Proceedings of the ASME 2020 39th International Conference on Ocean, Offshore and Arctic Engineering OMAE2020 August 3-7, 2020, Virtual, Online

OMAE2020-18628

INFLUENCE OF MEAN TENSION ON MOORING LINE FATIGUE LIFE

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

Thomas Sauder
Vegard Aksnes
SINTEF Ocean AS
Trondheim, Norway

Øystein Gabrielsen
Equinor ASA
Trondheim, Norway

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

ABSTRACT

Studies published in recent years have documented a significant mean load effect on fatigue capacity for offshore mooring chain, and show that a reduction of the mean load gives an increase in fatigue life. However, current S-N design curves are based on fatigue tests performed at a mean load of 20 % of minimum breaking load (MBL), which is well above the typical mean loads for most mooring systems.

This paper investigates the mean loads experienced during fatigue damage accumulation for the mooring system of a typical production semi-submersible, operating in Norwegian Sea conditions. The study is based on numerical, time-domain simulations, using environmental conditions defined from a series of hindcast data. A parameterized S-N design curve suggested by Fernández et al. (2019), incorporating a Smith-Watson-Topper mean stress correction model, is applied for fatigue damage calculation and compared to results for the S-N design curve prescribed by current standards.

For the semi-submersible unit considered there is negligible difference in basing the correction on 3-hour mean load compared to the mean load of individual stress cycles, due to small low frequency tension variations. On this basis, a single correction factor is proposed to allow for mean load correction based on results available from a standard fatigue analysis.

INTRODUCTION

Fatigue is a key challenge for design and service life extension of offshore mooring systems, and there is a need to better understand and quantify the fatigue capacity of mooring chain components. A large number of full-scale fatigue tests have therefore been performed by different parties during the last decade [1–4]. Although a mean load effect on fatigue capacity was suspected based on results at an early stage, it was hard to conclude at the time due to large uncertainties with respect to chain condition (corrosion and surface pits), different chain qualities and manufacturers, and statistical uncertainty. As more full-scale tests have been performed with an increasing awareness of mean load effects, combined with increasing knowledge sharing across initiatives, the general consensus is now that mean load effect on fatigue damage is significant [3–5].

Existing fatigue design curves for offshore mooring chain (e.g. DNVGL-OS-E301 [6]) are based on fatigue tests performed at a mean load of 20 % of minimum breaking load (MBL) [4, 5], and are used for fatigue design check regardless of actual mean

*Corresponding author: erling.lone@ntnu.no

loads. For systems operating at mean loads below 20 % MBL, this may imply a need for costly replacements at an earlier stage than strictly required. Likewise; for systems with mean loads above 20 % MBL, failure to account for the reduced fatigue capacity may lead to operations at an unacceptable reliability level.

Despite the consensus on significant mean load effect, a main challenge has been to quantify its practical importance. Fernández et al. [5] explore and discuss use of mean load correction models for mooring chain, and conclude that a Smith-Watson-Topper (SWT) model is preferred over alternative methods like Gerber and Goodman. The SWT model is defined as [5, 7]:

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

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. Fernandez et al. [5] used this model 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.

In this paper we use a numerical case study to investigate mean load properties. We then apply the S-N design curve proposed in [5] to provide an example on how the mean load effect on calculated fatigue damage may be quantified. Alternative ways of selecting mean loads associated with each stress cycle are applied and discussed.

NUMERICAL MODEL
Mooring system

A typical production semi-submersible operating at 300 m water depth in Norwegian Sea conditions is considered. The mooring system is composed by 16 lines, organized in clusters of four (Fig. 1). For the current study, the upper chain segment of one line from each cluster is considered (Tab. 1). All lines consist of a catenary chain-wire configuration, with studless chain for the upper (towards fairlead) and lower segments (towards anchor), and steel wire rope in-between (Fig. 2). Chain diameter is the same for all lines. The mooring pattern is slightly asymmetric, with shorter lines towards east. Lower pre-tension is applied for the westward cluster to reduce the extreme loads, as these lines point towards the dominating wave direction. Pre-tension is defined as the tension in the component when there are no environmental loads acting on the unit or the mooring lines.

TABLE 1: MOORING LINE CHAIN COMPONENTS CONSIDERED FOR FATIGUE DAMAGE ASSESSMENT.

Line	Cluster	Component	Pre-tension [% MBL]
1	South	At fairlead	12.0
5	West	At fairlead	11.0
9	North	At fairlead	12.0
13	East	At fairlead	12.2

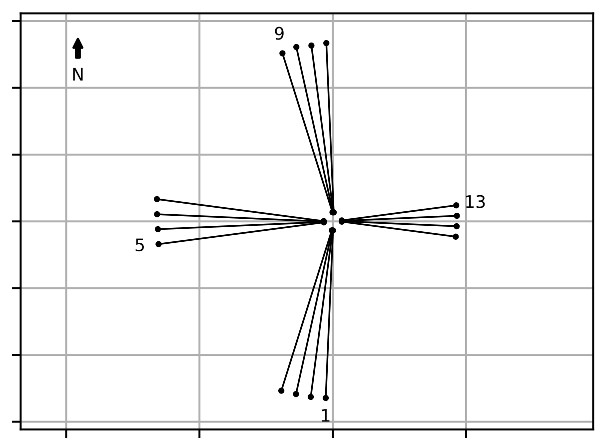


FIGURE 1: HORIZONTAL PROJECTION OF MOORING SYSTEM.

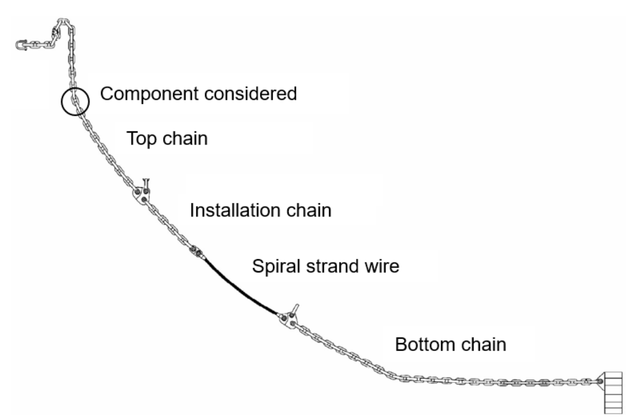


FIGURE 2: MOORING LINE COMPOSITION (NOT TO SCALE).

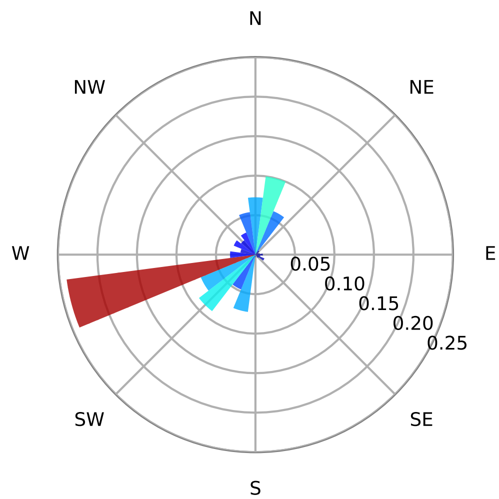


FIGURE 3: WAVE DIRECTION RELATIVE FREQUENCY OF OCCURRENCE. WAVES ARE COMING FROM THE DIRECTIONS SHOWN.

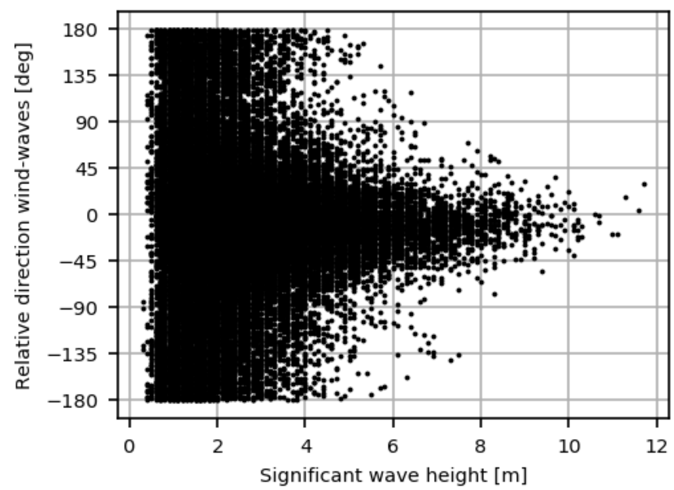


FIGURE 4: SCATTER PLOT OF RELATIVE DIRECTION WIND-WAVES VS. SIGNIFICANT WAVE HEIGHT.

Hindcast data

Environmental conditions are based on a hindcast data series [8], representing typical Norwegian Sea conditions. Each condition represents a 3-hour sea state, and is characterized by:

- significant wave height,
- wave spectral peak period,
- wind velocity,
- wave direction,
- wind direction.

Roughly 12 years of data are used, starting from September 1957. Current velocity and direction in each condition is estimated based on a simple wind to current relationship [9].

The distribution of wave directions is shown in Fig. 3. Although waves are the main contributors for dynamic loads, wind is equally important for the mean loads in the system. Within the data set applied, wind directions are more evenly distributed than waves directions. However; for sea states with significant wave height above 6-7 m, wind and wave directions are fairly correlated (Fig. 4). For the sea states that contribute the most to fatigue loads, the mean load contributions from wind and waves therefore act roughly in the same direction.

FATIGUE DAMAGE CALCULATION

Tension-tension fatigue is considered. Stress cycles are counted according to the Rainflow counting algorithm in section 5.4.4 of ASTM E1049-85 [10]. Fatigue capacity is expressed by a S-N design curve, defined as:

$$N \cdot S^m = a_D \,, \tag{3}$$

where N is number of cycles to failure at stress range S, m is the negative inverse slope parameter and a_D is the design curve intercept parameter. Fatigue damage is calculated as the Palmgren-Miner sum:

$$D = \sum_i \frac{n_i}{N_i} = \sum_i \frac{n_i \cdot S_i^m}{a_D} \,, \tag{4}$$

where n_i is number of stress cycles with range S_i, and N_i is the fatigue capacity for this stress range. An implication of Eqs. 3 and 4 is that fatigue capacity is proportional to the intercept parameter a_D, and that fatigue damage is proportional to the inverse of a_D.

Two different S-N curves are used:

1. DNVGL-OS-E301 [6] design curve for studless chain; $m = 3.0$, and $a_D = 6.0 \cdot 10^{10}$.
2. "SWT-curve"; $m = 3.0$, and a_D parameterized as function of the mean load.

The latter design curve is derived by Fernández et al. [5] using regression analysis on a SWT mean stress correction model applied at different mean load levels. They then performed a polynomial fit to fourth order for the intercept parameter to obtain:

$$a_D = 4.521 \cdot 10^5 \cdot x^4 - 6.173 \cdot 10^7 \cdot x^3 + 3.174 \cdot 10^9 \cdot x^2 \\ - 7.435 \cdot 10^{10} \cdot x + 6.989 \cdot 10^{11} \,. \tag{5}$$

Here, x is the mean load expressed in % of MBL and the intercept parameter obtained relates to stress ranges in MPa. From comparison of the two curves (Fig. 5), we see that they coincide at a mean load of 20 % MBL. For lower mean loads the SWT-curve yields a higher intercept parameter, hence predicts a higher fatigue capacity. Conversely, at mean loads above 20 % MBL the SWT-curve predicts lower fatigue capacity.

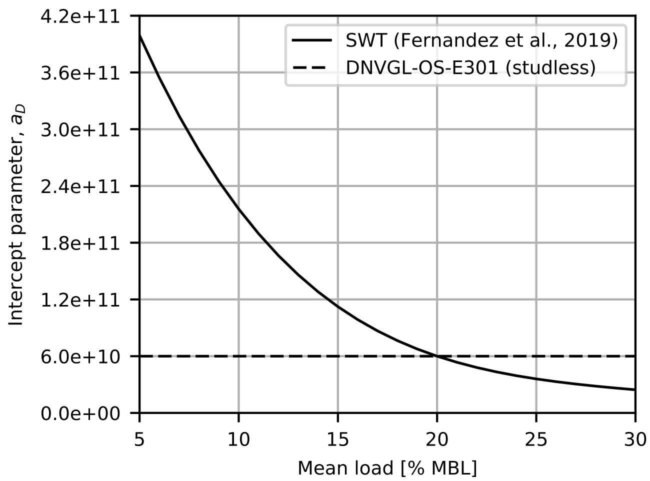


FIGURE 5: S-N CURVE INTERCEPT PARAMETER, a_D.

It should be noted that the design curve given by [5] and defined in Eq. 5 is based on fatigue tests of new chains only. According to Gabrielsen et al. [4], the negative effect of poor condition due to corrosion and surface pits may be equally important as the positive effect of low mean load. Moreover, corrosion is seen to impact fatigue capacity more negatively than what is obtained from the simple assessment required by e.g. [6]. One should therefore be careful about accounting for mean load alone, when assessing the remaining fatigue life of a mooring system chain component.

Mean load associated with each stress cycle is determined in three alternative ways:

- *Cycle mean*: calculated as average of maximum and minimum load in each individual cycle, consistent with [10].
- *3-hour mean*: represented by the component's 3-hour mean load for the sea state the cycle is encountered in.
- *Pre-tension*: represented by the component's pre-tension.

Pre-tension is not strictly representative as a mean load, but makes a tempting alternative due to its simplicity; it is a well defined operational parameter and would yield a constant S-N curve intercept parameter for all cycles and conditions (assuming that the draft is constant and there is no winching).

RESULTS

Fatigue Damage With Standard Design Curve

Accumulated fatigue damage history based on the S-N curve from DNVGL-OS-E301 is shown in Fig. 6. Despite pointing towards the dominating wave directions, line 5 (West) is seen to be the least critical line with respect to fatigue. This is primarily due to the lower pre-tension in this line, which yields a slightly softer tension characteristic and thereby reduces both low and wave frequency tension responses.

The highest fatigue damage is accumulated for line 13 (East), which is positioned opposite the dominating wave directions. It is therefore exposed to large in-line motions, and the mean load reduction it experiences does not compensate the higher pre-tension. This reasoning is supported by Fig. 7, which shows the relative fatigue damage contribution versus wave direction for line 1 (South). This line accumulates little damage from the western sectors, which act in a direction transverse to the line. Instead, fatigue damage is accumulated mostly with waves from the southwestern sectors. These waves are less frequent, but act more in-line and therefore induce larger motions in the tangential direction of the top end of the mooring line.

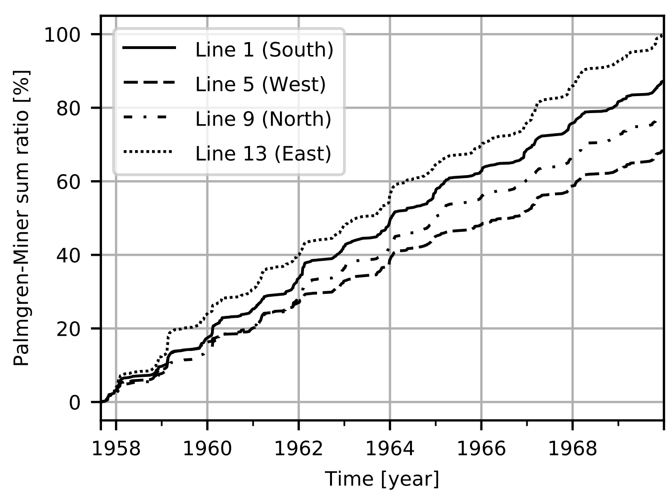
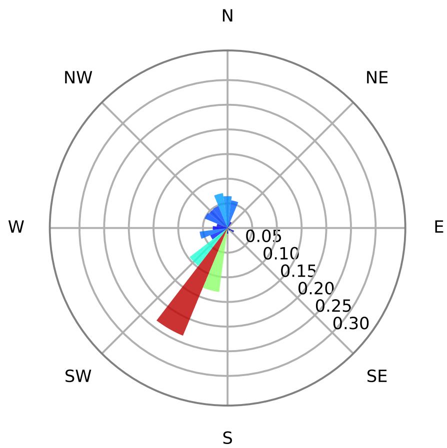
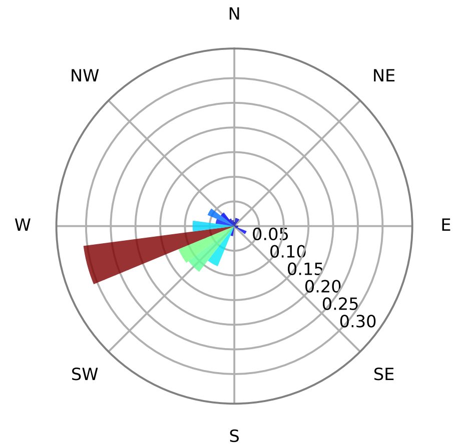


FIGURE 6: ACCUMULATED FATIGUE DAMAGE TIME HISTORY USING S-N CURVE FROM DNVGL-OS-E301, IN PERCENT OF DAMAGE AT END OF PERIOD FOR LINE 13.



(a) LINE 1 (SOUTH).



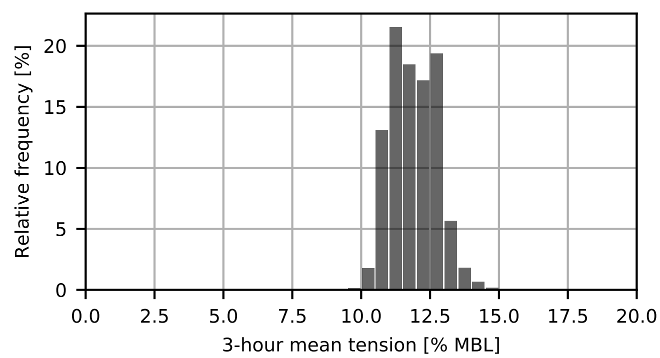
(b) LINE 13 (EAST).

FIGURE 7: RELATIVE FATIGUE DAMAGE CONTRIBUTION VS. WAVE DIRECTION (COMING FROM).

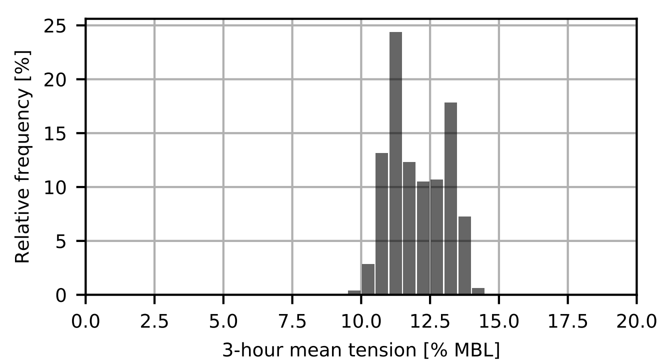
Mean Load Distribution

Histograms of 3-hour mean load for lines 1 (South) and 13 (East) are shown in Fig. 8. As expected, the 3-hour mean loads are seen to vary around the pre-tension (12.0 and 12.2 % MBL, respectively). Furthermore, variations are moderate, with mean tension within the range of 10 to 15 % MBL for the majority of sea states. Interestingly, the distributions of cycle mean show very small deviations from those of 3-hour mean (Fig. 9). Although the mean value of low frequency cycles will obviously be close to the 3-hour mean, one could expect the low frequency variations to cause some deviations for cycles governed by wave frequency tension. However; for the semi-submersible unit considered, low frequency tension variations are small compared to 3-hour mean as shown by the scatter plot in Fig. 10.

Cumulative histograms for 3-hour mean load are shown in Fig. 11, where frequency of occurrence is compared to the fatigue damage contribution from associated cycles. For line 1 (South), damage contribution is shifted towards higher mean loads, meaning that fatigue is mostly accumulated in sea states with mean load above average. The opposite effect is seen for line 13 (East), as damage accumulation is shifted towards cycles associated with 3-hour mean below average.

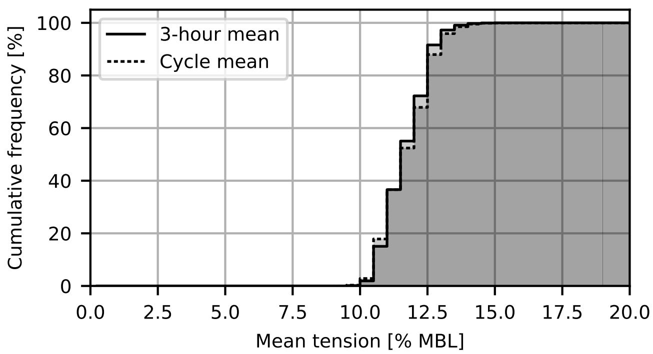


(a) LINE 1 (SOUTH).

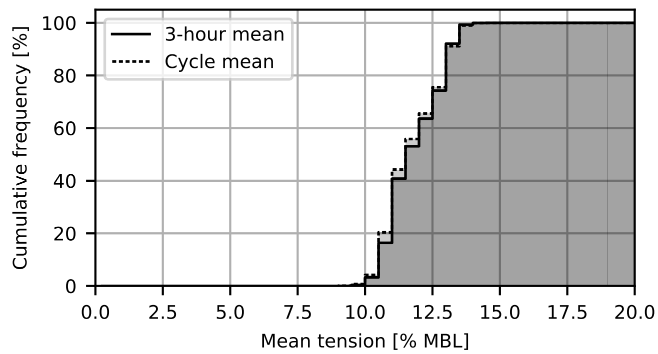


(b) LINE 13 (EAST).

FIGURE 8: FREQUENCY HISTOGRAM FOR 3-HOUR MEAN LOAD.

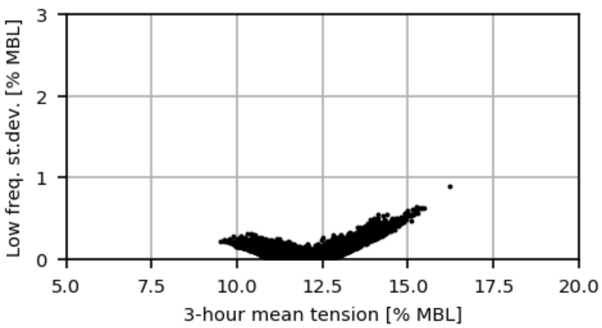


(a) LINE 1 (SOUTH).

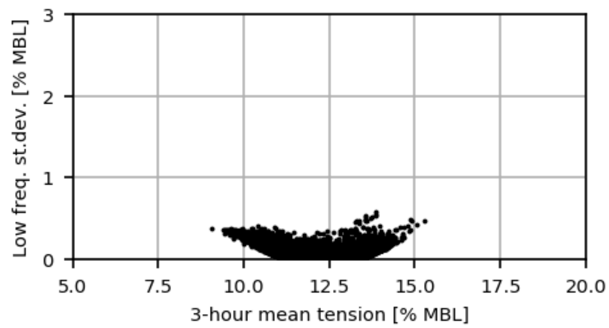


(b) LINE 13 (EAST).

FIGURE 9: CUMULATIVE FREQUENCY HISTOGRAM FOR 3-HOUR MEAN LOAD VS. CYCLE MEAN.

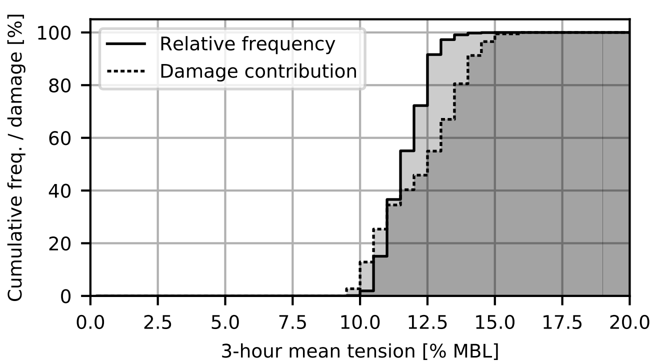


(a) LINE 1 (SOUTH).

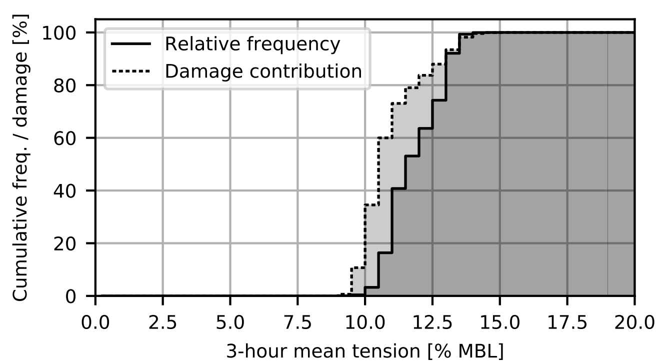


(b) LINE 13 (EAST).

FIGURE 10: LOW FREQUENCY STANDARD DEVIATION OF TENSION VS. 3-HOUR MEAN LOAD.



(a) LINE 1 (SOUTH).



(b) LINE 13 (EAST).

FIGURE 11: CUMULATIVE HISTOGRAMS FOR 3-HOUR MEAN LOAD: RELATIVE FREQUENCY AND DAMAGE CONTRIBUTION.

Fatigue Damage With Mean Load Correction

Accumulated damage history obtained with mean load correction is shown in Fig. 12, and results are compared to those based on the standard design curve (DNVGL-OS-E301) in Tab. 2. The mean load correction reduces calculated fatigue damage significantly for all lines, with the highest reduction for line 13 (East). For line 1 (South) fatigue damage is reduced slightly less, and this line now shows the highest accumulated damage. This is consistent with what could be expected based on the mean load distributions in Fig. 11, as line 13 accumulates fatigue damage at a lower mean load than line 1.

As expected from the cumulative frequency histograms, mean load correction based on 3-hour mean yields similar results as correction based on cycle mean. In fact, the difference between these approaches is less than 1 % for all lines – see Tab. 3. This is further supported by Fig. 13 which shows that the accumulated fatigue damage for line 1 – with mean load correction based on cycle mean and 3-hour mean, respectively – agree very well throughout the time history. The same consistency is seen also for the other lines.

Correction based on pre-tension, on the other hand, gives somewhat deviating results since the effect of environmental loads are not taken into account. For lines more or less on the windward side of the dominating wave directions (lines 1, 5 and 9), fatigue damage is underestimated by close to 15 % compared to correction based on actual mean loads. For line 13 (East), which is on leeward side of dominating wave directions, fatigue damage is correspondingly overestimated.

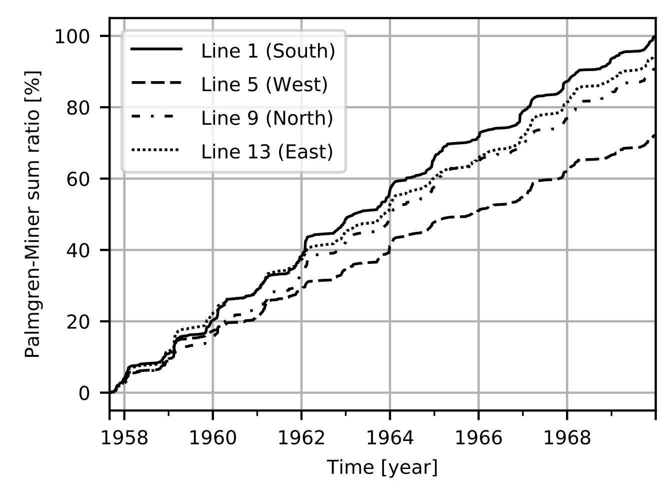


FIGURE 12: ACCUMULATED FATIGUE DAMAGE TIME HISTORY USING SWT-CURVE WITH CYCLE MEAN, IN PERCENT OF DAMAGE AT END OF PERIOD FOR LINE 1.

TABLE 2: RATIO OF FATIGUE DAMAGE OBTAINED WITH MEAN LOAD CORRECTION TO DAMAGE WITH STANDARD DESIGN CURVE (DNVGL-OS-E301).

Line	Cluster	SWT cycle mean	SWT 3-hr mean	SWT pre-tension
1	South	0.39	0.39	0.36
5	West	0.36	0.36	0.31
9	North	0.40	0.40	0.36
13	East	0.33	0.33	0.37

TABLE 3: RATIO OF MEAN LOAD CORRECTION BY 3-HOUR MEAN AND PRE-TENSION TO MEAN LOAD CORRECTION USING CYCLE MEAN

Line	Cluster	SWT 3-hr mean	SWT pre-tension
1	South	1.003	1.09
5	West	1.005	1.15
9	North	1.005	1.10
13	East	0.995	0.88

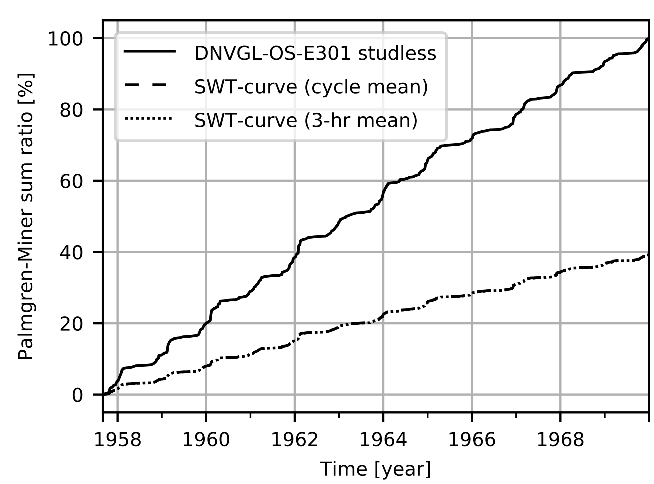


FIGURE 13: ACCUMULATED FATIGUE DAMAGE TIME HISTORY WITH AND WITHOUT MEAN LOAD CORRECTION FOR LINE 1 (SOUTH).

SINGLE CORRECTION FACTOR

When mean load is represented by the 3-hour mean value, the intercept parameter of the parameterized S-N curve is constant within each sea state. Mean load correction factor for a single sea state may then be expressed as:

$$\frac{\hat{d}_i}{d_i} = \frac{a_D}{\hat{a}_D(\overline{T}_i)} . \quad (6)$$

Here, $\hat{d}_i$ is the fatigue damage with mean load correction from sea state number i, d_i is the corresponding fatigue damage by use of standard design curve, a_D is the standard design curve intercept parameter, $\hat{a}_D$ is the parameterized intercept parameter, and $\overline{T}_i$ is the 3-hour mean load in the sea state considered. Total fatigue damage with mean load correction is obtained from summation over all sea states,

$$\hat{D} = \sum_i d_i \, \frac{a_D}{\hat{a}_D(\overline{T}_i)} . \quad (7)$$

A single correction factor for total fatigue damage may then be calculated as:

$$\frac{\hat{D}}{D} = \frac{1}{D} \sum_i d_i \, \frac{a_D}{\hat{a}_D(\overline{T}_i)} , \quad (8)$$

where D is the total fatigue damage by standard design curve. The single correction factor in Eq. 8 relies solely on results that are available from standard fatigue damage calculations. Hence; provided that cycle mean load may be represented by 3-hour mean load, the mean load correction may be calculated without the need for additional processing.

If pre-tension is used for a quick estimate, Eq. 8 simplifies to:

$$\frac{\hat{D}}{D} = \frac{a_D}{\hat{a}_D(T_0)} , \quad (9)$$

where T_0 is the pre-tension.

CONCLUSIONS

Application of mean load correction by use of a parameterized S-N curve has been investigated in this numerical case study. Potential for significant reduction of calculated fatigue damage has been demonstrated for a semi-submersible unit operating with pre-tension at around 11-12 % of MBL. The effect of mean load correction depends on orientation of the line. For lines at the same pre-tension level, the highest fatigue damage reduction is seen on leeward side of the dominating wave directions.

For the semi-submersible considered, results obtained with 3-hour mean load as basis for the mean load correction agree very well with those based on cycle mean. This is explained by small low frequency load variations, compared to the 3-hour mean load level. Using 3-hour mean load, a single mean load correction factor on total fatigue damage may therefore be calculated with results available from a standard fatigue analysis. Pre-tension may be used as a basis to provide a quick and simple estimate of the mean load correction. Compared with mean load correction based on cycle mean or 3-hour mean load, fatigue damage is then underestimated for windward lines (with respect to dominating wave directions) and overestimated for leeward lines.

This study has been based on one installation only, so further studies are needed for generalization of the results. Units operating at lower pre-tension levels may experience larger differences in mean load between lines at windward and leeward sides, and also larger variations in mean loads within each sea state. A relevant example is ship-shaped FPSOs, which typically experience larger low frequency motions than semi-submersible units. Another example is the mooring systems of floating wind turbines, which will experience high mean loads on windward side and correspondingly low mean loads on leeward side during power production. Finally, the negative effect on fatigue capacity due to corrosion has not been included. For a more realistic assessment of the fatigue damage, the effect of corrosion must also be accounted for.

ACKNOWLEDGMENT

This work was financed by the Research Council of Norway, NFR project 280705 LifeMoor. Equinor ASA is acknowledged for providing the hindcast data set used for this study.

REFERENCES

[1] Fernández, J., Storesund, W., and Navas, J., 2014. “Fatigue performance of grade R4 and R5 mooring chains in seawater”. In Proceedings of the ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering, Vol. 1A.

[2] Gabrielsen, Ø., Larsen, K., and Reinholdtsen, S. A., 2017. “Fatigue testing of used mooring chain”. In Proceedings of the ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering.

[3] Zhang, Y., and Smedley, P., 2019. “Fatigue Performance of High Strength and Large Diameter”. In Proceedings of the ASME 2019 38th International Conference on Ocean, Offshore and Arctic Engineering.

[4] Gabrielsen, Ø., Larsen, K., Dalane, O., Lie, H. B., and Reinholdtsen, S.-A., 2019. “Mean Load Impact on Moor-

ing Chain Fatigue Capacity: Lessons Learned From Full Scale Fatigue Testing of Used Chains". In Proceedings of the ASME 2019 38th International Conference on Ocean, Offshore and Arctic Engineering.

[5] Fernández, J., Arredondo, A., Storesund, W., and González, J. J., 2019. "Influence of the Mean Load on the Fatigue Performance of Mooring Chains". In Proceedings of the Annual Offshore Technology Conference, Vol. 2019 May.

[6] DNV GL, 2017. Offshore Standard - Position mooring (DNVGL-OS-E301), Edition July 2017.

[7] Dowling, N., and Thangjitham, S., 2000. "An Overview and Discussion of Basic Methodology for Fatigue". *Fatigue and Fracture Mechanics: 31st Volume*, pp. 3–36.

[8] Reistad, M., Breivik, Ø., Haakenstad, H., Aarnes, O. J., Furevik, B. R., and Bidlot, J.-R., 2011. "A high-resolution hindcast of wind and waves for the North Sea, the Norwegian Sea, and the Barents Sea". *Journal of Geophysical Research: Oceans,* ***116***(C05019), pp. 1–18.

[9] DNV GL, 2019. Recommended Practice - Environmental conditions and environmental loads (DNVGL-RP-C205), Edition September 2019.

[10] ASTM International, 2017. Standard practices for cycle counting in fatigue analysis (ASTM 1049-85), Reapproved 2017.