International Journal of Marine Engineering Innovation and Research, Vol. 8(2), Jun. 2023. 295-309
(pISSN: 2541-5972, eISSN: 2548-1479)

Fatigue Life Analysis of FSO Mooring Chain by Considering the Effects of Offloading Load

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(Received: 01 June 2023 / Revised: 01 June 2023 /Accepted: 07 June 2023)

Abstract*—mooring chains are critical components in the maritime industry used to secure ships and floating oil and gas platforms such as FSOs to stay in their designated positions. The loads exerted on mooring chains during routine operations and additional loads during offloading operations can cause structural fatigue. Therefore, fatigue life analysis of mooring chains is essential to ensure safety and optimal performance. This study aims to conduct fatigue analysis of mooring chains by considering an important factor, namely the influence of offloading. Offloading load refers to the additional load exerted on the mooring chain during loading and unloading operations. The mooring system configuration uses a spread mooring system of 8 chains (4x2), 87 mm in diameter, with 20% pretension. In the fatigue analysis, the "Palmgren-Miner" method was used to evaluate the accumulated damage caused by cyclic loads. Then, the "Rainflow Counting" method is used to identify and count the number of load cycles that occur so that later the fatigue life can be calculated and known. From the research results, it was found that the mooring system configuration design still meets the safety factor requirements recommended by API RP 2 SK both during SLS, ULS, and FLS analysis. In SLS and ULS conditions, the greatest tension value is when the FSO is in the Ballast load condition, with the maximum value of tension that occurs is 2207.4 kN in SLS conditions, and 4151.6 kN in extreme conditions. In the FLS condition analysis, it was found that with an offloading frequency of 24 times per year (1271.89 hours), in the design configuration, the influence of the offloading system can increase up to 7% of the fatigue damage that occurs, and the lowest fatigue life, reduced by 3 years. The least fatigue life occurs in Chain 1.2 at the splash zone segment, which is 67 years.

Keywords —fatigue, FLS, mooring chain, rainflow counting, SLS, spread mooring, tandem offloading, tension, ULS,

I. INTRODUCTION

Basically, there are two types of platforms in offshore oil and gas fields, known as fixed platforms and floating platforms [1]. If the platform will be designated as a storage platform, then the floating platform type will be used. One example is floating storage and offloading (FSO) which has been widely and frequently used in Indonesia. Floating platforms such as FSO must be able to maintain their position from all environmental conditions, therefore a mooring system is needed. The mooring system itself has a variety of configurations that can be used such as single point mooring, spread mooring, turret mooring, and others which will be selected according to the environmental conditions in the area [2]. As a storage facility, FSO requires a system that is able to distribute the production that has been stored. One of the transfer systems known today is tandem offloading where the shuttle tanker will be moored using a hawser behind or in front of the moored FSO using a spread mooring system to perform offloading. Currently, in the north of West Java, there are several clusters that are already in production, one of which is the ZULU cluster located offshore, more precisely in the north of Indramayu, West Java. Currently, the owner planning to develop several fields including the ZULU cluster to increase oil production. Therefore, it is necessary to plan the placement of a floating storage platform in the form of an FSO in the area [3]. The FSO plan to be used is a modification of the tanker MT. BRATASENA moored with spread mooring configuration and tandem offloading system.

In designing a floating platform such as FSO with its mooring arrangement, there are several factors that need to be considered, including the length of the anchor radius or anchor location distance, the number of chains, to determine the length and diameter of the chain (including pre-tension on the chain) [2]. In addition, it is necessary to analyze the strength to fatigue life of the parts of the structural system such as the mooring chain. This is because the majority of damage or failures in marine buildings such as FSOs are caused by failures in the mooring system, especially in chains due to fatigue [2]. The basis for estimating fatigue life is the load fluctuations that the structure will receive during its operational period. The load received is dominated by wave loads and several operating factors at a certain level which will increase the cyclic load so that the structure becomes increasingly critical [4].

Operating and offloading loads are a condition where the structure is exposed to operating loads of

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environmental conditions to operate and offloading loads which are loads borne by a structure or in this case the FSO due to the pull of the ship during the offloading process. If the conditions of these two loadings occur and are combined with the stress that hits them, it is likely that a mooring line will experience fatigue whose effects can be very dangerous [5]. Given the important role of the mooring system, maintaining the condition of the mooring system so that it can operate smoothly and safely is an important issue that should not be ignored, because if damage or failure occurs in the mooring system there is a risk of disrupting and endangering the oil loading and offloading process.

Research on the stress analysis of mooring ropes (mooring and hawser) has been carried out on the SSP floating building when it is in tandem offloading conditions [6]. In designing configurations for mooring systems, in addition to considering strength analysis, namely the amount of stress on the mooring rope, it is also necessary to analyze the fatigue life to determine the remaining fatigue life of the mooring rope. Research has been carried out related to the simplification method to analyze the fatigue life of the mooring system [7]. This is based on the magnitude of mooring system failures that occurred at that time. In the study, it was found that there is a formula approach that can be used to calculate fatigue life based on the results of strength analysis which of course needs to meet several parameters to get accurate results. From this research, it was found that the calculation formula is still better to be compared first with other methods such as the rainflow method to test its accuracy first. In addition, fatigue life analysis has also been carried out where the main parameter seen is the value of fatigue damage that occurs due to several factors that are often overlooked in the analysis, namely climate change and marine corrosion [8]. From the results of the study, it was found that both factors have a fairly significant effect on the distribution of mooring lines tension range and fatigue damage, so if you have complete data, it needs to be considered in fatigue life analysis.

Looking at the results of previous researchers, we can know that fatigue life analysis needs to be done properly, especially if you have data that can be used as a reference in calculating fatigue life. The influence of climate change and marine corrosion, which are often overlooked on chain fatigue life, illustrates that several other factors that are often overlooked also need to be considered. One of them that has not been done in previous studies is the effect of the offloading process, which is one of the core activities in the distribution of oil and gas, on the fatigue life of mooring chains. Therefore, this study will analyze the effect of offloading on the fatigue life of mooring chains using a method recommended to be more accurate by API RP 2 SK and from several previous studies, namely the rainflow counting method.

II. METHOD

A. Literature Study and Data Collection

At this stage, literature study activities are carried out. Literature study is an activity to study the literature related to research in this thesis. The literature studied is about reliability analysis, fatigue life and motion behavior of floating buildings and also mooring rope tension on floating building structures using numerical methods or using software assistance. In addition, the literature studied includes time domain-based analysis, mooring rope properties, waves, rules and codes regarding mooring systems and reliability in offshore mooring systems. And at this stage, the data collection used includes:

1) General Arrangment FSO and Export tanker
2) Principal Dimension of FSO and Export tanker
3) Metocean Data
4) Chain Data
5) etc.

Data is also required on the offloading system process that is planned to be carried out on the FSO. The main data required is data on the frequency of offloading and the length of offloading time per year.

B. 3D Modeling of FSO and Export Tanker Body

The 3D structural modeling of the FSO and Export tanker bodies in this thesis research was carried out using vessel modeling software software. In addition, vessel modeling software software is also used to find the motion behavior of FSO and Export tanker ships in free floating conditions. The ship structure modeling will be validated first before being used for further analysis. This is done to get modeling results that are as accurate as the original ship. Validation of FSO and export tanker structural modeling refers to ABS 2018, where the error of hydrostatic parameter data must be below 2% [9].

C. Motion Analysis of FSO dan Export Tanker

Analysis of ship motion behavior is carried out to find out the response and motion behavior of FSO and Export tankers in free floating conditions by looking for RAO (Response Amplituted Operator) in each condition of the environmental loading direction where in this study the loading heading directions used are 0°, 45°, 90°, 135°, and 180°. According to Chakrabarti, 1987 RAO can be defined as [10],

$$(\omega) = \frac{\mathbf{Xp}\ (\boldsymbol{\omega})}{\boldsymbol{\eta}\ (\boldsymbol{\omega}} \quad (1)$$

Where,
$Xp(\omega)$ = structure amplitude
$\eta(\omega)$ = wave amplitude

D. Mooring System Modeling

In this study, mooring line modeling was conducted using Dynamic analysis software software. Data on structural properties and configurations are input for analysis in the software. The mooring rope configurations modeled in this study are,

1) Spread Mooring System (4x2)
2) Catenary Mooring
3) Pretension 20%

The Tandem Offloading configuration will be divided into three load combinations whose load size is recommended by BKI FPI [11]. Of the three combinations, the loading condition with the highest tension will be used as a reference for fatigue analysis. The three loading combinations are

1) FSO Full Load – Export Tanker Ballast Load
2) FSO Half Load – Export Tanker Half Load
3) FSO Ballast Load – Export Tanker Full Load

Furthermore, after modeling, a dynamic analysis of the three configurations is carried out in moored conditions, with the aim of knowing the maximum tension value in the FSO mooring system both in stand-alone conditions (not offloading) and when offloading with a tandem system with three load combinations.

E. Dynamic Analysis of Mooring System

Movement of the floating structure due to the influence of environmental loads causes a pull on the mooring line. According to Faltinsen (1990), the maximum tension of the mooring line can be obtained using the following equation [12]:

$$T_{max} = T_H + wh \quad (2)$$

Where,

T_{max} = maximum tension of mooring line (tons)
T_H = horizontal pre-tension (ton)
w = chain weight in water (ton/m)
h = water depth (m)

The analysis of mooring line tension and FSO offset is performed with respect to the dynamic formulation of the floating body motion [13, 14, 15]. The variables in eq. (4) are the first-order wave excitation matrix $F^{(1)}j{-}wv$, wave excitation orde-2 $F^{(2)}j{-}wv$, current excitation $\mathbf{F}j{-}c$, wind excitation $\mathbf{F}j{-}w$, and excitation due to mooring system $\mathbf{F}j{-}m$.

$$\sum_{j=1}^{6}[-\omega^2(M_{jk}+A_{jk}) - i\omega B_{jk} + C_{jk} + C_{jk}^{m}]\zeta_j = F_j \quad (3)$$

Where,

j,k = 1, 2, 3 for translational motion in the direction of the x, y, and z axes, namely surge, sway, and heave, while 4, 5, 6 for rotational motion about the x, y, and z axes, namely roll, pitch, and yaw;
ω = frequency of the wave;
M_{jk} = the mass matrix of the floating structure and the moment of inertia of the mass about the reference axis;
A_{jk} = added mass matrix and added mass moment of inertia according to the motion mode of the floating structure;
B_{jk} = hydrodynamic damping matrix according to the motion mode of the floating structure;
C_{jk} = hydrostatic stiffness matrix of the floating structure;
F_j = the jth excitation force and moment matrix, which contains the following elements:

$$F_j = F_{j-wv}^{(1)} + F_{j-wv}^{(2)} + F_{j-c} + F_{j-w} + F_{j-m} \quad (4)$$

According to (DNVGL-OS-E301, 2015), domain simulation analysis on offshore buildings is divided into two (Time Domain Analysis and Frequency Domain Analysis) [16]. In this research, the dynamic analysis carried out uses the time domain analysis method where the approach taken in this method will use time integration procedures and produce a time history response based on the time function x(t). The advantage of this method over the frequency domain is that all non-linear types (system matrices and external loads) can be modeled more precisely. The disadvantage is that it requires a longer calculation time. According to (DNVGL-OS-E301, 2015), the minimum duration of time domain simulation to obtain a stable peak statistical response value that can represent the environment is 3 hours (10800 seconds) [16].

After knowing the stress influence factors, a limit must be determined for the stress of the mooring line material that must not be exceeded. The limit in the maximum stress of the mooring line in the case of engineering is called breaking strength, where the safe limit specified by API RP 2SK, for the maximum breaking strength is listed in table 1 below [17]

TABLE 1
MOORING LINE SAFETY FACTOR CRITERIA BASED ON API RP 2SK

Condition	Safety Factor
Intact	> 1.67
Damage	> 1.25

And as for the formula for determining the Safety Factor is:

$$SF = \frac{MBL}{Tmax} \quad (5)$$

where:

SF = Safety Factor
MBL = Minimum Breaking Load
Tmax = Tension Maximum

F. Analisis Fatigue Life

Using the calculation cycle with the Palmgren-Miner method applied to fatigue analysis in accordance with API RP 2 SK. In this stage, the equation for fatigue analysis using the Rainflow Counting method is used where wave scatter data containing wave height, direction of arrival of waves, chance of wave occurrence for one year is used as a reference. According to API RP 2 SK, there is a T-N curve used to determine the value of the K and M variables that will be used in fatigue analysis [17]. The following is the formula for describing the T-N Curve:

$$K = NR^M \quad (6)$$

Or in logarithmic formulated as follows:

$$\log(K) = \log(N) + M\log(R) \quad (7)$$

Where:

K = Fatigue constant of each component
N = Number of cycles
R = Ratio of tension range with reference breaking strength

Lm = Ratio of mean load to reference breaking strength for wire rope.

M and K values are described in table 2 below,

TABLE 2
M AND K VALUE BASED ON API RP 2SK

Component	M	K
Common Studlink	3.0	1,000
Common Studless Link	3.0	316
Baldt and Kenter Connecting Link	3.0	178
Six/Multi Stand Rope	4.09	$10^{(3.20-2.79L_m)}$
Spiral Strand Rop	5.05	$10^{(3.25-3.43L_m)}$

After calculating using the Rainflow Counting method and the Palmgren-Miner method, the amount of fatigue damage received by the object under review is obtained which is used to obtain the fatigue life of the mooring line. The fatigue damage value can be calculated using the following equation [17],

$$D_i = \frac{n_i}{K} E[R_i{}^M] \quad (8)$$

Where the values of M and K are known from Table 2 and n_i is the number of tension cycles that have been calculated using the rainflow counting method in each sea state-i per year. Whereas $E[R_i{}^M]$ is the value of the normalized tension R, power of M, in sea state-i. Furthermore, the fatigue life is obtained using the following equation,

$$\mathrm{N_f} = \frac{1}{\mathrm{D}} \, (years) \quad (9)$$

Where,
$\mathrm{N_f}$ = Fatigue Life

After obtaining the results of the fatigue life of the mooring line, it is then divided by the safety factor for fatigue analysis based on the API RP 2 SK standard to obtain the remaining allowable fatigue life target.

III. RESULTS AND DISCUSSION

A. Modeling of FSO and Export Tanker

The FSO and export tanker used in this research are MT. BRATASENA and MT. MANDALA. Modeling is done using vessel modeling software Modeler software with principal dimension and general arrangement data as shown in table 3 and figure 1 below [3]:

TABLE 3
PRINCIPAL DIMENSION OF FSO MT. BRATASENA [3]

Principal Dimension	Unit	Value
Length overall (LOA)	m	179.8
Length between perpendicular (LPP)	m	171
Breadth (B)	m	32.2
Depth (H)	m	18.8
Draft (T)	m	12.2
DWT	ton	about 45,000
Displacement (Full Load)	ton	55,081
LCG (fwd of MidShip)	m	3.23
TCG (to port)	m	0.00
VCG (above keel)	m	11.37

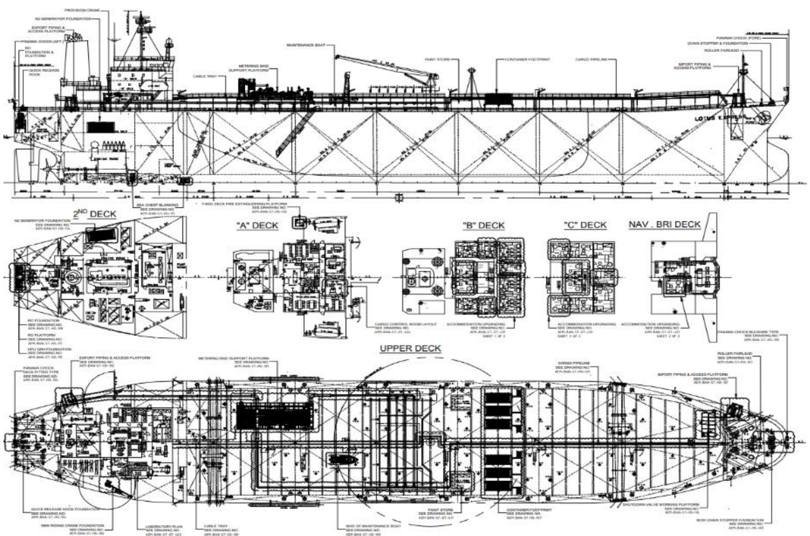


Figure 1. General Arrangement of FSO MT. BRATASENA [3]

The following is the results of modeling the FSO MT. MANDALA using the vessel modeling software Modeler in figure 2,

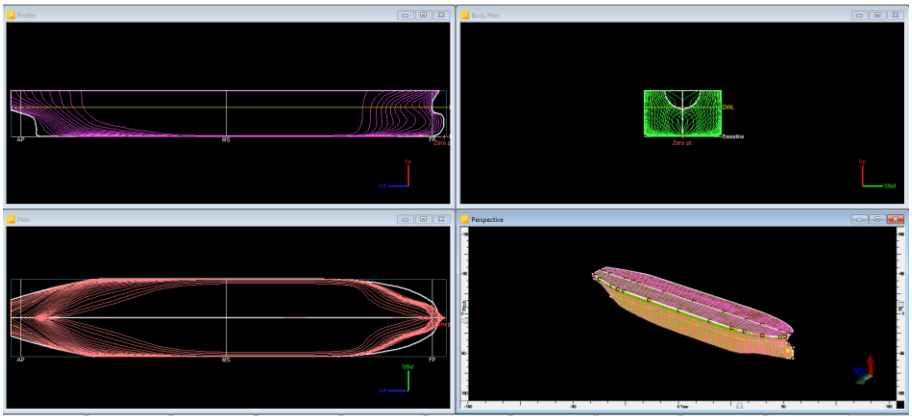


Figure 2. FSO Body Modeling using vessel modeling software Modeler

As for the export tanker, the principal dimension data can be seen in table 4 and below [3],

TABLE 4
PRINCIPAL DIMENSION OF EXPORT TANKER MT MANDALA [3]

Principal Dimension	Unit	Value
Length overall (LOA)	m	251.5
Length between perpendicular (LPP)	m	239
Breadth (B)	m	43.8
Depth (H)	m	21.3
Draft (T)	m	15
DWT	ton	about 113,500
Displacement (Full Load)	ton	134,502.3
LCG (fwd of MidShip)	m	3.009
TCG (to port)	m	0.00
VCG (above keel)	m	14.2

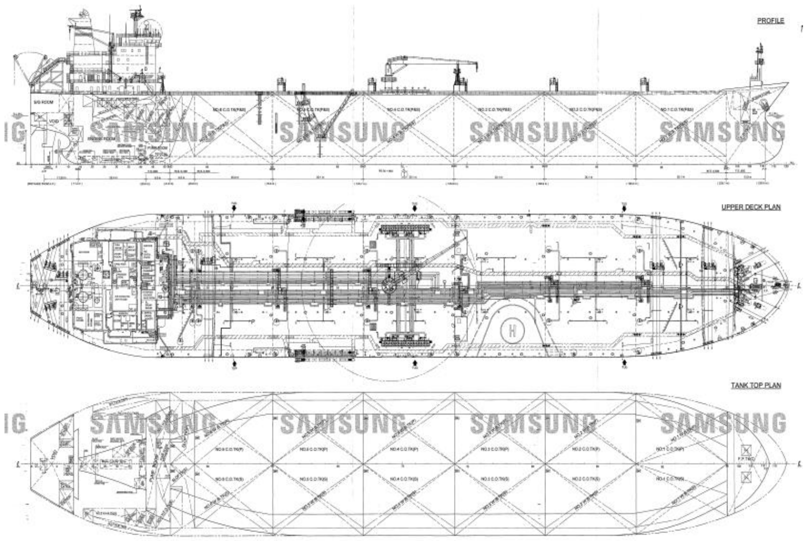


Figure 3. General Arrangement of export tanker MT. MANDALA [3]

The following export tanker body modeling results can be seen in figure 4.

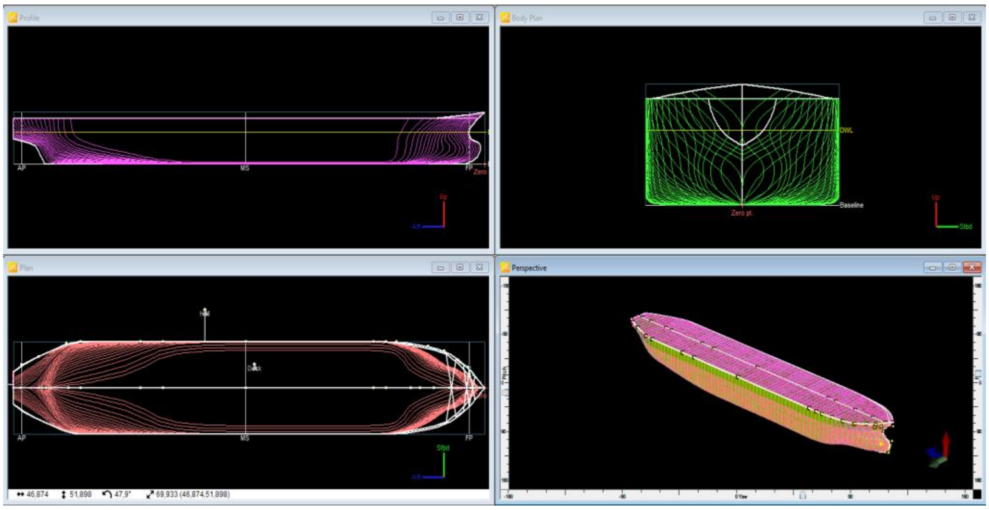


Figure 4. Export Tanker Body Modeling using vessel modeling software Modeler

B. Hydrostatic Validation

The model validation criteria used refer to ABS with a maximum displacement error of 2% [9]. The following table 5 is the result of modeling validation between the vessel modeling software model and displacement data in each FSO loading condition.

TABLE 5
VALIDATION RESULTS OF FSO MT. BRATASENA

Parameter	Vessel Condition	Data	Output	Validation
Draught (m)	Ballast	6.42	6.42	
Displacement (Te)	Ballast	27,647.00	27,510.68	0.49%
Draught (m)	Half Load	8.5	8.5	
Displacement (Te)	Half Load	37,583.00	37,356.73	0.60%
Draught (m)	Full Load	12.12	12.12	
Displacement (Te)	Full Load	55,081.00	54,853.89	0.41%

While table 6 below is the result of export tanker modeling validation,

TABLE 6
VALIDATION RESULTS OF EXPORT TANKER MT. MANDALA

Parameter	Vessel Condition	Data	Output	Validation
Draught (m)	Ballast	7.36	7.36	
Displacement (Te)	Ballast	60,713.80	61,279.88	0.93%
Draught (m)	Half Load	9.10	9.1	
Displacement (Te)	Half Load	77,725.82	77,320.37	0.52%
Draught (m)	Full Load	15.04	15.04	
Displacement (Te)	Full Load	134,502.30	133,615.61	0.66%

Criteria based on the errors contained in the table above which have values below the validation criteria mentioned by ABS [9], it can be concluded that the vessel modeling software model meets and is feasible.

C. Response Amplitude Operator (RAO) Analysis

Figure 5 below is an example result graph of the motion characteristics of the FSO in free floating conditions with half load loading conditions. Similarly, other loading conditions and motion characteristics of export tankers in free floating conditions are also taken into account.

The highest response from each load condition on both the FSO and export tanker for translational movements of surge, sway, heave, and rotational movements of roll, pitch, yaw, can be seen in table 7.

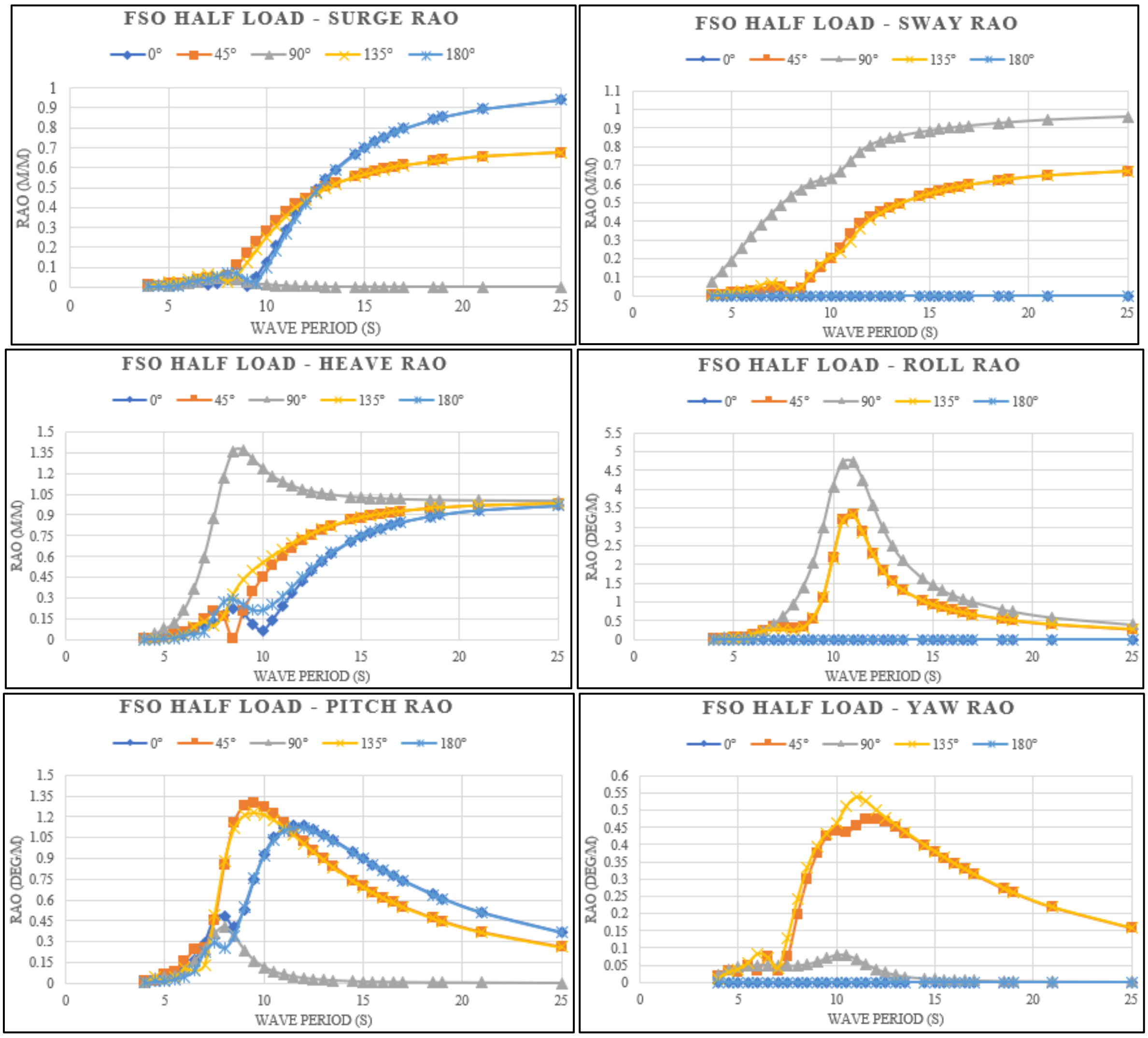


Figure 5. Motion RAO Results on FSO Free Floating Condition for FSO Half Load Condition

TABLE 7
MAXIMUM RAO RESPONSE IN EACH MOTION

Motion / Muatan FSO		Surge (m/m)	Sway (m/m)	Heave (m/m)	Roll (deg/m)	Pitch (deg/m)	Yaw (deg/m)
FSO	Full Load	0.926	0.953	1.411	2.215	1.704	0.502
	Half Load	0.939	0.961	1.369	4.721	1.294	0.537
	Ballast Load	0.946	0.968	1.199	5.851	1.118	0.490
Export Tanker	Full Load	0.882	0.936	1.570	2.608	1.054	0.354
	Half Load	0.904	0.957	1.212	4.479	0.796	0.383
	Ballast Load	0.911	0.966	1.096	5.104	0.757	0.350

D. Modeling in Dynamic Analysis Software

The FSO modeling to be analyzed refers to the geometry of the ship structure in accordance with the General Arrangement, namely MT. BRATASENA. Modeling of FSO on dynamic analysis software is done by entering hydrodynamic behavior from the analysis results on vessel modeling software and other parameters. The following figure 6 is the geometry of the FSO structure modeling in dynamic analysis software.

The modeling of the FSO mooring line configuration and the heading direction of the environmental load in the dynamic analysis software is as shown in Figure 7.

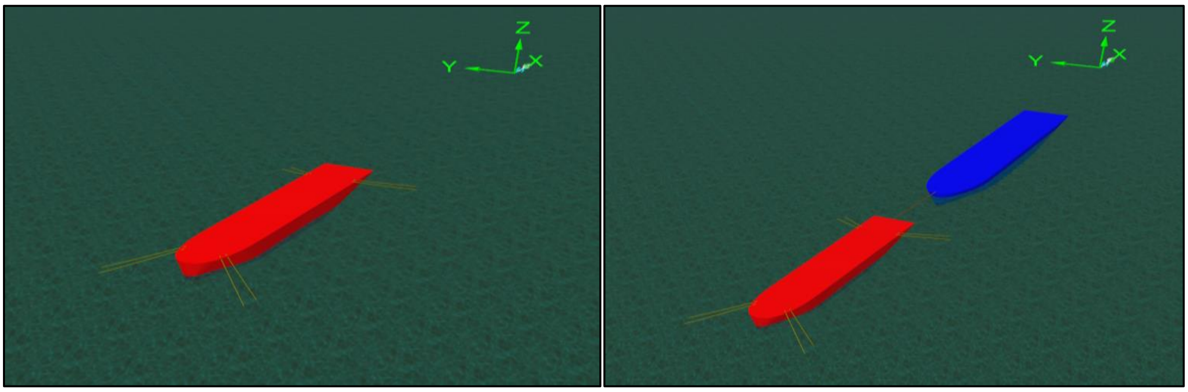


Figure 6. Modeling FSO Stand-alone and Tandem Offloading on Dynamic Analysis Software

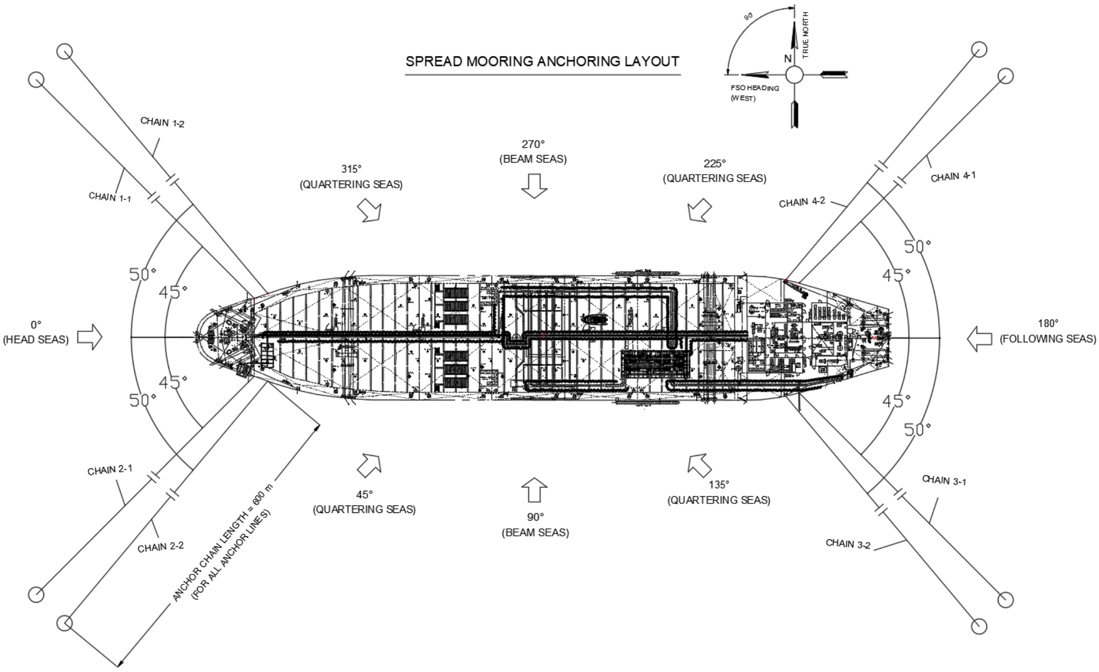


Figure 7. Configuration Modeling and Environmental Load Heading

The length of chain to be used in the analysis is 600 m with a diameter of 87 mm type R4, and a pretension of 20% of the MBL of the chain.

E. Chain Strength Analysis

The variation that will be carried out at the chain strength analysis stage is the variation of cargo combination between FSO and Export Tanker. The load variations include,

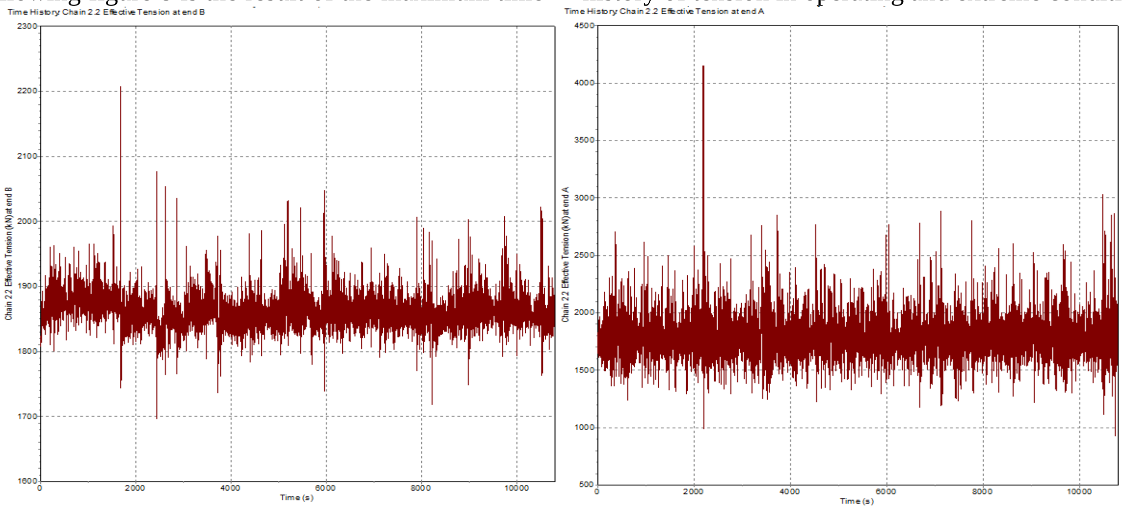
1) FSO Full Load – Export Tanker Ballast Load
2) FSO Half Load – Export Tanker Half Load
3) FSO Ballast Load – Export Tanker Full Load

Later, from the three variations above, a combination with the largest tension value will be sought which will be used for further analysis, namely fatigue life analysis. The limitation conditions carried out in strength analysis are SLS (Service Limit State) and ULS (Ultimate Limit State) conditions. The following table 8 is the conclusion of the strength analysis results for each load combination variation with environmental load directions of 0º, 45º, 90º, 135º, and 180º.

TABLE 8
MAX TENSION CONCLUSION RESULT ON STRENGTH ANALYSIS

Condition	Load		Max Tension	MBL (kN)	SF	Chain
	FSO	Export Tanker				
Operation (SLS)	Ballast	Full	2,207.40	7,682	3.48	Chain 2.2
	Half	Half	2,096.87	7,682	3.66	Chain 2.2
	Full	Ballast	2,050.48	7,682	3.75	Chain 2.2
Extreme (ULS)	Ballast	Full	4,151.60	7,682	1.85	Chain 2.2
	Half	Half	3,923.78	7,682	1.96	Chain 2.2
	Full	Ballast	3,329.66	7,682	2.31	Chain 2.2

The following figure 8 is the result of the maximum time history of tension in operating and extreme conditions,



(a) (b)

Figure 8. (a) Time History of Max Tension at Operating Condition (SLS) (b) Time History of Max Tension at extreme condition (ULS)

From the above results, it is found that the maximum tension in both SLS and ULS conditions is in the "FSO Ballast - Export Tanker Full" load combination with an SF (Safety Factor) value that still meets the API RP 2 SK requirements, which for intact conditions is greater than 1.67. Therefore, the load combination that will be used for fatigue analysis is the "FSO Ballast - Export Tanker Full" load combination".

F. Chain Fatigue Analysis

In the FLS (Fatigue Limit State) analysis, there are two scenarios to be analyzed, namely the FSO stand-alone condition scenario (without any offloading activities) and the condition scenario when Tandem Offloading is carried out. In this analysis, variations in significant wave height and peak period, as well as variations in the direction of environmental loading use wave scatter data available at that location. The wave scatter data can be seen in table 9.

TABLE 9
WAVE SCATTER DATA AT ZULU SITE [3]

Direction	Wave Height (m)						
	< 0.5	0.5 - 1.0	1.0 - 1.5	1.5 - 2.0	2.0 - 2.5	> 2.5	Total (%)
North	12.111	6.403	0.232	0.064	0.021	0.008	18.84
North East	12.309	3.968	0.099	0.018	0.000	0.000	16.39
East	10.370	1.863	0.391	0.058	0.004	0.000	12.69
South East	7.218	0.338	0.011	0.000	0.000	0.000	7.57
South	11.389	0.702	0.011	0.000	0.000	0.000	12.10
South West	6.396	0.937	0.195	0.021	0.007	0.040	7.60
West	8.874	5.109	1.118	0.041	0.000	0.000	15.14
North West	6.955	2.189	0.408	0.079	0.042	0.000	9.67
			Percentage of occurrence (%) =				100.00

In the dynamic analysis results with the time domain method, time history effective tension data will be obtained. The time history recording data will later be divided into 3 segment areas, namely the Splash Zone, Mid-catenary Zone, and Touch Down Zone (can be seen in Figure 9) The explanation of each segment is as follows,

a. Splash zone is the area where the anchor chain periodically enters and exits the water while the unit is at its operating depth. In general, this zone is between 5m above and 4m below the water surface.
b. Mid-catenary zone is the anchor chain area below the splash zone and always above the touch down zone.
c. Touch down zone the area when the chain starts to touch the sea bed until the anchor

With the help of Dynamic analysis software and the fatigue analysis module as well as the rainflow counting method, the time history effective tension data as shown in Figure 8 previously, the value of the stress range and the number of cycles for each stress range will be calculated into a histogram as shown in Figure 10.

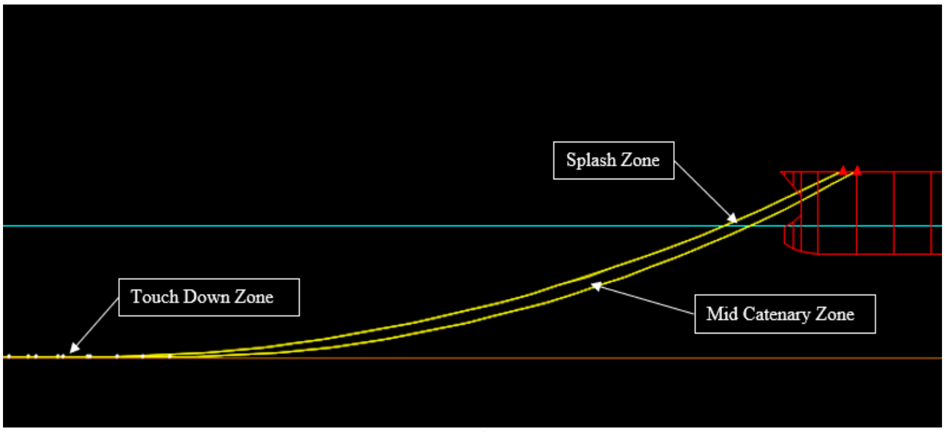


Figure 9. Division of 3 Segment Zones

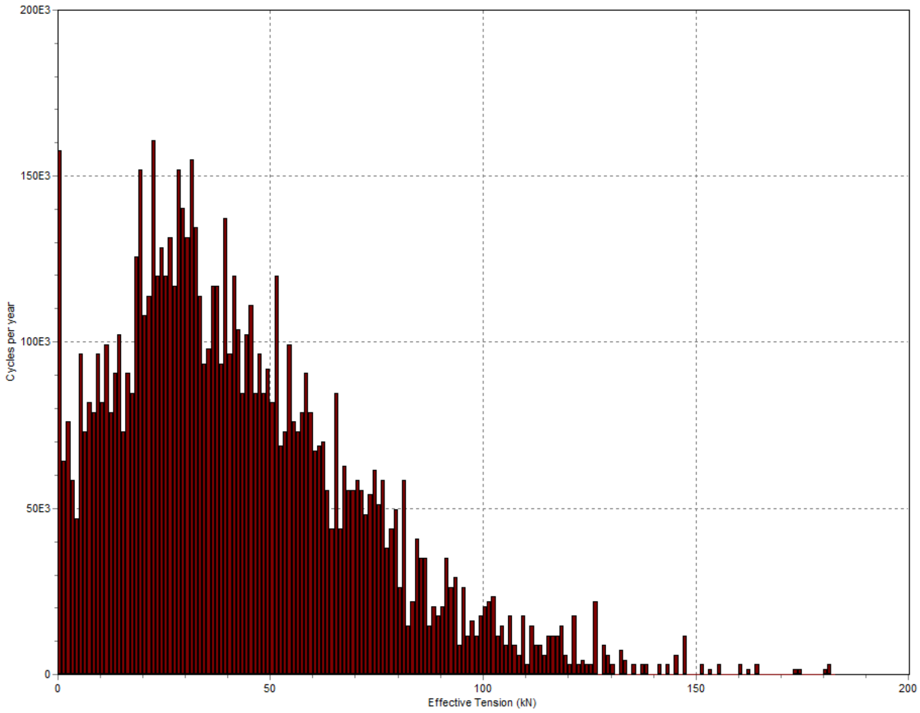


Figure 10. Example of Histogram of Rainflow Counting Effective Tension in Dynamic analysis software

From the rainflow counting histogram above, the results of the calculation of the number of cycles in each value of the stress range are obtained. Data is needed on the number of cycles of each chain and each chain segment, in each variation of Hs and the direction of environmental loads both in FSO stand-alone conditions and during tandem offloading conditions. From the number of cycles data, it will then be used to calculate fatigue damage as variable n_i by calculating the probability of occurrence in each direction according to the existing wave scatter data.

However, because the probability of each significant wave height variation is not the same in the real world, the number of cycles must be adjusted to the wave scatter or probability of significant wave height at the sea location used in the analysis. The cycle value that has been adjusted to the probability in the wave scatter will later be used for fatigue life calculation as variable n_i.

G. Fatigue Life Analysis on FSO Stand-alone Condition

Before calculating the fatigue life, the first thing to prepare is the T-N Curve value of the chain being analyzed because the calculation of the fatigue life uses the Palmgren-Miner rule. The following Table 10 and Figure 11 are the T-N Curve mooring line stud chains based on API RP 2SK [13] used in this calculation (see table 2).

By applying the number of cycles that occur during the year in each loading direction to the wave scatter, the fatigue damage obtained is also in the form of annual damage, so that the fatigue life achieved by the anchor chain can be calculated using the following formula

$$D_i = \frac{n_i}{K}[R_i{}^M] \quad (10)$$

The following table 10 is an example of the calculation of fatigue damage Chain 1.2, north direction, with Hs height is 1 m.

TABLE 10
CALCULATION OF FATIGUE DAMAGE VALUE IN THE NORTH DIRECTION & HS 1 M IN FSO STAND-ALONE CONDITION

Splash Zone								
Tension Range (kN)	Load case cycles per year	n_i	K	M	R	R^M	N	Di
		Cycles x Prob.	T-N Curve		$\frac{Tension\ Range}{MBL}$		$\frac{K}{R^M}$	$\frac{n_i}{N}$
1	1,262,561.188	80,838.796	1000	3	0.000130174	2.21E-12	5E+14	1.8E-10
2	771,565.170	49,401.486	1000	3	0.000260349	1.76E-11	6E+13	8.7E-10
3	420,853.729	26,946.265	1000	3	0.000390523	5.96E-11	2E+13	1.6E-09
4	596,209.450	38,173.875	1000	3	0.000520698	1.41E-10	7E+12	5.4E-09
5	561,138.306	35,928.353	1000	3	0.000650872	2.76E-10	4E+12	9.9E-09
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
995	0.0	0.0	1000	3	0.129523562	0.002173	5E+05	0
996	0.0	0.0	1000	3	0.129653736	0.002179	5E+05	0
997	0.0	0.0	1000	3	0.12978391	0.002186	5E+05	0
998	0.0	0.0	1000	3	0.129914085	0.002193	5E+05	0
999	0.0	0.0	1000	3	0.130044259	0.002199	5E+05	0
1000	0.0	0.0	1000	3	0.130174434	0.002206	5E+05	0
1001	0.0	0.0	1000	3	0.130304608	0.002212	5E+05	0
							∑Di	0.00804

From the fatigue damage value in each loading direction on the wave scatter, the cumulative damage value is obtained which is the total fatigue damage in each loading direction which will be used to determine the fatigue life of the anchor chain structure as shown in table 11 below,

TABLE 11
CALCULATION OF FATIGUE LIFE IN THE NORTH DIRECTION & HS 1 M IN FSO STAND-ALONE CONDITION

Splash Zone - Chain 1.2										
Direction	Damage						Total Damage Each Direction	Cumulative Fatigue Damage	Fatigue Life	Fatigue Life (With SF=3)
	Wave Height (m)									
	< 0.5	0.5 - 1.0	1.0 - 1.5	1.5 - 2.0	2.0 - 2.5	> 2.5				
North	1.74.E-03	8.04.E-03	1.66.E-03	1.07.E-03	1.80.E-04	5.54.E-05	1.27.E-02	1.43,E-02	70	23
North East	1.50.E-05	9.51.E-05	1.39.E-05	7.71.E-06	0.00.E+00	0.00.E+00	1.32.E-04			
East	1.32.E-06	1.92.E-06	1.03.E-06	3.19.E-07	4.86.E-08	0.00.E+00	4.63.E-06			
South East	1.13.E-05	1.21.E-05	2.21.E-06	0.00.E+00	0.00.E+00	0.00.E+00	2.56.E-05			
South	6.21.E-04	2.28.E-04	1.47.E-05	0.00.E+00	0.00.E+00	0.00.E+00	8.64.E-04			
South West	7.56.E-06	1.40.E-05	1.85.E-05	6.86.E-06	8.61.E-06	7.94.E-05	1.35.E-04			
West	7.82.E-07	2.11.E-06	1.66.E-06	1.44.E-07	0.00.E+00	0.00.E+00	4.70.E-06			
North West	6.41.E-05	1.24.E-04	7.20.E-05	3.62.E-05	6.61.E-05	0.00.E+00	3.63.E-04			

Mid Zone - Chain 1.2										
Direction	Damage						Total Damage Each Direction	Cumulative Fatigue Damage	Fatigue Life	Fatigue Life (With SF=3)
	Wave Height (m)									
	< 0.5	0.5 - 1.0	1.0 - 1.5	1.5 - 2.0	2.0 - 2.5	> 2.5				
North	1.72.E-03	7.76.E-03	1.62.E-03	1.05.E-03	1.78.E-04	5.50.E-05	1.24.E-02	1.39,E-02	72	24
North East	1.49.E-05	9.56.E-05	1.41.E-05	7.81.E-06	0.00.E+00	0.00.E+00	1.32.E-04			
East	1.38.E-06	1.99.E-06	1.08.E-06	3.42.E-07	5.26.E-08	0.00.E+00	4.86.E-06			
South East	1.16.E-05	1.24.E-05	2.29.E-06	0.00.E+00	0.00.E+00	0.00.E+00	2.63.E-05			
South	6.14.E-04	2.25.E-04	1.49.E-05	0.00.E+00	0.00.E+00	0.00.E+00	8.54.E-04			
South West	7.64.E-06	1.42.E-05	1.89.E-05	7.01.E-06	8.85.E-06	8.18.E-05	1.38.E-04			
West	7.16.E-07	2.00.E-06	1.51.E-06	1.29.E-07	0.00.E+00	0.00.E+00	4.36.E-06			
North West	6.36.E-05	1.24.E-04	7.29.E-05	3.68.E-05	6.77.E-05	0.00.E+00	3.65.E-04			

Touchdown Zone Chain 1.2										
Direction	Damage						Total Damage Each Direction	Cumulative Fatigue Damage	Fatigue Life	Fatigue Life (With SF=3)
	Wave Height (m)									
	< 0.5	0.5 - 1.0	1.0 - 1.5	1.5 - 2.0	2.0 - 2.5	> 2.5				
North	1.81.E-03	7.94.E-03	1.65.E-03	1.04.E-03	1.77.E-04	5.52.E-05	1.27.E-02	1.42,E-02	71	24
North East	1.60.E-05	9.84.E-05	1.42.E-05	7.86.E-06	0.00.E+00	0.00.E+00	1.36.E-04			
East	1.51.E-06	2.15.E-06	1.15.E-06	3.55.E-07	5.36.E-08	0.00.E+00	5.22.E-06			
South East	1.21.E-05	1.25.E-05	2.27.E-06	0.00.E+00	0.00.E+00	0.00.E+00	2.68.E-05			
South	6.43.E-04	2.32.E-04	1.49.E-05	0.00.E+00	0.00.E+00	0.00.E+00	8.89.E-04			
South West	8.16.E-06	1.48.E-05	1.92.E-05	7.05.E-06	8.79.E-06	8.08.E-05	1.39.E-04			
West	7.74.E-07	2.10.E-06	1.55.E-06	1.32.E-07	0.00.E+00	0.00.E+00	4.55.E-06			
North West	6.72.E-05	1.28.E-04	7.34.E-05	3.68.E-05	6.74.E-05	0.00.E+00	3.73.E-04			

The above calculation table is used to calculate the total fatigue life of each anchor chain segment. Thus, the fatigue life can be calculated in both FSO stand-alone conditions and summarized in table 12 below:

TABLE 12
SUMMARY OF CUMULATIVE DAMAGE VALUE OF EACH CHAIN IN FSO STAND-ALONE CONDITION

Chain Number	Fatigue Damage Per-Segment			Maximum Fatigue Damage
	Splash Zone	Mid-catenary Zone	Touchdown Zone	
Chain 1.1	0.0128	0.0125	0.0128	0.0128
Chain 1.2	0.0143	0.0139	0.0142	0.0143
Chain 2.1	0.0102	0.0077	0.0097	0.0102
Chain 2.2	0.0120	0.0090	0.0114	0.0120
Chain 3.1	0.0048	0.0036	0.0041	0.0048
Chain 3.2	0.0055	0.0041	0.0046	0.0055
Chain 4.1	0.0052	0.0040	0.0046	0.0052
Chain 4.2	0.0058	0.0044	0.0052	0.0058

From the fatigue damage above, the total fatigue life per-segment of each chain is obtained in table 13.

TABLE 13
SUMMARY OF FATIGUE LIFE VALUE OF EACH CHAIN IN FSO STAND-ALONE CONDITION

Chain Number	Fatigue Life Per-Segment			Minimum Fatigue Life
	Splash Zone	Mid-catenary Zone	Touchdown Zone	
Chain 1.1	77	79	78	77
Chain 1.2	70	72	71	70
Chain 2.1	98	130	103	98
Chain 2.2	83	111	88	83
Chain 3.1	208	274	244	208
Chain 3.2	183	241	217	183
Chain 4.1	193	253	219	193
Chain 4.2	172	225	192	172

From the calculation of the fatigue life of the structure, the table above shows that the anchor chain structure has a price of D < 1 so that the chain can be said to be still safe to use under operating conditions with the smallest structural fatigue life of 70 years, namely on Chain 1.2. The fatigue life of the structure is also in accordance with the safety factor criteria in API RP 2SK [17], which is at least 3 times the design life of the anchor chain where the design life is 15 years. So the design life target (with SF=3) become 45 years . The results of the fatigue life summary in the table are made into a comparison diagram of the fatigue life of each anchor chain segment under FSO stand-alone conditions as shown in Figure 11 and 12.

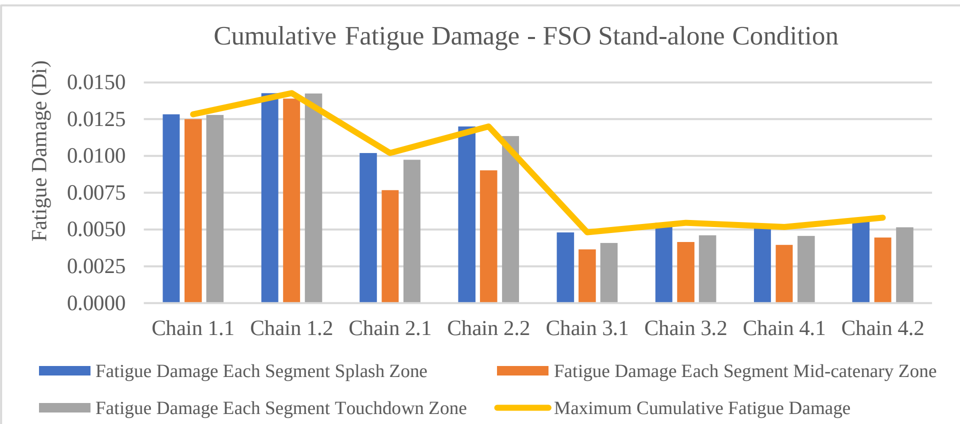


Figure 11. Comparison Diagram of Total Cumulative Fatigue Damage for Each Segment FSO Stand-alone Condition

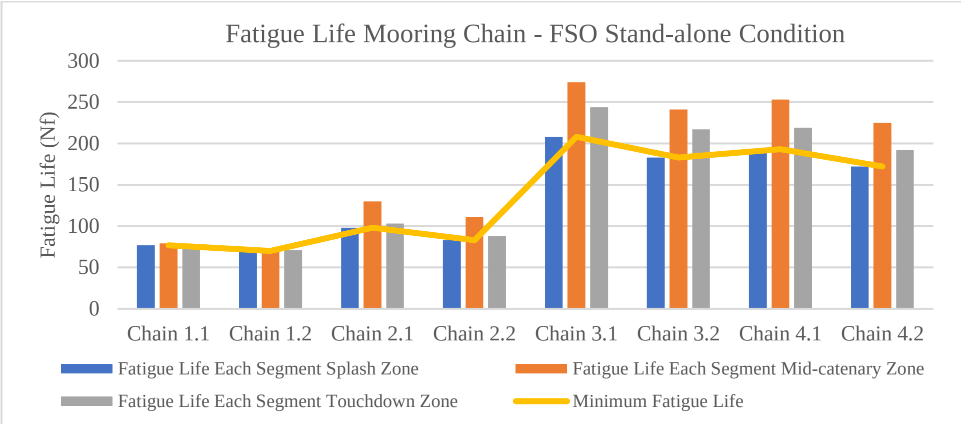


Figure 12. Comparison Diagram of Fatigue Life of Each Segment in Each Chain in FSO Stand-alone Condition

H. Analysis the Effect of Tandem Offloading System on Tension Chain Fatigue Life

It is the same as analyzing the fatigue life calculation in the FSO stand-alone condition. First, a dynamic analysis is performed to obtain the time history tension for each loading condition according to the wave scatter. From the results of the Histogram of Rainflow Counting Effective Tension in tandem conditions, by applying the number of cycles that occur during the year in each loading direction to the wave scatter, it can be calculated the fatigue life achieved by the anchor chain in tandem conditions as shown at table 14.

TABLE 14
CALCULATION OF FATIGUE DAMAGE VALUE IN THE NORTH DIRECTION & HS 1 M IN TANDEM CONDITION

Splash Zone								
Tension Range (kN)	Load case cycles per year	n_i	K	M	R	R^M	N	Di
		Cycles x Prob.	T-N Curve		$\frac{Tension\ Range}{MBL}$		$\frac{K}{R^M}$	$\frac{n_i}{N}$
1	1,052,144.067	67,366.287	1000	3	0.000130174	2.21E-12	5E+14	1.5E-10
2	491,000.564	31,437.600	1000	3	0.000260349	1.76E-11	6E+13	5.5E-10
3	491,000.564	31,437.600	1000	3	0.000390523	5.96E-11	2E+13	1.9E-09
4	596,214.971	38,174.229	1000	3	0.000520698	1.41E-10	7E+12	5.4E-09
5	491,000.564	31,437.600	1000	3	0.000650872	2.76E-10	4E+12	8.7E-09
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
995	0.0	0.0	1000	3	0.129523562	0.002173	5E+05	0
996	0.0	0.0	1000	3	0.129653736	0.002179	5E+05	0
997	0.0	0.0	1000	3	0.12978391	0.002186	5E+05	0
998	0.0	0.0	1000	3	0.129914085	0.002193	5E+05	0
999	0.0	0.0	1000	3	0.130044259	0.002199	5E+05	0
1000	0.0	0.0	1000	3	0.130174434	0.002206	5E+05	0
1001	0.0	0.0	1000	3	0.130304608	0.002212	5E+05	0
							∑Di	0.01046

The above calculation table is used to calculate the total fatigue life of each anchor chain segment. Thus, fatigue damage can be calculated under tandem offloading conditions and summarized in the following table 15:

TABLE 15
SUMMARY OF CUMULATIVE DAMAGE AND FATIGUE LIFE VALUES UNDER TANDEM OFFLOADING

Chain Number	Fatigue Damage Each Segment			Maximum Fatigue Damage
	Splash Zone	Mid-catenary Zone	Touchdown Zone	
Chain 1.1	0.0167	0.0163	0.0166	0.0167
Chain 1.2	0.0187	0.0183	0.0186	0.0187
Chain 2.1	0.0149	0.0113	0.0135	0.0149
Chain 2.2	0.0178	0.0134	0.0177	0.0178
Chain 3.1	0.0052	0.0040	0.0045	0.0052
Chain 3.2	0.0057	0.0043	0.0052	0.0057
Chain 4.1	0.0054	0.0041	0.0051	0.0054
Chain 4.2	0.0062	0.0047	0.0060	0.0062

After obtaining the Cumulative Damage value, then, the value needs to be multiplied by the percentage of occurrences of the offloading process in a year. Table 16 below is the calculation data for the length of the offloading process that will be carried out at the FSO in a year [3],

TABLE 16
CALCULATION OF OFFLOADING PROCESS TIME PER YEAR [3]

Parameter	Value
Cargo pump capacity (each); bbl/h	2,830
Cargo pump capacity (each); m3/h	450
Operating cargo pump number	1
Total cargo pump capacity; m3/h	450
Oil volume for each offloading; bbls	150,000
Oil volume for each offloading; m3	23,848
Offloading duration at maximum pump rate; h	53
Offloading cycle frequency per year	24
Total offloading hours per year	1,271.893
Percentage of offloading hours per year	14.52%

From the calculations in table 16 above, the calculation of cumulative damage during FSO stand-alone contained in table 12, multiplied by the percentage of FSO stand-alone events during the year, add with the cumulative damage during tandem offloading contained in table 15, multiplied by the percentage of offloading events during the year (see table 16). The results of the combined cumulative damage calculation (the effect of tandem offloading) are listed in table 17 below,

$$\sum D_i = (\sum D_{iF}\ x\ P_F) + (\sum D_{iT}\ x\ P_T) \quad (11)$$

With,

D_{iF} = cumulative fatigue damage of FSO stand-alone condition

D_{iT} = cumulative fatigue damage of tandem offloading

P_F = percentage of hours per year FSO stand-alone condition

P_T = percentage of hours per year for tandem offloading

TABLE 17
SUMMARY OF CUMULATIVE FATIGUE DAMAGE VALUES FOR CONSIDERING THE OFFLOADING EFFECT

Chain Number	Fatigue Damage Each Segment			Maximum Fatigue Damage
	Splash Zone	Mid-catenary Zone	Touchdown Zone	
Chain 1.1	0.0134	0.0131	0.0134	0.0134
Chain 1.2	0.0149	0.0146	0.0149	0.0149
Chain 2.1	0.0109	0.0082	0.0103	0.0109
Chain 2.2	0.0128	0.0097	0.0123	0.0128
Chain 3.1	0.0049	0.0037	0.0042	0.0049
Chain 3.2	0.0055	0.0042	0.0047	0.0055
Chain 4.1	0.0052	0.0040	0.0047	0.0052
Chain 4.2	0.0059	0.0045	0.0053	0.0059
Max. Fatigue Damage (Di)				0.0149
Fatigue Life (Nf), year				67

The results of the fatigue life summary in the table are made into a comparison diagram of the fatigue life of the anchor chain under FSO stand-alone conditions and under tandem offloading influence conditions as follows:

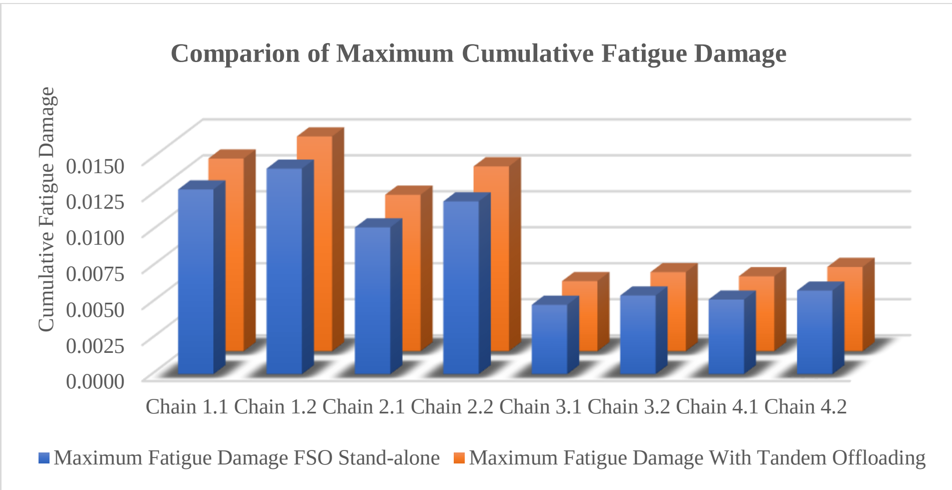


Figure 13. Comparison Diagram of Fatigue Life of Each Segment in Each Chain

IV. CONCLUSION

From the calculations and discussions that have been carried out, several conclusions can be drawn that,

1) The largest stress with this configuration is in ballast loading conditions with a tension value of 2207.4 kN in operating environment conditions (1 year) and 4151.6 kN in extreme environment conditions (100 years) with SF of 3.48 and 1.85 respectively which is still above the SF value required by API RP 2 SK which is 1.67 in SLS and ULS conditions.
2) For the fatigue life analysis, with this configuration under ballast conditions when only taking into

account the FSO stand-alone condition (without considering tandem offloading loads), the lowest fatigue life value being at Chain 1.2 which is 70 years.

3) From the results of the fatigue life analysis considering the tandem offloading effect, with a total offloading frequency of 24 times (1271.89 hours) per year. The the lowest fatigue life is obtained in the chain 1.2, which is 67 years and still met the safety factor requirements according to API RP 2 SK,
4) The influence of tandem offloading, increases the value of fatigue damage by 7%. Therefore, if the frequency of offloading per year is increased, it will allow the fatigue life value on the chain to decrease because the percentage of fatigue damage value on the tandem offloading hour per year becomes greater.

Based on the results of this study, there are several suggestions that can be made for the development of further research as follows:

1) Based on the above conclusions, the fatigue life value has only been analyzed under the condition of FSO ballast load and full export tanker load. It is necessary to consider the effect of load variations on both the FSO and export tanker on the fatigue life of the chain.
2) With the influence of the tandem offloading process on the fatigue life of the chain, it is necessary to analyze with variations in the total frequency of offloading per year.
3) With the same configuration, it is possible to analyze the effect of pretension variation at the time of design on the fatigue life of the chain.
4) It is possible to analyze the fatigue life using other methods, such as spectral method, by conducting local analysis on the chain.

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