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Mooring Design and Fatigue Damage on Variant Fairlead Positions During FPSO Operation – Case Study

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Abstract

This comprehensive case study delves into the intricate dynamics of deepwater mooring systems, specifically focusing on Floating Production Storage and Offloading (FPSO) operations. Our investigation centers on the Anoa Natuna FPSO, situated in the Arafura Sea. We examine how varying fairlead positions, employing a 4x3 chain configuration, influence structural integrity, operational stability, and fatigue damage. The research meticulously analyzes the response of the FPSO to environmental forces, providing a detailed understanding of the vessel's behavior under different fairlead positions. The results showcase the vessel's stability, elucidate variations in its motion response, and highlight the effects of fairlead positioning on structural fatigue, offering valuable insights for safe and efficient deepwater FPSO operations.

Keywords: Fairlead position; Fatigue damage; Mooring systems.

1. Introduction

Floating platforms and their associated mooring systems, face a diverse array of environmental factors, including fluctuating winds, shifting currents, and varying wave forces. These environmental variables can trigger fluctuated movements and exert dynamic stress on mooring systems, resulting in the gradual accumulation of fatigue damage. This concern has garnered substantial recognition in recent times, with a notable upsurge in documented cases of fatigue-related deterioration in practical projects. Consequently, the investigation of fatigue damage within mooring systems remains a crucial and actively pursued research area, with numerous scholars dedicating their endeavors to tackle this formidable challenge [1].

The successful operation of Floating Production Storage and Offloading (FPSO) vessels in deepwater environments is contingent upon the careful design and analysis of mooring systems. These systems serve as stability enhancer, enabling ships to remain securely anchored while conducting essential offshore activities. Among the myriad factors that influence the structural integrity and operational performance of FPSOs, fatigue analysis emerges as a paramount concern. The longevity and reliability of these complex systems depend on their ability to withstand the cyclic loading induced by changing environmental conditions, particularly in the context of ship mooring at substantial depths [2].

However, Mooring systems play a pivotal role in ensuring the safe and efficient operation of ships and floating platforms in offshore environments. In the context of deepwater operations, such as those at a depth of 1000 meters, the design and performance of mooring systems become even more critical. This paper embarks on an investigation into the mooring analysis of a specific floater, the Anoa Natuna FPSO, to be employed in the Abadi field

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within the Masela block of the Arafura Sea at coordinate of (09° 07' 51 "S / 130° 28' 00 " E)The primary objective is to optimize the mooring system to ensure operability, minimize line tension, and enhance strength while adhering to applicable regulations.

Deepwater operations pose unique challenges that demand a thorough examination of mooring patterns and system characteristics. The chosen mooring pattern for this study is a 4x3 chain configuration, and our investigation involves three distinct numerical analyses using Aqwa ANSYS software , each focusing on the fairlead connection point at varying positions relative to the ship draft (T). Specifically, we explore the impact of fairlead positions at 0.9T, 0.7T, and 0.4T, with three connection points on each side of the ship's corner (4 clusters with 3 lines in each cluster), each spaced 2 meters apart. These analyses are essential to understand how mooring performance is influenced by different fairlead locations in deepwater environments with analyzing the investigating of fatigue damage within mooring systems at limited environmental force exerted on the FPSO structure [3] [4].

2. Materials and Methods

2.1 Data Collection:

In the data collection process, researchers followed a meticulous approach to gather, model, and validate the essential data required for the mooring system analysis. This entailed collecting information on environmental forces, specifically wind, waves, and current at 0 direction, as well as dimensions of the operated FPSO. These parameters play a fundamental role in simulating and understanding the mooring system's performance.

- Environmental Forces:

Understanding the environmental forces that act on the mooring system is critical. Wind, waves, and current are the primary forces that influence the behavior of the mooring lines and the FPSO , The obtained data given in the table 1 b.

- Ship Dimensions:

The physical characteristics of the Anoa Natuna FPSO, such as its length, breadth, depth, draft, and Cb were meticulously recorded. These dimensions are given in the table 1 a .

Table 1. Data Collection [a - ship dimension and b – environmental forces]

Ship Dimensions		
Item	Value	Unit
Length Of All	270.70	meters
Breadth	40.30	meters
Depth	20.70	meters
Draft	16.70	meters
Displacement	81056	tons
Cb	0.93	---

(a)

	Environmental data	
Item	Magnitude	Direction
Wind	16.91 m/s (constant)	0 deg
Wave	Hs= 2 m/s Tp = 12 s	0 deg
Current	0.5 m/s at depth of 0, 250, 500, 750, 1000	0 deg

(b)

2.2 Mooring Pattern Configuration and Modelling:

The 4x3 chain configuration chosen for the mooring pattern in deepwater mooring systems is of significant importance. This selection's rationale and importance need to be clarified. Furthermore, it's essential to detail the parameters of this configuration and explain the presence of three catenaries at each corner of the ship. Additionally, our assumption is that the length of each catenary cable in each cluster is a constant 3000 m. However, the central cable's length was calculated using equation number (1), resulting in a value of 3470.2 m. The cable properties and configuration can be found in figure 1 [3]

$$l = h\sqrt{2\frac{T}{Ph} - 1} \qquad (1)$$

Property	Value
Diameter	0.1588 m
Length	140.208 m
Material	Chain on fairlead
Design	Studless R4
Wet Weight	19,563.30 kg/m
Axial Stiffness	1,842,397.80 kN
MBL	256,217.60 kN

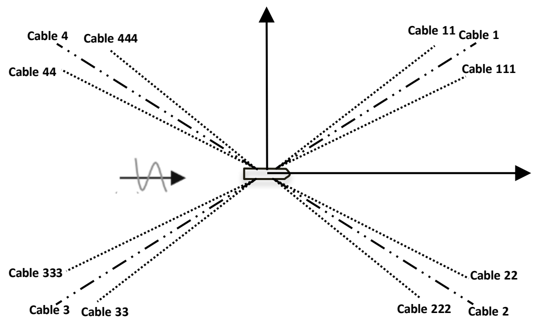


Fig. 1. Shows the mooring cables configurations and their properties

2.3 Numerical Analyses

Using Aqwa ANSYS software, examines mooring system behavior by positioning fairlead connection points at different fractions of the ship draft (0.9T, 0.75T, 0.4T) around the ship's corners. These positions significantly impact the mooring system's dynamics and stability.

2.4 Data Preprocessing

Efficient data preprocessing is crucial for optimizing the analysis process. we implemented specific strategies to streamline data processing, reduce computational load. the focus was placed on the highest probability values. By concentrating on the most likely scenarios. Moreover, all cases were analyzed with a limited of single direction exerted external forces on the structure (0 degrees) [5].

3. Results And Discussions:

In this section, we delve into the results of our numerical analysis for mooring system and the discussion is organized based on the primary areas of investigation as outlined in the introduction and methods as following:

3.1 Hydrostatic results:

The Center of Gravity (C_oG) is perfectly balanced at the origin (0, 0, 0), and it demonstrates significant hydrostatic stiffness, notably in heave, roll, and pitch indicating robust resistance to vertical and angular movements. The Center of Buoyancy (C_oB), positioned slightly below the C_oG at coordinates (5.16, 0.004, -7.82), contributes to the structure's self-righting capacity. Despite minor out-of-balance forces and moments, likely arising from modeling tolerances, the substantial cut water plane area demonstrates a high degree of resistance to forward motion. Moreover, significant metacentric heights (GMX and GMY) of 150.22 meters and 142.41 meters, along with high restoring moments per degree of rotation (MX, MY), underscore the structure's excellent stability against tilting and rolling motions. In summary, these results validate the structure's stability and suitability.

3.2 Response Amplitude Operator Curves Analysis:

To comprehensively assess the mooring

system's response to external forces patterns, RAO curves for all six free motions were analyzed in figure 2. The RAO curves provide valuable insights into how the vessel responds to various forces patterns and conditions. Differences between the fairlead positions (0.9T, 0.7T, and 0.4T) may highlight slight variations in vessel behavior and advantages associated with each position.

Motion Response Analysis of FPSO on Free Floating Condition The structure motion characteristics are presented in RAO graphic form, where the abscissa shows the period parameter and the ordinate shows the ratio between the amplitude of the movement in a certain period mode.

Transitional forces in FPSO motions vary significantly across different headings (0 deg, 45 deg, 90 deg, 135 deg, and 180 deg) as showing in table 2. Surge shows minimal variation at headings 0 deg (8.213 m/m) and 45 deg (8.214 m/m), over a prolonged period of 62.832 seconds. The most significant surge motion is observed at 90 deg, with an amplitude of 8.217 m/m over the same extended period. In contrast, sway is virtually non-existent at 0 deg and 180 deg, with amplitudes of 0.001 m/m. A noticeable increase in sway is observed at 45 deg (0.901 m/m), and the most substantial sway occurs at 90 deg (1.275 m/m). Heave exhibits variable amplitudes, with the most substantial heave motion at 45 deg (1.338 m/m) and consistent motion at 90 deg (1.193 m/m).

Table 2. RAO Amplitudes at Different Fairlead Positions per Domain of Time

RAO -RESPONSE AMPLITUDE OPERATOR												
	Transitional Forces m/m						Rotational Forces deg/m					
direction	PERIOD	X Surge	PERIOD	Y Sway	PERIOD	Z Heave	PERIOD	RX Roll	PERIOD	RY Pitch	PERIOD	RZ Yaw
0 deg	62.832	8.213	12.858	0.001	14.832	1.269	12.858	0.004	12.858	0.626	10.163	0.000
45 deg	62.832	8.214	62.832	0.901	12.858	1.338	27.371	2.582	12.858	1.703	11.353	0.311
90 deg	62.832	8.217	62.832	1.275	11.353	1.193	27.371	1.799	12.858	0.626	7.733	0.053
135 deg	62.832	8.219	62.832	0.901	62.832	0.984	27.371	2.582	12.858	2.303	11.353	0.312
180 deg	62.832	8.220	12.858	0.001	62.832	0.983	12.858	0.005	12.858	2.563	0.098	0.000

Rotational forces and angular motions are critical considerations for FPSO structural integrity. Roll motion is minimal at 0 deg (0.004 deg/m) and 180 deg (0.005 deg/m) but increases significantly at 45 deg (2.582 deg/m) over a 12.858-second period. Pitch motion varies, with the highest amplitude at 180 deg (2.563 deg/m) and smaller amplitudes at 0 deg and 90 deg (0.626 deg/m). At 45 deg and 135 deg, it increases to 1.703 deg/m and 2.303 deg/m, respectively, over the same period. Yaw motion is minimal at 0 deg and 180 deg but most substantial at 135 deg (0.312deg/m).

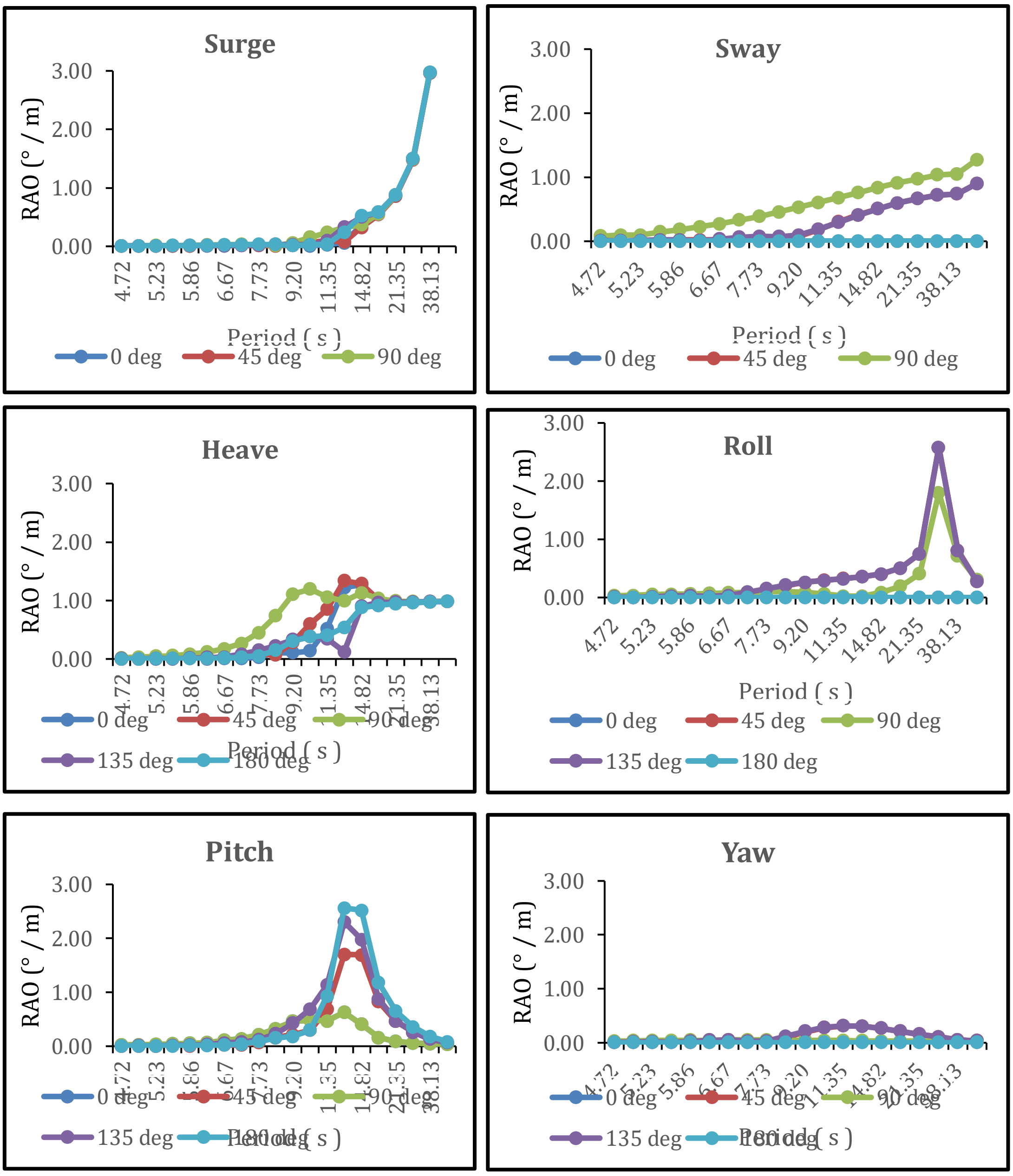


Fig. 2. RAO Amplitudes at Different Fairlead Positions per Domain of Time

3.3 Structure Position (Trajectory Motion):

At the loading condition of 0.9 T, the ship exhibited a surge of 12.2394 on the x-axis, coupled with a substantial backward drift of -48.0597 and a sway of -5.180. However, at 0.75 T, the ship showed a maximum surge of 12.3105 on the x-axis, similar to the 0.9 T condition, but with an even more backward drift of -48.2636 and a sway of -5.193. Eventually, at 0.4 T, the ship experienced a maximum surge of 14.839 on the x-axis. Although it exhibited backward drift as well, it was notably less severe at -46.4886, with a sway of -5.159.

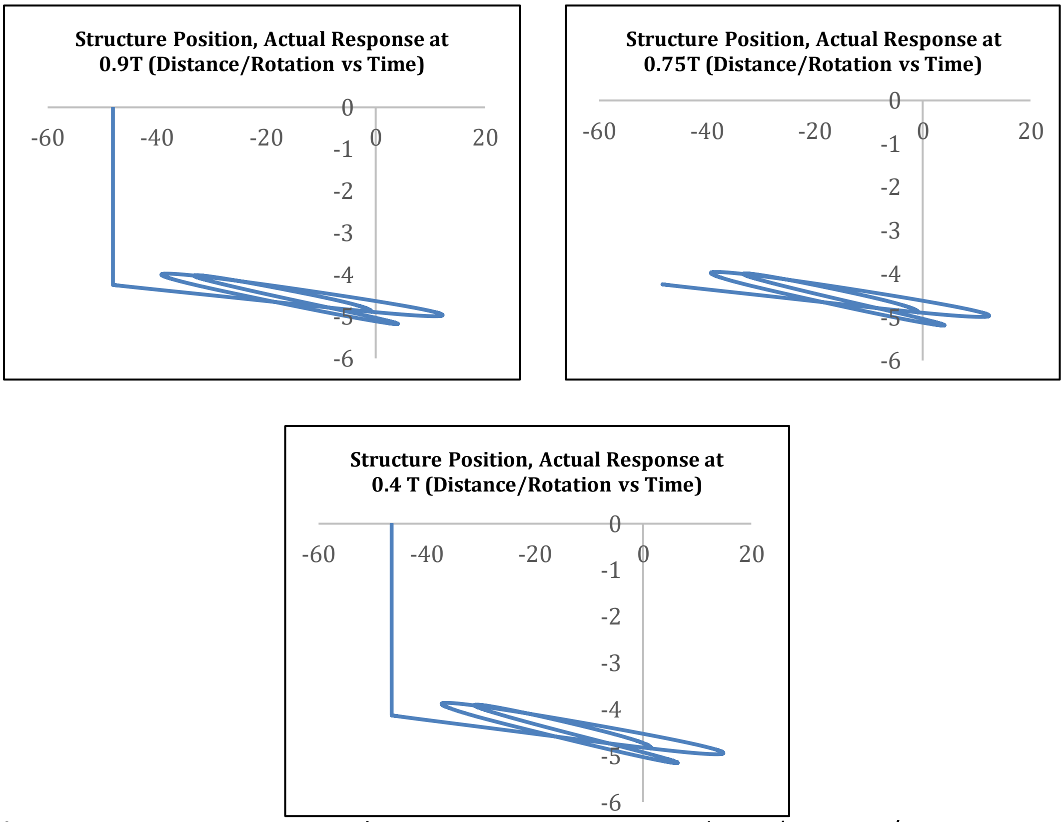


Fig. 3. Structure Position, Actual Response at 0.9T, 0.75T and 0.4T (Distance/Rotation vs Time)

3.4 Loads that Influence fatigue based on fairlead positions:

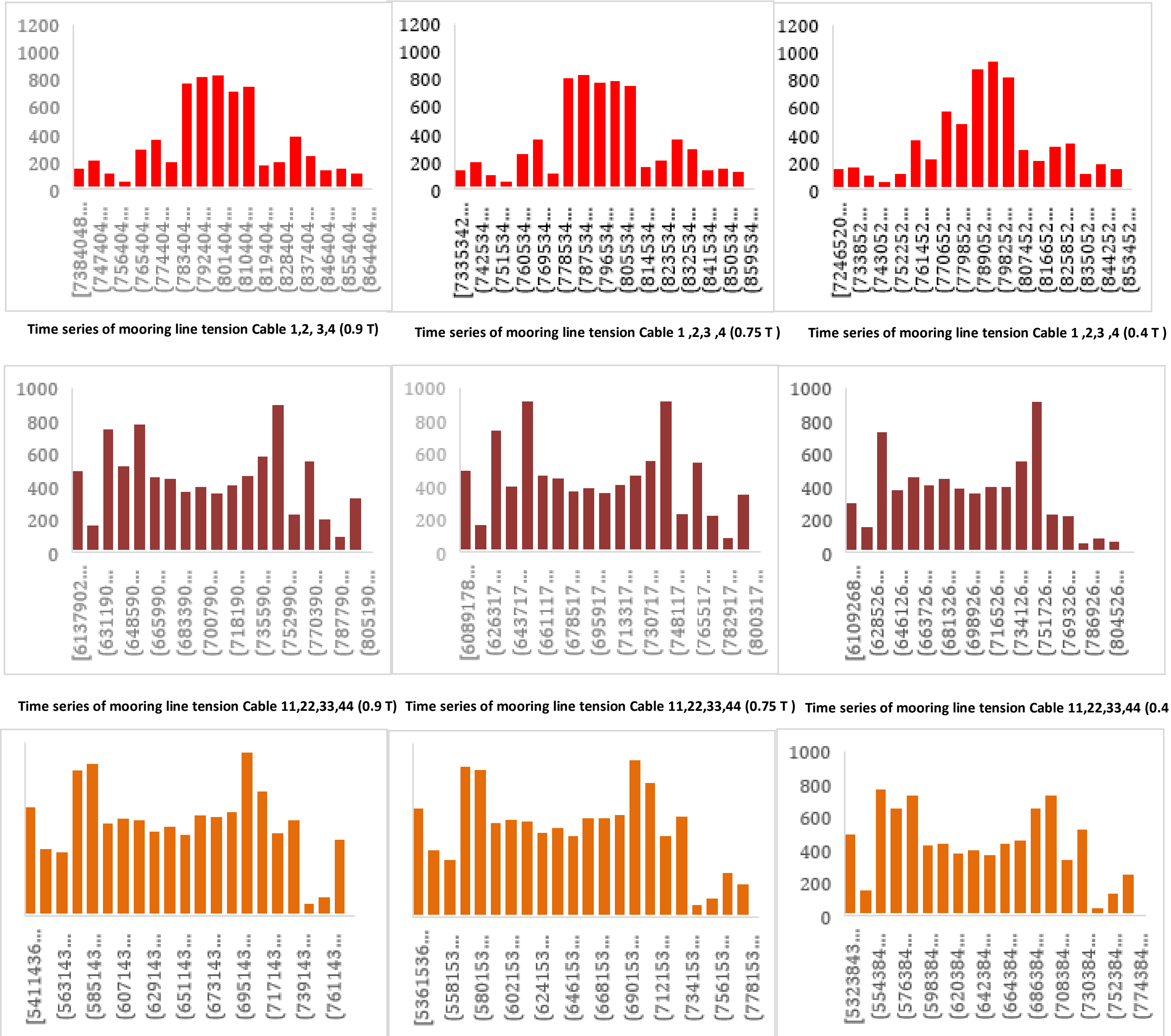
The implications of RAO and trajectory motion curves show there is a huge potential on fatigue damage can be occurred in the mooring system due to high instability of the structure as all and because of irregular distributions of stresses and loads in all catenaries. Figure 4 shows that the loads and stresses concentrated on the cable 111, 222, 333, 444 and in all cases with maximum value of 85055.2 KN undergone in cable 333 at position 0.75 T shown in table 3 with maximum number of cycles n_c range of 7.37 E+16 cycle. However, in the next section we will determine fatigue damages and its relevants determination for cable 333 in all cases due to most of stresses.

$$n_c(s) = a_D\, s^{-m} \qquad (2)$$

[($n_c(s)$ =Number of cycles , S stress range , a_D the intercept paramenter =1.2*10^11 , m the slope =3]

Table 3. Some determinants of the numerical analysis

Mooring Line	Fairlead Position	Length (m)	Max Line Tension kN	nc(S) Max	Max Stress Range (kN)	Max Fatigue Damage
Cable 1 , 2 , 3 , 4 (Dia 0.1588)	0.9 T = 15.03 m	3470.2	Cable 3 8663.936	4.76 E-17	8773.247	5.4184E+13
Cable 11, 22 ,33 ,44 (Dia 0.1588)	0.75 T= 12.53 m	3000	Cable 33 82839.816	6.8 E+16	82839.816	3.23173E+29
Cable 111, 222, 333, 444 (Dia 0.1588)	0.4 T= 6.68 m	3000	Cable 333 85055.2	7.37 E+16	85055.2	3.78E+29



Time series of mooring line tension Cable 1,2, 3,4 (0.9 T) **Time series of mooring line tension Cable 1 ,2,3 ,4 (0.75 T)** **Time series of mooring line tension Cable 1 ,2,3 ,4 (0.4 T)**

Time series of mooring line tension Cable 11,22,33,44 (0.9 T) **Time series of mooring line tension Cable 11,22,33,44 (0.75 T)** **Time series of mooring line tension Cable 11,22,33,44 (0.4 T)**

Time series of mooring line tension Cable 111,222,333,444 (0.9 T) **Time series of mooring line tension Cable 111,222,333,444 (0.75 T)** **Time series of mooring line tension Cable 111,222,333,444 (0.4 T)**

Fig. 4. Time series of mooring line tension cable at all cables for all fairlead positions

3.5 Fatigue Damage and stress on cable 333s:

Fatigue damage and stress on cable 333, it is evident that this specific cable bears a significant

burden under various conditions. The analysis conducted in section 3.5 delves into the intricate details of how cable 333 is affected by recurring stresses and loads. Regardless of the fairlead positions or environmental factors, cable 333 consistently experiences substantial stress levels, with the highest load recorded at 85055.2 KN. However the fatigue can be occurred with high possibility 0.9 T and then with less possibility in 0.75 T with best option to implement at 0.4 T as showing in figure 5 [6].

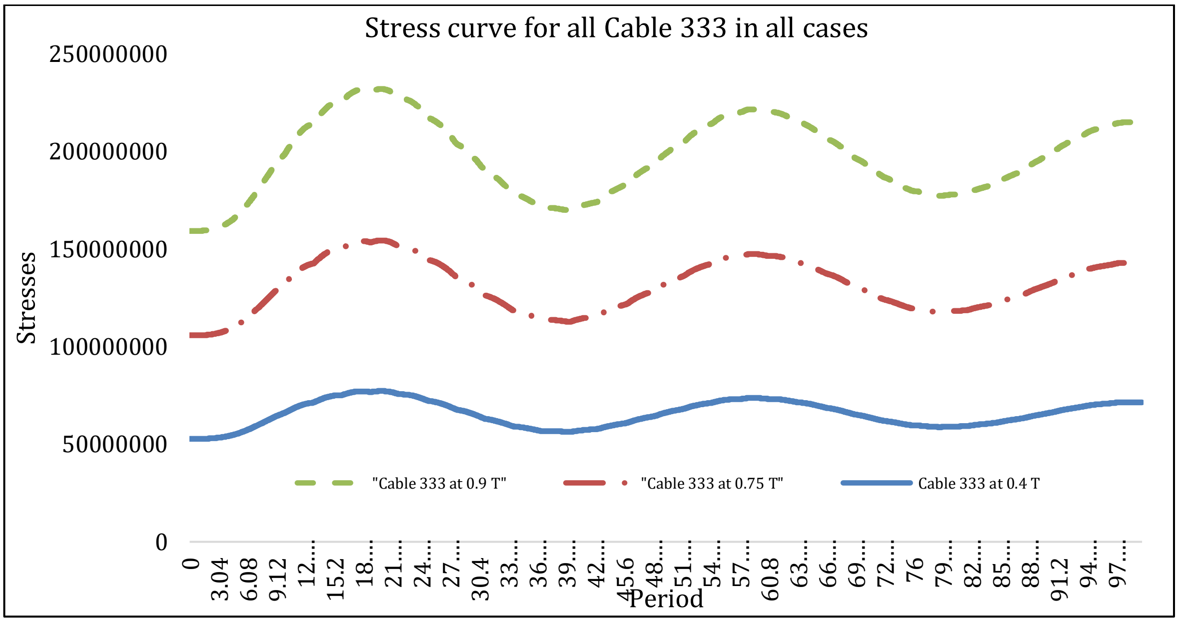


Fig. 5. Stresses applied on cable 333s over the domain of time

Last but not the least, The research attached with supported curve [figure 6] on the concept of the Ratio of tension to the Minimum Breaking Load (MBL) per cycle count (Nc) curve, which serves as a fundamental representation of material fatigue stemming from recurring loads [7]. The accuracy of this analysis is intricately tied to how the curve's slope parameter and intercept are defined and expressed in an analytical context as given in the formula below [3] :

$$NR^M = K \qquad (3)$$

[(K is intercept of T-N curve =316 , M is slope of T-N curve =3 , N is number of cycles, R is ratio of tension]

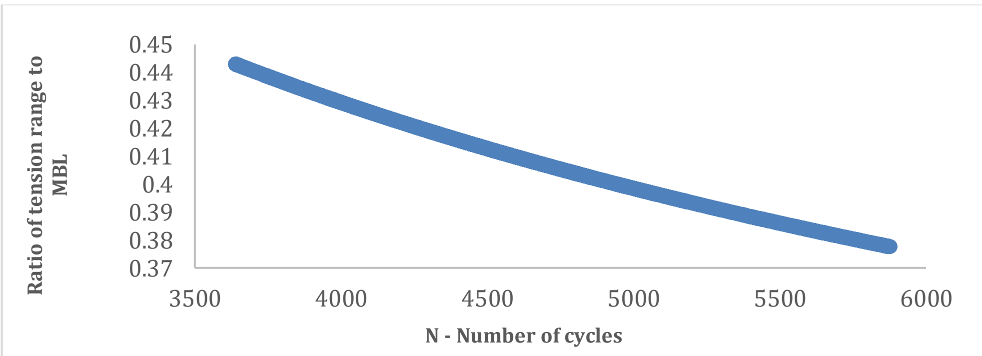


Fig. 6 . Ratio of tension to the Minimum Breaking Load (MBL) per cycle count (Nc) curve

4. Conclusions

Based on the outcomes of the analysis carried out as described earlier, the following results have been derived:

1. Comparing these results, it becomes evident that the condition with the least stability is the one at 0.75 T. Despite having a surge comparable to the 0.9 T condition, it stands out with an even greater backward drift. This significant drift implies a notable lack of stability in this particular fairlead position, calling for further evaluation and potential adjustments. In contrast, the other two conditions, at 0.9 T and 0.4 T, appear to offer relatively better stability, with the 0.4 T condition showing the most favorable results concerning stability due to its reduced drift.
2. The research highlights that cable 333 is particularly susceptible to significant stress, with the highest load recorded at 85055.2 KN. Fatigue damage is a real concern, with

higher risk at 0.9T and slightly less risk at 0.75T, making 0.4T the most favorable fairlead position for minimizing fatigue damage.

3. The study also utilizes the Ratio of tension to the Minimum Breaking Load (MBL) per cycle count (Nc) curve to represent material fatigue due to recurring loads.

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