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Fracture mechanics analysis for a mooring system subjected to tension and out-of-plane bending

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Abstract. A fracture mechanics analysis for the mooring system of a semi-submersible accounting for out-of-plane bending (OPB) is presented in this paper. Stress ranges acting on the mooring chain links are calculated based on tension and OPB of mooring chain links induced by motions of wave frequency (WF) and low frequency (LF). The narrow-banded method is used for predicting the combined mooring loading process. Initial cracks are assumed to propagate from surfaces of chain links and stress intensity factors are then calculated in terms of stress ranges determined by a finite element analysis. The influence of the OPB on the remaining service life of mooring chain links is investigated and the results show that the remaining service life of mooring chain links connecting to fairleads is significantly reduced due to the OPB effects.

1. Introduction

Fatigue failure is one of critical failure modes of offshore permanent mooring systems. Fontaine et al. [1] reviewed 107 offshore mooring accidents and they pointed out that the 29 mooring accidents are primarily due to fatigue. In particular, the occurrence of 3 of 29 mooring fatigue accidents was induced by the out-of-plane bending (OPB).

Traditionally, only mooring tensions are considered in mooring chain fatigue analysis. However, for fatigue analysis of mooring chain links connecting to chain wheels at fairleads, chain links passing over bending shoes, or chain linkers provided by chain hawse or chain stoppers, the effects of the OPB on the mooring fatigue should be considered [2, 3].

Vargas et al. [4] modelled mooring chains and a mooring chain wheel with seven pockets, and preformed a finite element (FE) analysis to investigate the influence of the OPB on mooring chain stresses. Ter Brake et al. [5] presented an S-N curve based fatigue analysis for mooring chains, in which the effects of the OPB on mooring chain stresses were determined by a FE analysis of chain links. Melis et al. [6] presented experimental results of mooring chain stresses induced by OPB. Vargas and Jean [7] compared mooring chain stresses calculated by FE method with experimental results of Melis et al. [6]. Lassen et al. [8] and Lassen et al. [9] performed a mooring chain fatigue life using an S-N curves based approach, and the behaviour of chain links subjected to tension and OPB was investigated by both experimental and FE methods.

In this paper, a fracture mechanics analysis for the mooring system of a semi-submersible accounting for OPB is presented. Stress ranges acting on the mooring chain links are calculated based on tension and OPB of mooring lines induced by motions of wave frequency (WF) and low frequency (LF). Initial cracks are assumed to propagate from surfaces of chain links and stress intensity factors are then calculated in terms of stress ranges determined by a finite element analysis. The influence of the OPB on the remaining service life of mooring chain links is investigated.

2. Mooring system

A semi-submersible with 16 mooring lines operated at OWA (Offshore Western Africa) is utilized for the mooring analysis in this paper [10].

The semi-submersible hull comprises a ring pontoon and four columns and it is symmetric in both east-west and south-north directions. The draft of the semi-submersible is 26 m. The cross-sections of the pontoon and columns are both rectangular. The cross-section of the pontoon is 22 m (Width) × 10 m (Height). The cross-sections of the columns are 22 m × 22 m with 4m corner radius.

The semi-submersible is operated at the water depth of 1829 m. A taut mooring system is designed for the semi-submersible. The semi-submersible is spread moored with 16 mooring lines in 4 clusters. Mooring lines are numbered counter-clockwise and the Line 1 is laying 37.5 degrees from north. Each adjacent mooring line in the same cluster is in 5 - degree separation. The layout of mooring system is shown in Figure 1.

Each mooring line consists a 6-inch R4 class studless bottom chain, a 267 mm polyester rope and a 6-inch R4 class studless top chain. The pretension of each line is set as 3152 kN (18% of minimum breaking strength of mooring chain link). The length of the top chain is 150 m, the bottom chain 210 m. The polyester rope is divided into four segments and the length of each segment is 650 m. In the fairlead of the mooring system, seven-pocket chain wheels are installed to guide the top chains operating around the semi-submersible. The sketch of a mooring chain wheel at the fairlead is shown in Figure 2 [11].

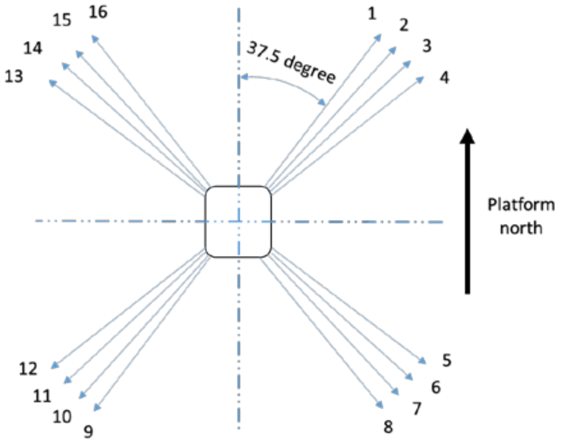


Figure 1. Layout of mooring system

Figure 2. Sketch of mooring chain wheel at fairlead [11]

The semi-submersible is operated at offshore West Africa (OWA). OWA environment is characterized by long period swells. In this paper, the wave, wind and swell effects are taken into account to examine the remaining service life of mooring chains as shown in Table 1. The environmental conditions can be referred to Wang et al. [12] and Wu et al. [10]. Ochi-Hubble spectrum [13] is used herein for the simulation of the semi-submersible motion induced by wave and swell, and Harris spectrum [14] is used for the simulation of the vessel motion induced by wind.

Table 1. Environmental conditions at OWA

Bin	**Swell**		**Wave**		**Wind speed (m/s)**	**Direction (degree)**	**Probability (100%)**
	Hs(m)	**Tp(s)**	**Hs(m)**	**Tp(s)**			
1	1.75	14	0.3	2.7	8	0	30.4
2	1.75	22	0.7	3.8	14	0	7.6
3	2.75	14	0.3	2.7	8	0	9.2
4	2.75	22	0.7	3.8	14	0	2.3
5	3.75	14	0.3	2.7	8	0	0.4
6	3.75	22	0.7	3.8	14	0	0.1
7	1.75	14	0.3	2.7	8	45	30.4
8	1.75	22	0.7	3.8	14	45	7.6
9	2.75	14	0.3	2.7	8	45	9.2
10	2.75	22	0.7	3.8	14	45	2.3
11	3.75	14	0.3	2.7	8	45	0.4
12	3.75	22	0.7	3.8	14	45	0.1

3. Mooring chain tension

The function of mooring chain tensions can be written as:

$$T = T_M + T_P + T_D \tag{1}$$

where T_M is the mooring tension due to the mean environmental loads including mean wind, swell and wave forces. T_P is the pretension of mooring chain. T_D is the dynamic mooring tension due to environmental loads, which is usually considered as the combined tension induced by low frequency (LF) and wave frequency (WF) motions.

Both LF and WF mooring chain tension processes are assumed to be Guassian processes. LF motions are estimated by a quasi-static method and WF motions are calculated by FE method through a numerical simulation.

In this paper, the narrow-band method is applied to predict the combined tension process, T_D. The probability density function of the amplitude of combined tension process, T_A, can be given as:

$$f(t_a) = \frac{t_a}{\sigma_D^2} e^{\left(-\frac{t_a^2}{2\sigma_D^2}\right)} \tag{2}$$

where σ_D is the standard deviation of T_D, and it can be written as

$$\sigma_D = \sqrt{\sigma_W^2 + \sigma_L^2} \tag{3}$$

where σ_W is the standard deviation of WF tension process, and σ_L is the standard deviation of LF tension process.

The mean zero up-crossing frequency of T_D is then formulated as

$$v = \sqrt{\frac{\sigma_W^2 v_W^2 + \sigma_L^2 v_L^2}{\sigma_W^2 + \sigma_L^2}} \tag{4}$$

where v_W is the mean zero up-crossing frequency of WF tension process, and v_L is the mean zero up-crossing frequency of LF tension process.

4. Out-of-plane bending (OPB) of mooring chain

It is indicated by industry experience that chain links connecting to fairleads, chain links passing over bending shoes, or chain linkers provided by chain hawses or chain stoppers, may be subjected to additional OPB, which may induce fatigue failures out of expectation [2, 3].

In traditional mooring fatigue analysis, the bending stiffness of the chain segments is neglected because of rolling and sliding between chain links. However, when the chain links are installed with high pretension, the high frictions between chain links would arise. Then the interlink angle between chain links would be locked, which leads to bending moments between the contact chain links. The definitions of OPB and interlink angle, applied load angle are shown in Figure 3.

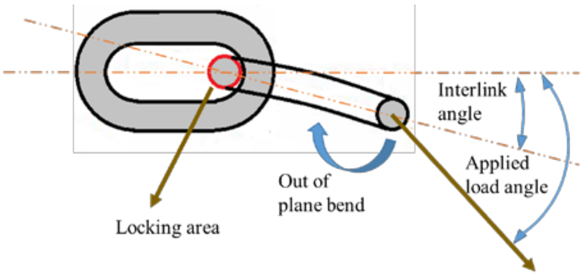


Figure 3. Sketch of out-of-plane bending (OPB) of mooring chain with deviation angles

5. Fracture mechanics analysis

In fracture mechanics analysis, the chain link is treated as a round bar and an initial semi-elliptical surface crack is assumed to propagate at the surface of the chain link.

The crack growth is predicted based on the Paris-Erdogan equation [15]:

$$\frac{da}{dn} = C(\Delta K)^m \tag{5}$$

where a is crack depth, n is the number of stress cycles. $C = 2.3\times10^{-12}$ and $m = 3$, which can be referred to BS7910 [16]. ΔK is the stress intensity factor range and stress intensity factor K can be calculated as

$$K = Y\sigma\sqrt{\pi a} \tag{6}$$

where Y is the stress intensity correction factor. In this paper, both membrane stress σ_m and bend stress σ_b acting on the cross-sections of chain links are considered in FM analysis, so $Y\sigma$ is defined as [16]:

$$Y\sigma = Mf_w(M_m k_{tm} M_{km}\sigma_m + M_b k_{tb} M_{kb}\sigma_b) \tag{7}$$

where k_{tm} and k_{tb} are stress concentration factors. For a semi-elliptical surface crack in a round bar, $M = f_w = M_{km} = M_{kb} = 1$, M_m and M_b can be referred to BS7910 [16].

The service life N_S based on fracture mechanics approach can be estimated by an integration procedure:

$$N_S = \int_{a_0}^{a_c} \frac{da}{C(\Delta K)^m} \tag{8}$$

where a_c is the critical crack depth and a_0 is the initial crack depth.

6. Finite element (FE) analysis

A FE analysis is performed to predict the stresses acting on the cross-sections of a studless chain link. R4 class common studless mooring chain links are main components suffered to fatigue damage in the designed mooring system. The chain links are modelled with standard dimensions where the length L and breadth B are given by:

$$L = 6D, B = 3.35D \tag{9}$$

where D is the nominal diameter of the chain link. The corrosion and wear allowance for 25 years is also considered for each link.

Three scenarios are considered in the FE analysis. In the Scenario 1, only tension loads are considered. In the Scenarios 2 and 3, the effects of OPB are taken into account.

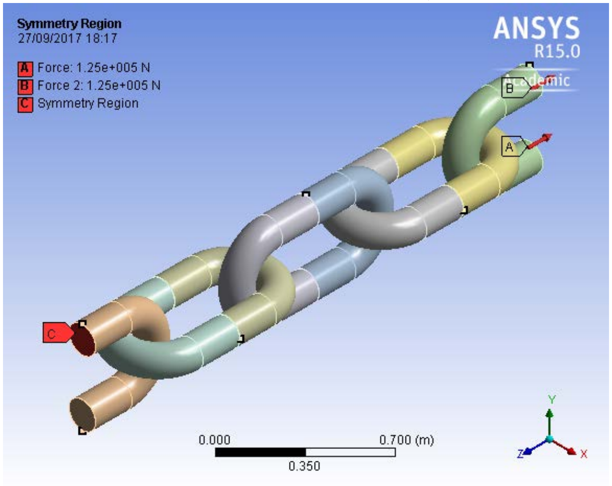


Figure 4. Finite element model of mooring chain links of Scenario 1

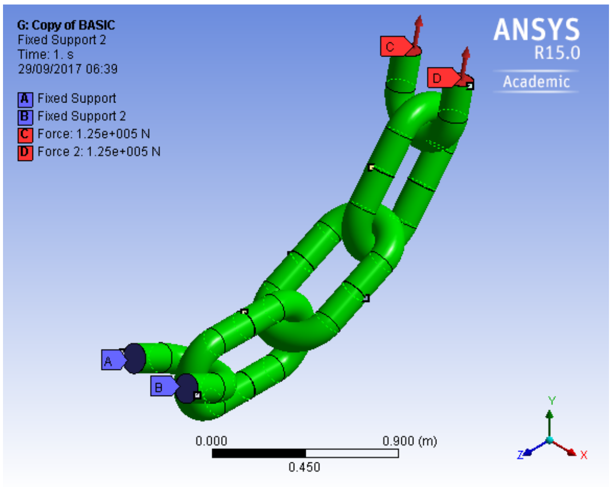


Figure 5. Finite element model of mooring chain links for Scenario 2

For Scenario 1, the interlink link angles of mooring chains are considered as 0 degrees, as the model shown in Figure 4. End face C of the half chain shown in Figure 4 is defined as a symmetry plane. The tension forces are applied at the end faces A and B, as shown in Figure 4.

For Scenarios 2 and 3, the chain links are assumed to lay on the seven-pocket chain wheel in the fairlead, and interlink link angles of mooring chains are considered as 25.71 degrees, as shown in Figure 5. The contact type between mooring chain links is set as bonded, which means neither sliding nor separation is available between contact surfaces and the angle between chain links is locked. In Scenario 2, end faces A and B are fixed. The tensions are applied at the end faces C and D. The surface contract effects between two mooring chains are considered and interlink angles between chain links are locked. Compared with Scenario 2, end faces A and B in Scenario 3 are simple supported. The details of each scenario are listed in the Table 2.

Table 2. Details of each scenario

	Boundary condition	Whether consider OPB?
Scenario 1	Symmetry	No
Scenario 2	Fixed support	Yes
Scenario 3	Simple support	Yes

7. Results and discussion

Due to the space limitation, only the results of frequency-domain mooring line analysis of mooring line 1 is presented in the Table 3, where T_W and T_L are mean time period of WF and LF motions, respectively.

Table 3. Mooring line tension at fairleads of Line 1

BIN	**T_W(s)**	**σ_W(kN)**	**T_L(s)**	**σ_L(kN)**
1	13.0	15.2	94.9	7.6
2	22.0	29.8	90.1	27.0
3	13.4	25.4	103.1	9.9
4	22.0	48.0	90.1	27.0
5	13.6	36.6	111.4	14.6
6	22.0	67.5	90.1	27.0
7	13.5	16.9	57.9	3.1
8	22.1	22.3	55.9	11.2
9	13.6	27.5	58.7	3.1
10	22.0	36.4	55.9	11.2
11	13.7	39.0	61.0	3.3
12	22.0	51.7	55.9	11.2

For Scenario 1, the outside of crown cross-section (C-C cross-section), the inner surface of the beginning of the bend area (B-B cross-section) and the inner surface of weld section (A-A cross-section), as shown in Figure 6, are treated herein as three potential locations that are prone to fatigue failure [6].

After the FE analysis, it is found that the stresses at the crown sections are larger than stresses at the bend sections or weld sections without considering stress concentration factors due to weld quality. A typical normal stress distribution of the crown section of a mooring chain is shown in Figure 7.

For Scenarios 2 and 3, the most critical location of mooring chain links prone to fatigue damage moves to the middle of crown section (D-D cross-section) as shown in Figure 8 [6-8]. Figure 9 shows a typical normal stress distribution over the cross-section described in Figure 8.

Then, a linearization of stress distribution over the cross-section is performed herein to divide the normal stresses into membrane and bending stresses and the detailed method can be referred to BS7910 [16]. These stresses are then used for the FM analysis for predicting the remaining service life of mooring chains at the fairleads.

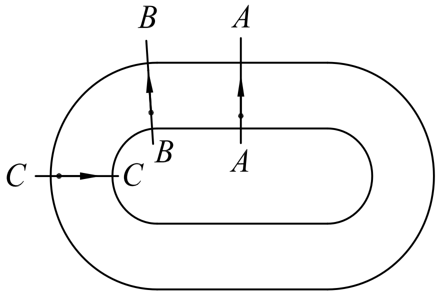


Figure 6. Scenario 1: locations of the chain link prone to fatigue damage in pure tension

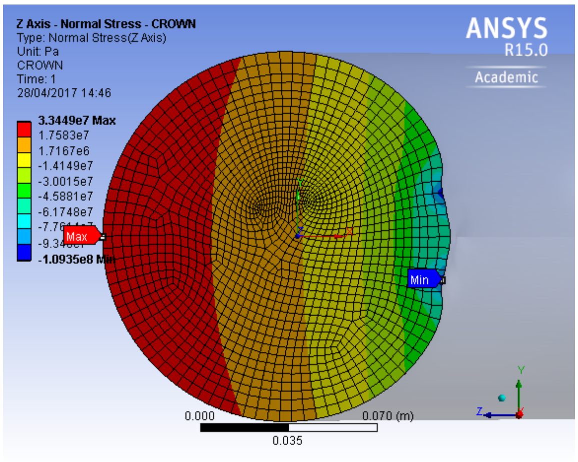


Figure 7. Normal stresses at the crown section of the chain link

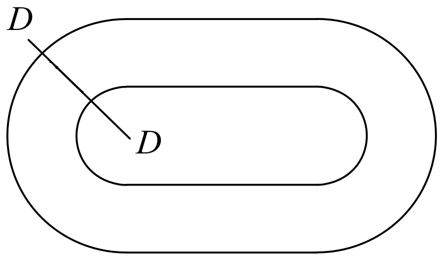


Figure 8. Scenarios 2 and 3: the critical location of the chain link prone to fatigue damage in coupled tension and out-of-plane bending (OPB)

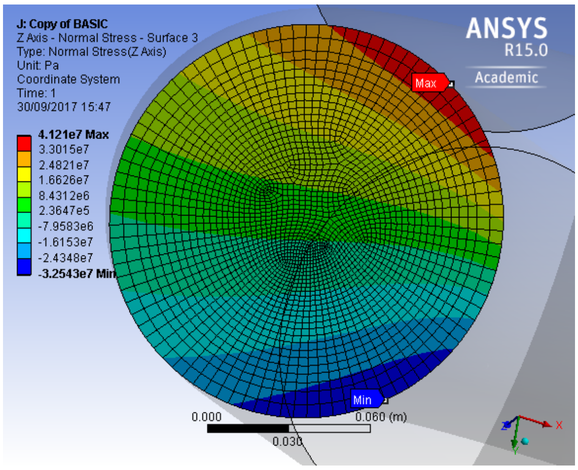
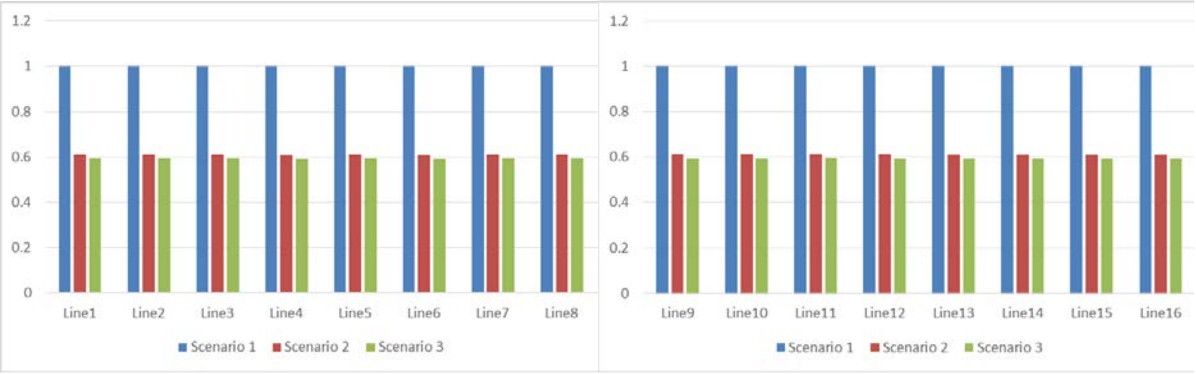


Figure 9. Normal stresses at the crown section of the chain link

As recommended by Mathisen and Larsen [17], the critical crack depths are set as 12% of the chain diameter at weld sections, 30% of the chain diameter at bend section, and 15% of the chain diameter at crown section. The initial crack depth is assumed to be 0.5 mm. The ratios of remaining service life of mooring chain links connecting to fairleads of the semi-submersible in Scenarios 2 and 3 to Scenario 1 are plotted in Figure 10.



(a) (b)

Figure 10. Ratios of remaining service life of mooring chain links in Scenarios 2 and 3 to Scenario 1: (a) Line 1 to Line 8; (2) Line 9 to Line 16

The result shows that the OPB effects on the remaining service life of mooring chain links at the fairleads is obvious. The service lives of mooring chains in Scenarios 2 and 3 are decreased as 39% and 41%, respectively, compared to those of Scenario 1. The effect of boundary condition setting in the FE analysis of Scenarios 2 and 3 is also evident, the remaining service life with the fixed support in Scenario 2 is 5% longer than those with the simple support.

8. Conclusion

This paper was to perform a fracture mechanics based analysis for mooring chains of a semi-submersible taking account into the OPB effects. The WF and LF load processes were regarded as two random processes. The load combination of these two processes was considered and the narrow-banded method were used for calculating the combined mooring chain loading process. The effects of the OPB on mooring chain pricipal stresses were determined by a FE analysis. The remaining service life of mooring chain links was calcuated based on the FM analysis.The influence of the OPB on the remaining service life of mooring chain is investigated and the results show that the remaining service life of mooring chain was significantly decreased due to the OPB effects.

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