# A Comparative Study on the Fatigue Life of Mooring Lines under Combined Stresses

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**Abstract.** Mooring lines are essential for offshore floating platforms, but accurately assessing their integrity and fatigue poses a challenge. Traditionally, fatigue calculations only considered tension loads, neglecting out-of-plane bending (OPB) stresses caused by plastic strains during the proof loading process in chain links. This oversight may lead to early failures. Bureau Veritas guidelines BV NI604 propose a fatigue analysis method that considers combined stresses for fatigue crack initiation. This study presents a comparative analysis of mooring line fatigue life, comparing traditional methods with BV NI604's approach. Two case studies are examined: one focuses on an FPSO vessel with a turret mooring system, experiencing significant out-of-plane bending due to turret rotation, while the other explores an FPSO vessel with a spread mooring system. The analysis highlights the importance of considering combined stresses and bending effects to ensure the safety of offshore installations.

**Keywords:** mooring lines, fatigue analysis, out-of-plane bending, in-plane bending, combined tension.

## 1 Introduction

Offshore floating platforms provide the means for various marine activities, such as oil and gas exploration, production, and renewable energy generation. In this context, mooring lines play a pivotal role in maintaining the position and stability of these platforms and must be designed to prevent environmental disasters and operational expenses.

Cyclic loads on mooring lines can result in stress that might cause premature structural failures due to fatigue. Thus, the need for studies to improve the quantification of this damage becomes crucial to ensure safety and optimize project costs. Traditional methods of evaluating chain fatigue exclusively consider tension stresses (TT) for damage calculation, ignoring the combined effects of cyclic stress and the various ways it happens. The development of fatigue models that assess the combined stress effects, including out-of-plane bending (OPB), in-plane bending (IPB) and tension phenomena is challenging due to the high number of required parameters in formulations and the variability of mooring configurations [1][2].

Recent advancements in engineering practices have highlighted the limitations of traditional fatigue analysis, particularly when mooring lines face high tension loads alongside substantial variations in top angles at the fairlead. Relatively recent cases of premature failures in operational units caused by fatigue have emphasized the significant influence of OPB and IPB phenomena. One of the most notable cases occurred in the Girassol region, off the coast of Angola, where three out of nine mooring lines attached to a buoy experienced ruptures after approximately 235 days of operation in 2002. This occurred despite a projected service life of 20 years [3]. This incident launched a Joint Industry Project (JIP) gathering 28 different companies with the objectives of understanding the mechanism of OPB and establishing recommendations for fatigue life design [4].

Since then, several studies have been conducted to develop methodologies that can evaluate combined stresses. Melis et al. [3] presented the mechanical properties of OPB and IPB phenomena, as well as obtained bending stress results for different diameters. The numerical influence of some parameters, such as nominal tension, friction coefficient, proof load and chain diameter, were studied for Lim et al. [5]. Kim et al. [6] and Hwang [7] assessed combined stresses in spread mooring systems.

In response to this challenge, the Bureau Veritas guidelines BV NI604 [8] have introduced a pioneering method for fatigue analysis considering combined stresses, based on extensive studies, experimental tests, and related works.

In this context, this study aims to conduct a comparative analysis between the results obtained from fatigue damage calculation methodologies considering tension and combined stresses. This analysis is carried out by examining two mooring line systems with different dynamic behaviors: turret and spread mooring.

## 2 Overall analysis procedure

The assessment of out-of-plane bending fatigue, in accordance with BV NI604, follows a systematic and comprehensive methodology.

**Development of Fatigue Sea States:** The first step in the combined fatigue analysis process involves the development of fatigue sea states, that must comprise a range of marine conditions which the structure is expected to encounter during its operational life.

**Development of Interlink Stiffness and Stress Concentration Factors:** These factors describe the interactions between chain links, considering the acting tension and relative angle. The BV NI604 guidance notes provide in its Appendix 1 an alternative way to assess interlink stiffness through post-processing calculations. A nonlinear expression for the interlink stiffness is provided as a relationship between the interlink angle, the tension in the line, and the interlink moment in OPB/IPB. This stiffness can be assumed equal for both OPB and IPB phenomena, as both phenomena are symmetrical. The interlink moment $M_i\ (\gamma_i, T, d)$, in N·mm, for both OPB and IPB, can be calculated according to eq. (1)

$$M_i(\gamma_i, T, d) = \frac{\pi d^3}{16} C \frac{P(\gamma_i)}{G + P(\gamma_i)} \left(\frac{T}{0.14 d^2}\right)^{a(\gamma_i)} \left(\frac{d}{100}\right)^{2a(\gamma_i) + b(\gamma_i)} \quad (1)$$

where $\gamma_i$ is the interlink angle between links in degrees, $T$ is the line tension in kN, $d$ is the nominal diameter of the mooring line in mm, $P(\gamma_i) = \gamma_i + 0.307\gamma_i^3 + 0.048\gamma_i^5$; $a(\gamma_i) = a_1 + a_2 \tanh(a_3\gamma_i)$; $b(\gamma_i) = b_1 + b_2 \tanh(b_3\gamma_i)$; $C = 354$, $G = 0.93$, $a_1 = 0.439$, $a_2 = 0.532$, $a_3 = 1.02$, $b_1 = -0.433$, $b_2 = -1.64$, and $b_3 = 1.32$.

**Global Response Analysis and Local Modeling:** The aim of this step is to estimate tension and bending moment profiles for chain links within a specific fatigue sea state. This analysis involves two key steps: a comprehensive assessment of the global vessel-line response, determining line tension and relative angles, and a detailed local chain-connection modeling, which converts these angles into interlink angles and moments. Typically conducted in the time domain due to complexity, this methodology relies on simulation results.

**Stress Calculation and Cycle Counting:** The tension and moment time series are utilized to compute the nominal tension, OPB, and IPB stress components at chain links. The total stress at OPB hotspots is then determined by applying appropriate stress concentration factors to the nominal stress components. Each chain link end encompasses four hotspots (Fig. 1). For studless chain links, Appendix 1 of BV NI 604 provides a table with stress concentration factors (SCF) values for all the hotspots, considering the different modes (TT, IPB, and OPB). For studded chain links, it is recommended numerical modeling and experimental tests of the links under TT, OPB, and IPB conditions.

The total combined stress time series at each OPB hotspot can be estimated from eq. (2).

$$\sigma_{combined} = SCF_{TT} \cdot \sigma_{TT,nom} \pm SCF_{OPB} \cdot \sigma_{OPB,nom} \pm SCF_{IPB} \cdot \sigma_{IPB,nom} \quad (2)$$

where $\sigma_{combined}$ is the total combined stress; $SCF_{TT}$, $SCF_{OPB}$, $SCF_{IPB}$ are the stress concentration factors for the different loadings, i.e., tension, out-of-plane bending and in-plane bending, respectively; $\sigma_{TT,nom}$ is the tensile nominal stress, $\sigma_{OPB,nom}$ is the OPB nominal stress and $\sigma_{IPB,nom}$ is the IPB nominal stress. Figure 2 illustrates a link under tension, in-plane bending, and out-of-plane bending loads and schematically details the contributions of the tension and bending efforts on the stress signals within the hotspot groups. From this representation, it is observed that eq. 2 encompasses the 4 combinations of stresses inherent to the problem.

Concluding this step, a rain-flow cycle counting procedure is employed on the overall stress time series to construct the stress range histogram for each sea state. The long-term stress range histogram is then compiled from these individual sea state histograms and their corresponding probability of occurrence.

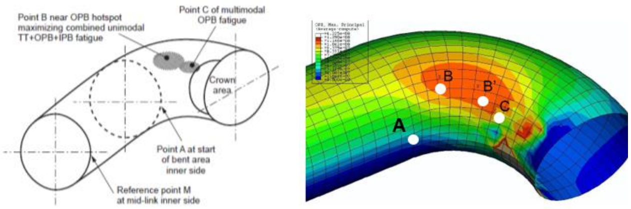


Figure 1. Hotspots on a chain link for combined fatigue at the top chain (BV NI 604, 2014).

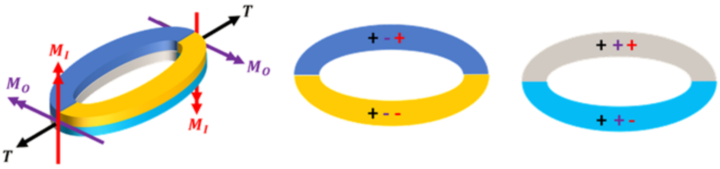


Figure 2. Contributions of tension and bending efforts in the stress signals within the hotspot groups.

# 3 Methodology

Following an extensive and comprehensive investigation into the mechanism of fatigue of mooring chain links under combined stresses, the analysis and design methodology outlined in BV NI604 has been integrated into the Dynasim software [9]. Dynasim is a software used for the time domain, coupled simulation and analysis of dynamic responses of marine systems and structures. Developed by PETROBRAS, it incorporates advanced numerical techniques to simulate various environmental conditions, such as waves, currents, wind, and vessel motions, allowing for the assessment of structural integrity, fatigue, and performance under dynamic loads.

Using the Dynasim software, two hypothetical offshore production systems were modeled, defining the case studies examined in this research: an FPSO with turret mooring system and an FPSO with spread mooring system. In both cases, all mooring lines were modeled using finite element method (FEM). The obtained results aim at comparing the fatigue life estimated through the traditional design methodology with the fatigue life derived from the combined stresses fatigue methodology.

# 4 Case studies

The case study comprises two distinct FPSO mooring systems. The first system features a turret mooring arrangement and operates at a water depth of 870 meters. It comprises eight mooring lines and 24 risers, utilizing studless chains at the extremities and steel wire ropes in intermediate segments (Fig. 3a). The second case study consists of FPSO with a spread mooring system positioned in waters of 1240 meters depth. Comprising 18 mooring lines and 76 risers, this system adopts studless chains and polyester ropes for different sections (Fig. 3b). For both cases, the analysis encompasses 11 draft levels and 108 fatigue sea states, considering diverse wave directions to comprehensively address potential operational scenarios.

# 5 Results and discussion

Table 2 and Tab.3 present an overview of fatigue life estimation for the FPSO with turret mooring system and spread mooring systems, respectively, considering both the traditional and combined stresses methodology. Results reveal a substantial reduction in the estimated fatigue life of the mooring lines when the calculation accounts for combined stresses. This observation highlights the importance of incorporating the effects of OPB and IPB stresses in fatigue assessments. Additionally, results indicate hotspot C as the critical one at the top chain link. which shows that the chain link is particularly vulnerable to fatigue failure induced by bending mechanisms. Thus, it becomes evident that the conventional approach could potentially lead to an underestimation of the fatigue damage of mooring lines. In contrast, the methodology proposed in this study, which incorporates combined stresses, provides a more comprehensive and accurate assessment of the structural integrity of these crucial components.

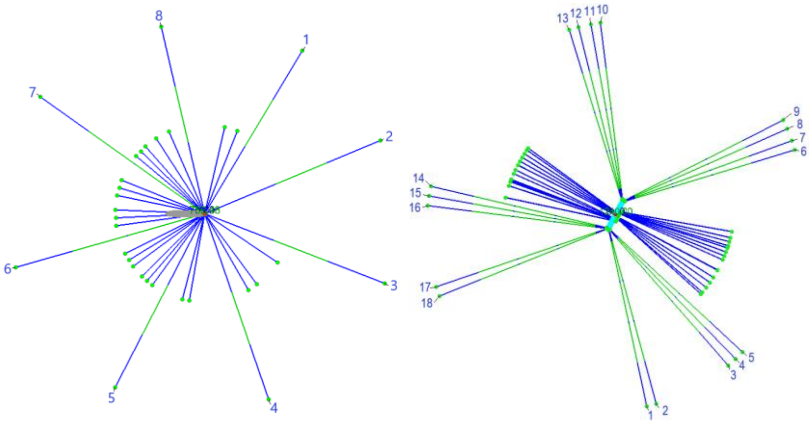


Figure 3. Layouts of the case studies systems: (a) FPSO with turret mooring and (b) FPSO with spread mooring.

Table 2. Fatigue life estimation [yr] for tension (TT) and combined stresses (TT + OPB + IPB) in case study 1.

| Line | TT stresses | Combined stresses/ Crit. Link, Hotspot | |
|---|---|---|---|
| 1 | 321 | 0.44 | ++C |
| 2 | 267 | 0.47 | ++C |
| 3 | 328 | 0.96 | +-C |
| 4 | 137 | 0.53 | -+C |
| 5 | 285 | 0.56 | --C |
| 6 | 307 | 0.64 | --C |
| 7 | 290 | 0.81 | +-C |
| 8 | 644 | 1.37 | +-C |

Table 3. Fatigue life estimation [yr] for tension (TT) and combined stresses (TT + OPB + IPB) in case study 2.

| Line | TT stresses | Combined stresses/ Crit. Link, Hotspot | |
|---|---|---|---|
| 1 | 44 | 0.12 | --C |
| 2 | 44 | 0.12 | --C |
| 3 | 44 | 0.11 | -+C |
| 4 | 44 | 0.11 | -+C |
| 5 | 44 | 0.11 | -+C |
| 6 | 38 | 0.47 | -+C |
| 7 | 38 | 0.51 | -+C |
| 8 | 39 | 0.56 | -+C |
| 9 | 39 | 0.58 | ++C |
| 10 | 50 | 0.23 | +-C |
| 11 | 52 | 0.23 | +-C |
| 12 | 54 | 0.23 | +-C |
| 13 | 56 | 0.24 | ++C |
| 14 | 26 | 0.15 | --C |
| 15 | 25 | 0.15 | --C |
| 16 | 24 | 0.16 | +-C |
| 17 | 28 | 0.23 | --C |
| 18 | 28 | 0.22 | --C |

The significance of incorporating tension contributions from both OPB and IPB into fatigue damage calculations becomes evident through the graphs presented in Fig 3, which illustrate the stress time series for each respective loading mode (TT, OPB and IPB). Although stress due to tension may exhibit a higher average magnitude, the OPB stress range is more substantial. This observation justifies the reduction in estimated service life when considering combined stresses in damage calculations, instead of only considering tensile stress. This behavior was verified in both spread mooring and turret mooring configurations.

It is important to highlight that the behavior and magnitude of these bending effects are highly dependent on the considered model, varying based on factors such as vessel motion dynamics, draft level, mooring layout, line properties, environmental conditions, among others. Thus, generalizing this behavior is not appropriate due to the complexity and variability inherent in different system dynamics.

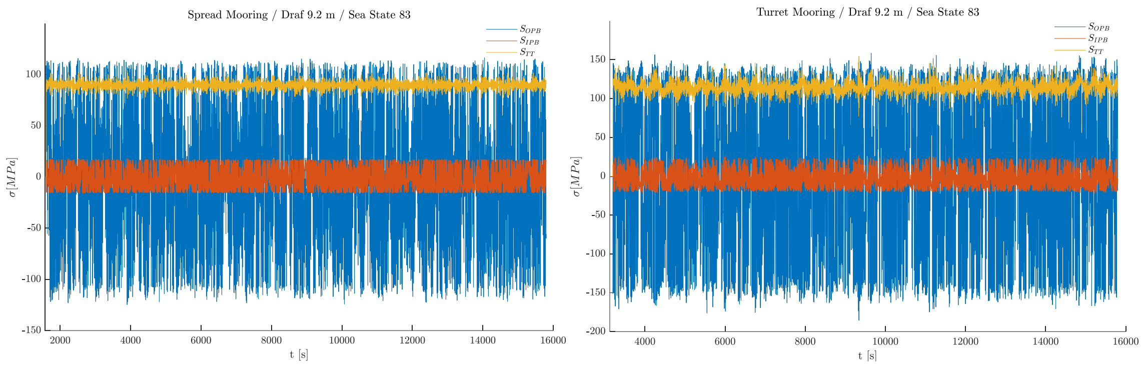


Figure 3. Time series of tension stress, in-plane bending stress, and out-of-plane bending stress for sea state 83.

# 6 Conclusions

In the field of offshore engineering, assessing the integrity and fatigue life of mooring lines holds significant importance in ensuring the stability and safety of offshore floating platforms. Traditional fatigue methods that solely consider tension loads have been overtaken by modern insights that highlight the notable impact of OPB and IPB on fatigue crack initiation and propagation. Integrating the BV NI604 guidelines, which account for combined stresses and stress concentration factors, has emerged as a robust approach to predicting fatigue life more accurately. The comparative study on FPSO vessels with turret and spread mooring systems has shed light on the considerable influence of combined stresses on fatigue life predictions. The data in Tab. 2 and Tab. 3 underscore the importance of factoring in bending effects in structural design and fatigue analysis.

In conclusion, this study emphasizes the importance of adopting a comprehensive approach that considers the combined effect of tension and bending stresses in mooring line fatigue analysis. This will enhance the accuracy of structural integrity assessments, contributing to the safety and reliability of offshore installations. Further research is encouraged to explore the nuances of combined stress effects in diverse situations, refining methodologies, and guidelines for robust fatigue life prediction in the dynamic environment of offshore operations.

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