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FATIGUE ASSESSMENT OF MOORING CHAIN CONSIDERING THE EFFECTS OF MEAN LOAD AND CORROSION

Erling N. Lone*
Norwegian University of Science and Technology
Trondheim, Norway

Thomas Sauder
SINTEF Ocean AS
Norwegian University of Science and Technology
Trondheim, Norway

Kjell Larsen
Equinor ASA
Norwegian University of Science and Technology
Trondheim, Norway

Bernt J. Leira
Norwegian University of Science and Technology
Trondheim, Norway

ABSTRACT

Results from full scale fatigue tests of offshore mooring chains performed in recent years have revealed considerable influence of both mean load and corrosion condition on the fatigue capacity. It has been shown that a reduction of the mean load gives an increase in fatigue life, whereas the corrosion experienced by used chains have a significant negative impact. Neither of these effects are properly addressed by current S-N design curves or design practice.

This paper suggests an extended S-N curve formulation, that includes the effects of mean load and corrosion condition. The parameters of the extended formulation are estimated empirically from mooring chain test data that includes new and used chains, with various mean loads and with different degrees of corrosion. The fitted capacity model is then used for fatigue calculation for the mooring system of a semi-submersible, showing the importance of using realistic mean loads and mooring chain corrosion in fatigue assessments.

1 INTRODUCTION

Fatigue damage is a key challenge for design and service life extension of offshore mooring systems [1,2], and there is a need to better understand and quantify the fatigue capacity of mooring chain components [3]. A large number of full scale fatigue tests have therefore been performed by different parties during the last decade, both for new chains [4,5] and for used chains retrieved from operation offshore [3,6–8]. The results from these tests have revealed that a reduction of the mean load gives an increase in the fatigue life [4,5,9], but also that the degradation due to corrosion may reduce the fatigue life significantly compared to new chain when tested at similar mean load levels [8,9].

1.1 Effect of Mean Load

Existing fatigue design curves for offshore mooring chain (e.g. DNVGL-OS-E301 [10]) are based on fatigue tests performed at a mean load of 20% of minimum breaking load (MBL) [9], and are used for fatigue design check regardless of actual mean loads.

Gabrielsen et al. [9] summarized the fatigue tests conducted by Equinor for used chains retrieved from platforms in the North Sea. These tests were mostly performed at mean loads below 20% MBL, that were representative for the operation of the respective platforms. They concluded that the chains that were tested at the lower mean loads performed considerably better than those tested at higher mean loads, and in some cases even better than expected for new chains – despite degradation due to corrosion.

Zhang and Smedley [4] presented fatigue test results for new chains of high strength and large diameter studless links, with the majority of the tests performed at a mean load of 20% MBL. One

*Corresponding author: erling.lone@ntnu.no

chain section was however tested at a mean load of 10% MBL, and obtained a fatigue life that was significantly longer than the chains that were tested with the same stress range but at the higher mean load. A similar case was studied numerically by Martinez Perez et al. [11], and it was confirmed that a reduced mean load had a positive effect on the fatigue life of the mooring link considered.

Fernández et al. [5] presented tests performed for new chain of similar strength and size as those reported in [4], but at mean loads in the range 7-15% MBL. By comparison to results from previous tests performed at 20% MBL, they showed that the effect of the lower mean load was considerable in terms of improved fatigue performance. They further explored and discussed the use of mean stress correction models on mooring chain, and concluded that a Smith-Watson-Topper (SWT) model is preferred over alternative methods like Gerber and Goodman. The SWT model is defined as [5, 12]:

$$\sigma_{a,0} = \sqrt{\sigma_{max}\,\sigma_a} \qquad (\sigma_{max} > 0) \tag{1}$$

where $\sigma_{a,0}$ is an equivalent stress amplitude that has the same fatigue effect at zero mean stress as a stress cycle with amplitude σ_a and maximum value σ_{max} at a non-zero mean stress level. This model was used to transform stress amplitudes at a given mean stress level to their equivalent amplitudes at another mean stress level, by requiring that they represent the same zero mean stress amplitude $\sigma_{a,0}$.

$$\frac{\sigma_{a,1}}{\sigma_{a,2}} = \frac{\sigma_{max,2}}{\sigma_{max,1}} \tag{2}$$

where indices $(1,2)$ indicate different mean stress levels. Based on this transformation, they calculated S-N curve parameters at different mean load levels and established a S-N design curve for studless chain with parameterized dependence on mean load. Lone et al. [13] used this capacity model to calculate mooring line fatigue damage for a typical production semi-submersible in the Norwegian Sea, and showed that the calculated fatigue damage was reduced by a factor of 2.5-3.0 depending on the orientation of the line. These factors should however be regarded as upper limits for fatigue damage reduction for the unit considered, as the negative effect of corrosion was not accounted for.

1.2 Effect of Corrosion Condition

DNVGL-OS-E301 [10] requires that a corrosion allowance is included to account for the degradation due to corrosion. This allowance is expressed as a uniform corrosion rate, which gives a reduction of the chain link diameter and therefore the cross sectional area. For fatigue assessment, this reduction of the area effectively yields an increase in the calculated stress ranges, thereby reducing the calculated fatigue life. Additional effects of corrosion, such as stress concentrations due to pits and increased surface roughness, are not accounted for.

Gabrielsen et al. [3, 7, 9] reported that these effects had a considerable negative impact on the fatigue life for used and corroded chain, and that fatigue capacity was significantly reduced compared to new chains when tested at comparable mean load levels. The effect of corrosion was found to be more severe than that prescribed by standards such as e.g. DNVGL-OS-E301. Similar results were also reported by Ma et al. [8].

Mendoza et al. [14] suggested a fatigue capacity model that includes the degradation due to corrosion. The corrosion effect was estimated from fatigue tests of used and corroded chains, and they demonstrated that pitting corrosion had a significant negative impact on the fatigue reliability of mooring lines.

1.3 Fatigue Capacity (S-N Curve)

The fatigue capacity of mooring chain components are described by S-N (stress-life) curves, defined as

$$N = A \cdot S^{-m} \tag{3}$$

where N is number of cycles to failure at stress range S (with unit MPa), m is the slope parameter and A is the intercept parameter. In logarithmic form, the curve is given by

$$\log N = \log A - m \cdot \log S \tag{4}$$

where $\log(.)$ is the common logarithm. Hence, a linear relationship between $\log N$ and $\log S$ is assumed. It is worth noting that the two prevailing industry standards for mooring systems use different load definitions for the fatigue capacity curves for chains. API-RP-2SK [15] uses tension range normalized with respect to the breaking strength of a reference quality of same diameter as the chain considered ("T-N" curves), whereas the curves in DNVGL-OS-E301 [10] refer to the nominal stress range ("S-N" curves). In this study, focus is on the latter definition.

For mooring chains, the parameters m and A are estimated by fitting Eqn. (4) to the results of constant amplitude full scale tests, typically by use of linear regression analysis [16]. However; the slope is normally fixed at $m = 3$ for mooring chains [4, 10, 15]. In this case, only the intercept parameter is estimated from the tests.

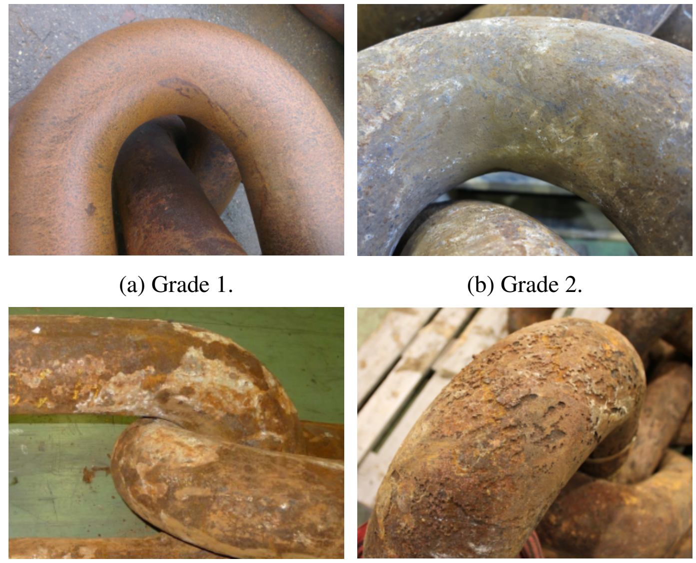
The fitted curve is commonly referred to as the *mean curve*, as it represents the expected value of $\log N$ conditional on $\log S$. The *design curve* is associated with a 97.7% survival probability, and is commonly derived by applying an offset on the intercept value:

$$\log A_D = \log A - k \cdot s_{\log A} \tag{5}$$

where $s_{\log A}$ is the standard deviation of $\log N$ given $\log S$, and $\log N$ is assumed to follow a normal distribution. The factor k is greater than 2 depending on the amount of test data used to estimate the parameters and the required confidence level [10, 17].

Equation (3) suggests that for a given set of the S-N curve parameters m and A, the fatigue life (N) depends solely on the stress range applied. Other influencing factors such as mean load or corrosion must then be accounted for either by estimating the parameters specifically for different subsets (with different values for these factors), or by adjusting the stress ranges used to calculate the fatigue effect. Examples of the latter are mean stress correction factors, or stress scaling factors to account for stress concentration or reduced cross section area due to corrosion.

In this paper, based on a data set described in Section 2, we suggest an extended S-N formulation with additional terms to describe the effects of respectively mean load and corrosion (Section 3). The parameters of the extended formulation are then estimated empirically from mooring chain test data for various mean loads and with different degrees of corrosion (Section 4). Finally, the fitted capacity model is used for fatigue calculation for the mooring system of a typical production semi-submersible, to demonstrate the importance of realistic mean loads and mooring chain corrosion condition in fatigue assessments (Section 5).



(a) Grade 1. (b) Grade 2.

(c) Grade 4. (d) Grade 7.

FIGURE 1: Examples of corrosion grades.

2 FATIGUE TEST DATA

2.1 Description of Test Database

The basis for the work presented in this paper is a number of full scale fatigue tests of both used and new chain links, as summarized in Tab. 1. The used chains have been retrieved after operation at eight different platforms in the North Sea, and several of these test results have previously been presented in refs. [3,6,7,9]. The test set also includes tests #3 and #6 from [8]. Some of the test results for used chain are yet to be published in details. The tests for new chains stem from two joint industry projects; the Noble Denton (ND) joint industry study on 76 mm studless chain of grade R3 and R4 [18], and the TWI joint industry project on fatigue performance of high strength and large diameter studless chain [4].

Certain characteristics of the tests are worth noting:

- All tests are for studless links.
- All tests were performed in sea water. The TWI set originally includes one test performed in air, but this test is not included in the present study.
- Only the first fractures are included in the data analysis. For the ND and TWI sets, the tests were continued after first fracture to obtain additional failures. These are not considered in the present study.
- Different number of chain links were used in the test rigs. For the used chains, number of links varied from 3 to 6 with the majority of the tests at 5 links. The ND tests were performed with 7 links, whereas the TWI tests were performed with 7 links for 127 mm chains and 11 links for the 76 mm chains.
- For used chains, prior fatigue loads accumulated during operation offshore are disregarded.

Each of the chain samples have been assigned a corrosion grade to describe its surface condition and the severity of the corrosion it has been exposed to. For the used chains, these grades have been given based on visual inspection, according to categories ranging from 1 (new chain or mild corrosion) to 7 (severe corrosion) as previously reported by Mendoza et al. [14]. A description of the corrosion categories is given in Tab. 2, and examples are shown in Fig. 1. There are some obvious shortcomings in using this grade system, as it involves a certain subjectivity in the assessment of each sample. Nevertheless, it makes it possible to take into account both the amount of corrosion and the depth and location of corrosion pits, implicitly taking into consideration their presumed impact on fatigue life.

As the fatigue test results will be used to establish a capacity model that accounts for the effects of mean load and corrosion, it is of interest to consider the joint occurrences of these parameters in the test database (Fig. 2). Since more than a third of the database consists of new chain results, the combination of corrosion grade 1 and mean load 20% MBL (which was used for all new chain tests except one) is very much represented. For used chain, the most common combinations are corrosion grades in the range 4-7 and mean load in the range 12-18% MBL. There are generally few tests with mean load below 12% MBL, and none of these are for corrosion grade 2-4. It should also be noted that there are no test results for corrosion grade 7 with mean load 17-20% MBL, and no tests with mean load above 20% MBL.

TABLE 1: Overview of fatigue test database.

Used chain						
Platform	Number of tests	Diameter [mm]	Material grade	Mean load [% MBL]	Corrosion grade	Service life [years]
1	19	114	R4	15.7 - 20.0	2, 4, 5, 6	10.5 - 20
2	9	142	R4	14.0	1	12
3	4	138	R4	14.0	1	7
4	11	126, 136	R4	11.9, 13.5	2, 5, 7	12, 19
5	8	130	R4	6.4, 20.0	5, 6, 7	16, 20
6	12	114, 137	R3, R4	13.4 - 16.8	4, 7	5, 18
7	4	145	R4	9.7	1	15
8	10	130, 139	R4	16.0, 17.0	2, 5, 7	16, 19
Total	77					
New chain						
Project	Number of tests	Diameter [mm]	Material grade	Mean load [% MBL]	Corrosion grade	Service life [years]
ND	26	76	R3, R4	20.0	1	-
TWI	22	76, 127	R4, R5	10.0, 20.0	1	-
Total	48					

TABLE 2: Description of corrosion grades [14].

Grade	Description
1	New chain, or mild uniform corrosion.
2	Some scattered pitting, with pits less than 1 mm deep.
3	Larger areas affected than level 2, with pit depths ca. 1 mm.
4	Large area affected by pitting, with pit depths ca. 1-3 mm; crown area affected by pitting.
5	Severe and widespread pitting, with pit depths up to 4 mm.
6	Severe and widespread pitting, with pit depths up to 6 mm.
7	Severe and widespread pitting, with heavily attacked crown; sharp pits, most being 3 to 6 mm deep, and some even larger.

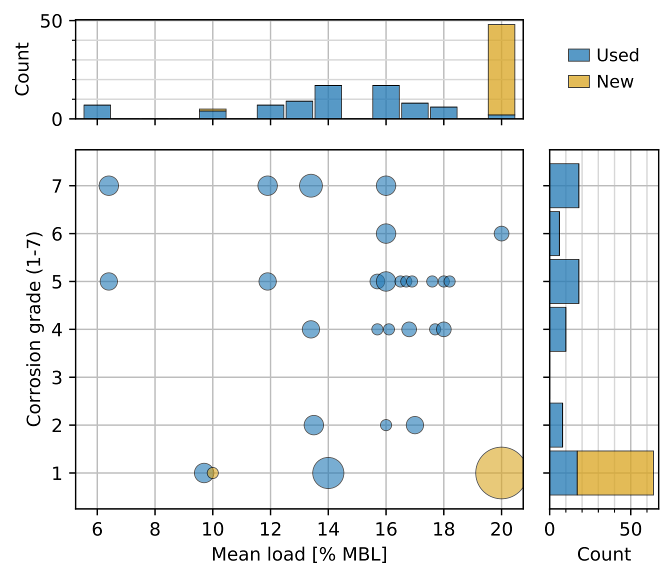
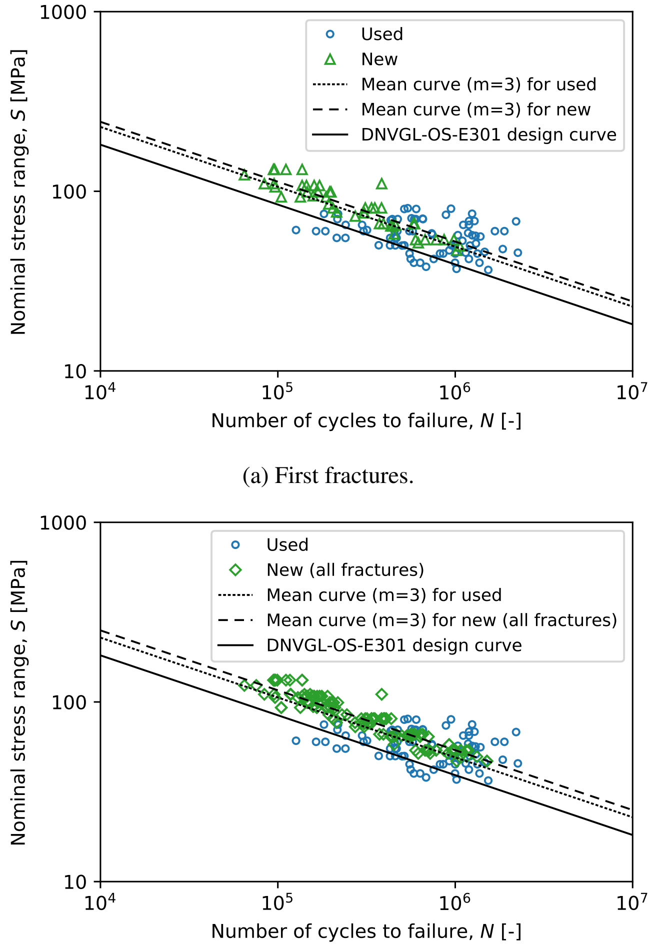


FIGURE 2: Combinations of mean load and corrosion grade, and their marginal histograms. Bubble size indicates number of samples for a given combination.

2.2 Fatigue Test Results

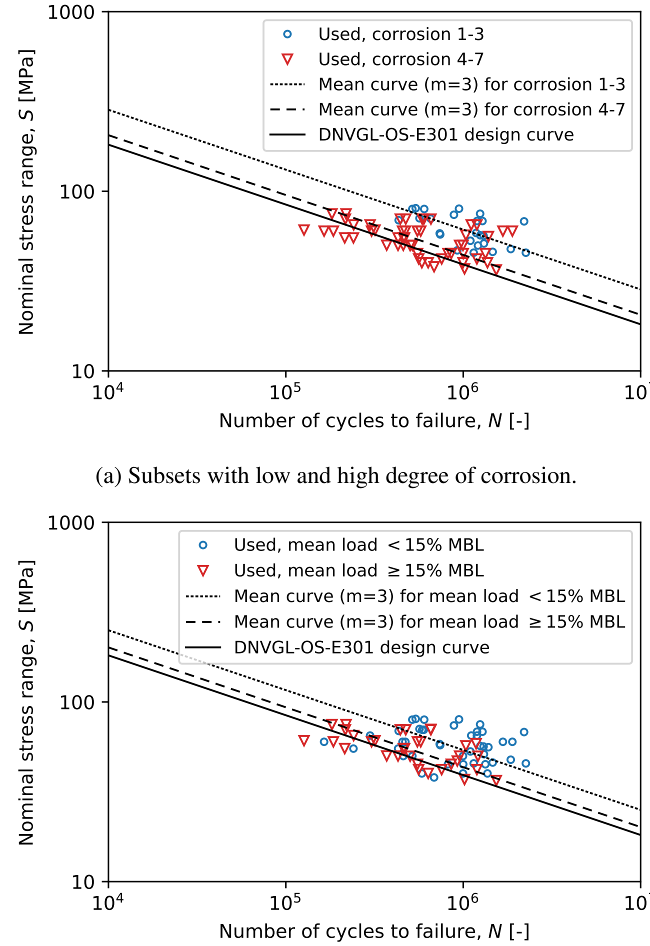
In Fig. 3a, the number of cycles to failure obtained from the fatigue tests are plotted against the applied nominal stress ranges in log-log scale. The design curve for studless mooring chain from DNVGL-OS-E301 [10] is included for reference, along with mean curves estimated by linear least-squares regression with the sloped fixed at $m = 3$. When comparing the fatigue life obtained for used chains to that for new chains, the following distinct observations are made; (i) the mean curve for used chains is slightly shifted towards lower fatigue life than the mean curve



(a) First fractures.

(b) Incl. additional fractures for new chain.

FIGURE 3: S-N plot of all data.



(a) Subsets with low and high degree of corrosion.

(b) Subsets with low and high mean load.

FIGURE 4: S-N plot of used chains.

for new chains, (ii) the used chains exhibit a considerably larger scatter (in terms of deviation from the mean curve), (iii) several of the used chains obtained a fatigue life significantly below that of new chains or even the reference design curve, and (iv) a number of the used chains performed remarkably better than the new chains. The latter could possibly be partially attributed to the number of links applied in the tests, as the weakest out of 7 or 11 links (new chain tests) is likely to fail before the weakest of 3-6 links (used chain tests). However; if the additional fractures obtained for new chains are included, we still see that several used chain samples perform better than new chains at the same stress range level (Fig. 3b).

A more plausible explanation for the observations seem to be the diversity of corrosion grades and mean loads represented in the test set for used chains. This is supported by dividing the samples into subsets of low and high corrosion, and low and high mean load, respectively. Figure 4a shows that the chain samples with the most severe corrosion (here: grade 4-7) are distinctly shifted towards shorter fatigue life, with a few exceptions. In Fig. 4b, we see that the chains with low mean load (here: below 15% MBL) are generally shifted towards higher fatigue life than those with high mean load. Finally, by comparison of these two figures we see that the chains which performed well despite severe corrosion were tested at the lower mean loads, whereas the chains that failed at a low number of cycles despite low mean load were associated with a high corrosion grade.

3 INCLUDING THE MEAN LOAD AND CORROSION DEPENDENCIES

3.1 S-N Curve Formulation

Recalling the S-N curve formulation in logarithmic form (Eqn. (4)):

$$\log N = \log A - m \cdot \log S \tag{6}$$

we recognize that the intercept parameter, $\log A$, controls the position of the curve in log-log space; a higher intercept parameter shifts the curve towards higher fatigue life, and vice versa. A simple yet effective way to include the dependency to mean load and corrosion is therefore to express the intercept parameter as a function of these parameters:

$$\log A(\sigma_m, c) = b_0 + b_1 \cdot g_1(\sigma_m) + b_2 \cdot g_2(c) \tag{7}$$

where $(b_j)_{j\in\{0,1,2\}}$ are constant coefficients and $(g_j)_{j\in\{1,2\}}$ are functions of the mean stress (σ_m) and the corrosion grade (c), respectively. Although Eqn. (7) describes a linear combination, the functions $g_{1,2}(.)$ may generally be nonlinear. The choice of these functions will be discussed subsequently.

By inserting Eqn. (7) into Eqn. (6), we obtain the extended S-N formulation:

$$\log N = b_0 + b_1 \cdot g_1(\sigma_m) + b_2 \cdot g_2(c) - m \cdot \log S \tag{8}$$

A major advantage of this expression is its suitability for the multiple regression analysis that will be described in the next subsection.

3.2 Regression Analysis

The coefficients of the extended S-N curve formulation are fitted to the test data by means of multiple linear regression, see e.g. Ang & Tang [19, Chapter 8]. In our regression model, the dependent variable is the left hand side of the S-N curve formulation ($\log N$), and we have three independent variables, or *regressors*; $g_1(\sigma_m)$, $g_2(c)$ and $\log S$. The regression coefficients are estimated from

$$\hat{\boldsymbol{\beta}} = (\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T\mathbf{y} \tag{9}$$

where $\hat{\boldsymbol{\beta}}$ is a vector containing estimates of the regression coefficients, $\mathbf{y}$ is a vector with l observations of $\log N$, and $\mathbf{X}$ is a l by 4 matrix of the associated regressors:

$$\begin{aligned}
\mathbf{y} &= \begin{bmatrix} \log N_1 & \log N_2 & \dots & \log N_l \end{bmatrix}^T \\
\mathbf{X} &= \begin{bmatrix} 1 & g_1(\sigma_{m,1}) & g_2(c_1) & \log S_1 \\ 1 & g_1(\sigma_{m,2}) & g_2(c_2) & \log S_2 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & g_1(\sigma_{m,l}) & g_2(c_l) & \log S_l \end{bmatrix} \\
\hat{\boldsymbol{\beta}} &= \begin{bmatrix} b_0 & b_1 & b_2 & -m \end{bmatrix}^T
\end{aligned} \tag{10}$$

In our analysis, we will however assume the slope parameter m to be fixed at a predefined value. In this special case, we include the stress range effect in the dependent variable and not among the regressors. That is, Eqn. (10) is substituted by

$$\begin{aligned}
\mathbf{y}' &= \begin{bmatrix} \log N_1 + m\log S_1 & \dots & \log N_l + m\log S_l \end{bmatrix}^T \\
\mathbf{X}' &= \begin{bmatrix} 1 & g_1(\sigma_{m,1}) & g_2(c_1) \\ \vdots & \vdots & \vdots \\ 1 & g_1(\sigma_{m,l}) & g_2(c_l) \end{bmatrix} \\
\hat{\boldsymbol{\beta}}' &= \begin{bmatrix} b_0 & b_1 & b_2 \end{bmatrix}^T
\end{aligned} \tag{11}$$

The *standard error* will be used to quantify the variability of the data set given the fitted model, and is defined as the unbiased estimate of the conditional standard deviation of $\log N$:

$$s_{\log N|\mathbf{X},\hat{\boldsymbol{\beta}}} = \sqrt{\frac{(\mathbf{y}-\mathbf{X}\hat{\boldsymbol{\beta}})^T(\mathbf{y}-\mathbf{X}\hat{\boldsymbol{\beta}})}{l-k-1}} \tag{12}$$

where k is the number of independent variables, and $s_{\log N|\mathbf{X},\hat{\boldsymbol{\beta}}}$ is sometimes referred to as $s_{\log A}$.

The *coefficient of determination* (R^2) will serve as a measure of the overall performance of the regression model:

$$R^2 = 1 - \frac{s^2_{\log N|\mathbf{X},\hat{\boldsymbol{\beta}}}}{s^2_{\log N}} \tag{13}$$

where $s^2_{\log N}$ is the unbiased and unconditional estimate of the variance of $\log N$.

Both the standard error and the coefficient of determination will be calculated based on the definitions given in Eqn. (10), regardless of whether a fixed slope parameter is used or not in the fitting procedure – the rationale being that the ultimate goal of the regression model is to predict $\log N$ satisfactorily.

3.3 Regressors

Although a linear regression model is applied, the regressors are not required to be linear functions of the underlying variables. That is, $g_1(.)$ and $g_2(.)$ may be any linear or nonlinear function of σ_m and c, respectively, as long as they are predetermined. Table 3 lists the functions that have been selected as candidates for the present study.

For mean load, the first function is simply the absolute (nominal) mean stress, σ_m, with unit MPa for consistency with the stress range unit. Next, we include the mean load ratio, defined as

$$\lambda_m = \frac{\sigma_m}{\sigma_u} \cdot 100\% \tag{14}$$

where σ_u is the ultimate tensile strength (UTS). One may wonder about the choice of referring to the unit of λ_m as % MBL, when

TABLE 3: Regressors.

Mean load		**Corrosion grade**	
$g_1(\sigma_m)$	Unit	$g_2(c)$	Unit
σ_m	MPa	c	-
λ_m	% MBL	$\log c$	-
$\sqrt{\lambda_m}$	$\sqrt{\% \text{ MBL}}$		
$\log \sigma_m$	-		
$\log \lambda_m$	-		

we could use the strictly more correct term % UTS or even define it as a non-dimensional decimal. However; in the current context, % MBL and % UTS are equivalent since we refer to nominal stresses, and the use of a decimal number instead of percentage would only imply a factor of 100 on the associated regression coefficient. The former is therefore preferred, for consistency with previous studies [5, 9]. The square root of the mean load ratio, $\sqrt{\lambda_m}$, was included as the preliminary results made it interesting to consider a function with an alternative exponent compared to λ_m. For corrosion condition, we use the corrosion grade, c, on the scale from 1 to 7 as defined previously. Finally, we also include the logarithm of the respective variables, as an analogy to the stress range effect ($\log S$).

4 RESULTS AND DISCUSSION

4.1 Fitted S-N Curves

The results of the regression analysis are presented in Tab. 4, where they have been given labels (A1-A10) for easier reference to each of the curves. The first observation is that the regressors that are based on the mean load ratio, λ_m, generally perform better than those based on the absolute mean stress, σ_m. The implications of choosing one over the other will not be discussed here[1], but based on the higher R^2 values obtained we choose to focus on the curves that are based on λ_m and disregard those based on σ_m in the following.

In the figures that follow, we will present and discuss how the intercept parameter varies as a function of mean load and corrosion grade, respectively. For consistent comparison to reference curves we present the *design* value, obtained from

$$A_D = 10^{\log A_D} = 10^{\{b_0 + b_1 \cdot g_1 + b_2 \cdot g_2 - k \cdot s_{\log A}\}} \quad (15)$$

Here, $k = 2.03$ is calculated based on the number of fatigue tests included in the regression analysis, in accordance with [10]. Keep in mind that the fatigue capacity (or fatigue life) is proportional to the intercept parameter, cf. Eqn. (3).

[1]A brief discussion on how the mean load ratio introduces an implicit material grade effect is given by Fernández et al. [5].

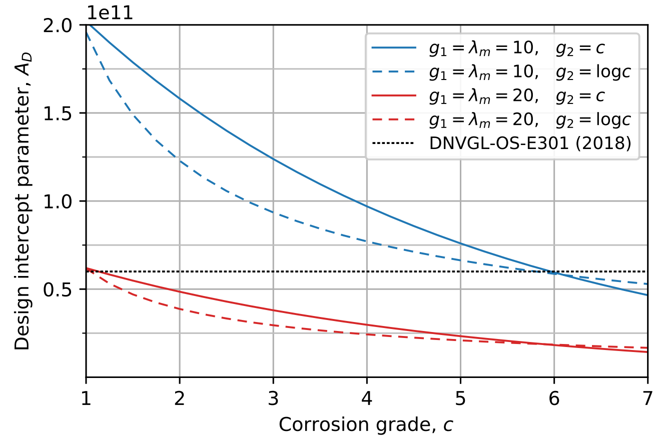


FIGURE 5: Design intercept parameter as function of corrosion grade (curve fits: A3, A4).

Based on the R^2 values in Tab. 4, there is little difference in the performance of the corrosion grade functions considered, although $g_2 = c$ seems to perform marginally better than $g_2 = \log c$ throughout the pairwise comparable results. In Fig. 5, they are compared for two different mean load levels, with $g_1 = \lambda_m$. The corrosion grade functions agree well at $c = 1$, and intersect again at a grade of close to 6. The main difference is for the intermediate grades. As the corrosion grade increases from 1, the fatigue capacity is more quickly degraded when using $g_2 = \log c$ compared to $g_2 = c$. The difference is up to about 30% for both mean load levels. At $c = 7$, the difference is about 15% with $g_2 = \log c$ on the high side. Since the model is purely empirical and provides limited basis for evaluation besides the statistical measures presented, it is difficult to determine which of the functions provides the best description of the capacity degradation due to corrosion. One could argue that $g_2 = \log c$ is a conservative choice for most of the corrosion grade scale, but on the other hand, $g_2 = c$ performs slightly better in terms of R^2. Therefore, the latter will be used for assessment of the mean load functions, whereas both will be considered in the calculation example presented subsequently.

Figure 5 also includes the design curve from DNVGL-OS-E301 [10] with $A_D = 6 \cdot 10^{10}$. Both corrosion functions are consistent with this reference value for new chain ($c = 1$) at a mean load of 20% MBL. It is further observed that the reference design curve intersects with the curves representing $\lambda_m = 10$ at a corrosion grade close to 6. The implication is that for the model shown here, similar fatigue capacity is foreseen for a corrosion grade of around 6 with a mean load of 10% MBL as for new chain with a mean load of 20% MBL.

Mean load functions are compared in Fig. 6. The differences between them are consistent across the three corrosion levels shown. When compared for a given corrosion grade, they agree well for mean loads between 10% and 20% MBL with at most 10% difference within this range. For mean loads above 20% MBL they show a similar monotonic decrease in fatigue ca-

TABLE 4: S-N curve coefficients fitted to all data with different regressors.

Label	m	g_1	g_2	b_0	b_1	b_2	$s_{\log A}$ (a)	R^2
A1	3.0	σ_m	c	12.020	-0.00617	-0.104	0.18	0.76
A2	3.0	σ_m	$\log c$	11.909	-0.00601	-0.659	0.19	0.74
A3	3.0	λ_m	c	12.254	-0.0513	-0.106	0.16	0.81
A4	3.0	λ_m	$\log c$	12.138	-0.0501	-0.673	0.17	0.79
A5	3.0	$\sqrt{\lambda_m}$	c	12.964	-0.387	-0.106	0.16	0.82
A6	3.0	$\sqrt{\lambda_m}$	$\log c$	12.819	-0.375	-0.665	0.17	0.80
A7	3.0	$\log \sigma_m$	c	13.998	-1.309	-0.106	0.17	0.79
A8	3.0	$\log \sigma_m$	$\log c$	13.780	-1.249	-0.662	0.18	0.76
A9	3.0	$\log \lambda_m$	c	13.337	-1.608	-0.104	0.15	0.83
A10	3.0	$\log \lambda_m$	$\log c$	13.170	-1.551	-0.654	0.16	0.80

(a) Standard error of regression model. Strictly the standard deviation of $\log N$ conditional on the data set and the regression coefficients, as defined in Eqn. (12), but referred to as $s_{\log A}$ for simplicity.

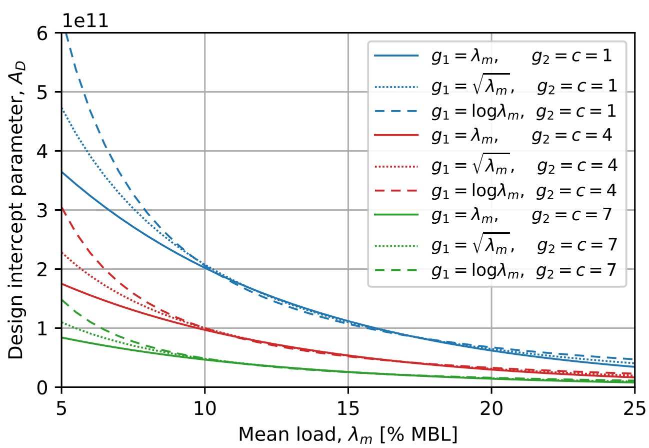


FIGURE 6: Design intercept parameter as function of mean load (curve fits: A3, A5, A9).

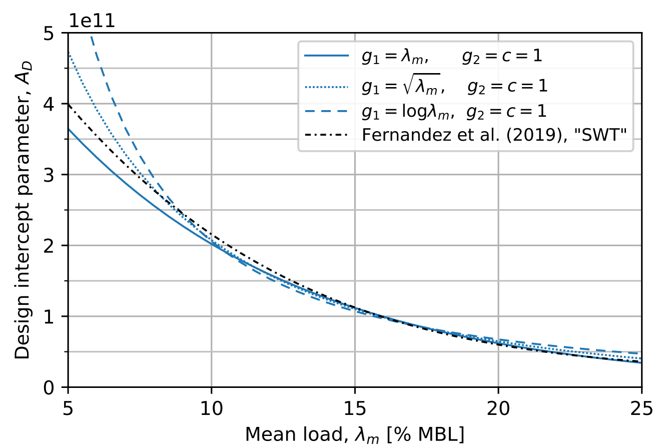


FIGURE 7: Design intercept parameter as function of mean load compared to reference curve (curve fits: A3, A5, A9).

pacity, although with a higher relative difference. In any case, the behavior at such high mean loads is not emphasized as they are beyond those represented in the current data set. On the opposite side, large differences are seen for mean loads below 10% MBL. In particular, $g_1 = \log \lambda_m$ describes a very rapid increase in the fatigue capacity for decreasing mean loads compared to the alternative functions. Hence; despite the promising R^2 values obtained for $g_1 = \log \lambda_m$, it seems unreasonable to adopt this formulation without further justification. In light of the small number of tests with mean load below 10% MBL that are included in the data set, it could be that the performance of this function is somewhat fictitious. This concern is strengthened by comparing with the mean load dependent intercept parameter proposed by Fernández et al. [5], which will be referred to as the SWT curve. The comparison is done for $c = 1$, since the SWT curve was based on tests for new chains. Figure 7 shows that $g_1 = \log \lambda_m$ predicts a fatigue capacity well above the SWT curve for mean loads below roughly 8% MBL. A more moderate prediction is provided by $g_1 = \sqrt{\lambda_m}$, but still on the high side of the SWT curve.

On this basis, it seems more prudent until more experimental results are available, to adopt the mean load function $g_1 = \lambda_m$. It agrees reasonably well with the SWT curve for mean loads in the range from 15% to 25% MBL, and remains on the conservative side for decreasing mean loads. Nevertheless, the mean load correction introduced by this function should be used with caution for mean loads below 10% MBL, considering the limited fatigue test data in this range.

A minor inconsistency between the adopted curves (A3 and A4) is that the mean load effect coefficients (b_1) are slightly

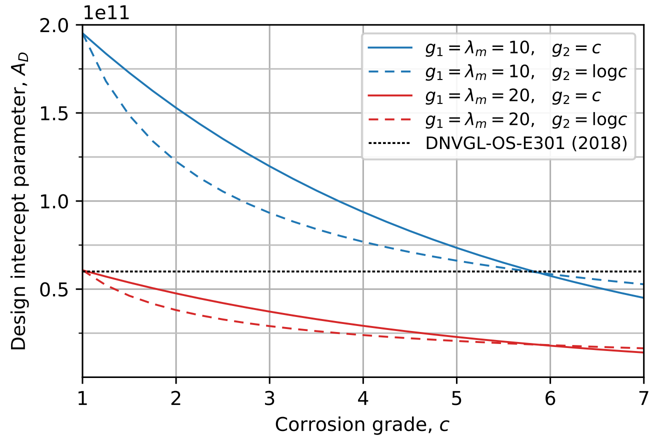


FIGURE 8: Design intercept parameter as function of corrosion grade for the adopted models.

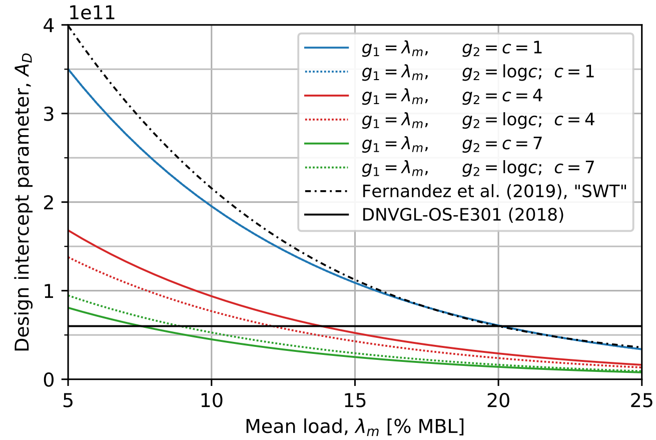


FIGURE 9: Design intercept parameter as function of mean load for the adopted models.

different, despite using the same mean load function ($g_1 = \lambda_m$). Further, these two models will lead to slightly different $\log A$ values for new chain at a mean load of 20% MBL, which may be considered as a convenient reference case. This inconsistency is caused by uncertainties in the coefficient estimates, and possibly interaction between the mean load and corrosion effects in the data set. The following measures are therefore taken to unify the adopted curves:

- The mean load coefficient is taken as the average of the respective b_1 values.
- The b_0 coefficients are adjusted so that the curves yield the same value of $\log A$ for $\{\lambda_m = 20, c = 1\}$.

The functions and parameters of the adopted models for S-N curve including the effect of mean stress and corrosion, as defined by Eqn. (8), are listed in Tab. 5. The corresponding design intercept parameter is visualized for a range of corrosion levels and mean loads in Figs. 8 and 9.

TABLE 5: Adopted models (mean curves).

m	g_1	g_2	b_0 [(a)]	b_1	b_2
3.0	λ_m	c	12.249	-0.0507	-0.106
3.0	λ_m	$\log c$	12.143	-0.0507	-0.673

(a) Design curves are obtained by substituting the value of b_0 by 11.904 and 11.797, respectively.

4.2 Stress Range Transformation

By using the extended S-N formulation, we may derive a stress range transformation analogous to that defined by Eqn. (2) for the SWT model. Let us assume that the stress range S_1 is associated with the parameters $\{\sigma_{m,1}, c_1\}$, and we want to transform it to an equivalent stress range S_2 which is associated with a different mean load level and corrosion grade, $\{\sigma_{m,2}, c_2\}$. The term *equivalent* here implies that they result in the same fatigue life, i.e. we require that $N_2 = N_1$. From Eqn. (8) we then get

$$\begin{aligned} b_0 + b_1 \cdot g_1(\sigma_{m,1}) + b_2 \cdot g_2(c_1) - m \cdot \log S_1 = \\ b_0 + b_1 \cdot g_1(\sigma_{m,2}) + b_2 \cdot g_2(c_2) - m \cdot \log S_2 \end{aligned} \tag{16}$$

which may be reorganized to

$$\begin{aligned} \log S_2 - \log S_1 = \frac{1}{m}\Big(b_1 \cdot \big[g_1(\sigma_{m,2}) - g_1(\sigma_{m,1})\big] \\ + b_2 \cdot \big[g_2(c_2) - g_2(c_1)\big]\Big) \end{aligned} \tag{17}$$

By inverting the logarithm we obtain

$$\frac{S_2}{S_1} = 10^{\frac{b_1}{m}\left[g_1(\sigma_{m,2}) - g_1(\sigma_{m,1})\right]} \cdot 10^{\frac{b_2}{m}\left[g_2(c_2) - g_2(c_1)\right]} \tag{18}$$

Here, the stress range transformation has been split into two factors to separate the mean load correction (first factor) from the corrosion grade correction (second factor).

The stress range transformation has been applied to the fatigue test data to obtain the S-N plot in Fig. 10. The scatter exhibited by the data points for used chain is significantly reduced compared to the previous S-N plot (Fig. 3a), and is now more comparable to that of new chains. This indicates that the adopted model is able to describe the mean load and corrosion effects reasonably well.

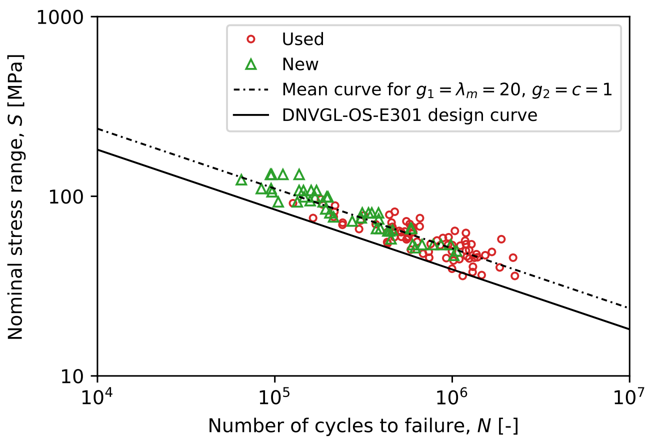


FIGURE 10: S-N plot with stress ranges transformed to represent $\lambda_m = 20$ [% MBL] and $c = 1$.

4.3 Fatigue Life Correction

Similarly, a correction factor that relates the fatigue life at one state, $\{\sigma_{m,2}, c_2\}$, to the capacity described at another, $\{\sigma_{m,1}, c_1\}$, may be obtained from Eqn. (8) by requiring that $S_2 = S_1$:

$$\frac{N_2}{N_1} = 10^{b_1 \left[g_1(\sigma_{m,2}) - g_1(\sigma_{m,1}) \right]} \cdot 10^{b_2 \left[g_2(c_2) - g_2(c_1) \right]} \quad (19)$$

This expression is equivalent to what we would obtain from calculating the ratio of the respective intercept parameters, $A(\sigma_{m,2}, c_2)/A(\sigma_{m,1}, c_1)$, based on Eqn. (7).

4.4 Limitations

It is emphasized that the work and results presented in this paper are subject to certain limitations:

- The corrosion grade is a *subjective* measure. It is therefore a source of uncertainty both with respect to describing the chain degradation and for application to an arbitrary chain segment. The categorization is a work in progress within the LifeMoor project [20], and the goal is to develop an improved and more objective measure.
- The data set for used chain is preliminary. Additional tests for used chain at various mean load levels are ongoing.
- The fatigue test data set contains a limited number of tests for the combination of high corrosion grade and high mean load, and for the combination of low corrosion grade and low mean load. Inclusion of additional test results for both used and new chains, conducted at a range of mean load levels, is expected to increase the confidence in the suggested capacity model.
- Chain segments with different number of links were used in the fatigue tests; 3-6 links for used chains and 7-11 links for new chains. As a consequence the results of the fatigue tests are not entirely consistent, since a chain segment is likely to fail sooner the more links it consists of[2]. This has not been addressed in the current study.
- To address the uncertainty in the estimated coefficients and in application of the corrosion grade scale, one could argue that more than two standard deviations should be subtracted from $\log A$ to derive the design curve. Alternatively; that the regression coefficients $\{b_1, b_2\}$ could be shifted towards conservative values for the design curve. This has not been addressed in the current study.

5 IMPACT ON CALCULATED MOORING LINE FATIGUE LIFE

To demonstrate the impact on calculated fatigue life when both mean load and corrosion grade are accounted for, we will consider an example based on the case presented by Lone et al. [13]. They calculated mooring line fatigue for a typical semi-submersible operating in the Norwegian Sea, with mean loads in the range from 10% to 15% MBL. Mean load dependency was included by means of the SWT curve proposed by Fernández et al. [5] (cf. Fig. 9). For the mooring line with the largest mean load effect it was found that the fatigue damage was reduced to 33% of the fatigue damage obtained with the standard design curve [10], or equivalently; the fatigue life was increased by a factor of 3. This corresponds to an equivalent mean load of 11.3% MBL. That is, for this mean load, the ratio of the intercept parameter of the SWT curve to the intercept parameter of the standard design curve is equal to 3.

Let us consider this mooring line, and for the sake of this example we assume a service life of 10 years. We further assume that fatigue loads are accumulated at a constant rate, i.e. no seasonal or annual variations. Based on the S-N curves adopted in the present study (Tab. 5), the following cases are compared:

- Mean load 20% MBL, without corrosion (i.e. $c = 1$). This corresponds to fatigue damage by means of the standard design curve [10]. This case serves as the reference value.
- Mean load 11.3% MBL, without corrosion (i.e. $c = 1$). This case is similar to fatigue damage by means of the SWT curve, but with the mean load effect represented by the model established in this paper.
- Mean load 11.3% MBL, with corrosion included as required by the standard [10] (i.e. through a reduction of the chain diameter, and a corresponding increase in the stress ranges). A uniform corrosion rate of 0.8 mm/year is assumed.
- Mean load 11.3% MBL, with corrosion effect according to the models in this paper (with $g_2 = \{c, \log c\}$, respectively). The corrosion grade is assumed to increase linearly from 1 at installation to 5 at the end of the service life.

[2] In addition, the most frequent failure locations for new chains are bend, crown and straight part, whereas used chains with corrosion pits tend to fail more often at the crown – see Gabrielsen et al. [3]. This effect is however implicit in the test results.

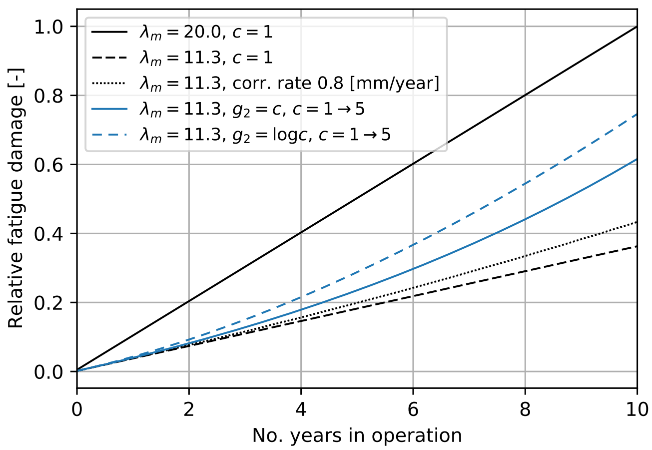


FIGURE 11: Fatigue damage relative to damage at end of service life with $\lambda_m = 20$ [% MBL] and $c = 1$. Effect of corrosion grade dependency.

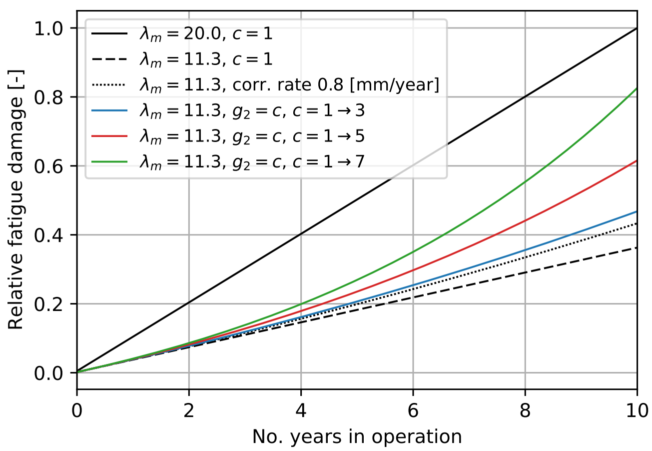


FIGURE 12: Fatigue damage relative to damage at end of service life with $\lambda_m = 20$ [% MBL] and $c = 1$. Effect of corrosion grade at end of service life.

The resulting fatigue damage is shown in Fig. 11. When only the mean load effect is included, the fatigue damage at the end of the service life is 36% of the reference value. This is slightly higher than reported in [13], which is consistent with the previous comparison to the SWT curve (Fig. 7). With corrosion included by means of the uniform corrosion rate, the fatigue damage is increased by 20%. This is considerably less than if a corrosion grade of 5 is assumed at the end of the service life. In this case, the fatigue damage is increased by about 70% ($g_2 = c$) and 110% ($g_2 = \log c$) compared to mildly corroded chains at the same mean load level ($\lambda_m = 11.3$, $c = 1$). Despite the significant corrosion here assumed at the end of the service life, the fatigue damage is still on the lower side of the standard design curve with new or mildly corroded chains ($\lambda_m = 20$, $c = 1$).

Figure 12 includes the fatigue damage for two additional corrosion grades, with $g_2 = c$. With $c = 3$ at the end of the service life, the fatigue damage is about 9% higher than the case with uniform corrosion rate. For $c = 7$, the fatigue damage is considerably higher (95% above uniform corrosion rate, and 130% above $c = 1$).

Note that the same differences with respect to corrosion effect would have resulted if the example had been presented for a mooring line operating at a higher mean load. For instance, for a mean load of 20% MBL with $c = 5$ at the end of the service life; the calculated fatigue damage would be 70-110% higher than $c = 1$ and 40-75% higher than with the uniform corrosion rate used here.

This example demonstrates that the negative effect of corrosion *must* be properly accounted for, in particular if the positive effect of a low mean load is realized or if the system is operated at high mean loads. In that connection, it should be noted that a more rapid and nonlinear development of the corrosion grade from $c = 1$ to its final value would result in higher fatigue damages than those obtained with a linear progress.

6 CONCLUSIONS

Based on full scale fatigue test data for used and new chains, the following extended S-N curve formulations have been found to provide the best and most reasonable fits to the data set:

$$\log N = 12.249 - 0.0507 \cdot \lambda_m - 0.106 \cdot c - 3.0 \cdot \log S \quad (20)$$

$$\log N = 12.143 - 0.0507 \cdot \lambda_m - 0.673 \cdot \log c - 3.0 \cdot \log S \quad (21)$$

where λ_m is the mean load ratio expressed in % MBL and c is a corrosion grade on a scale from 1 (new chain) to 7 (severe corrosion). The corresponding design curves are given by

$$\log N = 11.904 - 0.0507 \cdot \lambda_m - 0.106 \cdot c - 3.0 \cdot \log S \quad (22)$$

$$\log N = 11.797 - 0.0507 \cdot \lambda_m - 0.673 \cdot \log c - 3.0 \cdot \log S \quad (23)$$

These formulations differ in how they include the corrosion effect. Equations (21) and (23) (with $\log c$) describes a more rapid degradation of the fatigue capacity when the corrosion grade increases from $c = 1$, compared to Eqns. (20) and (22).

The selected curves are believed to describe the mean load effect reasonably well for mean loads in the range from 5% to 20% MBL. However; for mean loads below 10% MBL the model should be used with caution, since the data set used to establish it contains few tests at low mean load levels. The curve is highly uncertain for application to mean loads above 20% MBL, as the data set did not contain any tests for mean loads above this level.

Using this model, it has been shown that the negative effect of corrosion is larger than that prescribed by standards such as DNVGL-OS-E301, and therefore must be properly accounted for. On the other hand, the effect of severe corrosion may be compensated by a sufficiently low mean load.

It is emphasized that the model should be regarded as preliminary, as the fitting is based on a preliminary data set. Furthermore, the corrosion grade categorization is subject to uncertainty. The model may be improved if a better and more objective corrosion measure is developed.

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