HOSTED BY unisel

Selangor Science &Technology Review
Special Issue: Science and Technology for Society
Vol 5 No 5 (2021)

Parametric Study and Risk Analysis of SPM Chain Line due to Fatigue and Corrosion Effect

Yusuf Nurhuda[1*], A A B Dinariyana[2], Yeyes Mulyadi[3]

[1]Department of Marine Engineering, Institut Teknologi Sepuluh Nopember Surabaya
yusufnurhuda13@gmail.com
[2]Department of Marine Engineering, Institut Teknologi Sepuluh Nopember Surabaya
dinariyana@yahoo.com
[3]Department of Ocean Engineering, Institut Teknologi Sepuluh Nopember Surabaya
yeyesmulyadi@gmail.com

Abstract: In process of unloading on tankers there are several obstacles, one of obstacles is breaking of SPM mooring line when unloading process is in progress. This can endanger safety of crew and ship buildings due to colliding with other floating structures. This factor is reason for need an analysis to determine value of strength structure on mooring line, so that operability and safety of mooring system can be maintained. Therefore, there is a need for a risk analysis study on SPM chain line structure which is carried out using FTA-FMEA method, where risk analysis of chain line structure in this study is caused by fatigue under stress loads and dimensional reduction due to corrosion effect. Results showed that variations in diameter SPM affect fatigue in mooring line series where larger diameter SPM and higher significant wave load in operational environment, the greater nominal stress and deformation in each loading and environmental conditions. Results of age on chain line structure still meet safety standards. Mitigation measures on critical risk indicate that interpretation of minimum cut set is a failure in form of a broken chain line in SPM mooring line, minimum cut set for SPM chain line component which has a critical risk of 3.3%. Mitigation step in risk analysis that should be taken to reduce causes described by minimum cut set is to implement periodic inspections that are more stringent in frequency on mooring line series, besides that it is necessary to apply preventive maintenance which previously only applied corrective maintenance.

Keywords: Chain Line, Corrosion, Fatigue, Risk Analysis

1. Introduction

Single Point Mooring (SPM) is a floating building structure that works as a mooring and interconnection for unloading cargo on ships. During the unloading process, there are several obstacles, one of the obstacles that can occur in mooring system is a break in mooring line during the unloading process. In this case it can endanger safety of crew and other floating structures. Assessment has always been a serious concern in marine transportation because shipping can pose problems of potential hazards to human life, commodities, and the aquatic environment. This factor is a reason for need for an analysis to determine the strength of mooring line, so that the operability and safety of mooring system can be maintained, and can determine value of stress strength on mooring line due to fatigue factor and dimension reduction caused by the corrosion rate on mooring line. SPM chain line structure.

Variations in wind, current, and wave loads produce variable motion and stress in mooring system. Connection to mooring system, water depth and influence of wave loads are parameters that affect fatigue life of mooring line (Sabana, 2018). In addition, reduction in dimensions of degradation chain structure due to the corrosion rate can result in significant structural degradation in SPM structure chain path, further structural degradation will result in structural failure. Therefore, it is necessary to study the risk of failure in SPM chain line structure. SPM type Catenary Anchor Leg Mooring (CALM) structure and operations which can be seen in Figure 1.

(a) (b)

Fig. 1 (a) Structure SPM CALM type (b) SPM operations

Fatigue factor and the influence of corrosion on SPM chain line structure will affect the reliability of mooring line structure series. In this study, we will discuss why a parametric study and a study of the risk analysis of SPM chain line due to fatigue and corrosion effect. SPM structure that will be used as the object of analysis is SPM with Catenary Anchor Leg Mooring (CALM) type. Focus of this research is how to analyze parametric studies and study the risk of failure to determine effect of strength chain line as a whole.

2. Methodology

2.1 Structure SPM and Environment Conditions

This analysis begins with the stage of collecting structural data that will be used as modeling in actual conditions. Data obtained in this analysis were obtained from the location of offsite and marine units in the sea of Tuban Indonesia. The data includes on the waters of the Tuban sea and dimensional structure data from SPM. Data to be used in this analysis can be seen in Table 1 and Table 2.

Table 1. Properties SPM and Properties Mooring Line

Single Point Mooring		**Mooring Line SPM**	
Description	**Quantity**	**Description**	**Quantity**
Size	10.2 x 14,2 *m*	Grade Chain	RQ3S
Height	9 *m*	Number of Legs	3 x 2, 300 *m*
Weight	250 Te	Chain Breaking Load	5454 kN
Draft	3.99 *m*	Stiffness Chain Line	498400 kN

Table 2. Tuban sea environment conditions

Description	**Unit**	**Description**	**Unit**
Water Depth	27.5 *m*	Maximum Wave Height	4.6 *m*
Higher Lower Water	28.2 - 26.4 *m*	Maximum Wave Period	8.7 *Sec*
Significant Wave Height	3.1 *m*	Wind Speed	21,2 *m/s*
Significant Wave Period	6.9 *Sec*	Current Speed	0,95 *m/s*

Selangor Science &Technology Review
Special Issue: Science and Technology for Society
Vol 5 No 5 (2021)

2.2 Structural Response Analysis

Chakrabarti (1987) the initial concept of this system is as a binder for ship to remain in the initial position of transfer process so that the unloading system can run smoothly. Movement of SPM structure is caused by the forces acting on mooring system including (inertial force, restore force and damping force) in mooring system. Movement of the six degrees of freedom can be divided into two types of movement, namely translational movement and rotational movement. RAO (Response Amplitudo Operator) is obtained from the frequency domain numerical simulation (Bhattacharya, 1978)

$$RAO(\omega) = \frac{\zeta k0(\omega)}{\zeta 0\ (\omega)}\ (m/m) \qquad (1)$$

The stage of getting RAO value is followed by analysis of the response to structure, which can be known by multiplying RAO squared with wave spectrum. Wave spectrum serves to determine the characteristics and amount of wave energy in the environment. The response spectrum can be defined as the energy of structure due to wave, if it is formulated the equation is obtained:

$$S\,R = [\ RAO\ (\omega)]^2\ S(\omega) \qquad (2)$$

SPM operates in Java Sea waters, especially Tuban Sea which is a closed water area, so it is necessary to use JONSWAP spectrum because the formulation of JONSWAP spectrum has a more complex shape. Tuban sea follows the equation in JONSWAP spectrum.

2.3 Maximum Stress Analysis at Chain Line

Analysis of the maximum stress on chain line is carried out to obtain the value of maximum stress force on chain line. Results of the maximum stress force are used as load input for the analysis of the strength of chain line structure. Analysis of the maximum stress on chain line is done by simulating time domain analysis at full load conditions. To produce the maximum stress on chain line, 3 hours (10800 s) simulation is required according to the recommendation of (DNVGL E301, 2015). Results of the tension analysis on chain line still meet safety limit according to API RP 2SK $2nd$ edition standard.

$$\frac{\text{Minimum Breaking Load}}{\text{Maximum tension}} > 1{,}67 \qquad (3)$$

2.4 Analysis of Structural Strength and Dimensional Reduction

Axial stress or normal stress is the stress that acts perpendicular to the cross section of structure. Axial stress can be generated from tension or compressive forces. Whereas shear stress is the intensity of the force at a point parallel to the cross section. The equations of axial stress and shear stress are as follows:

$$\text{Axial Stress Equation}\quad \tau = \frac{F}{A} \qquad (4)$$

$$\text{Shear Stress Equation}\quad \tau = \frac{V}{A} \qquad (5)$$

Selangor Science &Technology Review
Special Issue: Science and Technology for Society
Vol 5 No 5 (2021)

At stage of analyzing the strength of structure and reducing the dimensions of chain line, namely by reducing the dimensions of chain line structure due to the corrosion rate by reducing thickness of structure by using the weigh gain loss method by using the equation.

$$R = \frac{K \times \Delta W}{A \times T \times D} \quad (6)$$

2.5 Fatigue Life Analysis on Chain Line Stucture

Du et al. (2020) Floating offshore platform systems are widely used for the exploitation of marine resources, such as offshore oil and gas, wind energy, and wave energy. These systems are designed to operate for up to 20 or even 30 years, during which the floating platform and its mooring system are continuously subjected to complex and harsh marine environment loads (particularly cyclic wave loading). As more permanent floating structures are installed, the need to assess fatigue performance of moorings becomes increasingly important (Xu et al., 2014). Fatigue damage to offshore structures is predominantly caused by wave loads. The stress caused by this load always changes direction and magnitude and takes place randomly. This stress is divided into various stress groupings which cumulatively result in total fatigue damage. Friction in fatigue lifetime is assumed by a given stress range in one year as a ratio of the number of cycles in that stress range causing damage, S-N Curve or Wohler curve is a plot of Stress (S) versus number of cycles (N). The formulation of fatigue life of a structure is as follows:

$$\text{Fatigue Life} = \frac{\text{Design Life}}{D} \quad (7)$$

2.6 Risk Analysis and Determination of Mitigation

In recent years, a number of failure risks are considered high in the analysis of mooring system of floating structures. So it is necessary to do a failure risk analysis on a series of mooring systems in floating building structures, which aims to improve operational safety on the building structure. Fault tree analysis (FTA) is an example of a graphical model that shows the logistical combination of multiple failures that will result in an event. The combination can involve component failure, human error, and management system failure. FTA produces a failure model that uses Boolean logic gates (AND, OR) to explain how equipment failure and human error can lead to major system failures (Vesely & Goldberg, 1981). In the FTA section, the calculation of the failure probability (PF) for each gate is carried out based on the following formulation:

$$\text{Gate OR, } PF = 1-[(1-P_1)(1-P_2)] \quad (8)$$

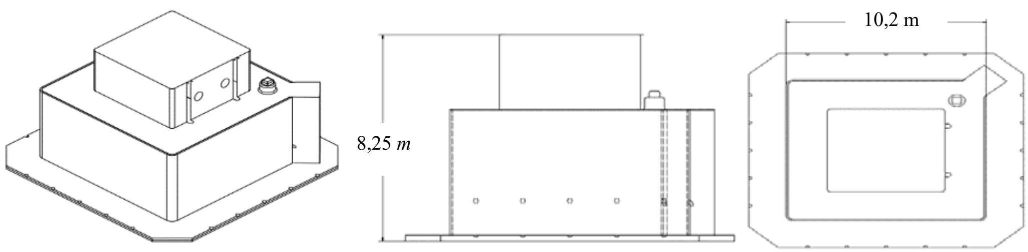
$$\text{Gate AND, } PF = P_1 \times P_2 \quad (9)$$

The method used in this study in analyzing the risk of failure in a series of mooring systems is to use FMEA (Failure Mode and Effect Analysis) method. FMEA could identify, analyze and estimate possible faults in system and the manifestations (Ahire & Relkar, 2012). Where when conducting a risk assessment through modifications to mooring system the analysis used the Failure Modes and Effects Analysis (FMEA) method, with the aim of studying the relationship between failure modes and their effect on the probability of failure of entire mooring system (Kang et al., 2017).

3. Result and Discussion

3.1 Modeling and Validation of SPM Models

SPM modeling using Solidworks software is carried out to obtain hydrostatic models and data that will be used as a comparison of results of modeling and validation of models that have been made. Hydrostatic modeling and data are then used as input to get the RAO SPM value. Validation of SPM model needs to be done because it aims to display an appropriate structural modeling in the actual situation, so that SPM structure model can be used as an object of analysis. The weight of structure in SPM model is 249.502 tons, while the weight of structure known from SPM general arrangement data is 250 tons, if the difference is calculated there is a difference of 0.19%. The correction allowed for the difference between model and the original structure is only 0.5%. The following is a floating buoy model of SPM, isometric SPM floating buoy modeling, front view and top view can be seen in Fig 2.



(a) (b) (c)

Fig. 2 (a) Isometric SPM model (b) SPM side view (c) SPM top view

The variation of SPM model is done by varying size of D and T which is done 3 times, so that structural modeling in SPM has 3 types of models. This is done in order to obtain sufficient data for the manufacture of mathematical models. Description of diameter variation in SPM model can be seen in Table 3.

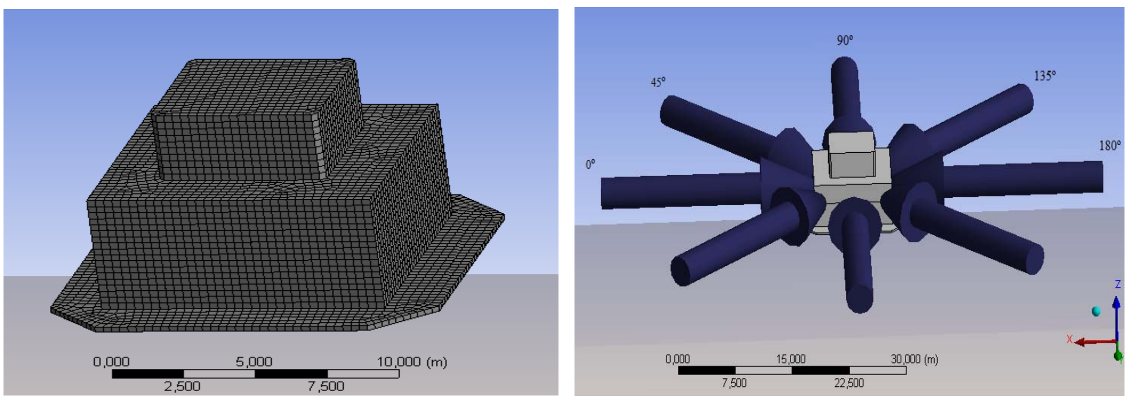
Table 3. SPM model variations

Reference	Model Variation 1	Model Authentic	Model Variation 2
Size (*m*)	8,2 x 8,2	10,2 x 10,2	12,2 x 12,2
Height (*m*)	8,25	8,25	8,25
Weight (*ton*)	206,429	249,502	318,730
Draft (*m*)	4,2	4,0	3,8

In this study, variations in diameter of SPM model were carried out with the aim of knowing the output results of fatigue in SPM chain line structure. Variation of D/T parameters for this parametric study was carried out within the limits of Buoy Weight. This D/T value adjusts to width, diameter and depth.

3.2 Results of Structural Movement Analysis

The RAO analysis stage on SPM structure is started by using the Ansys software which has been converted from results of model that has been created using Solidworks software. the next step is to adjust the existing geometry in Ansys AQWA before meshing process is carried out on SPM model. After meshing process has been carried out on SPM structure, next stage is a simulation process using variations in the direction of the incoming wave as shown in Figure 3. Results of the simulation obtained are in form of an RAO value based on frequency as the largest movement response from other movement responses. RAO motion behavior in regular waves which includes movement of 6 degrees of freedom (rotational motion and translational motion). Results of the RAO are six degrees of freedom, namely surge, sway, sway, roll, pitch and yaw. From the tables below, it can be identified maximum value of response of each RAO movement in the modeling of SPM structure with each direction of wave arrival. Based on the results from the tables above, it can be seen that the movement of the Variation 2 SPM model has the highest RAO value compared to other model variations. Next step is to analyze the wave spectrum calculation with the environmental conditions in which the SPM operates.



(a) (b)

Fig. 3 (a) Meshing SPM model (b) Variations in direction of incoming wave

Structural motion analysis was performed on each SPM model. The results from RAO analysis are obtained in form of RAO SPM which are presented in Table 4 to Table 6.

Table 4. RAO SPM free floating variation 1

Heading	Surge *m/m*	Sway *m/m*	Heave *m/m*	Roll *deg/m*	Pitch *deg/m*	Yaw *deg/m*
0º	0,66	0,06	0,88	0,43	0,85	0,06
45º	0,25	0,45	3,90	0,60	0,68	0,01
90º	0,18	0,65	3,86	0,72	0,36	0,08
135º	0,24	0,46	3,86	0,68	0,64	0,07
180º	0,65	0,64	0,12	0,44	0,85	0,06
RAO max.	0,66	0,65	3,90	0,72	0,85	0,08

Table 5. RAO SPM free floating authentic

Heading	Surge *m/m*	Sway *m/m*	Heave *m/m*	Roll *deg/m*	Pitch *deg/m*	Yaw *deg/m*
0°	0,69	0,06	0,94	0,44	0,93	0,08
45°	0,25	0,48	4,12	0,68	0,73	0,01
90°	0,18	0,68	4,10	0,87	0,37	0,08
135°	0,25	0,48	4,10	0,68	0,65	0,10
180°	0,67	0,66	0,12	0,45	0,93	0,08
RAO max.	0,69	0,68	4,12	0,87	0,93	0,10

Table 6. RAO SPM free floating variation 2

Heading	Surge *m/m*	Sway *m/m*	Heave *m/m*	Roll *deg/m*	Pitch *deg/m*	Yaw *deg/m*
0°	0,71	0,06	1,05	0,45	1,01	0,09
45°	0,26	0,49	4,30	0,79	0,78	0,01
90°	0,18	0,71	4,32	1,02	0,38	0,08
135°	0,26	0,52	4,32	0,68	0,67	0,12
180°	0,68	0,67	0,12	0,45	1,01	0,09
RAO max.	0,71	0,71	4,32	1,02	1,01	0,12

In this study, SPM used as the object of analysis operates in Java Sea waters, especially Tuban sea. Next step is to calculate structural response of SPM which is the energy density of structure due to waves. The response spectra were obtained by multiplying wave spectrum and RAO squared. The process of calculating response spectra aims to determine the conditions at random waves where SPM operates, variations are carried out based on the direction of the angle of arrival of waves and height of waves. The response spectra were obtained by multiplying RAO^2 by wave spectrum. The following is maximum value of response spectra in several variations of SPM model, which can be seen in Table 7 - 9.

Table 7. Spectra response SPM variation 1

Motion	Unit	0°	45°	90°	135°	180°	Max.
Surge	$m^2/(rad/s)$	2,0073	0,0002	0,0001	0,0006	0,0042	2,0073
Sway	$m^2/(rad/s)$	0,0002	0,0010	0,0008	0,0002	0,0001	0,0010
Heave	$m^2/(rad/s)$	10,2080	0,1016	0,0010	2,0782	11,0944	11,0944
Roll	$deg^2/(rad/s)$	0,0963	0,1866	3,8601	0,1088	0,0780	3,8601
Pitch	$deg^2/(rad/s)$	0,5086	0,2490	0,2608	0,29	2,0006	2,0006
Yaw	$deg^2/(rad/s)$	0,0002	0,0308	0,0002	0,0002	0,0032	0,0308

Table 8. Spectra response SPM authentic

Motion	Unit	0°	45°	90°	135°	180°	Max.
Surge	$m^2/(rad/s)$	3,1272	0,0004	0,0001	0,0006	0,0122	3,1272
Sway	$m^2/(rad/s)$	0,0002	0,0010	0,0012	0,0002	0,0001	0,0012
Heave	$m^2/(rad/s)$	11,5290	0,2109	0,0016	5,1582	14,0488	14,0488
Roll	$deg^2/(rad/s)$	0,0988	0,1410	4,0151	0,1148	0,0720	4,0151
Pitch	$deg^2/(rad/s)$	0,5724	0,2722	0,2712	0,2708	2,0026	2,0026
Yaw	$deg^2/(rad/s)$	0,0002	0,0465	0,0004	0,0002	0,0043	0,0465

Table 9. Spectra response SPM variation 2

Motion	Unit	0º	45º	90º	135º	180º	Max.
Surge	*$m^2/(rad/s)$*	5,7342	0,0080	0,0001	0,0062	0,0420	5,7342
Sway	*$m^2/(rad/s)$*	0,0002	0,0010	0,0156	0,0002	0,0001	0,0156
Heave	*$m^2/(rad/s)$*	11,8212	0,2109	0,0010	11,8253	17,4412	17,4412
Roll	*$deg^2/(rad/s)$*	0,0902	0,1814	5,0168	0,1184	0,0790	5,0168
Pitch	*$deg^2/(rad/s)$*	0,5775	0,2755	0,2712	0,2920	3,2612	3,2612
Yaw	*$deg^2/(rad/s)$*	0,0002	0,0402	0,0004	0,0002	0,0004	0,0402

3.3 Chain Line Maximum Stress Analysis

Chain line stress analysis aims to determine output value of the maximum stress on chain line. Loads that are included in this analysis are wave loads, wind loads and 100-year current loads. Analysis of the tension chain line was carried out using ANSYS Aqwa software with a simulation of time domain analysis. To produce the maximum stress on chain line, 3 hours (10800 s) simulation is required according to DNVGL OS E301 (2015) standard. An image of SPM configuration is presented in Figure 4.

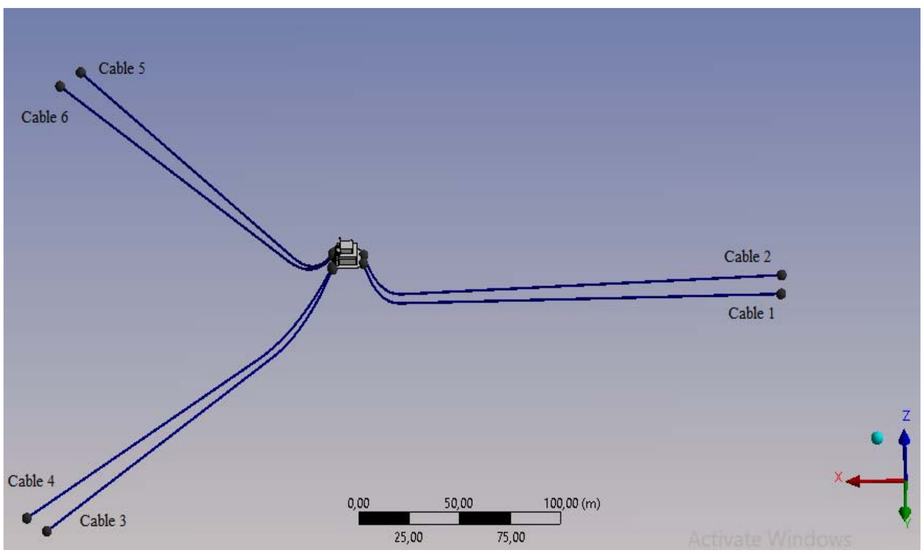


Fig. 4 SPM Configuration

Results of the maximum stress will be used for loading in next stage of the simulation process. The greatest stress value occurs in SPM chain line variation 2 which is found in cable 6 which is at 45º heading in direction of wave, which is 2424873.0 N. Result of the maximum stress on chain line has a safety factor value of 2.24. Safety factor value on chain line is greater than the recommended safety factor according to API RP 2SK 2nd edition standard.

Table 10. Value of chain line stress on SPM variation 1

Chain Line	Maximum Tension for each heading				
	0º	**45º**	**90º**	**135º**	**180º**
Cable 1	415.900,3	1.250.199,9	1.342.983,5	1.399.120,0	2.314.870,0
Cable 2	421.784,1	1.394.902,8	1.387.727,6	1.378.474,6	2.313.385,9
Cable 3	930.186,6	1.338.980,2	428.252,4	37.984,0	683.937,1
Cable 4	1.482.473,0	2.159.876,7	520.193,3	911.032,5	665.997,7
Cable 5	973.317,1	1.908.096,2	1.608.810,3	2.018.096,4	654.081,9
Cable 6	2.128.809,2	2.315.210,0	1.193.975,1	1.898.068,8	602.588,3
Time (*sec*)	1080	10800	1310	1354	10800
Safety Factor	2,56	2,35	3,39	2,70	2,35

Table 11. Value of chain line stress on SPM authentic

Chain Line	Maximum Tension for each heading				
	0º	**45º**	**90º**	**135º**	**180º**
Cable 1	417.512,2	1.254.829,1	1.384.020,5	1.412.020,0	2.380.890,5
Cable 2	438.786,1	1.395.372,4	1.410.627,2	1.381.223,2	2.376.985,0
Cable 3	930.248,3	1.339.219,2	428.783,9	38.018,2	684.530,3
Cable 4	1.590.557,0	2.191.285,7	522.473,3	913.212,9	667.417,5
Cable 5	974.934,1	1.940.026,3	1.642.010,5	2.047.926,1	654.892,1
Cable 6	2.176.975,2	2.380.071,0	1.201.072,1	1.987.318,6	602.810,5
Time (*sec*)	1060	10800	1310	1360	10800
Safety Factor	2,50	2,29	3,32	2,66	2,29

Table 12. Value of chain line stress on SPM variation 2

Chain Line	Maximum Tension for each heading				
	0º	**45º**	**90º**	**135º**	**180º**
Cable 1	421.520,3	1.255.899,9	1.400.083,9	1.421.850,0	2.424.870,0
Cable 2	469.786,4	1.395.812,8	1.440.727,5	1.383.473,6	2.421.175,2
Cable 3	930.351,2	1.339.255,2	429.652,4	39.302,1	685.536,3
Cable 4	1.680.699,0	2.232.175,7	524.573,3	914.832,9	669.497,9
Cable 5	975.017,1	1.981.096,3	1.688.010,9	2.091.926,1	655.296,1
Cable 6	2.228.690,6	2.424.873,0	1.210.595,1	2.000.073,8	603.375,5
Time (*sec*)	1058	10800	1317	1360	10800
Safety Factor	2,44	2,24	3,23	2,60	2,24

3.4 Chain Line Structure Strength Analysis

The initial stage in analysis of chain line stress is to do modeling as much as possible to represent the state of structure. Modeling of this structure is done by using General Notes on chain line. After chain line modeling is imported, then the meshing process is carried out on model that has been created. The meshing will affect the literacy time of solver, so it is necessary to analyze the meshing sensitivity after giving meshing and loading on chain line. Meshing chain line model process on chain line can be seen in Figure 5.

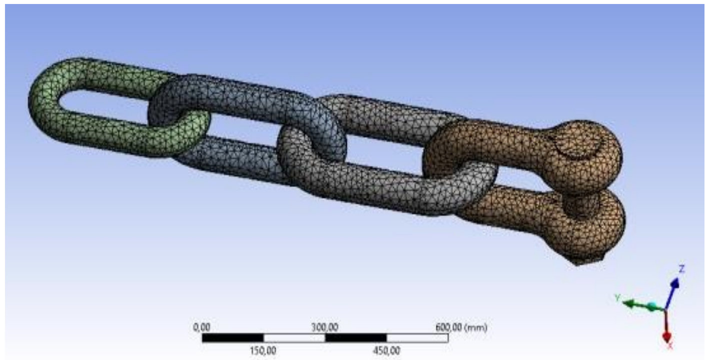
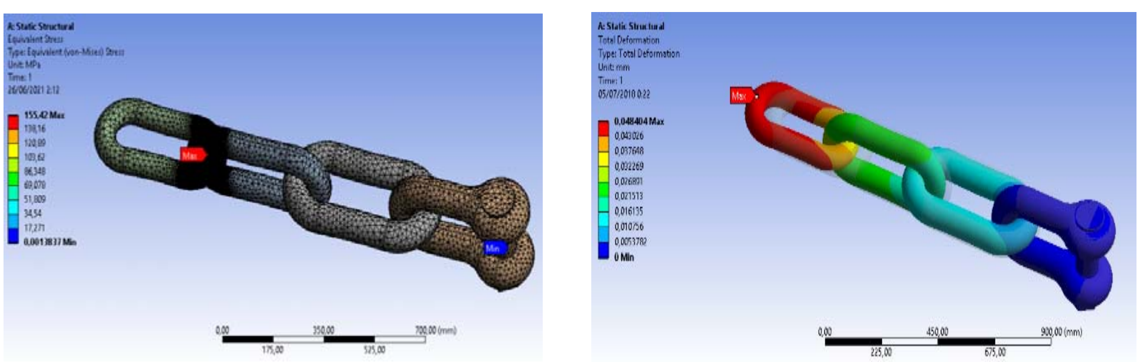


Fig. 5 Meshing chain line model

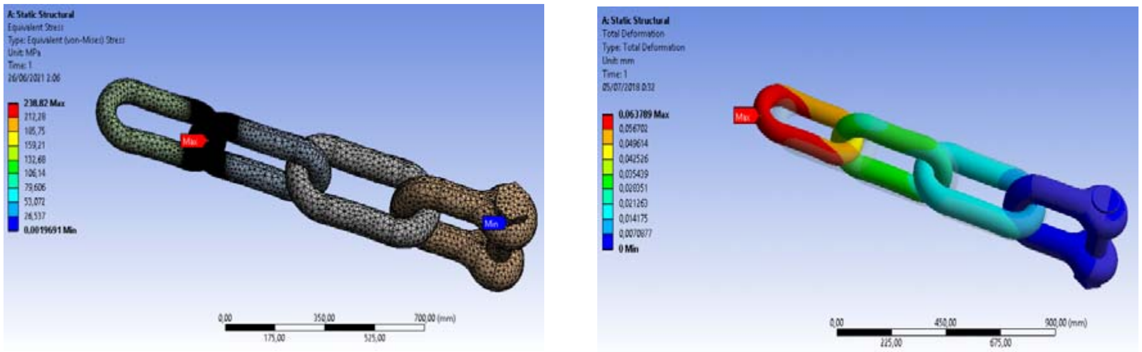
Next stage is to find out how strong chain line structure is when there is maximum tension and deformation or changes in shape experienced by chain line structure. According to standard DNVGL OS E301 Section E200, corrosion rate on material chain with catenary type shows a reduction in dimensions of 0.2 mm/yr. The strength of chain line structure when receiving a working load is at a safe criterion that does not exceed the maximum value of Yield Strength according to the reference. DNVGL OS E301 standard is 441 MPa. Results of analysis of the strength of chain line structure in SPM obtained a stress result of 155.42 MPa using the Ansys Static Structural simulation using General Notes data at the beginning of chain line installation, whereas if the estimation with a time period of 30 years ahead of chain line installation obtained the stress result of 238.82 MPa. Simulation of analysis strength chain line structure in form maximum stress value and the deformation value of structure can be seen in Figure 6.



(a) (b)

Fig. 6 (a) Max. stress Installation (b) Deformation Installation

Selangor Science &Technology Review
Special Issue: Science and Technology for Society
Vol 5 No 5 (2021)



(c) (d)

Fig. 6 (c) Max. stress Est. 30 yr (d) Deformation Est. 30 yr

Results of analysis of the strength of chain line structure are in form of the maximum stress value and the deformation value in chain line structure which can be seen in Table 13.

Table 13. Maximum stress and deformation on chain line

Reference	Year	Presentase	Max. Stress	Deformation
Installation	2005	100%	155,42 MPa	0,048404 *mm*
Est. 30 yr	2035	92,1%	238,82 MPa	0,063789 *mm*

From this analysis, it shows that chain line is able to accept working loads and is still within the safe criteria or does not exceed the maximum value limit in 30 years of operation.

3.5 Results of Fatigue Life Analysis

Analysis of structural strength of chain line under loading conditions and environmental conditions was carried out with the aim of estimating fatigue life of chain line structural components from several variations of SPM model. Significant wave heights and their distribution in this analysis serve as parameters used to describe the state of sea in Tuban sea waters. Meanwhile, distribution of wave data in Tuban sea and probability of the occurrence of waves can be seen in Table 14.

Table 14. Wave height at location SPM

Hs (*m*)	Tp (*s*)					
	0.0 - 2.0	2.0 - 4.0	4.0 - 6.0	6.0 - 8.0	8.0 - 10.0	Total
0.00 – 0.50	18164	16598	0	0	0	34762
0.50 – 1.00	0	4449	12280	0	0	16728
1.00 – 1.75	0	1	9706	4467	0	14174
1.75 – 3.50	0	0	3	1240	3	1395
Total	18164	21047	21989	5707	152	67059

After obtaining wave height data, next step is to find value of the largest stress on mooring line series that occurs in SPM chain line which is at heading 45º direction of wave. The maximum stress value for each model when heading 45º direction of wave will be used for loading using significant wave height and wave period. After obtaining the maximum stress results for each SPM model heading at 45º direction of wave, next step is to find the nominal stress value in SPM chain line model. After obtaining the maximum stress value on chain line model structure during installation, an estimate of 10 years, an estimate of 20 years and an estimate of 30 years. Results of dimension reduction analysis on chain line structure can be seen in Table 15.

Table 15. Dimension reduction in chain line structure

Type	Installation Diameter Reduct. -	Est. 10 yr Diameter Reduct. 2 *mm*	Est. 20 yr Diameter Reduct. 4 *mm*	Est. 30 yr Diameter Reduct. 6 *mm*
Common Link	76 *mm*	74 *mm*	72 *mm*	70 *mm*
Enlarged Link	84 *mm*	82 *mm*	80 *mm*	78 *mm*
End Link	92 *mm*	90 *mm*	88 *mm*	86 *mm*
Joining Shackle	99 *mm*	97 *mm*	95 *mm*	93 *mm*

Calculation of fatigue life in this study using S-N Curve method based on the law of failure of palmgren miner based on S-N Curve API RP 2SK, by estimating cumulative fatigue damage. After obtaining the total value of ni and Ni, it is continued to calculate the value of fatigue damage and fatigue life. Estimated fatigue life for each chain line is chosen conservatively as the minimum estimated life of all fatigue load cases. After obtaining the value of fatigue life on chain line from several variations of SPM model, several different presets were obtained in each variation of SPM form model, which can be seen in Table 16.

Table 16. Fatigue life from several variation of SPM Model

Reference	Diameter Reduction	Fatigue Life on SPM Model Variation		
		Variation 1	Authentic	Variation 2
Installation	-	70,83 yr	68,98 yr	67,13 yr
Estimated 10 yr	2 *mm*	59,61 yr	58,05 yr	56,33 yr
Estimated 20 yr	4 *mm*	47,65 yr	46,07 yr	44,49 yr
Estimated 30 yr	6 *mm*	35,29 yr	33,67 yr	32,04 yr

Each SPM model has a different model of shape, structure weight, center of gravity and characteristics. From results of the calculation of fatigue life on chain line structure at time of installation up to an estimated time of 30 years of operation, the value of chain line life due to fatigue factors is obtained which still meets the safety standards (design life) according to Blue Water Energy (2005), namely SPM with CALM type, which is 30 years. operational.

3.6 Results of Risk Analysis and Mitigation

After knowing fatigue value on SPM chain line, next step is to identify the dangers of the operating SPM mooring line. The next analysis is an understanding of some of the activities that take place on mooring line to get some of the hazard factors. The existence of a dimension reduction phenomenon due to corrosion rate and fatigue factor as a result of the interaction between cyclical loads on mooring line series, it is necessary to analyze the hazard identification of the maintenance schedule on mooring line series. At the risk analysis stage, data processing related to the analyzed risk will be carried out. The risk that becomes analysis will be carried out further calculations to find out the risk opportunities. In risk analysis, this research focuses on a series of mooring lines. Mooring line itself consists of chain line, anchor, chainstopper. As for calculating the probability value, it is determined beforehand from fault tree of each failure mode that has been obtained and then the frequency of occurrence of damage to SPM mooring line will be calculated. Probability value of each mooring line component can be seen in Table 17.

Table 17. Calculation of component probability

No.	Component Mooring Line	Failure Mode	Probability of Failure
1	Chain Line	Chain Line broken	0,033124
2	Anchor	Anchor loose	0,009025
3	Chainstopper	Chainstopper broken	0,009025

The next stage is an analysis of probability of each failure mode using Fault Tree Analysis (FTA) method. Highest failure mode or top event value is obtained. The following is a list of the top events or failure modes of each component mooring line SPM. In table 17 above, it can be seen that component that has the highest risk is chain line. Determination of minimum cut set for critical risk, namely on chain line components that have a failure mode of chain line fracture. Fault tree for failure in SPM chain line can be seen in Figure 7.

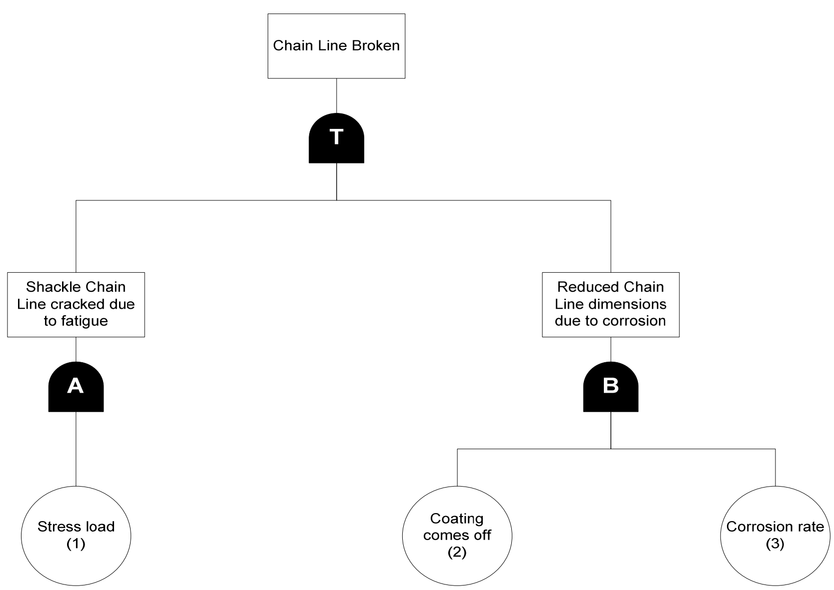


Fig. 7 Fault tree chain line components

The following is a detailed explanation of fault tree for failure in SPM chain line:

a) Shackle chain line has a crack which can lead to a break chain line in mooring line at SPM. Shackles chain line are made of steel, and that is what makes the material fatigue. Fatigue is caused by the stress load on chain line structure.

b) Dimensions of chain line structure are reduced which can lead to a break chain line in mooring line at SPM. Cause of the reduced chain line dimensions is influenced by the release of coating on chain line material and corrosion rate in chain line dimensions.

The following is determination of minimum cut set for chain line components in SPM which has a critical risk, which is 0.033124 or 3.3%.

T		

(a)

A	B	

(b)

1	B	

(c)

1	2	3

(d)

Fig. 8 Fault tree solution matrix of chain line components

The solution of fault tree matrix of chain line components above is as follows:
Cut set I : 1, 2, 3
Minimum Cut set I : 1, 2, 3
Minimum cut set is occurrence of failure in form of a broken chain line at SPM is [1, 2, 3], this figure can be interpreted as follows. Failure in form of chain line fractures caused by stress loads from shackle chain line material which cracked due to fatigue loads and detached coatings and a reduction in dimensions of chain line due to corrosion rates.

4. Conclusion

Variations in SPM diameter size affect fatigue in mooring line series, namely the greater variation in SPM diameter size and the higher significant wave in the greater fatigue results in operational environment condition. Dimensional reduction due to corrosion rate on SPM chain line structure produces a maximum stress value that still meets the safety factor according to DNVGL OS E301, and shows differences in fatigue damage results obtained from SN Curve API RP 2SK. Results for risk analysis are in accordance with SOLAS (2012), the mitigation step in risk analysis that should be taken to reduce causes described by the minimum cut set is to implement periodic inspections that are more stringent in frequency on mooring line series, besides that it is necessary to apply the previous preventive maintenance implement corrective maintenance.

5. References

Ahire, C.P., & Relkar, A.S. (2012). *Correlating Failure Mode Effect Analysis* (FMEA) & *Over All Equipment Effectiveness* (OEE).

API RP 2SK, (2005), *Recommended Practice for Design and Analysis of station Keeping System for Floating Structures*, USA.

Bhattacharya, R. (1978). *Dynamic of Marine Vehicles*, John Wiley and Sons Inc. New York, USA.

Bluewater (2005). *TUBAN SPM Turret CALM Buoy and PLEM*, Operations Training, Netherlands.

Chakrabarti, S.K. (1987). *Hydrodinamics of Offshore Structures*, Computational Mechanics Publications Southampton. Boston, USA.

DNV GL OS E301, (2015). *Position Mooring* - Rules and Standarts, Norway.

DNV GL OS E302, (2015). *Offshore Mooring Chain* - Rules and Standarts, Norway.

Du, J., Wang, H., Wang, S., Song, X., Wang, J., & Chang, A. (2020). *Fatigue Damage Assessment of Mooring Lines Under the Effect of Wave Climate Change and Marine Corrosion*, Shandong, China.

Faltinsen, O.M. (1990). *Sea Loads on Ships and Offshore Structures*, Cambridge University Press., Cambridge, UK.

Kang, J., Sun, L., Sun, H., & Wu, C. (2017). *Risk Assessment of Floating Offshore Wind Turbine Based on Correlation-FMEA*, China.

Sabana, N.M. (2018). *Parametric Study of Fatigue Analysis on External Turret Mooring Line*, ITS, Surabaya.

SOLAS (2012). *Consolidated Edition*. London: IMO (International Maritime Organization).

Vesely, W.E., & Goldberg, F.F. (1981). *Fault Tree Handbook*. U.S. Nuclear Regulatory Commision. Washington DC, USA.

Xu, T.J., Zhao, Y.P., Dong, G.H., & Bi, C.W. (2014). *Fatigue analysis of mooring system for net Cage under random loads. Elsevier,* 59-68.