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USING METAMODELS TO PREDICT CUTTING FORCES IN BOP

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Abstract. Cutting drill string inside BOP (BlowOut Preventer) may be required if Dynamic Positioning System fails to maintain an offshore drilling platform at a fixed point in the ocean. The required force to cut the string is traditionally determined by analytical models and commissioning tests, which can be far from the real situations. Depending on boundary conditions of this tubular, the BOP may fail to cut it, which can lead to catastrophic events. In this way, the proposed work aims to define a metamodel to predict required forces for BOP to cut API S-135 6.63'' 40.87 ppf drill pipes, with different boundary conditions. Simulations were performed using FEM, with material and failure modelled according to Johnson-Cook model (1986), with parameters obtained from literature. Different simulations in combined conditions, including initial traction and torque, pipe decentralization and ram offsetting, were performed in order to find the required force in indentator to cut the pipe. Such data were used to develop a metamodel using feed a machine learning algorithm and its results were validated with real test data. Situations with more realistic boundary conditions concludes that current BOP cutting models may underestimate the required force.

Keywords: Offshore drilling, BlowOut Preventer, Finite Element Method,

1 Introduction

Real mechanical systems may be too complex or even unfeasible to model analytically due to the geometry, large number of variables and initial boundary conditions involved. Moreover, when the real system in strongly nonlinear, it is desirable to have a model that relates these variables to the system behavior. One possibility to reach this goal is to develop a metamodel that is based on the results of a sample of designed experiments in which the variables are the input. Metamodel is defined as the model of the model and it is used to simplify and reduce complexities of a real mechanical system. In a first approach, the real system is represented in a convergent numerical model and then controlled simulations are performed on this model to generate results which are analyzed.

In this paper it is studied the effect of external loading and positioning variables in the required force to cut a pipe inside the BOP (BlowOut Preventer). BOP is the name given to a large valve used in deep water drilling, which is installed in the wellhead. It is designed mainly to close, seal, control and monitor oil and gas on wells to prevent blowouts (uncontrolled release of crude oil and/or natural gas), in an operation named "well control". BOP was first designed by James Smither Abercrombie and Harry S. Cameron in 1922 and was brought to market in 1924 by Cameron Iron Works. It is made of stacked valves which can be divided in basically three different groups, according to their mechanism and function: annular, pipe rams and shear rams. Both annular and pipe rams are designed to close and seal the well when a pipe is through the BOP, without damaging it. On the other hand, in case of loss of dynamic positioning, the shear ram preventer is actuated and must be capable to close the well, cutting any drill string existing inside the BOP [3]. However, in a real situation, such string may be loaded and decentralized from the well bore, as well as BOP factors such as ram offsetting and wearing affect shearing capability. Once such variables are not accurately real-time measurable during BOP operations, a mathematical model to estimate the risk of performing a successfully cutting operation may be available.

The pioneer work about modeling the failure of the pipe in BOP is from Childs *et al* [5]. They proposed an analytical solution by supposing a pure and uniform shear state on the cross section of the pipe. In such model, the shear force is proportional to the steel degree (minimum yield stress) and the tubular cross sectional area. Once the pipe deforms and the stress state is not exactly a pure shear stress state, the authors proposed corrections based on empirical linear correlations to correct the shear force. This analytical model was adopted by most of BOP manufactures. However, such model could not account the contribution of external loading and geometrical variables (pipe centralizing and rams offsets) in the shear force. Even in controlled commissioning shear testing, they noticed a large dispersion in the values for the required forces to cut the tube. Such aspects were found to be critical after Macondo incident (2010) investigation. In such event, a drilling rig caused a blowout in Golf of Mexico leading to the death of 11 personal, 800 million of liters of oil spilled in the ocean and a loss estimated in US$82 billion. It is considered one of the greatest catastrophic events in the modern history. Despite operational failures, BOP failure in cutting the ongoing operation used pipe as one of the accident root causes.

In order to predict more realistic forces to cut the pipes in BOP, this problem has been analyzed trough FEM (Finite Element Method). On such technique, loading and geometric effects could be analyzed with flexibility and precision. The post processing tools available in most of the modern FEM softwares allows a detailed stress analysis and, consequently, more accurate understanding of the mechanisms. The first study using FEM was attributed to Telkin [13] who identified variables that could affect the ultimate force necessary to cut the pipe. Koutsolelos [10] contributed by performing a systematic study to find an optimized shear ram geometry based on Bai-Wierzbiski failure criterion. Tulimilli *et al* [14] found the effect of the centralization of pipe in the BOP bore as well as the increase in force to shear when the tubular is compressed. Han [7] explored the shearing problem using Johnson-Cook failure criterion and found good agreement with experimental results. Castilho [4] compared analytical and numerical solutions of shearing forces concluding that the first models fails in predict the pipe ductility, which determinates the shearing forces. Liu [11] repeated Koutsolelos work using a micromechanical modeling of the material failure. McCleney [14] concluded that water effects due to influx in a blowout situation are negligible in the forces to shear a pipe. However, until nowadays there is no systematic study to provide a model that can be used in operational situations to evaluate the necessary force to cut the tube in uncertain situations. BOP operator usually consider shear testing in accordance to API standards as a measure of BOP cutting capacity [1]. In the next sections, it will be proposed a method to evaluate it.

2 Materials and Methods

This work follows the procedure summarized in the following flowchart detailed in Figure 1. Basically, the work is divided into three steps: the material model definition and calibration, design of the problem geometry including the initial and boundary conditions limits definition and, finally, metamodel development. The pipe in study is a 6 5/8'' 40.87ppf landing string drill pipe (DP) made of API S-135 steel, probably the most used material in drilling strings manufacturing. Such pipe has a *D/t* ratio of 10.6 and can be considered thin walled, having homogenous stress along radial path of its cross-section wall. Pipe main dimensions are shown in Figure 2.

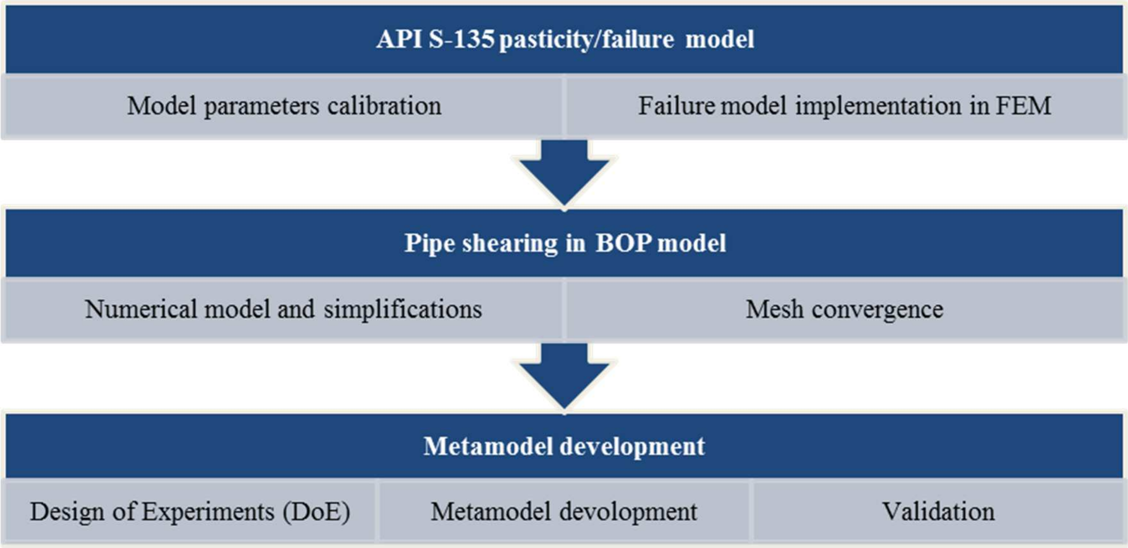

Figure 1 - Schematic flowchart of the metamodel development. Source: personal file.

Table 1 - 6 5/8'' 40.87ppf pipe geometric parameters. Source: personal file.

Parameter/ property	Symbol	Value	Unit
Tubular external diameter	***OD***	168.3	*mm*
Tubular wall thickness	***t***	15.88	*mm*
Tubular cross sectional area	***A***	8931.0	mm^2

Figure 2 shows the geometry details of the modelled BOP problem. The model has as an indenter (ram) with perpendicular contact with the pipe. The indenters are double "*V*" shaped and are dimensioned as proposed by Koutsolelos [10] and API standards [2]. In the transversal plane, there is an offset "*h*" between the upper and lower indenter and the pipe have its center with a predetermined distance "*d*" from the BOP center. The pipe have length 1750mm, is clamped in its lower edge and is only allowed to move in the longitudinal axis in the upper edge. External loads (normal traction, compression and torque) are applied on the upper edge of the pipe and independent variable pressures acts in external and internal faces of the pipe.

The rams are drived by a shaft (main rod), which in turn is drived by a hydraulic piston (main piston). In order to multiply force, some rams have a second pair of rod and piston (booster) which is connected to the main system as illustrated in Figure 3. The actuating pressure varies from 3,000psi up to 5,000psi. The ram system is also provided with a mechanical locking device in order to maintain the ram in a fixed position in case of lost of supply pressure on the pistons. The intenders are considered perfectly rigid and moves with constant velocity of 20mm/s.

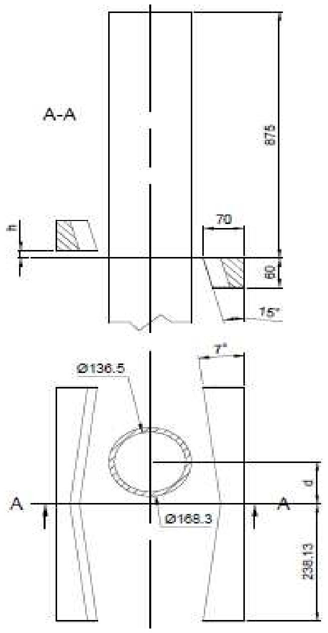

Figure 2 - Geometry of the studied problem. Source: personal file.

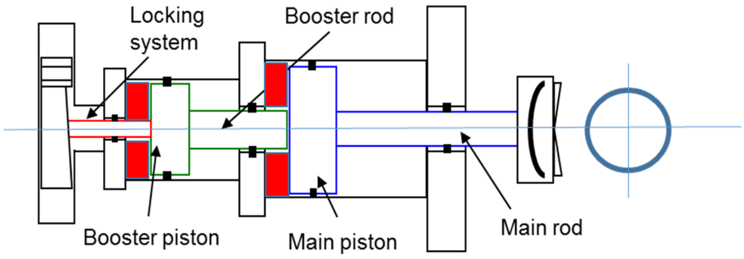

Figure 3 - Schematics of BOP ram hydraulic system with booster. Source: Petrobras.

Both material plasticity and failure are modeled by Johnson-Cook (J-C) formulation (Equations 1 and 2) calibrated with parameters found in literature [8][9].

$$\sigma_y = A + B(\bar{\varepsilon}^{pl})^n \tag{1}$$

$$\bar{\varepsilon}_D^{pl} = D_1 + D_2 e^{-D_3 \eta} \tag{2}$$

where, $\bar{\varepsilon}^{pl}$ is the equivalent plastic strain, $\bar{\varepsilon}_D^{pl}$ is the equivalent plastic strain at the onset of damage, η is the stress triaxiality defined as the ratio of the hydrostatic (average) stress and the equivalent stress, which can also be described in terms of characteristic equation stress invariants.

$$\eta = \frac{\sigma_h}{\sigma_{eq}} = \frac{1}{3\sqrt{3}}\frac{I_\sigma}{\sqrt{II_s}} \tag{3}$$

Once damage is initiated, it follows an evolution law, until it reaches a critical value (D_c), at which the element is removed from the mesh.

$$D = \sum \frac{\Delta\varepsilon^{pl}}{\varepsilon_f^{pl}} \tag{7}$$

In accordance to ABAQUS software, the plastic strain at failure (ε_f^{pl}) is calculated in terms of Hillerborg energy required to open a unit area of crack (G_f) and element is deleted from the mesh when its damage reaches a pre-defined value [6]. G_f can be obtained from the experimental load-displacement curves of the material according to,

$$G_f = \int_0^{\bar{u}_f^{pl}} \sigma_y d\bar{u}^{pl} = \int_{\bar{\varepsilon}_0^{pl}}^{\bar{\varepsilon}_f^{pl}} \sigma_y L d\bar{\varepsilon}^{pl} \tag{8}$$

where $\bar{u}^{pl}$ is the local plastic displacement, $\bar{\varepsilon}^{pl}$ is the local plastic strain and L is the characteristic length of element. It should be noted that J-C failure model, ductility is only dependent of stress triaxiality. Material data was extracted from Miscow [12] and the element removal from mesh is triggered after reaching D_c. The tubular material properties are resumed in Table 2.

Table 2 – API S-135 steel properties. Source: (Lukin, 2020).

Parameter/ property	**Symbol**	**Value**
Density	ρ	7.6 g/cm^3
Elastic Modulus	E	165 GPa
Poisson's ratio	ν	0.25
Yield Stress	A	890 MPa
Ultimate Stress	σ_u	1050 MPa
Nominal strain at NN failure (elongation)	ε_{cr}	0.12
Friction coefficient	f	0.3
Damage at failure	D_{cr}	0.048
Energy dissipation parameter	$\frac{G_f}{L}$	12.5 J/mm^3

J-C Plasticity model parameters	B	775 MPa
	n	0.43
J-C Failure model parameters	D_1	0
	D_2	0.08
	D_3	-3.4
Tubular traction to rupture	N_u	9236.3 *kN*
Tubular pressure capacity	$P_{i,u}$	204.9 *MPa*
Tubular colapse pressure	$P_{e,u}$	207.6 *MPa*
Tubular torque to rupture	T_u	3.60E+08 *N.mm*

In order to study the effect of each input variables X_k in the mechanical system response Y, upper and lower limits $X_{k_{max}}$ and $X_{k_{min}}$ were stablished based on operational values and numerical limitations which are shown in Table 3. It is supposed that the pipe force (F) is affected by normal loads (N), torques (T), internal (P_i) and external (P_e) pressures, as well as its centralization (d) and the offset of the indenters (h). Those variables are inputs for the simulations. Traction is limited by the maximum weigh the rig can support and by bucking on the tubular. Torque usually is limited by the connection on the drill string. Pressure should never exceed the well control equipment capability. Geometric factors such as indenter offset and pipe decentralization from well center are restricted by BOP dimensions. Those variable intervals were further discretized in equal parts and numerical experiments were drawn with no repetition of inputted values, in accordance with Latin hypercube sample optimization design, to form sets i of initial conditions to the numerical simulations in accordance with equation (9). An extra set of randomly sorted simulations were used to cross-validate and check the accuracy of the proposed metamodel.

$$X_{k,\mathrm{i},n} = X_{k_{min}} + \frac{r(n)}{2^n}\Delta X_k \tag{9}$$

Table 3 – Boundary and initial conditions limits. Source: personal file.

	N(Traction)	*T(Torque)*	P_i *(Int. pres.)*	P_e *(Ext. pres.)*	*h*	*d*
Max	800 kips (3.5 MN)	40 klbf.ft (54.2kNm)	9.5kpsi (65MPa)	9.5kpsi (65MPa)	2.0 mm	84.0 mm
Min	-10 kips (-0.05 MN)	0 klbf.ft (0 kNm)	0 psi (0kPa)	0 psi (0kPa)	0.1 mm	0.0 mm

The ultimate forces to cut the pipe are measured by the peak of resultant horizontal forces that acts in one of the indenters, prior to the rupture. After the simulations were performed, the resultant data was analyzed through linear regression. It is considered that each variable has linear influence on the ultimate force and superposition principle can be applied. Experimental data obtained from BOP commissioning tests were collected and used to validate the proposed model.

3 Results and Discussion

At a first step, results from field tests for BOP commissioning were collected for validation of the proposed metamodel (Figure 4). According to Petrobras records, there were done 8 cutting actions on 6 5/8'' 40.88ppf drill pipes following API procedure [1]. It is assumed an internal friction of 540kN on the BOP. One example of a cut pipe is shown in Figure 5.

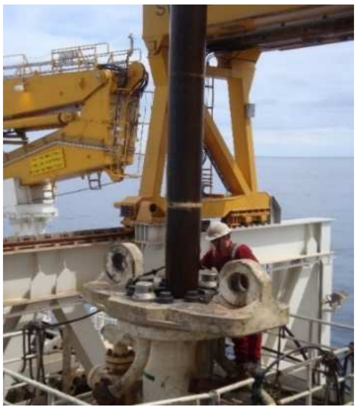

Figure 4 - Pipe cut in BOP commissioning test. Source: Petrobras.

Figure 5 - Drill pipe cut in BOP. Source: Petrobras.

In a second step, it was performed a mesh convergence by comparing the shearing force of experimental results with numerical models with different mesh. Due to computational cost the pipe is modeled constituted by 4-node shell elements with reduced integration (S4R) in ABAQUS general purpose finite element software (Figure 6). As the mesh was refined, it was observed convergence to experimental results. The model with 12.5mm element size mesh was chosen to be used in numerical simulations to build the metamodel.

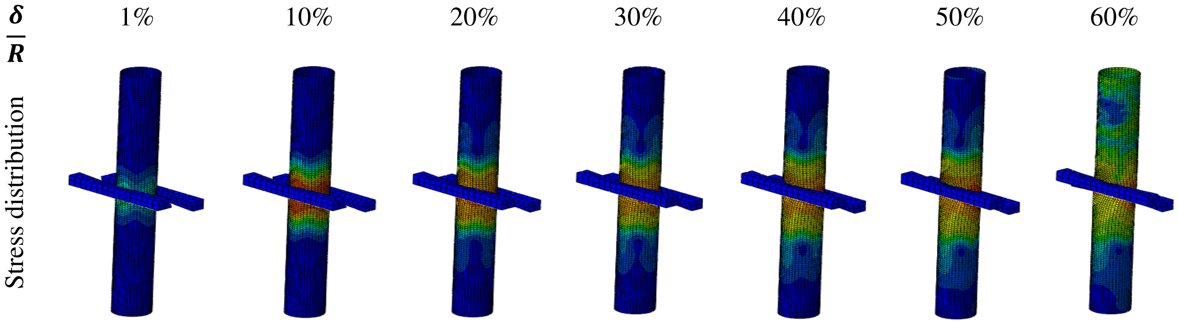

Figure 6 – Pipe cutting simulation in different ram displacements (δ). Source: personal file.

As soon as the model parameters were defined, a set of designed simulations according to (10) were performed. In order to avoid bad matricial conditioning, both input and output variables were pre-processed by normalizing it with the equivalent fracture parameters (Table 4), provided by the tubular manufacturer (Table 1 and Table 2). Results are analyzed by linear multivariable regression technique to find the metamodel parameters, which tends to converge as the number of performed simulations is increased (Figure 7). A set of 10 random simulation sample was used to test the model generalization. The converged metamodel parameters values are shown in Equation 10.

$$F^* = 0.392 + 0.039N^* + 0.083T^* + 0.684{P_i}^* - 0.649{P_e}^* - 0.101d^* + 0.007h^* \tag{10}$$

Table 4 - Normalized variables. Source: personal file.

Variable	Normalization
Required cutting force	$F^* = \frac{F}{N_u}$
Tubular tension	$N^* = \frac{N}{N_u}$
Tubular torque	$T^* = \frac{T}{T_u}$
Tubular internal pressure	$P_i^* = \frac{P_i}{P_{i,u}}$
Tubular external pressure	$P_e^* = \frac{P_e}{P_{e,u}}$
Indenter offset	$h^* = \frac{h}{h_{max}}$
Tubular centralization	$d^* = \frac{2d}{OD}$

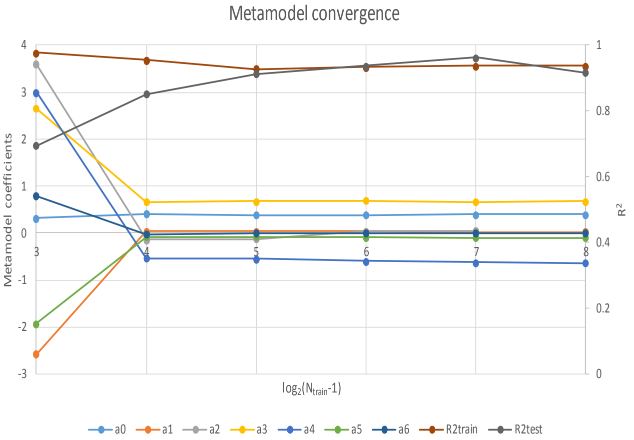

Figure 7 - Metamodel parameters values variation with number of performed simulations. Source: personal file.

A comparison of the obtained metamodel and data points is shown in Figure 8, Figure 9 and Figure 10. On those figures, it is represented the obtained plain metamodel surface and data points on the same graphic.

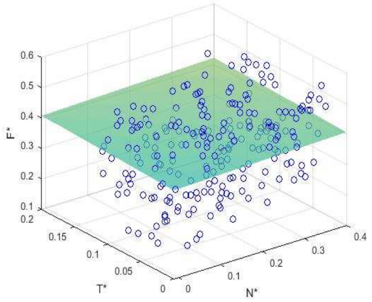

Figure 8 - Effect of N^* and T^* on F^*. Source: personal file.

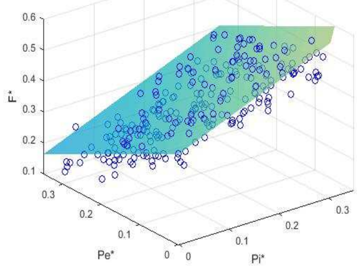

Figure 9 - Effect of $P_e{}^*$ and $P_i{}^*$ on F^*. Source: personal file.

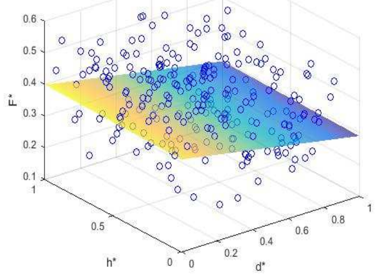

Figure 10 - Effect of d^* and h^* on F^*. Source: personal file.

It is observed that the boundary conditions exerts influence on the required force to cut the pipe when sufficient data is enough to remove noise effects. For the boundary conditions studied, the required force to shear tends to increase with tension, torque, internal pressure and ram offset. On the other side, it tends to decrease with external pressure and pipe offsetting. Considering the boundary conditions domain, the maximum required force to cut the BOP plus internal frictions are found to be 6.48MN. Independently of the ram mechanical resistance, such force could not be reached in some BOP rams systems due to limitations of actuating force.

4 Conclusions

The pipe cutting in BOP was successfully modeled using shell elements in FEM. Comparison with experimental results performed on BOP commissioning reveled that the required shearing force calculated by the model was about 91% of average experimental measurement discounted friction. It was also found similarities in the profile of the indenter force with its displacement during the cut process.

With the validated material and numerical model, the influence of external loading on the tube (internal and external pressure, traction and torque) as well as geometrical factors (pipe and ram offsetting) was studied trough a series of simulations based on Latin Hypercube designed experiments. Using linear regression, the tendencies of changes in the required shearing force due to those variables were captured for a sufficiently large data, since the obtained metamodel coefficients converged with increase of simulations. From a sample of at least 32 designed simulations, it is provided a good correlation with inputted data (R_{train}^2=93%) and was also found good generalization for random test sample (R_{test}^2=91%). It was observed that increase in external traction and torque tends to increase shearing force, which is interpreted as the structural geometric stiffness of bending promoted by those loadings. Increase in internal over external pressures also increase the required force to cut the pipe by aiding the tubular to maintain its original shape preventing its deformation. It was found that the increase in pipe misalignment relative to BOP center tends to help cutting process by concentrating forces. On the other hand, the increase in indenter offset creates bending effects that converts external work into strain energy demanding more required force to cut the pipe. The metamodel also aware that within certain boundary conditions, BOP rams will not be able to cut the required pipe.

Finally, it is important to highlight that such conclusions must be limited to the boundary condition ranges considered here. Variations found on experimental pipe cut forces are attributed to uncontrolled boundary conditions changes.

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References

[1] API (American Petroleum Institute). 2018. "*API Technical Report 16TR1: BOP Shear Ram Performance Test Protocol"*. Washington, DC : (API) American Petroleum Institute, 2018.

[2] —. 2000. *Spec 5DP: Specification for Drill Pipe.* Washington DC : API, 2000.

[3] Cai , B., Liun, Y., Liu, Z., Tian, X., Zhang, Y. Liu, J., 2012, *"Performance evaluation of subsea blowout preventer systems with common-cause failures"* J. Petroleum Science and Eng. 90–91 (2012) 18–25.

[4] Castilho, F. V. 2016. *Estudo do processo de corte de tubos em BOP submarino em poços de petróleo.* Rio de Janeiro : CEFET-RJ, 2016.

[5] Childs, G., Sattler, J., Williamson, R., 2004. *Shear Study for U.S. Minerals Management Service, Requisition No. 2-1011-1003.* s.l. : U.S. Minerals Management Service, 2004.

[6] Dassault Systèmes Simulia Corp, 2015 "*Abaqus Analysis User's Manual"*, Providence: Dassault Systèmes Simulia Corp, 2009.

[7] Han, C. 2015. *"Study of the damage and failure of the shear ram of the blowout preventer in the shearing process".* Engineering Failure Analysis. 2015, 58, pp. 83-95.

[8] Johnson, G. R., Cook, W. H. 1985. "*Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures",* Engineering Fracture Mechanics, pp. 31–48, 21, 1985

[9] Johnson, G.R., Cook, W.H. 1983, *"A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures",* Proceedings of the 7th International Symposium on Ballistics: 541–547, retrieved 2009-05-13

[10] Koutsolelos, E. 2012. "*Numerical analysis of a shear ram and experimental determination of fracture parameters"*. Thesis (Nav. E. and S.M.), Massachusetts Institute of Technology, Dept. of Mechanical Engineering, 2012.

[11] Liu, Z. G. 2017. *"Force Prediction in blowout preventer shearing of drill pipes"*. Engineering Failure Analysis. 2017, 74, pp. 159-171.

[12] Miscow, G. F., de Miranda P. E. V., Netto T. A., Plácido J. C. R., Sampaio Jr J. H. B., 2001. "*Real Scale Drill-pipe Steel Fatigue"*. Conference: Simpósio Materia 2001, *At Mexico*, DOI: 10.13140/2.1.2440.0160.

[13] Telkin, A. 2010. "*Blind shear ram blowout preventers: estimation of shear force and optimization of ram geometry"*. Thesis, The Ohio State University, Houston, 2010.

[14] Tulimilli B. R., Naik P., Chakraborty A., Sawant S., Whooley A., 2014, "*Design study of BOP shear rams based on validated simulation model and sensitivity studies*", Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering, (OMAE2014), June 8-13, 2014, San Francisco, California, USA.