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A study on the fatigue of mooring chains under out-of-plane bending

E.N. Mamiya *, F.C. Castro, G.V. Ferreira, E.L.S.A. Nunes Filho, F.A. Canut, R.S. Neves, L. Malcher

Universidade de Brasília, Department of Mechanical Engineering, Asa Norte, 70910-900 Brasília, DF, Brazil.

* Corresponding author. Email address: mamiya@unb.br

Abstract: The study focuses on the fatigue failure of mooring chains of Floating Production Storage and Offloading (FPSO) units which have exhibited fatigue cracks after less than one year of service. Crack initiation are correlated to out-of-plane bending of the links as a result of the interaction between the chain and the FPSO's fairlead sheave. The device designed to replicate the out-of-plane bending on chain links consists of a horizontal frame which submits a set of nine chain links to a static tensile preload, while a hydraulic actuator applies variable transversal loads upon the central link. The larger deformed contact surface between the links due to the proof load, together with the static preload during tests, makes rolling between adjacent chain links (as they interact with the fairlead's chain sheave) harder, resulting in out-of-plane bending of the chain elements. The experiment provides the data necessary to understand the fatigue failure mechanisms, as well as to assess the modeling of the multiaxial fatigue problem.

Keywords: mooring systems, FPSOs, out-of-plane bending, fatigue failure

INTRODUCTION

A high number of incidents involving failure of mooring chains of deep water Floating Production Storage and Offloading (FPSO) units have been reported (Gordon et al., 2014). In some cases, failures have been observed after less than eight months of operation (Rampi et al., 2015), because of out-of-plane bending (OPB) associated with friction between chain links under tension, at locations including fairleads, bending shoes, hawse pipes, etc.

This paper focuses on the study of fatigue failure in chain links submitted to out-of-plane bending, together with tensile preload. Preliminary results show that tensile preload, of the order of 15% of the Minimum Breaking Load (MBL), combined out-of-plane bending forces can induce fatigue failure within a life of less than 10^5 cycles.

MATERIAL AND EXPERIMENTAL SETUP

Fatigue specimens consisted of sets of nine chain links produced from ¾", grade U2 (SAE 1524) steel rods, with chemical composition listed in Table 1. Each chain was heated to 890 ºC for 30 min and then water quenched. After that, it was tempered by heating it at 500 ºC for 60 min followed by cooling in water. Finally, it was submitted to a proof load of 233 kN (70% of the Minimum Breaking Load, $MBL = 333\ kN$), as a standard procedure in the manufacturing of mooring chains. The mechanical properties after the heat treatment were: $E\ 200\ GPa$, $\sigma_y = 896\ MPa$, $\sigma_{R\ U2} = 1100\ MPa$. A consequence of the preloading process is the increase and shape accommodation of contact surfaces between links, leading such contact surfaces to act as cantilevers when the chain is subjected to tension.

Table 1 – Chemical composition of the grade U2 (SAE 1524) steel

C %	Si %	Mn %	P %	S %	Cr %	Ni %	Mo %	Cu %
0.22	0.24	1.48	0.02	0.004	0.18	0.10	0.02	0.17

The device designed to replicate the out-of-plane bending on the chain links consists of a frame which submits the set of nine chain links to a static tensile preload, while a hydraulic actuator applies variable transversal loads upon the central link, as illustrated in Fig. 1. The central link is positioned in a vertical plane, hence positioning the adjacent links horizontally. The hydraulic jack responsible for the axial preload can apply a force of up to 200 kN on the chain links. The frame is mounted on an MTS 322 series testing machine with a 100 kN capacity actuator responsible for the transversal variable loads. The frame position can be tunned longitudinally, ensuring a proper alignment between the transversal actuator and the central link it is acting on.

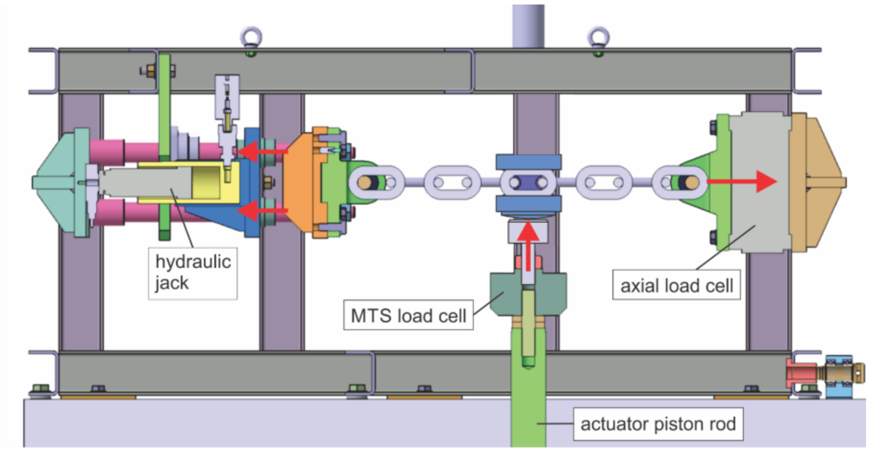

Figure 1 – Experimental setup

Figure 2.a illustrates a chain specimen mounted on the experimental device. Figure 2.b shows the hydraulic jack employed to apply the preload and the inner columns which transmit the pulling force to the chain links. During tests, the outer columns replace the hydraulic jack in maintaining the axial tension load.

a)

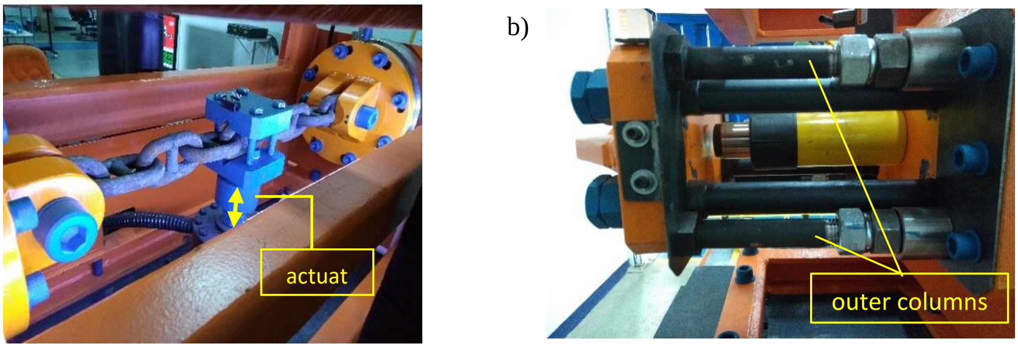

Figure 2 – Details of the setup: (a) chain specimen installed in the experimental setup and the transversal actuator, (b) hydraulic jack and the set of outer columns.

TESTING PROGRAM AND RESULTS

As a first approach, all fatigue tests were conducted in air environment, focusing on the purely mechanical aspects associated to the out-of-plane bending problem. Two sets of fully reversed axial fatigue tests were conducted on cylindrical specimens to characterize the material. The first set of tests was performed on specimens with standard ground specimens, while the second one was conducted on specimens with not ground, heat treatment oxidized surfaces mimicking the surface conditions of the chains. The stress amplitudes and the corresponding fatigue lives are listed in Table 2.

Table 2 – Stress amplitudes and cycles to failure for fully reversed axial fatigue tests of the grade U2 steel

Ground specimens		Not ground specimens	
σ_a MPa	N_f cycles	σ_a MPa	N_f Cycles
600.	63,408	420.	135,576
600.	54,211	420.	93,293
575.	67,395	395.	1,330,083
575.	66,882	395.	195,130
550.	432,002	369.	> 2e6
550.	129,590		
525.	288,552		
525.	128,167		
500.	346,800		
500.	> 2e6		

Forces and displacements referred to in the sequence are illustrated in Fig. 3. Chains were tested with preload values $36\ kN$, $47\ kN$ and $57\ kN$. During each test, the central link was submitted to a prescribed harmonic vertical displacement program *V(t)* such that the target forces $F_{H\,max}$ and $F_{H\,min}$ were attained. Table 2 lists the load parameters for each one of the 12 fatigue tests.

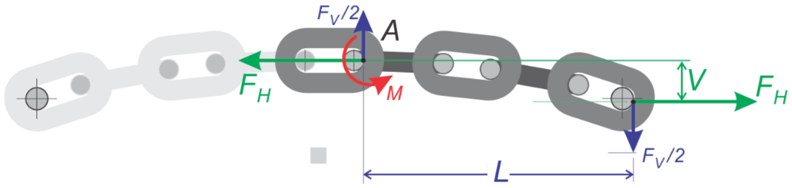

Figure 3 - Forces acting on the right branch of the chain due to tension and bending.

Table 3 – Loading and fatigue parameters, fatigue lives

#	F_{H0} kN	$F_{H\,min}$ kN	$F_{H\,max}$ kN	$F_{V\,min}$ kN	$F_{V\,max}$ kN	V_{min} mm	V_{max} mm	f Hz	P_{MC} MPa	N_f $cycles$
1	41	43.4	81.3	1.10	15.30	10.40	24.40	1.5	345.3	71,634
2	39	40.5	60.6	1.54	8.96	10.88	17.90	1.75	258.2	194,640
3	46	49.8	94.7	2.33	19.37	16.38	27.62	1.5	398.9	38,583
4	36	50.9	95.9	4.50	20.10	20.50	29.90	1.5	314.1	78,858
5	57	57.0	111.0	1.50	23.10	11.80	29.60	1.2	375.5	78,515
6	60	63.0	94.0	2.50	15.30	12.40	21.40	2.3	364.6	65,827
7	57	61.0	91.0	2.01	15,07	10.70	20.10	1.5	416.5	55,569
8	58	60.0	85.0	2.36	13.04	13.41	20.81	1.75	312.0	106,035
9	57	61.0	71.0	1.10	6.70	9.70	15.20	5.5	151.1	$> 10^6$
10	56	61.0	82.0	2.90	12.50	11.90	18.90	3.0	333.3	$> 10^6$

Measured maximum vertical forces $F_{V\,max}/2$ were consistently greater than the maximum vertical components $F_H \tan\theta$ of the tensile force acting on the chain, F_H being the force measured on the longitudinal load cell, as illustrated in Fig. 3. The difference:

$$F_{bend} = \frac{F_V}{2} - F_H \frac{V}{L} \tag{1}$$

produces bending on each branch of the chain. Consequently, moments $M = L\,F_{bend}$ are applied by the central link on each adjacent out-of-plane chain link, as is illustrated in Fig. 3.

Normal stresses at the position of the observed fatigue fracture were estimated by the formula:

$$\sigma_{hspot} = \frac{2\,k_t F_H}{\pi d^2} + \frac{16\,L}{\pi\,d^3}\left(\frac{F_V}{2} - F_H \frac{V}{L}\right), \tag{2}$$

where $d = 19.05\ mm$ is the diâmeter of the chain link, while $k_t = 1.88$ is the ratio between the rupture strength of the material, $\sigma_{R\,U2} = 1{,}100\ MPa$), and the nominal rupture strength of the chain, $\sigma_{R\,chain} = MBL\ /\ area = 584\ MPa$. Figure 4 shows the Modified Crossland fatigue parameter:

$$P_{MC} = \frac{1}{\sqrt{2}} S_{a\,MPH} + \sigma_{h\,max}, \tag{3}$$

where $S_{a\,MPH} = \max_{\Theta} \sqrt{\sum_i a_i^2(\Theta)}$ is the shear stress amplitude based on the method of the Maximum Prismatic Hull (Mamiya et al., 2011), while $\sigma_{h\,max}$ is the maximum hydrostatic stress acting on the material point along the loading cycle. For the stress estimate produced by Eq. (2):

$$S_{a\,MPH} = \frac{1}{2\sqrt{3}}\,(\sigma_{max} - \sigma_{min}), \quad \sigma_{h\,max} = \frac{1}{3}\,\sigma_{max}, \tag{4}$$

and hence the fatigue parameter specializes to:

$$P_{MC} = \left(\frac{1}{2\sqrt{3}} + \frac{1}{3}\right)\,\sigma_{max} - \frac{1}{2\sqrt{3}}\,\sigma_{min}. \tag{5}$$

Figure 4 shows the picture of typical fatigue failure due to out-of-plane bending. The links consistently failed at regions where the maximum bending moment are observed.

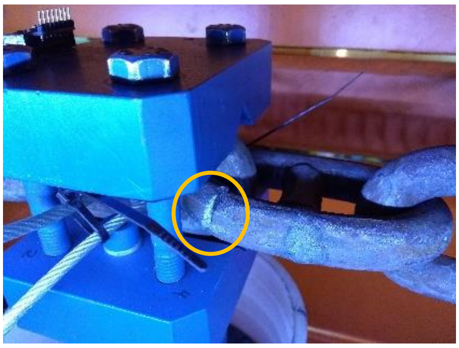

Figure 4 – Fatigue failure due to out-of-plane bending.

For each test, the solid circular, triangular and square markers in the graphics of Fig. 5 relates the fatigue parameter, P_{MC}, at the hotspot to the corresponding fatigue life, N_f. The values for each result are listed in Table 3. The diamond shaped markers in the same figure represent the results for the axial fatigue tests with not ground specimens, while solid line represents the corresponding fitted curve:

$$P_{MC} = 4.72 \times 10^{3}\,N_f^{-0.226}. \tag{6}$$

The dotted lines bound the experimental data set within a factor of two in fatigue life. The same figure shows the experimental data for the ground surface specimens, which exhibit much higher lives for the corresponding stress amplitudes.

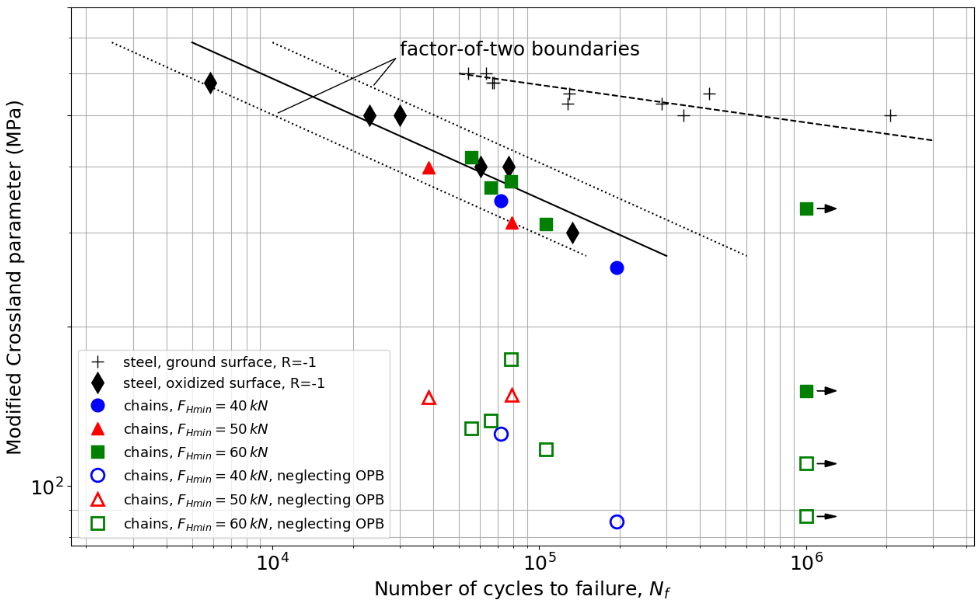

Figure 5 – Fatigue parameter vs life to failure for chains tested under out-of-plane bending conditions.

The results from the experiments on chains correlates very well with the life estimation curve from Eq. (6) corresponding to not ground specimens. Further, the results show a substantially small scattering – within a factor of 1,7 in terms of cycles to failure – under a range of loading and preload conditions. This indicates that the fatigue parameter P_{MC} satisfactorily quantifies the driving force for the fatigue degradation under several cyclic loading conditions.

The importance of the out-of-plane bending on the fatigue life can be illustrated by observing the unfilled markers in Fig. 5, where the fatigue parameter P_{MC} was computed without considering the out-of-plane bending term in Eq. (2).

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