0129, do not explicitly account for the uncertainty due to the use of small specimen data for the fatigue life prediction of full scale structures. Multiple papers (amongst others Ohta et al. 2002, Lotsberg 2016, Deul et al. 2022) have shown the effect of different scale effects. First of all, a ship structure will normally have parallel load paths. At first deterioration, the weaker points will be unloaded and the other parts will take over, hence elongating the life of the first point. Secondly, the constraints and residual stresses in small scale specimens are different from those in a real ship which causes differences in the effective load level at the hot spot.

5 CONCLUSIONS

This paper has shown how a deterministic approach for fatigue analysis can be adapted to incorporate probabilistic information based on the DNV-CG -0129 approach. A model has been set up to find the conditional PoF based on the uncertainties in the three main parameters: the global and local model uncertainties, and the critical damage. With this model, the effective FAT class can be selected, which can be used in a deterministic approach to obtain the desired (conditional) PoF for a specific structural detail. From this work, the following conclusions can be drawn:

1. The model is verified by comparing results to literature and found sufficiently reliable
2. Based on a desired PoF, equivalent FAT curves can be obtained which are lower than the deterministic FAT curve
3. Uncertainties are based on DNV and JCSS, and distinct differences between the upper and lower

bound of DNV, as well between DNV and JCSS have been found

4. The selection of an effective FAT class does not require the designer to alter the fatigue assessment approach, it merely changes one of the input parameters. It is thereby assumed that this method can easily be implemented in the design and analysis practice.

Recommendations are made to:

– improve and revisit the probabilistic input, as a function of the location of the detail within the vessel, the building process specific to the ship type, ship yard and operational profile.
– identify the relation between the operational area, ship length and the Weibull shape parameter.
– obtain realistic histograms from measurements to reflect the realistic distribution of the load.
– apply e.g. Bayesian statistics to infer the distributions from, if available, full-scale fatigue specimens (e.g. Dijkstra et al. 1998, Fricke & Paetzold 2010). These specimens should incorporate the redundancy in terms of parallel load paths, as well as the actual residual stress levels and distributions. Suggestions are to test ship sections and complex assemblies to expand the database.

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