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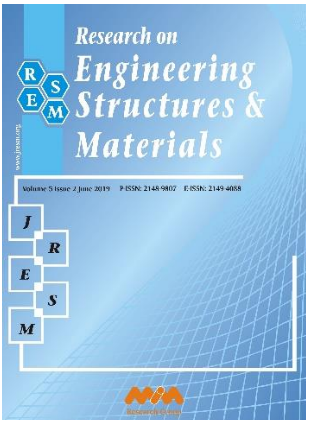

Numerical evaluation of the mechanical behavior of an FPSO mooring system fairleads foundations due to maximum environmental loads

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Research Article

Numerical evaluation of the mechanical behavior of an FPSO mooring system fairleads foundations due to maximum environmental loads

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Abstract

The present work aimed to study the mechanical behavior of the fairlead support brackets of a FPSO (Floating, Production, Storage and Offloading) mooring system located in the Campos Basin (22°58'14''S, 42°01'36''O to 20°19'08''S, 40°20'16''O) using numerical simulation. For an inextensible anchor line, the maximum stresses from the environmental loading of waves, winds and currents were determined. The stresses acting on the anchor line were applied to the centroid of the fairlead and the reactions to these, generated in the brackets, were applied in the internal region of the hole that receives the fairlead support axis. The brackets are fixed to the side of the hull by 3 vertical and 1 horizontal points. Their initial proposed geometry was based on models currently in operation on platforms P66 and P67 (Petrobras platforms capable of stocking 1.67 mi oil barrels each, with 288 m of length overall, they are designed to anchor at depth of 2200 m). The numerical simulation process was performed using the Mechanical APDL tool of ANSYS software with a computational model composed by three-dimensional (3D) finite elements. The results indicated that for the proposed geometry the mechanical integrity of the brackets is assured, considering that von Mises maximum stresses did not extrapolate the yielding stress limit of the steel.

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1. Introduction

The discovery of petroleum basins in ocean regions with a water layer deeper than 200 m made necessary the use of ships capable to produce and storage that petroleum [1]. The floating solution for the petroleum extraction create the necessity of ensure the permanence of the vessel in the project position. In such context, the mooring system one of the most important systems on the platform.

To solve this problem, the mooring systems were developed to minimize the effects of environmental loads, reducing the offset positioning of platforms. Many types of mooring systems were elaborated and applied, focusing in reduce the surge, sway and heave movements. The preset position has a huge importance and losing that position can cause risk to integrity of the vessel, equipment and environment [2].

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One of the most used types of mooring applied on the industry is the Spread Mooring. It consists in multiple mooring lines around the vessel. The distribution of the lines gives to the platform the stability to support the environmental loads in every direction, ensuring the set position in any sea condition. The Fig. 1 exemplifies the usual arrangement of equipment from the Spread Mooring.

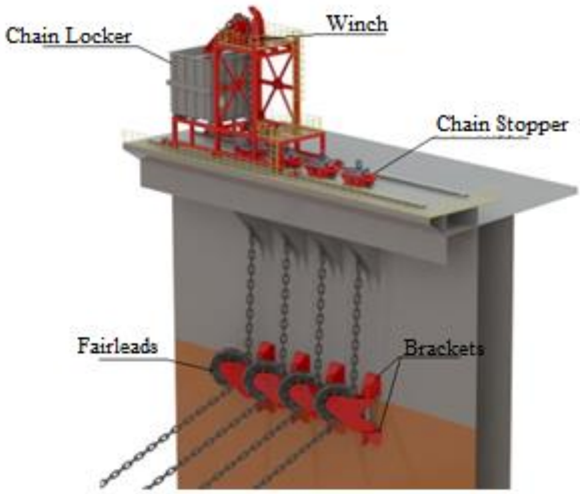

Fig. 1. Example of anchorage system of the Spread Mooring type.

On the side of the hull are the fairleads (see Fig. 1), which have the function of guiding the lines from the ocean side to the main deck level, avoiding the action of torsional loads on the winches and the other equipment on deck.

Consequently, the integrity of all other equipment and the system depends on correct project, manufacture, installation and operation of the fairlead and their foundation (the brackets), as well as of the mooring line.

The mooring system became object of many researches in the last years, but many of them were focused on the line comportment and composition, like Finucane [3], Qiao et al. [4] and Vargas et al. [5]. Although there are researches about brackets or foundations with similar application, as Kumar et al. [6], none of them is focused on naval equipment or fairlead foundations.

The importance of studies about the fairleads is shown by Gordon et al. [7] when it is stated the criticality of the equipment in the system.

The Det Norske Veritas (DNV) [8] stipulates three types of loading that need to be considered on the project of fairleads and their foundations: the Ultimate Limit State (ULS) is the situation with the environmental loads on their maximum value; the Accidental Limit State (ALS) consider the same loads of the ULS, however the number of the mooring lines is smaller since the other lines must maintain the position of the platform in the case of failure of some line; and the Fatigue Limit State (FLS) must be used to analyze the cyclical loads. DNV undertakes classification, certification, and other verification and consultancy services relating to quality of ships, offshore units and installations, and onshore industries worldwide, and carries out research in relation to these functions.

Therefore, the main objective of this paper is analyzing the effects of the environmental loads on the brackets of the fairleads in a mooring system of a FPSO platform, using numerical simulation through the tool Mechanical APDL of ANSYS software. This platform is placed on Brazilian coast, more specifically on Campos Basin (22°58'14''S, 42°01'36''O to 20°19'08''S, 40°20'16''O). DNV is an autonomous and independent foundation with the objectives of safeguarding life, property and the environment, at sea and onshore.

2. Methodology

As a first stage for the project of the system, adopt the lines as inextensible is a normal premise. Lacerda [9] analyzed the effects of the extensibility on the catenary mooring lines, concluding that the break up loads on the inextensible lines are 40% less than in tensioned lines. It was demonstrated that using inextensible lines is a more conservative approach. Figs. 2 and 3 shows a scheme of an inextensible catenary mooring line and its division on an infinitesimal element.

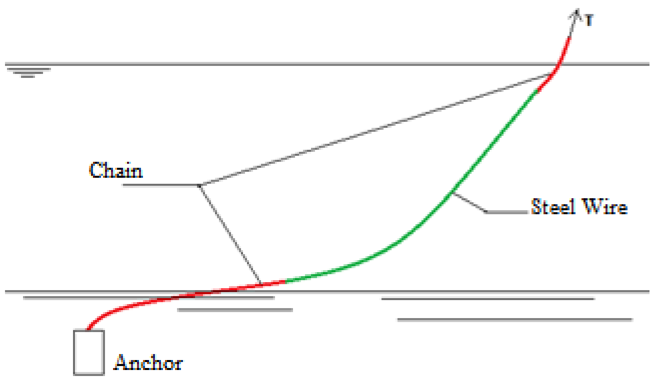

Fig. 2. Line composition commonly adopted in mooring.

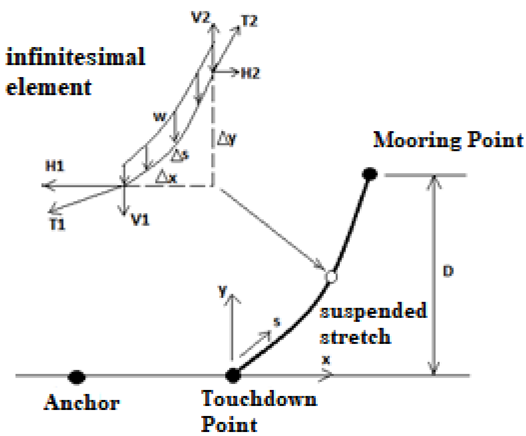

Fig. 3. The infinitesimal element of the catenary mooring line.

To define the loads created by the environment on the lines the methodology proposed by Nazário [10] was adopted. The premises of plane surface on the deep ocean and infinite axial rigidity of the mooring line must be assumed so that the equation is valid. If the sum of horizontal loads is null (see Fig. 3):

$$\Sigma Fh = 0 = H_2 - H_1 \quad (1)$$

where:

$$H_1 = T_1.\cos(\theta_1) \quad (2)$$

$$H_2 = T_2.\cos(\theta_2) \quad (3)$$

Considering the sum of vertical loads equal to zero (see Fig. 3):

$$\Sigma Fv = 0 = V_2 - V_1 - (w.\Delta s) \quad (4)$$

where:

$$V_1 = T_1.\mathrm{sen}(\theta_1) \quad (5)$$

$$V_2 = T_2.\mathrm{sen}(\theta_2) \quad (6)$$

being: w the linear weight of submerged line and Δs the infinitesimal element length.

The boundary conditions application allows to define the relation between the depth (d) and the mooring radius (r). Hence, it is possible to determine the inclination of the line in the fairlead spot.

$$d = \frac{H}{w}.\cosh\left(\frac{w.r}{H}\right) - 1 \quad (7)$$

$$r = \frac{H}{w}.\cosh^{-1}\left(\frac{w.d}{H}\right) + 1 \quad (8)$$

Nazário [10] mentioned the importance of considering the submerged weight on the equations. The submerged weight is the weight of the line subtracted of the buoyancy. This difference of the weight results in a higher mooring radius (r), once the variable values on the equations are only the weight and the environmental loads.

The longest length on the line also creates a different inclination on the line and it affects the loads on the fairleads and brackets.

The environmental loads can be predicted from eight different sources, according with DNV [11]:

- wind;
- waves;
- current;
- earthquakes;
- ice and snow;
- storms;
- extreme temperatures;
- action of animals;
- algae and other marine creatures.

The most common and easier of measurability sources are those generated by winds, currents and waves. In this sense, in this research, the environmental loads were composed by only these three parcels. To do so, the environmental load concerning current or wind can be obtained as:

$$F = \frac{1}{2}.\rho.c.A.v^2 \tag{9}$$

where: ρ is the fluid density (kg/m^3), C is the drag coefficient, A is the platform area suffering the effects of the load (m^2) and v is the incidence velocity of the load (m/s).

All the factors are related to a certain incidence angle of the load. So, Eq. (9), is applicable for both the wind and the current portion, but only the wind load comes from the aerodynamic drag acting on the platform region above the water slide, while the stream portion is generated by the interaction of the flow with the submerged region of the vessel.

The load generated by the waves was obtained through a conservative analysis, proposed by Bergdahl and Kofoed [12], which assumes that their object of study fully reflects the average wave, making their analysis applicable in irregular wave. The equation of the load generated by the waves incidence is given by:

$$F_w = \frac{\rho.g.H_s.Aw}{32} \tag{10}$$

where: g is the gravity acceleration (m/s^2), Aw is the area of the platform that suffer incidence of the load (m^2) and Hs is the average height of the waves (m).

For the case under study, a mixed anchor line was established between ropes of model R4, with a diameter of 120 mm, and Spiral Strand type steel cables, grade 2, class A, galvanized steel A586, with diameter of 102 mm.

DNV proposes angles of incidence for each of the three environmental loads in relation to the others, but in this work the same angle was adopted for all the loads. Figure 4 shows a comparison between the recommendation of the standard, Fig. 4 (a), and what was used in this work, Fig. 4 (b).

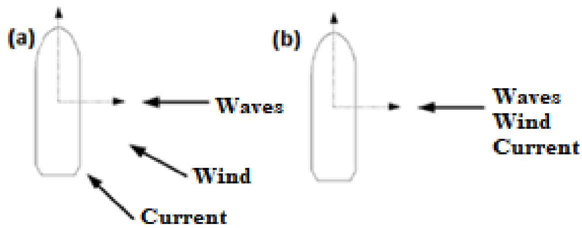

Fig. 4. Comparison between recommended angles of incidence (a) and applied in the study (b). (Adapted from DNV, 2015).

The calculated loads were applied to the centroid of the fairlead and later, through the equations of static equilibrium, applied in the inner region of the bracket hole, which receives the fairlead axis, visible in Fig. 5.

Fig. 5. Bracket used in the P66 and P67 platforms of Petrobras.

The proposed geometry for simulation through ANSYS for the set of brackets is based on the equipment used in the replicating projects of the FPSOs P66 and P67 of Petrobras [13]. The simulation employed the finite element SOLID186, which is composed of 20 nodes, having 3 degrees of freedom per node, being these the translation in the axes *x*, *y* and *z*.

The SOLID186 finite element has a mixed formulation capability, allowing to simulate deformations of elastoplastic materials, although in this study only a linear elastic analysis is performed. The use of this element will provide, in future studies, an elastoplastic analysis of the region where the highest tensions are concentrated [14].

The mesh was generated with finite tetrahedral elements [15]. For the definition of mesh refinement to be adopted, a mesh convergence test was performed. From this, the computational model was verified.

3. Computational Model Verification

To verify the computational model, an example of a three-dimensional bracket with simpler geometry was performed, as shown in Fig. 6. The study proposed by Moussa [16] was replicated by changing only the finite element used in the simulation, from PLANE82 to SOLID186. It is worth to highlight that both elements are available in ANSYS software.

The finite element PLANE82 composed of 8 nodes, has 2 degrees of freedom, allowing translation around *x* and *y* axes, presenting less precision in comparison to the finite element applied in this study (SOLID186).

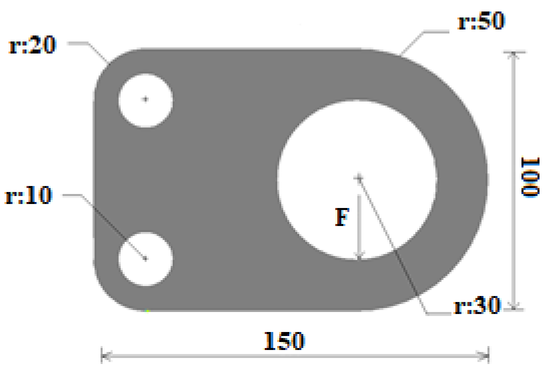

Fig. 6. Bracket used to verify the computational model (dimensions in mm).

The steel plate of the bracket has a thickness of 20 mm and its dimensions of length and maximum height are 150 mm × 100 mm. The inner areas of the two smaller holes are considered clamped and the load (*F*) applied internally to the larger hole is 1000 N. Table 1 presents the results of the mesh convergence test in the current study, with finite element SOLID186.

Table 1. Comparison between the values obtained in the model verification.

Analysis	Maximum displacement (mm)	Maximum von Mises stress (MPa)
1211 nodes	34	15.9
1392 nodes	37	15.5
2016 nodes	38	15.3

The difference in the values obtained among the different meshes shows that the mesh with 2016 nodes is in a region of asymptotic behavior, being considered as independent mesh. The meshes with 1392 and 2016 nodes have a variation of approximately 2% for the maximum displacement and maximum von Mises stress.

The results obtained by Moussa [16] were 33 mm for the maximum displacement and 16.9 MPa for the maximum von Mises stress. Comparing these results with those obtained in the present study it is possible to consider that the model was verified, taking into account that the SOLID186 is a more accurate finite element than PLANE82.

Figure 7 shows a comparison between the von Mises stress distribution obtained in the present study and by Moussa [16]. It is important to note that not only the values found are similar (13.15% for maximum displacement 9.5% and von Mises stress), but also the mechanical behavior of the bracket and the regions with the highest stress concentration are similar.

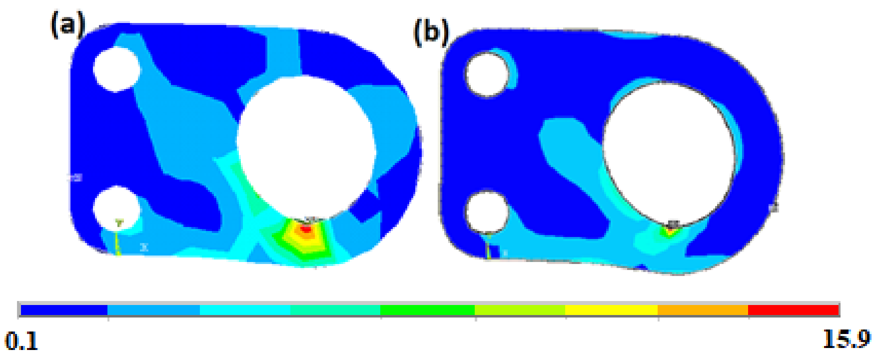

Fig. 7. Distribution of von Mises stress (in MPa) obtained with the present study (a) and the presented in Moussa (b).

4. Results

The environmental loads data on the characteristics of waves, winds and current, in the Campos Basin region, were extracted from the standards of DNV. These data are depicted in Tab.2.

Table 2. Data on the environmental conditions of the Campos Basin (DNV, 2015).

Data	Value
Medium wave height (Hs)	8 m
Medium wave period (Tp)	13 s
Wind velocity (νw)	35 m/s
Current velocity (νc)	1.6 m/s

The depth considered in the study is 1355 m referring to the region of Jubarte field (located on the coast of the brazilian state of Espírito Santo, 76 km from Pontal de Ubu, in the municipality of Anchieta) [17]. The set of brackets and fairlead were arranged 8 m above the level of the water slide and 12 m of deck equipment.

The area of the platform that suffer action of wave and current environmental loads were determined considering the region with deep water characteristics [18]. Thus, for current, the area of action is limited by the deepest height with water particle displacement, determined by:

$$2. Hmpap = L = \frac{g\,.(Tp)^2}{2\,.\pi} \tag{11}$$

where: $Hmpap$ is the maximum height of particle move to depth water (m), L is the wave length (m), g is the gravity acceleration (m/s^2) and Tp is the period of the medium wave (s).

Considering the synodal movement of the waves the double of the medium height determines the region that suffers action of this specific load. The platform length was adopted as 300 m and its height outside the water as 20 m. The platform draft is of 10 m, within the region of action of the current.

Since each side of the platform is equipped with 12 anchor lines in a traditional Spread Mooring System, the maximum load found is divided by the number of lines. The weight values per meter of the anchor line for the moorings were obtained through the Brasil Amarras [19] catalogs.

Therefore, with the data and assumptions adopted, it was possible to obtain the environmental loading and consequently the tensions for an anchor line. The values obtained are shown in Tab. 3.

Table 3. Environmental loads and loads applied on mooring lines.

Load	Value (MN)
Wind parcel	9.5
Current parcel	7.9
Waves parcel	12.2
Horizontal environmental load per line (H)	2.5

To determine the bracket stresses, the line stresses were applied to the fairlead centroid, located 1.7 m away from the brackets on the x axis and half the distance between the brackets on the *y* axis. The distance between the brackets is 2.3 m and the 14-ton weight of the fairlead was included in the calculations.

It is important to note that the bracket arranged at the top of the shaft has no restrictions on the movement on the *y* axis, and thus all loads on this axle are supported by the lower bracket.

Figure 8 shows an outline of the free-body diagram of the system under study. The inclination of the fairlead in relation to the hull can vary, according to the need of design and demand of efforts according to the angle of incidence of the environmental loads.

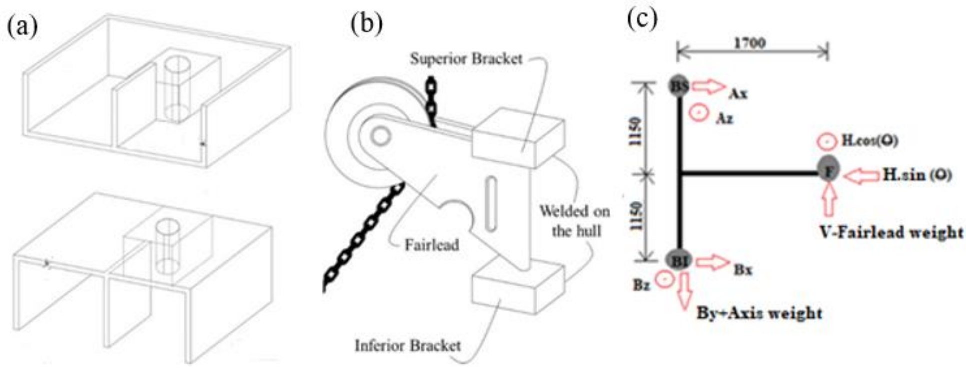

Fig. 8. Sketches of: (a) basic bracket geometry; (b) basic brackets-fairlead assemble; (c) free-body diagram of the problem.

For the analysis an inclination fairlead angle of 15° was adopted, however, even with the inclination of the fairlead, no displacement of the centroid of the equipment with respect to the *z* axis was considered.

We performed separate simulations for each bracket, aiming to propose recommendations about the distribution of stresses and displacements in the lower and upper brackets. In each case a mesh convergence test was carried out. The Tabs. 4 and 5 present the values obtained in the simulations for maximum von Mises stress and maximum displacement for the upper and lower brackets, respectively.

Table 4. Mesh convergence test for the upper bracket.

Nº Elements Mesh	von Mises stress (MPa)	Maximum displacement (mm)
3512	11.34	0.4
4931	13.04	0.4
6185	12.65	0.4
6718	11.85	0.4

Table 5. Mesh convergence test for the lower bracket.

Nº Elements Mesh	von Mises stress (MPa)	Maximum displacement (mm)
3587	57.98	1.7
4343	56.45	1.7
6444	64.08	1.7
6939	59.99	1.7

From Tabs. 4 and 5 it is possible to observe the mesh convergence through the slight variation of the values. The maximum von Mises stress found in the brackets were 11.85 MPa and 64.08 MPa for the upper and lower bracket, respectively, which corresponded to the expectations of the study, considering that they did not exceed the yield limit of the steel (355 MPa for the AH36 steel), which could compromise the structure of the equipment. Figures 9 and 10 illustrate the distribution of von Mises stresses in the upper and lower brackets, respectively.

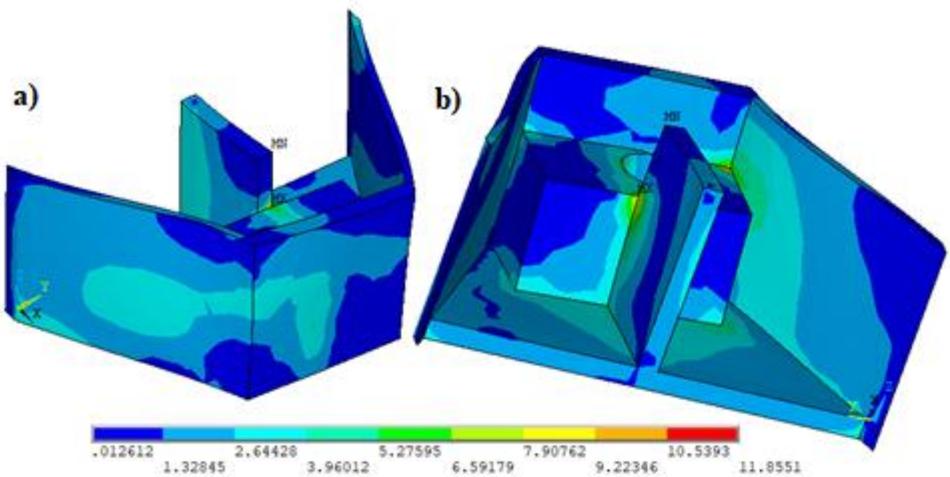

Fig. 9. von Mises stress distribution in upper bracket simulations (in MPa).

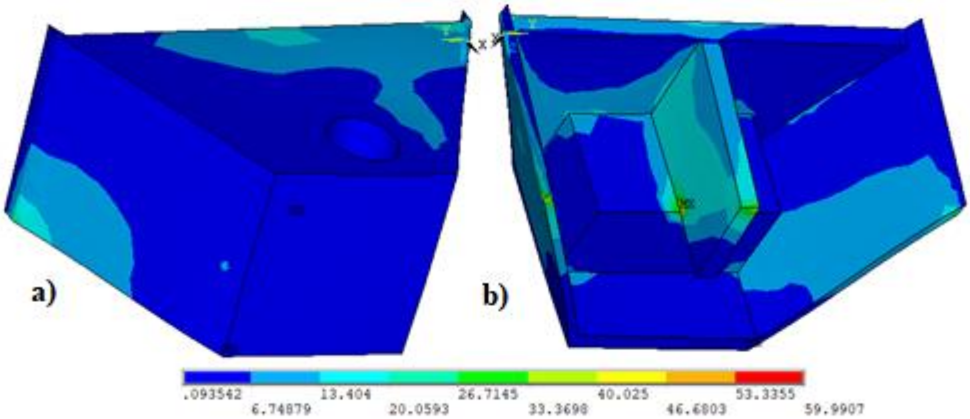

Fig. 10. von Mises stress distribution in lower bracket simulations (in MPa).

It is possible to observe that the spots with higher von Mises stress values are on the join of the solid around the hole, where the loads were applied, and the vertical plates welded on the hull.

5. Conclusion

It was observed through the numerical simulations that the structure did not suffer from mechanical failure risk for the proposed geometry in relation to the maximum environmental load under the imposed conditions of ULS analysis.

The stresses in the brackets did not exceed the yield limit of the steel. This can be justified by the fact that the study considered only the maximum environmental load, and not the other loads proposed by DNV, although it made use of a geometry based on an equipment in which was designed to support all three types of requests.

Finally, it is important to emphasize that the proposal to approach the problem with a 3D model adds precision to the analysis, even more when compared with studies in 2D models, such as that used in the verification of the model of this study.

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