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STUDY OF THE INTEGRITY OF MOORING SYSTEMS FOR OIL EXPLORATION PLATFORMS

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Abstract. *This project proposes the application of the finite element method, using the software called ABAQUS, version 6.14 for the study and analysis of chain links without mallet belonging to the FPSO ship anchoring system. For the purpose of this analysis, it was considered the cyclical flexion that occurred outside the main plane of the links, known as OPB (Out of Plane Bending) and IPB (In Plane Bending). The OPB generates a considerably greater influence on fatigue life compared to the IPB. For this reason, only bending moments from that flexion were considered. According to the API (American Petroleum Institute) design recommendations, the dimensioning of the chain links of the FPSO ship anchoring system considers only the normal stress generated by axial loads arising from the contact between the links, disregarding any bending moment. Nevertheless, this moment occurs, because large loads raise the resulting frictional force in the contact between the links, making it behave like a bezel and, consequently, the action of transverse forces would result in a flexion of the link in the main plane. As a result, FPSO platform ships that are designed to last more than 20 years, supporting various factors of nature, as well as operating conditions of the platform itself, supporting transport loads and elevation of the oil, reported cases of failure in the anchoring system in less than 2 years. As a way of validating this study, the full scale mooring-fairlead set was modeled on the ABAQUS, a simplified model of the anchoring system containing only a set of 5 links and 2 semi-links, guided through the fairlead. In this modeling, the material of the links was defined as offshore steel belonging to grade R4, a material capable of withstanding very high loads, whereas the fairlead was defined as a rigid body, since it was not deemed necessary to analyze its stress and deformation fields. Finally, the modeling went through several simulations considering the distribution of stress generated in the links from the different working angles of the moorings, more specifically analyzing the winding angles of 17°, 30°, 45° and 60°, being applied on currents, normal stresses oscillating between 200 ton and 400 ton. With the result of this analysis it is possible to identify the hotspots in the links and to identify the effect that the degree of winding of the mooring-fairlead set has on the life of the link.*

Keywords: *anchoring system; mooring-fairlead; OPB; hotspots.*

1. INTRODUCTION

The need for technologies that enable oil extraction in deep waters resulted in the emergence of offshore oil platforms. These platforms have enough technology and powerful structure that allows its fixation and stabilization in the ocean in the ocean. A FPSO floating unit is a floating vessel that operates in deep waters. It is capable of producing, storing, processing and transferring oil from wells over 2000 meters deep; while also storing 1.4 million of barrels of oil (P&Q, 2017).

This offshore structure is fixed to the seabed by a mooring system, a system that can be either homogeneous or heterogeneous (made from different types of materials). The heterogeneous mooring system is commonly used to reduce suspended weight, combining steel ties and synthetic material. In this case study, the mooring lines are made up of stretches of polyester chains that add up to about three kilometers in length, connected to high-strength steel chains of about 300 to 400 meters at each end, both on the stretch closer to the platform and on the stretch that touches the bottom of the ocean (Carbono, 2005).

These moorings leave the ship through a fairlead guide, forming the mooring-fairlead system, illustrated in Fig. 1 (b). The fairlead has a crown that allows the rotation of the chain link in relation to the neighboring links, allowing a variation on the angulation of the chains which generates an important degree of freedom for adjustment of the chain lines due to the agitation of the water and the movement of the platform.

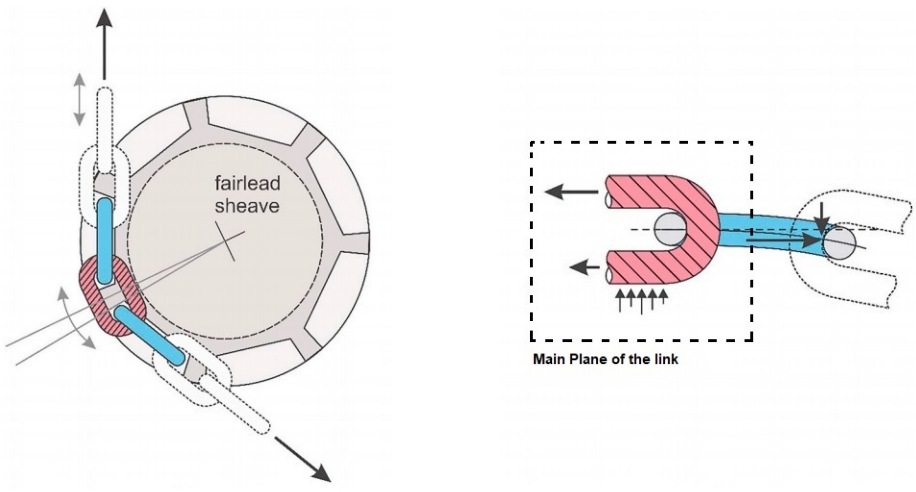
Oil rigs are designed to extract oil in the long term; they are capable of withstanding a useful life in excess of 20 years. Since the anchoring system must resist for a period of time equivalent to the platform's operation, an offshore grade R4 steel is generally used in the links, which has a higher strength.

(a) (b) .

Figure 1: (a) FPSO ship (Agency, 2017) and (b) Mooring-fairlead set (IHC, 2020).

Even though such moorings have an expected life cycle of more than 30 years and the chains have been designed according to API (American Petroleum Institute) regulations, it was reported that chain links have ruptured in less than 2 years of operations (Neves, 2020). This events led to studies that identified failures in the links of the chain guide region, more specifically in the first free link, after the crown of the fairlead. This rupture is mainly caused by the occurrence of a bending moment outside the main planes of the links (plane that contains the oval shape of the link).

In theory, the sizing standards of the links relied only on normal operating stresses. However, during the operation, the moorings suffer from high service loads, increasing the friction force in the contact between the links, which makes this contact behave similarly to a bezel, completely blocking any movement between them. This clamping, the performance of transversal efforts and the poor accommodation of the link in the fairlead generate an out of plane bending (OPB), as shown in Fig. 2 (b), or in plane bending (IPB), which was dropped from the analysis as it was significantly less harmful to fatigue life compared to OPB.



(a) (b)

Figure 2: (a) Layout of the mooring-fairlead set and (b) Main plane of link and OPB (Mamiya *et al.*, 2019).

Note that bending moments can occur in any link in the length of the chain, but the bending moments that generate a greater angle are located in the links close to the exit of the fairlead, where the cases of link breakage were precisely evidenced.

In addition to the forces causing bending, it is important to emphasize the influence of the performance of the proof load in the quality control process of manufacturing the links, where a load of 75% of the MBL (Minimum Breaking Load) is applied. This process increases the lifetime of fatigue due to traction-traction, but generates a plastic deformation that enlarges the contact region of the links, increasing the friction force and inducing even more the crimping behavior in the contact between the links (Neves, 2020).

This work aims to evaluate the mechanical behavior of ungated links that integrate FPSO ship mooring systems simulated in the finite element program ABAQUS. The simulation takes into account the different output angles of the link and the variation of the actuating load, in addition to considering the proof load in the quality control process in the fabrication of the link. More specifically, the work aims to analyze critical links that are outside the fairlead plane, study the voltage distribution and identify the hotspots, or critical points, present in them.

2. METHODOLOGY

2.1 Mechanical characteristics of the material

To support higher magnitude loads, chains must be made of an extremely resistant material, such as offshore steel grade R4, commonly used for this type of service. In order to obtain a higher strength and to be classified as grade R4 offshore steel, this material is manufactured following a specific chemical composition, detailed by Tab. 1, which guarantees the properties required for operations in the most rigorous exploration environments.

Table 1: Chemical composition of grade R4 steel (%).

Material	**C**	**Mn**	**P**	**S**	**Si**	**Cu**	**Al**	**Ti**	**Cr**	**Ni**
Grade R4	0,21	1,04	0,012	0,01	0,25	0,18	0,02	0,0018	1,12	0,53

Furthermore, in order to characterize the behavior of this material, it is necessary to obtain its monotonic and cyclic properties.

- **Monotonic properties of grade R4 offshore steel.**

  The monotonic properties are obtained from a tensile test. For this report, the properties measured by Neves (2020) were considered. The monotonic properties obtained are listed in Tab. 2, in addition to the properties considered of the R4 grade offshore steel itself, such as the Poisson coefficient and its modulus of elasticity. The steel density, assumed for this work, was set equal to 7.6 g/cm³.

Table 2: Monotonic properties of grade R4 offshore steel (Neves, 2020).

Monotonic properties	**Value**
Modulus of elasticity (E)	207,4 GPa
Poisson's Coefficient (ν)	0,3
Initial yield stress (σ_y)	836,6 MPa
Ultimate engineering stress (σ_u)	888,7 MPa
Engineering Breakdown stress (σ_r)	475 MPa
Percent elongation (EL)	24,2%
Area reduction (AR)	0,693

- **Cyclic properties of grade R4 offshore steel.**

  In order to determine the elasto-plastic behavior under cyclic loading, it is necessary to define its stress-strain curve. The behavior of this curve has been studied for years and, to define this same curve in the plastic properties of the material in the ABAQUS simulation, the Ramberg-Osgood relationship (1943) was adopted. The parameters found for this relationship are presented in Tab. 3.

Table 3: Cyclic properties of grade R4 offshore steel (Neves, 2020).

Cyclic properties	**Value**
Cyclic Resistance Coefficient ($K\acute{}$)	1730,2 MPa
cyclic strain-hardening exponent ($n\acute{}$)	0,1185
Cyclic yield stress (σ_y^*)	720,3 MPa

2.2 Stress analysis in critical regions of the links

In order to analytically calculate the critical stresses at each critical point of the link, the study Mamiya *et al.* (2019) was used as a basis, which obtained experimental data through fatigue testing in small-scale moorings. This analysis began with the representation of the reduced-scale free-body diagram of the problem, Fig. 3.

From this diagram, we can state that the links are undergoing a vertical displacement (V) in the central link. This displacement generates contact forces between the represented links, which can be decomposed into F_H (Horizontal forces) and F_V (Vertical forces), and a bending moment in the main plane of the link M_{OPB}, in addition acts as the restraint of the fairlead in the moorings. According to Newton's third law, these forces produce binaries, i.e., reaction forces of the same magnitude and opposite direction. Reactions can be transmitted from link to link, but will be represented in the contact between link and the pin. It is assumed that the pin is lubricated and does not transmit momentum on its

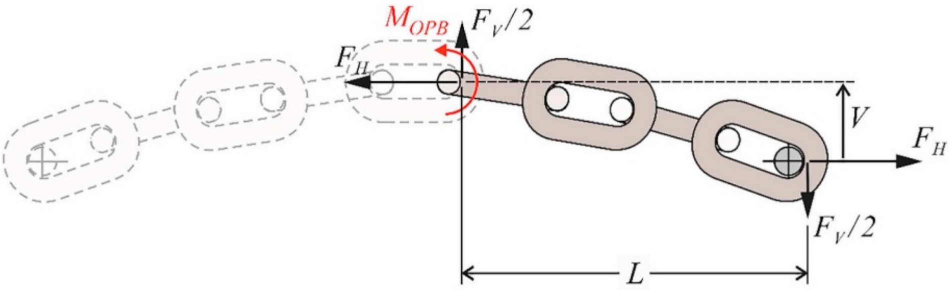


Figure 3: Free-body diagram of the mooring-fairlead set, Mamiya *et al.* (2019).

contact surface. As these forces alone do not balance, it is concluded that there is a bending moment in the plane (M_{OPB}) defined by the balance of moments, given by Eq. (1).

$$M_{OPB} = \frac{F_V}{2} L - F_H V \tag{1}$$

Where L is the horizontal distance of the last link represented in relation to the central link and V is the vertical distance between the contact point of the central link with its adjacent link and the pin contact point with the last link represented in the diagram. Thus, the factors responsible for fatigue failure at the critical point due to normal stress were estimated: due to traction (axial load) and due to the moment in the main plane of the link. This influence on the normal stress is represented in Eq. (2).

$$\sigma_{hotspot} = \sigma_{axial} + \sigma_{OPB} \tag{2}$$

The contribution given by the axial load is better detailed in Eq. (3). And the contribution given by OPB is better detailed in Eq. (4).

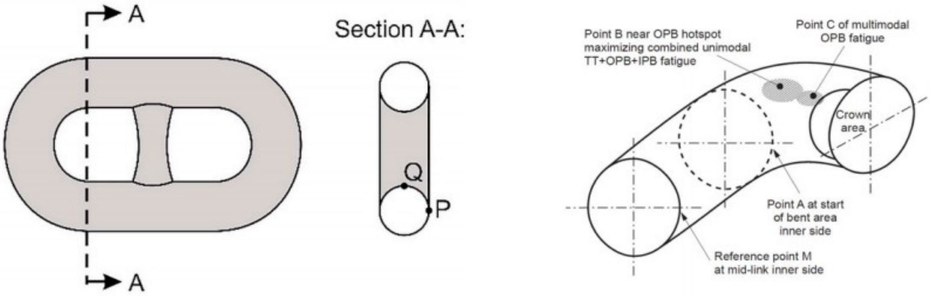
$$\sigma_{axial} = C \frac{2F_H}{\pi d^2} \tag{3}$$

$$\sigma_{OPB} = \frac{16L}{\pi d^3} \left(\frac{F_V}{2} - F_H \frac{V}{L} \right) \tag{4}$$

Where d is the diameter of the link and C is the geometric correction factor proposed by Mamiya *et al.* (2019), defined as the ratio between the rupture stress of the material and the nominal rupture stress of the link. Thus, it can be estimated that the critical tension in the link is given by Eq. (5).

$$\sigma_{hotspot} = C \frac{2F_H}{\pi d^2} + \frac{16L}{\pi d^3} \left(\frac{F_V}{2} - F_H \frac{V}{L} \right) \tag{5}$$

The identification of the probable rupture points and the probable location of critical points was made from two articles, Mamiya *et al.* (2019) and Choung and bin Lee (2018). The first identified point of failure experimentally through fatigue tests on small-scale chains. The second identified by numerical analysis made by the linear superposition of induced stresses in the probable crack initiation points. Figure 4 shows the location of likely hotspots for both articles.



(a) (b)

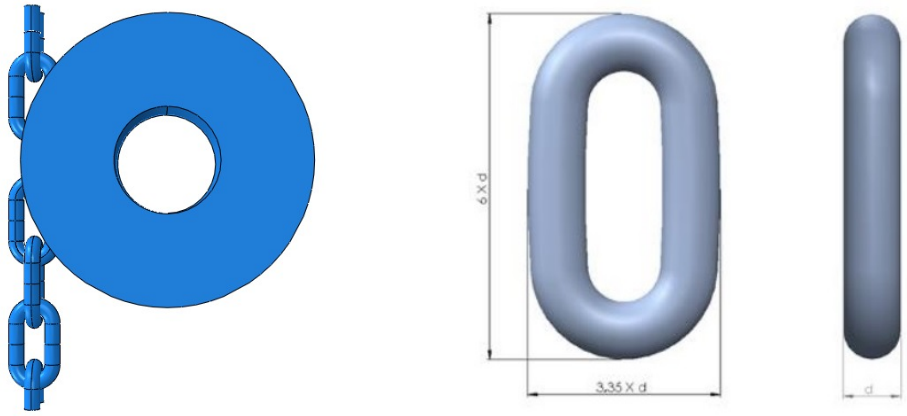
Figure 4: Probable crack initiation points: (a) (Mamiya *et al.* (2019) and (b) (Choung and bin Lee, 2018).

3. FINITE ELEMENT PROBLEM MODELING

To perform the simulation, we opted for a simplification of the mooring-fairlead set. So, a set of 5 links, 2 semi links and the fairlead turnstile was used, considered sufficient for the simulation as it covers the study area.

3.1 Modeling

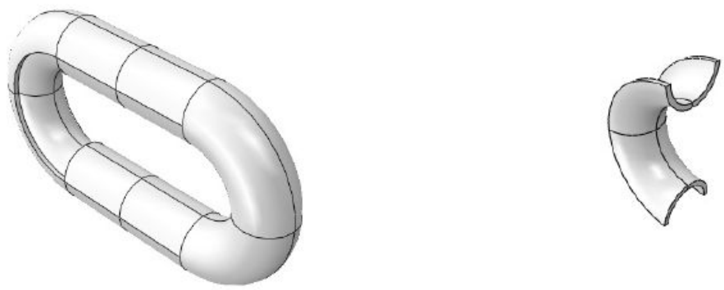
The modeled set of 5 links and 2 semi-links is represented in Fig. 5, together with the standardized dimensions of the chain links. The link was modeled with a diameter of 120 mm.



(a) (b)

Figure 5: (a) Simplification of the mooring system and (b) Chain link dimensions (Evangelista, 2017).

In addition, independent solids were modeled in the contact region between the chain links to generate a finer mesh and improve the study with a better solution of the region. These different parts of the contact region are illustrated in Fig. 6.



(a) (b)

Figure 6: (a) Sectioned link and (b) Contact section.

As this modeling was done simulating a simplification of the mooring-fairlead set, it was necessary to simulate the behavior of the links prior to this set, when applied to loads in the order of 400 tons.To simulate the maximum displacement that these links suffer during the operation, we chose to model 2 cylinders with properties that would be equivalent to the properties of the previous links and position them on the faces of the upper half-links of the set, Fig. 7. These cylinders simulate the displacement variation of the links prior to entering the fairlead, their modulus of elasticity must be equivalent to the set of these links. To determine this property, from the previous mooring section to the fairlead entrance, it was necessary to estimate the number of links that belong to this stretch of chain. By establishing its length equivalent to 15 m, a total of 30 links were then estimated to be present in the same stretch (considering the deformation of the links caused during the application of the proof load). The internal length variation of each link was determined via numerical simulation, corresponding to 3.58 mm and, consequently, the total variation in the length of the chain preceding the fairlead corresponding to 107.6 mm. Thus, it defined the properties of the cylinders as 660 MPa elasticity modulus and 0.3 of Poisson's coefficient.

From the modeling of each specific component, the assembly of the mooring-fairlead set was then made, where it was necessary to establish some contact conditions between the links, the semi-links and the fairlead. The normal contact conditions were defined taking into account a "*Hard*" Contact for the contact activation pressure, and assuming

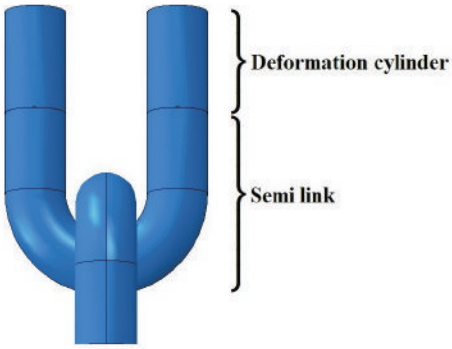


Figure 7: Position of the deformation cylinders in the semi-link.

the contact imposition method "*Default*" (Lagrangean formulation). The tangential contact type was assumed to have a friction coefficient equal to 0.7 and the friction formulation adopted was the "penalty" type. In addition, the contact slip formulation was considered to be of the "large displacement" type and the contact surface discretization method was the surface-to-surface type.

3.2 Mesh

The discretization of the links, semi-links and cylinders belonging to the chains was made from linear hexahedral finite elements with full integration. The fairlead discretization was made of quadrilateral and triangular finite elements, both linear with reduced integration. As previously described, a partition was made in the link, which, together with a contact section with more detailed discretization, obtained the resulting discretized link illustrated in Fig. 8.

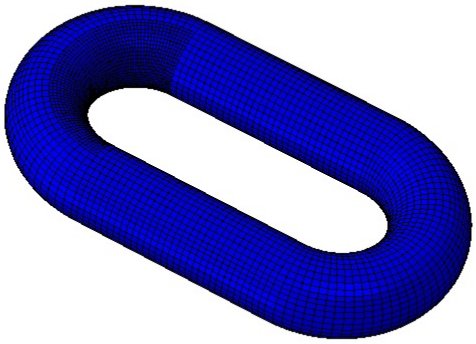


Figure 8: Resulting mesh in the link

3.3 Loadings

Initially, all chain links in their manufacture go through a quality control process, where a load of 75% of the MBL (Minimum Breaking Load) is applied, a process that increases the fatigue life by traction-traction by accumulating residuals stresses. By definition, the MBL is given by 1292 ton and the percentage used of this charge corresponds to 970 ton. Transforming to kN and using gravity as 9.81 m/s^2, 75% of MBL corresponds to 9511kN.

After the performance of the proof load, the chains will undergo diverse loads, which vary considerably. To define the maximum operating load of the chain links, took into consideration that the chain act at a load magnitude close to 1/3 of the MBL, that is, approximately 400 tons. For the definition of the minimum operating load, it was considered that the platform ship would be operating without oil storage and without external operating conditions, therefore, the weight of the structure was estimated at approximately 200 tons. It is therefore concluded that the slings operate on loads oscillating between 200 tons (minimum load) and 400 tons (maximum load). Figure 9 shows the performance of the proof load and the oscillatory load during the simulation.

Thinking about the definition of the winding angles and, consequently, their simulation, we used the model of the mooring-fairlead set built by the company AmClyde, which is employed in situations similar to those studied in this report. This model has an operating range of winding angles ranging from 17^o to 60^o. From this, the winding angles to be simulated were defined, corresponding to 17^o, 30^o, 45^o and 60^o, thereby obtaining a large variety of angles and an almost equal step between them, data that would enable a good analysis of the behavior of the mooring.

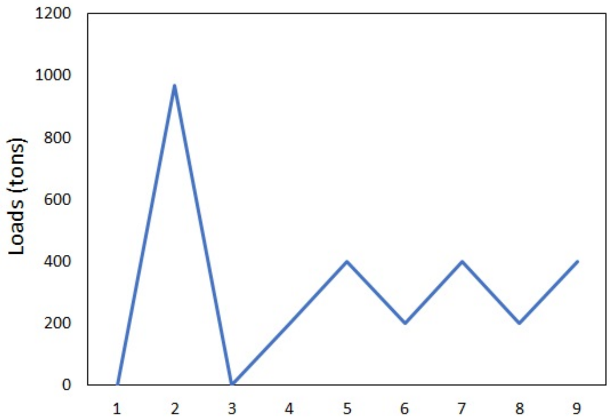
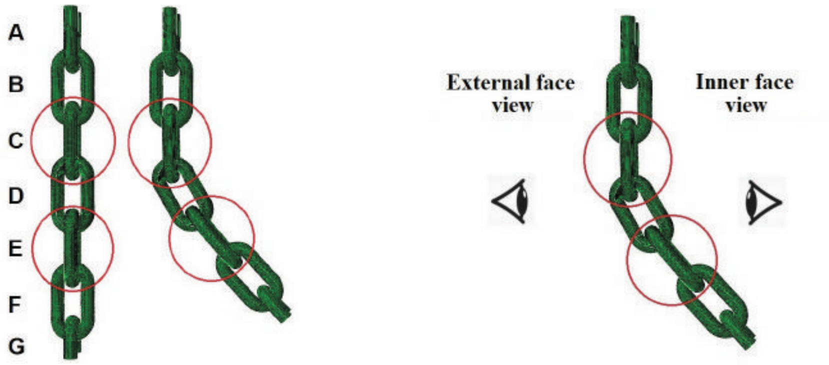


Figure 9: Load oscillation in time.

4. RESULTS

To identify the critical points, or hotspots in the links, the results of the analysis of stresses suffered by the the mooring-fairlead set were obtained according to the degree of angulation of the chain. As not all chain links suffer OPB in the main plane of the link, the stresses were analyzed only in the links that most admit that effect: the link in contact with the guide face of the fairlead and the link right after leaving it. Those studied links are better identified in Fig. 10, as links C and E. In addition to identifying the faces of each link.



(a) (b)

Figure 10: (a) Link identification and (b) Views of the faces of the links.

In the simulation, right after the performance and removal of the proof load, the windings of the moorings in the fairlead are simulated. As discussed in the previous chapter and illustrated in Fig. 11, the simulated winding angles were 17°, 30°, 45° and 60° and these angles represent the variation in the operation of the chain.

From this simulation, it was observed that the external face of each link suffers a greater effect of recurrent stress of the bending, however, it is possible to analyze the evolution of its critical points through the inner face and study its behavior with the variation of the winding angle. Therefore, Fig. 12 and Fig. 13 were created with sections of the internal face of the link, seeking a better visualization of the studied points. These images show the evolution of hotspots in both links, resulted from the increase in the degree of winding of the chain, both for minimum and maximum load.

In addition to the differences between the internal and external faces of the links, it was possible to observe that, as the winding angles increased, the equivalent stresses present in the links were greater and, consequently, the hotspots on the internal faces of the links and in the larger winding angles were more evident.

Regarding the difference observed between the links studied, it was possible to notice that link C presented a slight definition of the critical point in the initial winding angles (17° and 30°), while link E only presented a clear definition of the critical point at the final winding angles (45° and 60°). This difference was observed on the internal faces of the links C and E, under the action of both the minimum and maximum loads, illustrated by Figures 12 and 13, respectively.

It is noteworthy that the Von Mises stress limits determined in the simulation were within the range of 300 MPa and 1000 MPa, values chosen for disregarding both the high contact stresses and the very low and insignificant values acting on the link body.

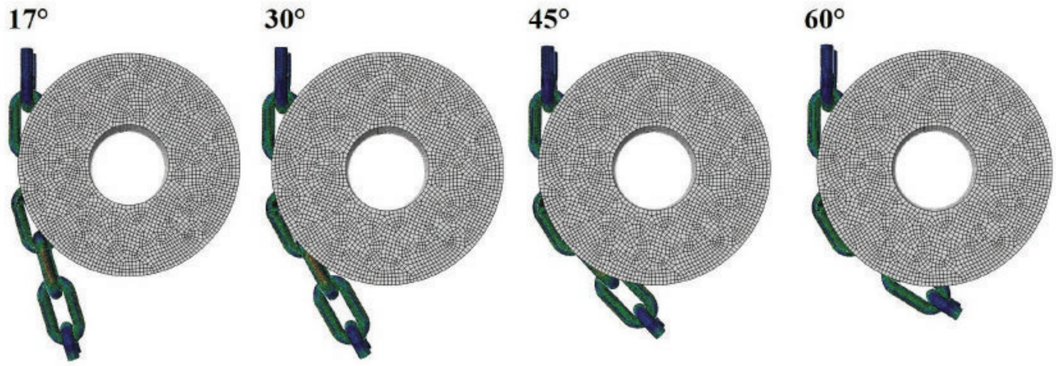


Figure 11: Mooring angulations on fairlead.

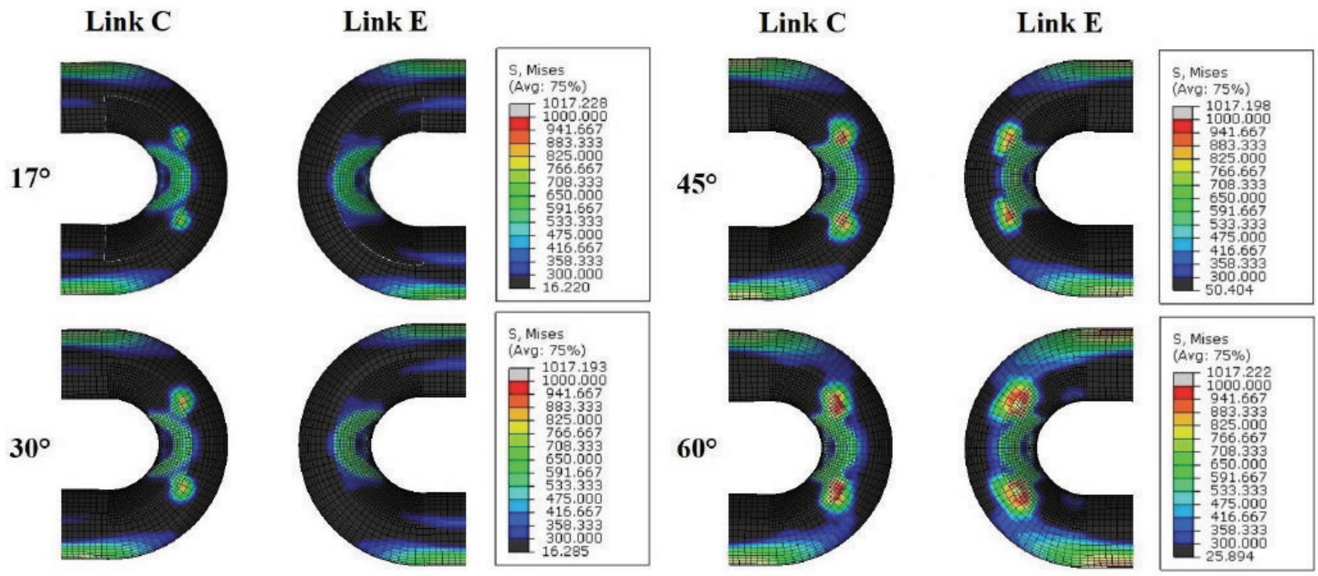


Figure 12: Stress variation on the inner face of the links under minimum load.

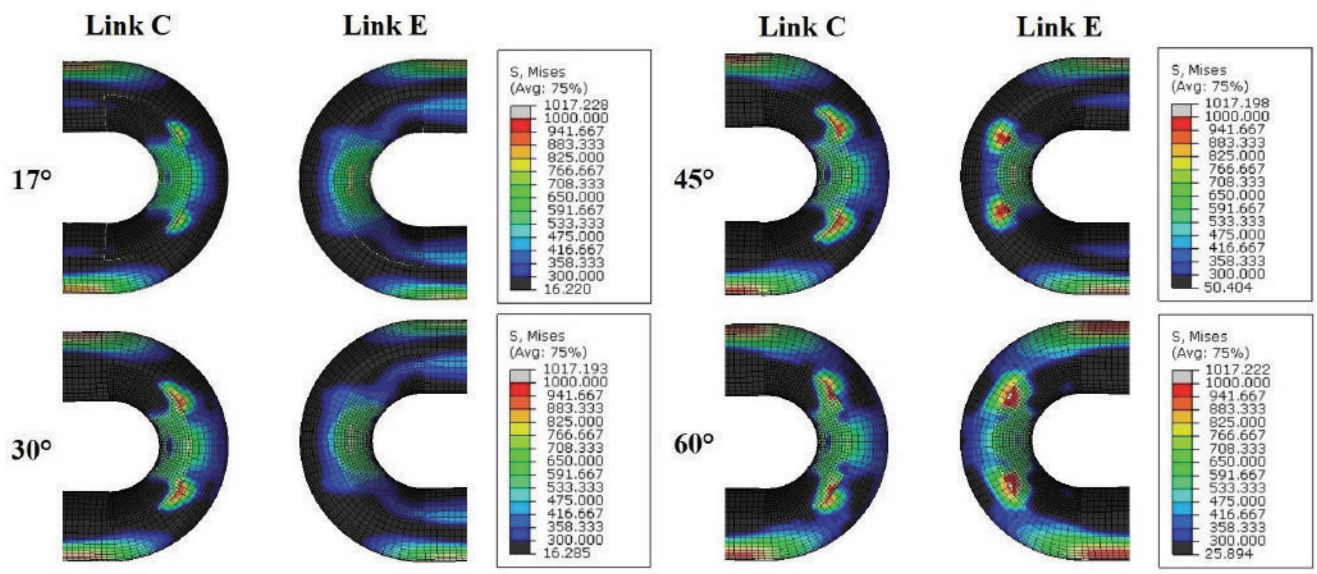


Figure 13: Stress variation on the inner face of the links under maximum load.

5. CONCLUSION

Due to the presented analyses, it was possible to observe the behavior of the chain links present in the mooring-fairlead set of the FPSO platform-ships anchoring system, when submitted to different angulations. As these anchorage systems were failing much sooner than expected, was studied the effect of OPB in the main plane of the link, caused by the angulation of the chain, an effect disregarded by API (American Petroleum Institute). This Institute took into account only the tensions generated by traction-traction and disregarded the fact that the contact between the links under high loads acted as a crimp, which led every force acting perpendicular to this plane generate a bending in the link. It is important to emphasize that the higher the angulation of the chains on the fairlead, the higher the decomposed force that acts as a bending moment.

Given what was exposed in the report and the simulation analyzed, it was possible to conclude that the higher the angle of the mooring on the fairlead, the higher the equivalent stress in the link, mainly due to the OPB. Furthermore, it was observed that higher loads (400 ton) also exert greater stresses on the link, compared to the minimum loads (200 ton). Furthermore, it was observed that higher loads (400 ton) also exert greater stresses on the link, compared to the minimum loads (200 ton). This happens due to the fact that the decomposed forces are greater and result in some more intense bending in the main plane of the link.

Also, considering that cyclic loadings generate lower yield stress and, from the stress concentration at critical points, it is possible to predict the fatigue life of the links, it was possible to compare operating conditions that would generate failures earlier than expected in the mooring systems for FPSO ships. As a higher evidence of the hotspot in the link indicate a lower resistance to fatigue, it was possible to conclude that the greater the angulations of the moorings on the fairlead, the shorter it is fatigue life. Another analysis indicated that links C and E also differed from each other, and that if the link C operated only between the 17° and 30° angulations, it would have a shorter fatigue life compared to the link E. On the other hand, if link E operated between 45° and 60° angulations, it would have a shorter fatigue life compared to link C.

Although this study simulated the model with high loads and constant amplitudes, a fact that is far from what happens in real life, it is still possible to extrapolate the problem to random load conditions that represent a dynamic behavior of the platform.

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