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DESAFIOS E IMPACTO DAS ENGENHARIAS NO BRASIL E NO MUNDO

Carlos Augusto Zilli
(Organizador)

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APRESENTAÇÃO

Esta obra, intitulada “Desafios e Impacto das Engenharias no Brasil e no Mundo”, apresenta 17 capítulos que abordam pesquisas relevantes sobre os impactos e desafios enfrentados pela engenharia mundo afora, tais como: Saneamento Básico, Concreto em Situações de Incêndio, Sistemas de Monitoramento Térmico em Construções, Estabilidade de Solos, Auditoria de Barragens, Rotas Rodofluviais, Políticas Públicas e Compostos Bioativos.

Desta forma, esta obra se mostra potencialmente disponível para contribuir com discussões e análises aprofundadas acerca de assuntos atuais e relevantes, servindo como base referencial para futuras investigações.

Deixo, aos autores dos capítulos, um agradecimento especial, e aos futuros leitores, anseio que esta obra sirva como fonte inspiradora e reflexiva.

Esta obra é indicada para os mais diversos leitores, tendo em vista que foi produzida por meio de linguagem fluída e abordagem prática, o que favorece a compreensão dos conceitos apresentados pelos mais diversos públicos, sendo indicada, em especial, aos amantes da área de engenharia.

Carlos Augusto Zilli

SUMÁRIO

SUMÁRIO

CAPÍTULO 2

DESIGN FAILURE MODE AND EFFECTS ANALYSIS (DFMEA) OF THE ROD OF THE SUBSEA PIPELINE LOCKING SYSTEM IN AN OPEN PLET

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ABSTRACT: One of the most important equipment in a subsea oil and gas production field is the PLET (pipeline end termination), which in its open configuration (open PLET) allows the locking of part of this pipeline at a time after the launch of the equipment itself. Based on preliminary analytical calculation and assumptions made, it was found that the critical component of this system is the locking rod, reason why, in addition to the mentioned calculation, a finite element analysis was performed, obtaining displacement and stress. However, the detection of the regions most susceptible to failure cannot be ruled out only by the calculated safety factors corresponding to these regions. To perform a more comprehensive mapping, a design failure mode and effects analysis (DFMEA) was conducted, resulting in an ordination of the critical regions of the studied component. As the main result, the DFMEA presented the transition region between the thread rod and the slender cylinder as the critical one, both with regard to compression and torsion combined, as well as when the referred efforts are aggregated to the contact with the mobile pin thread.

KEYWORDS: DFMEA, FMEA, structural analysis, open PLET, subsea pipeline.

1 I INTRODUCTION

Fossil fuels are responsible for about 85% of world's energy consumption, being oil and gas representative of around 65% of fossil fuels. The exploration of these natural resources in deep and ultra-deep water depth (off shore) makes required process more expensive when compared to surface (on shore). From this perspective, there is a continuous search for cost reduction, mainly in what refers to installation and retrieval time, according to Bai and Bai (2012). Therefore, in the scope of this industry, the research plays an important role, highlighting the care to extract these products with the maximum efficiency (due to being a non-renewable resource) and safety (being operationally effective without failures).

1.1 Open PLET

In an improvement context, a newly developed version of the PLET is presented in an open configuration. The main difference between the open PLET and the conventional one (see Figure 1) is that in the former the pipeline and the open PLET are installed separately (the pipeline is installed on the seabed and posteriorly the open PLET is installed, or the PLET can be installed first, waiting for the lowering of the pipeline). No matter the selected sequence, at the end of installation, the pipeline will be locked in the open PLET by the locking system. This type of configuration is employed mainly in situations where the loads imposed by the environment on the conventional PLET are estimated to be very high or when the weight of the PLET may damage the seabed in the installation.

The design of the equipment intrinsically addresses the restrictions about the possible installation methods of the pipeline. In Figure 2, in the first step, the pipeline is vertically lowered and landed on the seabed (the open PLET is subsequently lowered). The second step consists of landing the PLET over the pipeline. Third step is the axial fine adjustment between the two. The fourth step is the pipeline lifting to fit in the receptacle of the PLET. The last step is the locking of the pipeline in the operational position via the four mechanical lock assemblies.

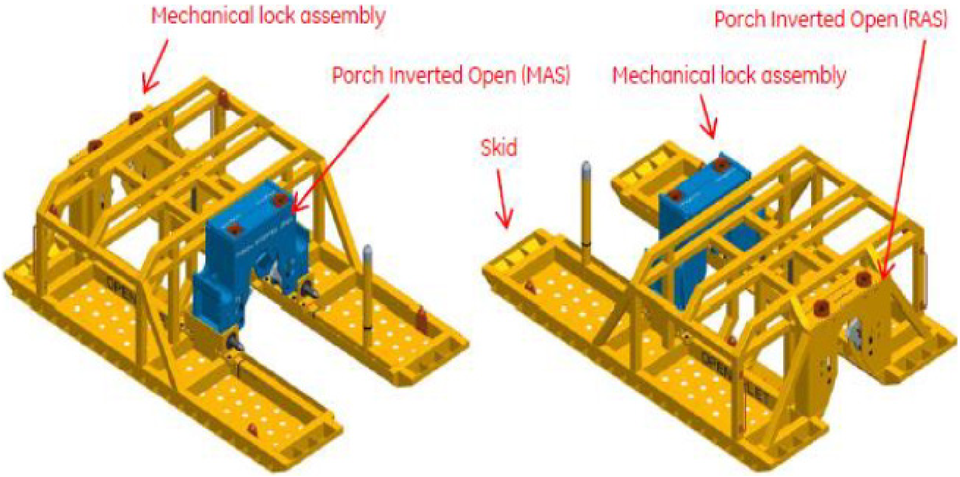

FIGURE 1. Main components of an open PLET.

Source: adapted from Thorsen (2012).

The rear alignment structure (RAS) and the main alignment structure (MAS) are designed to provide orientation, alignment and vertical locking of the pipeline. The former receives the pipeline in the rear part (inlet) of the open PLET, while the latter is where the outlet of the pipeline is locked. There are two mechanical lock assemblies at each alignment structure, totalizing then four mechanical lock assemblies in an open PLET. The skid refers to the structure itself to house the locking system, support, and transfer all the loading to the seabed.

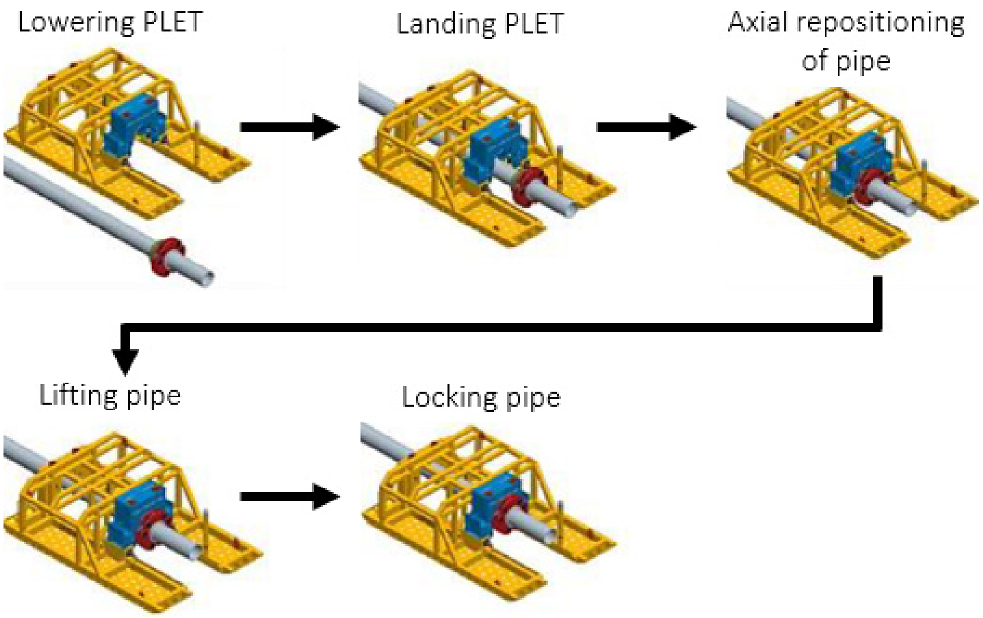

FIGURE 2. Steps for installation of a pipeline in an open PLET.

Source: adapted from Thorsen (2012).

Upon this open PLET configuration and coherently with the installation sequence, the pipe locking step (last step in Figure 2) requires a subsystem to lock (or unlock in the case of retrieval of the equipment), which is shown in Figure 3, highlighting its main components. In order to operate the mechanical lock assembly, a torque tool and a remotely operated vehicle (ROV) are required. The former is the tool responsible to apply directly the torque on the hex interface to activate the entire locking mechanism and the latter is the referred robot to operate the torque tool.

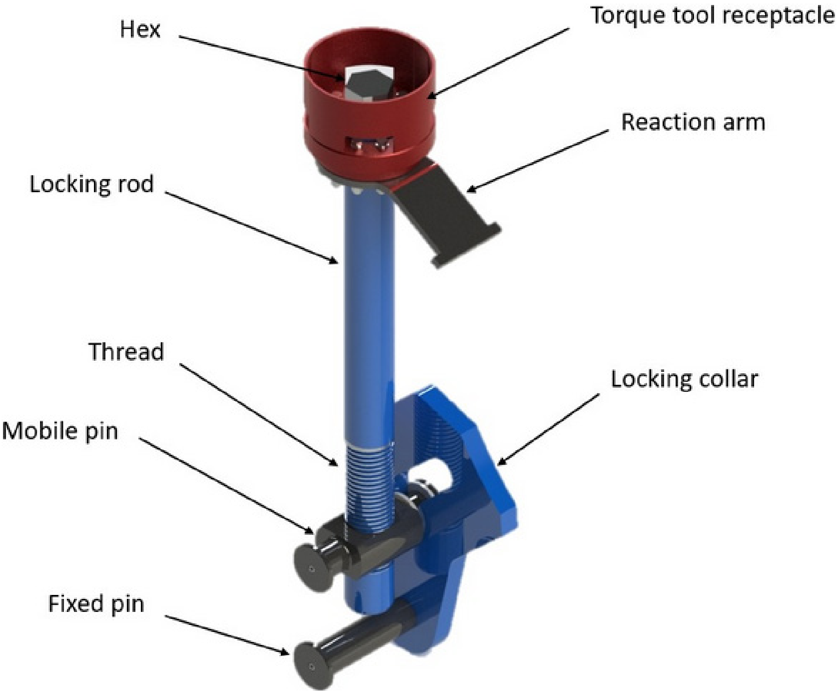

FIGURE 3. Main components of the mechanical lock assembly.

Source: own authorship (2020).

The torque tool receptacle is responsible to keep the hex end of the locking rod protected from accidental loads and allow the first alignment of the torque tool during loosening or tightening operations. It also has a reaction arm attached to it in order to lock the rotation due to its contact with other parts of the structure. The fixed pin supports the rotation of the locking collar and the mobile pin is reciprocal to the locking rod, pushing the locking collar to rotate and lock the pipeline in its position. Finally, the locking rod is responsible to transmit the work done by the torque tool to the locking collar through the mobile pin. The locking rod is the object of calculation of this paper. Its possible working positions are shown in Figure 4.

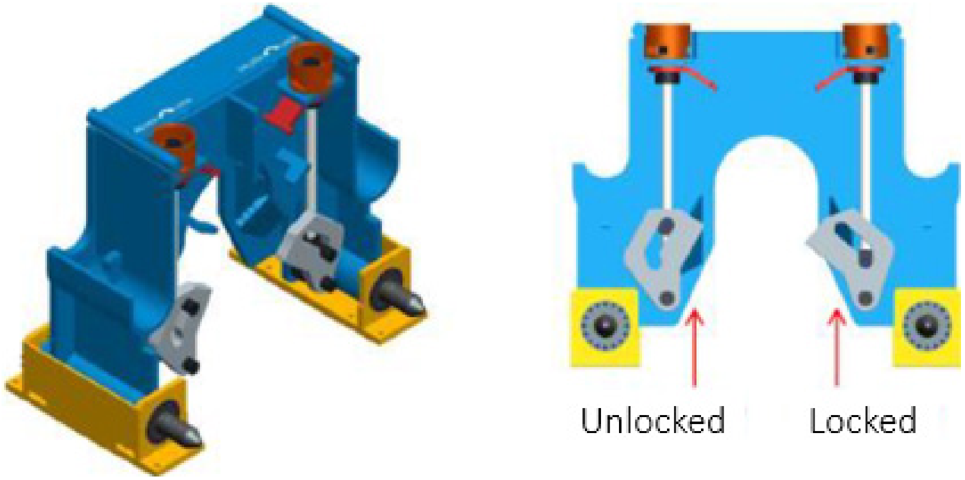

FIGURE 4. Working positions of the locking system.

Source: adapted from Thorsen (2012).

1.2 Design Failure Mode and Effects Analysis (DFMEA)

According to Stamatis (2003), FMEA consists of an engineering technique mainly used to define, identify, and eliminate known and/or potential failures, errors, etc. in systems, designs, processes and/or services before they are delivered to the customers, which requirements must be attended. It is widely employed in the most diverse types of industries due to its applicability and potential to generate financial return. As mentioned by Peeters et al. (2018), it is a bottom-up method, since the analysis starts from the component level to the assembly. It is also used for reducing the potential failures, therefore increasing reliability (Liu et al., 2013). In addition, from a strategic point of view, FMEA provides enough information to support risk management decisions (Jacoby, 2012).

The whole process is conducted at first mapping all the failure modes and their corresponding effects. Thenceforth, for each failure mode a grade is attributed in the following categories: (a) severity; (b) occurrence; and (c) detection. For each category, a table is commonly used to relate a description to a grade. The risk priority number, RPN, is therefore generated by multiplying the grades from the three categories, as mentioned by McDermott et al. (2008) in Equation 1, where S stands for severity (see Table 1), O for occurrence (see Table 2), and D for detection (see Table 3):

$$RPN = S\ O\ D. \tag{1}$$

In order to clarify the descriptions of Tables 1 and 3, some terms employed must be enlightened. The word “customer” in Table 1 may have different meanings. For example, if a company has only the design as scope of work, then the customer is outside. However, if the referred company also covers post-design processes such as manufacturing, assembly, testing, painting, etc., then the customer is inside the company itself. Supplier means the design team or members, whereas performance in design refers to evaluation in a simulation or calculation. The context of the word "product" refers to the virtual product created in computer softwares.

Severity Categories	
Description	**Grade**
The discrepancy is imperceptible by the customer.	1
The discrepancy is insignificant.	2
Customer dissatisfied, with slight effect on product.	3
Customer dissatisfied, communication with the supplier, modifications necessary.	4
Customer complains, with moderate effect on product performance.	5
Failure of at least one subsystem, impairing functionality.	6
Customer now considers an alternative supplier, if it is possible.	7
The product is not functioning.	8
Critical effect on customer satisfaction with threat to property.	9
Threat to life; company image under risk. Failure occurs suddenly.	10

TABLE 1. Severity categories adopted.

Source: adapted from Stamatis (2003).

Occurrence categories		
Probability (%)	**Description**	**Grade**
0 – 20	Failure does not occur or the chance is low.	2
21 – 40	The failure probability is lower than that of not occurring.	4
41 – 60	The probability of occurrence of failure is a little lower, equal, or a little higher than that of not occurring.	6
61 – 80	The failure probability is much greater than that of not occurring.	8
81 – 100	The failure is almost a natural consequence of the design.	10

TABLE 2. Occurrence categories adopted.

Source: own authorship (2020).

Detection categories		
Phase	**Description**	**Grade**
Initial specification	Failure to understand customer specifications/standards.	1.25
Preliminary calculation	Failure in calculation to provide initial dimensions (proportionality between components).	2.5
Conceptual design	Failure occurs when the concepts and functioning of the product are defined.	3.75
Calculation	Failure in calculation to provide almost definitive design dimensions.	5
Detailed design	Failure when providing dimensions, material, surface finish, geometrical characteristics, etc. to the product.	6.25
Virtual assemblage test	Failure to virtually assembly all the components under the information provided.	7.5
Design verification	Failure detected in the verification process related to the work done up to this stage.	8.75
Design approval	Failure detected in the approval process related to the work done up to this stage.	10

TABLE 3. Detection categories adopted.

Source: own authorship (2020).

Research related to FMEA has been conducted all over the years, even with little emphasis on DFMEA. Peeters et al. (2018) combined FMEA with fault tree analysis (FTA) in an additive manufacturing system. Mashaqbeh et al. (2019) proposed a method to optimize FMEA through an application in a power plant. Kulcsár et al. (2020) introduced a pairwise comparison based FMEA which allows the estimation of indices of the previously not evaluated risks.

Related specifically to DFMEA, Chang and Wen (2010) proposed a novel approach for DFMEA (combining 2-tuple and the ordered weighted averaging, OWA, operator). Nonato and Pastoukhov (2012) implemented DFMEA calculation on a structural frame similar to a PLET. Tamaldin et al. (2013) performed a design optimization of a vehicle system using DFMEA and other analyses. Torres et al. (2018) created a probabilistic Boolean network modeling and model check as surrogate approach for DFMEA of manufacturing systems.

2 I MATERIALS AND METHODS

The analysis of the locking rod was made considering that the process is isothermal and isochoric, the material is homogeneous and isotropic, and that Saint Venant’s principle is observed (concentration factors are taken into account). The material of the locking rod is the AISI 4130, normalized at 870ºC, exception made for the hex part and for the thread, which are suddenly cold when the heating reaches 855ºC (quenching process). The material properties of this component are presented in Table 4.

Quantity	NORMALIZED PART	Magnitude	QUENCHED PART	Magnitude
Brinell hardness (HB)		163		241
Ultimate tensile strength (MPa)		615		841
Yield tensile strength (MPa)		400		655
Modulus of elasticity (GPa)		205		205
Poisson’s ratio		0.29		0.29
Elongation at break (%)		27.0		20.5
Reduction of area (%)		61.2		63.6

TABLE 4. Locking rod material properties (AISI 4130). Source: Matweb (2020).

2.1 Free Body Diagram

This diagram is made to input the analytical calculation and the finite element analysis performed to output the DFMEA. The particular situation in which this design is performed occurs at exact moment of the pipeline locking. This can be described by the torque tool applying its maximum torque on the locking rod, besides the existence of the weight force from the assembly composed by the torque tool and ROV (considered partially). The complete free body diagram is shown in Figure 5, in which the nomenclature is understood as follows: variables initiating with letter “D” stand for diameters; “F” for forces; “L” for lengths; and “M” for moments, which values (geometrical and loading) are listed in Table 5. The values contained in this table are only magnitudes, not reflecting the vector representation related to the coordinate axes. For details about directions, refer to Figure 5.

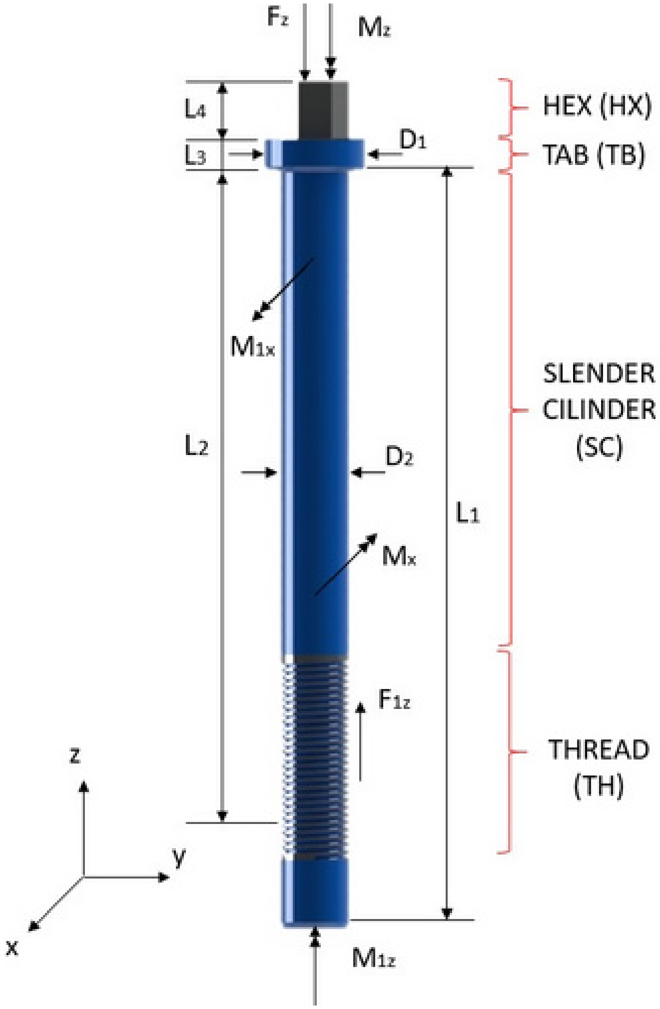

FIGURE 5. Free body diagram of the locking rod.

Source: own authorship (2020).

	Quantity	Magnitude (mm)		Quantity	Magnitude
GEOMETRICAL	Length L_1	1300.0	LOADING	Force F_z	4542 N
	Length L_2	1183.0		Force F_{1z}	4542 N
	Length L_3	50.000		Moment M_{1x}	91771852.5 Nmm
	Length L_4	100.00		Moment M_x	91771852.5 Nmm
	Diameter D_1	138.00		Moment M_z	2700000 Nmm
	Diameter D_2	114.30		Moment M_{1z}	2700000 Nmm

TABLE 5. Values of the geometrical and loading quantities.

Source: own authorship (2020).

The force F_z comes from the partially considered weight of the ROV and the full weight of the torque tool from up above in the operation. The torsional moment M_z is transferred to the locking rod via torque tool. The moment M_x originates due to the weight of the pipeline on the collar and the distance between the mass center of the pipeline and the center of the mobile pin. The other loadings are reactions due to F_z, M_x, and M_z. The reaction F_{1z} is caused directly by F_z when the locking rod thread touches the mobile pin thread, i.e. it is due to the threaded connection of the mobile pin (when the pipeline lands over the locking collar, the latter intends to lower the mobile pin and the locking rod). The reaction moment M_{1x} is due to a support in the structure, preventing the upper part of the slender cylinder to bend. The moment M_{1z} concerns the impossibility to rotate locking rod related to the mobile pin via threaded interface.

2.2 Analytical Calculation and Finite Element Analysis (FEA)

The analytical calculation was performed by applying the classical solid mechanics formulation for stresses and safety factors for ductile materials. The stress concentration phenomenon was taken into account by the stress concentration factor associated to the mean actuating stress, selecting the most suitable concentration factors available for the geometrical transitions found in this design. The infinitesimal elements selected are potentially the most critical and are under plane stress state. These elements are located at: (a) transition between hex and tab, but at hex; (b) the edge of the torque tool touches the edge of the hex; (c) periphery of the cylindrical surface of the tab; (d) lower surface of the tab; (e) transition between the slender cylinder and the tab, but at the slender cylinder; (f) mid-span of the slender cylinder; (g) transition between the slender cylinder and thread, but at the thread; (h) thread flank.

The main equations applied in this work are compression, torsion, bending, contact stresses, and critical load from buckling, which are expressed, respectively, by Equations 2, 3, 4, 5, and 6:

$$\sigma_{COM} = \frac{F}{A}, \tag{2}$$

$$\tau_T = \frac{M_T\, r}{I_P}, \tag{3}$$

$$\sigma_B = \frac{M_B\, y}{I}, \tag{4}$$

$$\sigma_C = \frac{F_C}{A_P}, \tag{5}$$

$$F_{CRI} = K_B \left(\frac{\pi}{L}\right)^2 E\, I, \tag{6}$$

in which F is the force normal to the analyzed plane, and A is the area under compression (which normal to the plane under analysis is parallel to the compression force vector and opposite in direction to it. M_T is the torsional moment, r is the radius of the region under torsion, and I_P is the polar moment of inertia. The bending moment is M_B, the distance between the neutral axis and the point to calculate is y, and I is the moment of inertia related to the rotation axis. F_C is the contact force and A_P is the area of a component projected on the other. $K_B = 1$ (one end fixed, the other articulated) is the support condition for buckling, F_{CRI} is the critical load magnitude to provoke the buckling phenomenon, L is the length under buckling, and E is the elasticity modulus.

The combination of stresses is made when and where necessary to compose the principal stresses in plane stress state. These principal stresses are introduced in von Mises failure criterion to calculate the safety factor N (Equation 7) of each infinitesimal element mentioned based on yield strength.

$$N = \frac{S_Y}{\left(\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2\right)^{\frac{1}{2}}}, \qquad (7)$$

After the analytical calculation, a finite element analysis (FEA) was performed in Ansys® software. The results are given in terms of displacements and stresses. The analysis followed the free body diagram, in which material parameters were taken from Table 4, and geometrical and loading parameters were extracted from Table 5.

3 | RESULTS AND CONCLUSIONS

The free body diagram shown in Figure 5 and the data contained in Tables 4 and 5 were input for the calculation performed. The finite element analysis performed is represented graphically in Figure 6 (mesh adopted, and stress in hex and tab regions), Figure 7 (stress in transition from the slender cylinder to the thread, and displacement in hex and tab regions). The edge sizes of the largest and the smallest of the tetrahedral finite elements employed are 7.5 and 2.5 mm, respectively (using the curvature-based mesh).

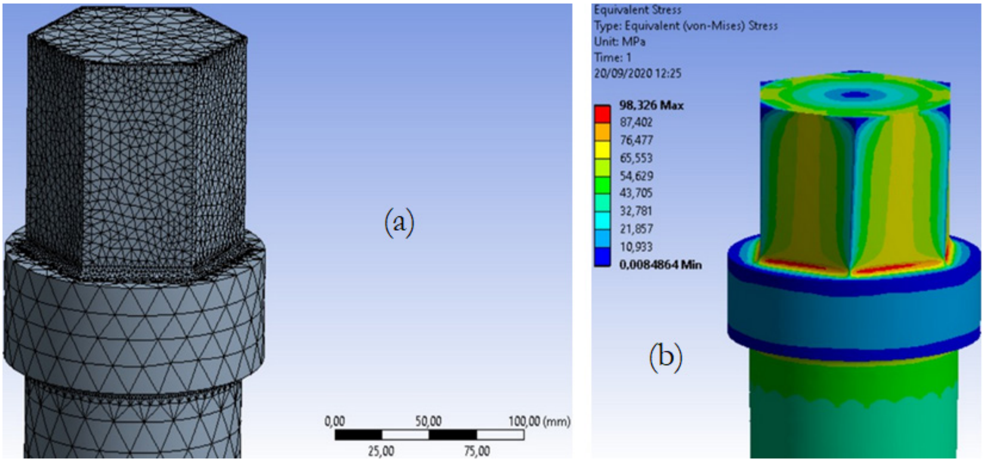

FIGURE 6. (a) Mesh in hex and tab regions of the locking rod; (b) Stress in hex and tab regions of the locking rod.

Source: own authorship (2020).

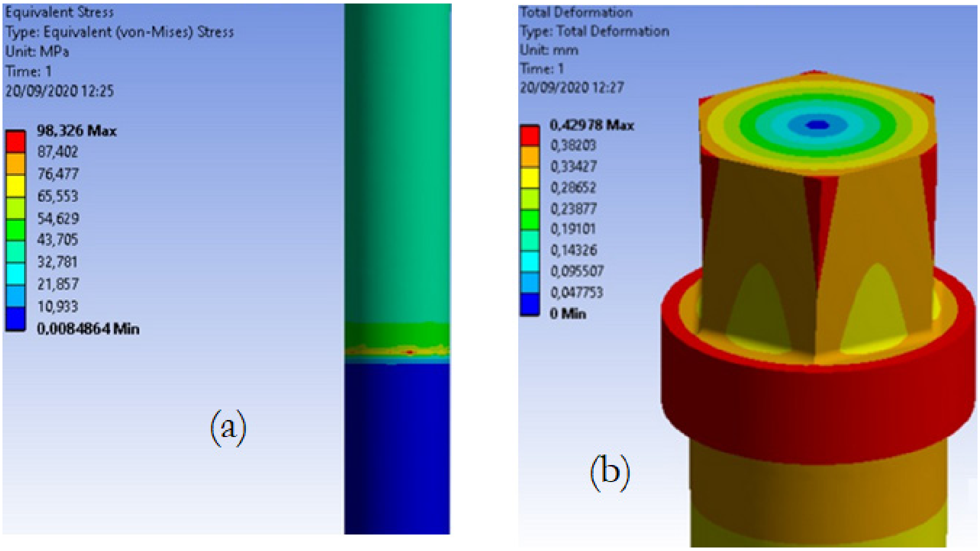

FIGURE 7. (a) Stress in transition between the slender cylinder and the thread of the locking rod; (b) Displacement in hex and tab regions of the locking rod.

Source: own authorship (2020).

For simplification purposes and highlighting the focus on the output DFMEA, the analytical calculation is summarized by the safety factors of each region of the locking rod. The proposed initial design could not support the bending moment M_x from the pipeline weight acting over the rod. Therefore, a new design had to be proposed, eliminating the bending moment by the addition of a support plate behind the rod. Besides the desired effect, a friction coefficient equal to 0.12, as indicated by Stachowiak and Batchelor (2013) between the rod and the plate surfaces now exist, generating a resistant torque and an axial force not present in the old design. The safety factors for the old and new designs are presented in Table 6. It can be noted that the situation in which combined stresses (compression, torsion, and bending) in the slender cylinder result in a safety factor of 0.637 in the old design, which is obviously not acceptable. Adding the referred plate to the design, a new safety factor of 5.711 results, besides also changing the safety factors corresponding to the other regions analyzed. The possible effects related to the failure modes identified in Table 6 are listed in Table 7.

Region of the locking rod	**Type of stress or phenomenon**	**Code of failure mode**	**Old safety factor**	**New safety factor**
Hex	Compression and torsion	1	15.963	8.535
	Contact	2	14.846	8.022
Tab	Compression and torsion	3	43.825	23.327
	Contact	4	408.004	41.414
Slender cylinder	Compression, torsion, and bending	5	0.637	8.257
	Buckling	6	2209.124	224.232
Thread	Compression and torsion	7	12.626	6.725
	Contact	8	309.713b	31.437

TABLE 6. Safety factors for the old and new designs.

Source: own authorship (2020).

It is important to note that, although the safety factors corresponding to the new design are relatively high, one of the most important premises of oil and gas industry (besides efficiency and safety) is the maintenance frequency. In other words, during the expected operational life, it is not desired to retrieve the equipment from its operation, for example, to perform maintenance, no matter how small or simple it may be. Other reasons undergo the uncertainties related to every information related to the design (estimations, assumptions, considerations, etc.).

Effect	**Code of effect**
Instability condition	1
Inutilization (substitution is required)	2
Significant geometry change	3
Warpage	4
Plastification	5
Ovalization	6

Flattening	7
Buckling	8
Functionality loss (repair is possible)	9
Additional difficulty to function	10

TABLE 7. Effects related to the failure modes and their codes.

Source: own authorship (2020).

The DFMEA was performed based on the new design assumed (presented in Table 8). As can be noted, in terms of failure and effects, the critical region is the thread. This is mainly explained by the fact that the stresses amplify their magnitudes in the transition from the slender cylinder to the thread, which is a common stress concentration region. Any damage to the thread may imply strong difficulty in locking system operation or even the loss of functionality. The second most critical region is the slender cylinder, according to the results of the DFMEA performed here (Table 8). The stress concentration phenomenon is present at both ends (interface with the thread and the tab). Because it is the most slender region, buckling was checked. In the third position, the hex region may be geometrically mangled, making hexagonal fitting difficult with the torque tool. Therefore, the efficiency and efficacy of the operation may not be achieved.

From this perspective, if the failure occurs, the region corresponding to the transition between the thread and the slender cylinder will be the most critical, producing the effect of making the locking mechanism inoperable. If the damage allows the pipeline to be locked in its working position, the open PLET may even operate as it is. Otherwise, extra time and money will be spent in the substitution of the mechanical lock assembly to recover the equipment functionalities.

Code of failure modes	Effects	Severity	Occurrence	Detection	RPN	Aggregated RPN
1	3, 4, 7, 10	5	4	3.75	75	105
2	5	2	4	3.75	30	
3	4, 5, 6, 7	1	2	2.5	5	10
4	5, 7, 10	1	2	2.5	5	
5	5, 7	8	4	5	160	250
6	1, 3, 4, 5, 6, 8, 10	9	2	5	90	
7	2, 3, 5, 9	9	6	6.25	338	412.5
8	5	6	2	6.25	75	

TABLE 8. DFMEA of the locking rod.

Source: own authorship (2020).

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ÍNDICE REMISSIVO

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