

MECSOL 2019 – Prediction of Shear Ram BOP Cutting Force via Finite Element Analysis

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Abstract: The disaster concerning the "Deepwater Horizon" platform at the macondo Gulf of Mexico in 2010 raised the discussion on the efficiency of the safety of systems employed on offshore well, more specifically Shear Ram BOP (Blow Out Preventer) - SHEAR RAM BOP, or BOPs of shear Rams. The use of such equipment is the last resource, in cases of extreme risks, to maintain the environmental and material safety of a marine platform. When a "Blowout" or "well kick" happens – which is an abrupt gases and oil eruption, the BOP keeps the sealing and security of well exploration. The function of the SHEAR RAM BOP is to cut down the production or the drilling pipe, allowing a safety seal of the well, as the last resource in case of a risk situation. After the accident, it was estimated a high increase in insurance costs for equipment and facilities of offshore explorations, being 50% for Deepwater wells. These new rules affect directly the Brazilian Pre-Salt operations. Thus, this work aims to study the shear force estimation of an SHEAR RAM BOP using the Finite Element Method (FEM) with element-deletion approach, considering a material failure criterion.

Keywords: Blow Out Preventer, Finite Elements Analysis

INTRODUCTION

Shear Ram Blowout preventer (SHEAR RAM BOP) is an important part of the “BOP” assembly, presented on Fig. 1, composed by one annular BOP, and the others ram BOPs, including SHEAR RAM BOP. This safety set-up can reach several tons that must be installed above the wellhead in order to seal it in case of emergency and accidents.

The SHEAR RAM BOP can be described as a cast steel body with one vertical principal hole that allows the pipe to pass thru it in order to drilling, completion and production activities. And it has other concurrent holes where are installed linear actuators with shear rams.

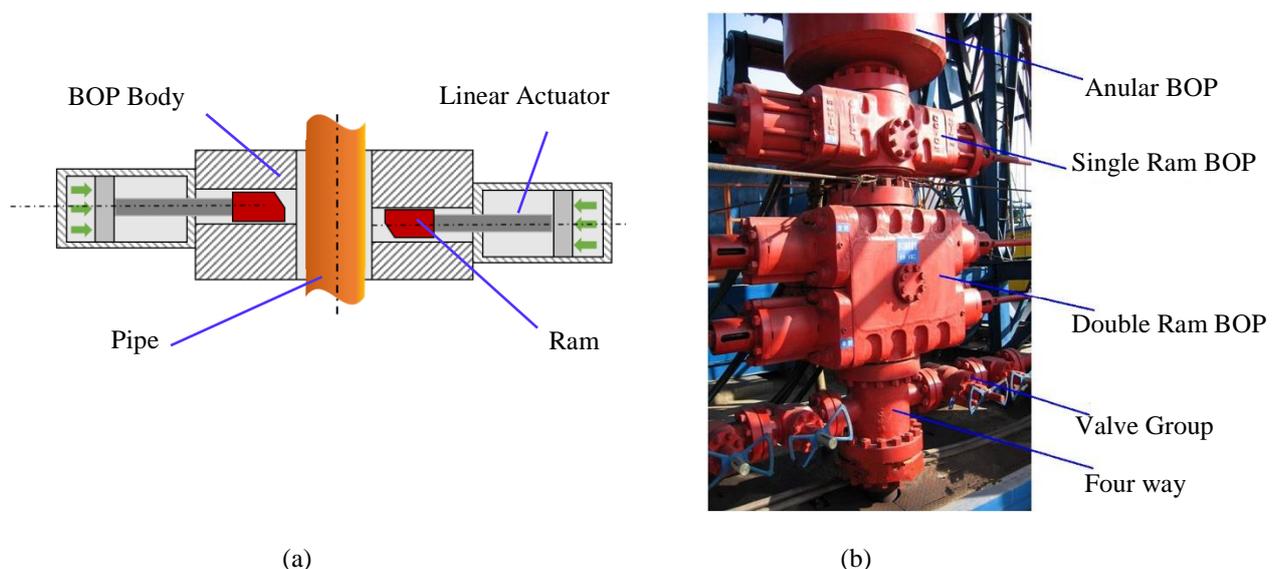


Figure 1. Shear Ram BOP (a) Shear Ram BOP scheme, (b) Bop tree, Han (2015)

This cutting process splits the pipe into two parts, as shown in Fig.2, releasing the superior pipe part, allowing another BOP types to seal wellhead. In addition, depending on ram type, SHEAR RAM BOP can crush the bottom pipe length, on the top end, sealing production pipe.

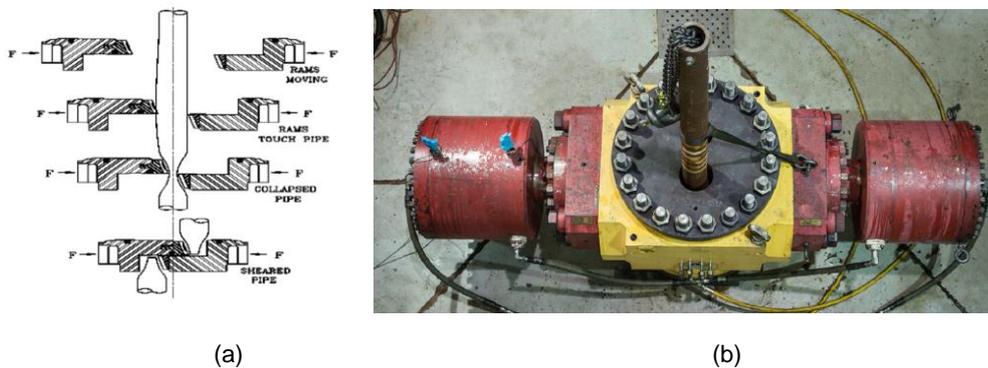


Figure 2. (a): Pipe cutting process Tekin *et al.* (2015); (b): Typical SHEAR RAM BOP, Cameron (2017)

The BOP is already critical equipment for safety, logistics, installation and operations as Read (2016). It became even more critical after the Gulf accident, Fig.3, with the Deepwater Horizon platform as related by Mackowsky *et al.* (2010). This accident made platforms insurance costs increase significantly, according to Niemeyer (2011), moving the pre-salt investments to a more difficult position as Petrobras (2015).

The SHEAR RAM BOPs reliability depends on its own cutting reliability as CSB (2014) and other important safety requirements for offshore industry. Moreover, shear rams and linear actuators play an important role in this operation because the linear actuator is responsible to apply shear force and rams responsible for cutting the pipe wall without damages, assuring pipe sealing.



Figure 3. Macondo Accident, Mackowsky *et al.* (2010).

International standards as API (2012 and 2017) controls SHEAR RAM BOPs installations, allowing different ram types. For instance, the Blind RAM type at Fig. 4, presents a blade flat face of contact with the tube, to cut and seal the well inferior pipe part. The Casing type, as Fig. 4, with blade geometry in "V" or "U" shapes, to cut everything that is passing through the BOP.

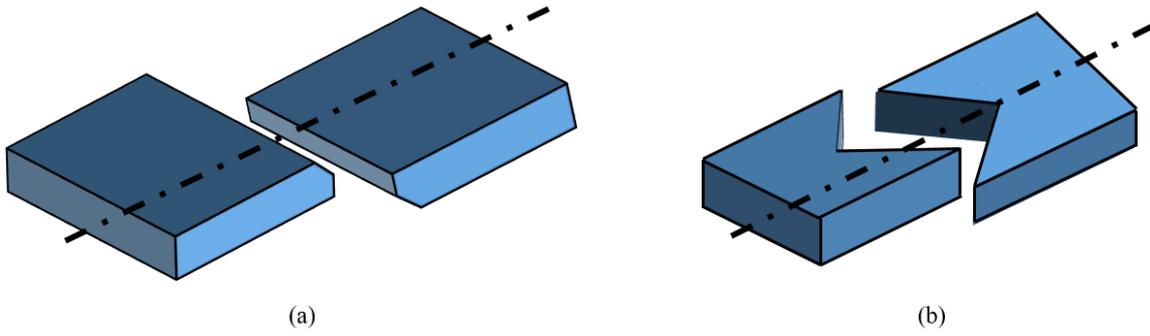


Figure 4. Ram types (a) “Blind”, (b) “Casing”;

In a real cutting process, it might have many loads as the fluid flow, the well axial load, the external pressure, plus fluids internal pressure, induced vibration and temperature gradient also. As boundary conditions, it might have pipe and rams misalignment, piping previous global buckling and any kind of friction. Moreover, pipe or drawers can have defects, as well as hydraulic systems may not work perfectly. Furthermore, this cutting process may occur over a pipe joining sleeve, Wierzbicki (2012). All of those different variables can affect the piping cutting process and should be studied in order to identify each one of their influences. But, as an initial work on Subsea Shear Ram BOP cutting process study, this paper aims to define a reliable FEM modeling methodology to analyze a simple and ideal case: pipe and rams are considered aligned, with no pressure, flows, or axial loads. This work also considers the cutting force as a quasi-static load, applied in 01s (one second), taking into account the pipe material hardening, as Johnson & Cook (1983). And, in order to verify the FEM modeling reliability, is planned to calculate the expected cutting force by the empirical equations, provided by BSEE (2004), manufacturer approaches, as Tulimilli *et al* (2014) and Forming empirical equation, as Schuler (1998) in order to compare to FEM prediction.

METODOLOGY

As aforementioned, this paper main aim at defining an initial reliable FEM model to estimate SHEAR RAM BOP cutting force and to use knowledge empirical approaches plus previous and reliable works as references in a comparison.

Previous Analytical Models

BSEE (2004) developed the statistical force prediction formula as Eq. (1) based on experiments records for S-135, G-105 and E-75 pipes grades, using material tensile properties, Maximum Distortion Energy Theory as Budynas (2011), in a linear regression analysis. This formula can be applied to general steel pipe, with some special changes, depending on the pipe material grade.

$$F = 4.448 * \{ [35.28 + 0.47 * 1.045(0.577 * S_u * A) + 6.629 * \epsilon_l] + 2 * 75.15 * 1.65 \} \quad (1)$$

Where S_u is the ultimate Tensile Strength, in KN . A is the pipe cross section in “ in^2 ” and ϵ_l is the material elongation at break.

Liu *et al.* (2017) developed SHEAR RAM BOP cutting force study based on the Distortion Energy Theory and a numerical model, using Extended Mohr Coulomb (EMC) fracture criterion to estimate cutting shear force for AL-2024-T351 pipe. Tulimilli *et al* (2014) performed a similar study, using pipe API 5D S-135 type, to compare numerical model results to Original Equipment Manufacturer (OME) equations which provide the pipe cutting pressure in ksi . One of OME equations is the “Pound per Feet” - PPF, Eq. (2) that takes into account the pipe linear weight, material properties and BOPs characteristics. In addition. The other OME equation, is the Dimensional Method, Eq. (3) which considers parameters from a laboratory test for various pipe grades and ram types.

$$F_{ppf} = \frac{[c_3 * ppf * S_y]}{c_1} \quad (2)$$

$$F_{DM} = \frac{[c_3 * S_y * (OD^2 - ID^2) * 2.92]}{c_1} \quad (3)$$

On both equations, C_3 is an empirical constant obtained from laboratory test to various pipe grades and ram types (for S-135 pipe C_3 is 0.23). The C_1 is another constant that corresponds to the piston closing area (in²), with 37, 228 and 615 as the minimum, average and maximum values respectively according to Rungrujirat (2013). And Schuler (1998), has another empirical equation, derived from the metal forming technology, to estimate needed the shear force in the guillotining process, Eq. (4).

$$F_{stat} = K_s * A \quad (4)$$

Where K_s is the material shear strength, (defined between 0.7 and 0.8 of S_u) and A is the pipe cross section area.

Previous Numerical Models

Green *et al.* (2017) presents a Finite Element Model (FEM) for SHEAR RAM BOP, by explicit transient solver, using 8-node linear brick element, with reduced integration and hourglass control, considering Johnson & Cook (1983) – JC strain hardening model and Johnson & Cook (1985) material failure model, with minimum time step: 1e-7s, friction factor: 0,5 and variable ram travel speeds. They compare their model to another proposed by MSCKenny (2013) which considers elastic plastic material response with progressive ductile and shear in the pipe wall. Both studies achieved the same level of force results for 3.5in, 13.3lb/ft S-135 API 5D (2001) pipe. Another work, from Liu *et al* (2017) considered void coalescence influence in an Extended Mohr Coulomb (EMC) failure criteria in Finite Element for shear fracture developed by Bai and Wierzbicki (2010) with element deletion model, resulting in some correlation to smaller void fracture simulation results and experiments, for TRIP690 steel and 2024-T351 Aluminum. Moreover, Koutsolelos (2012) uses Modified Mohr Coulomb Criteria, based on principal stress invariants combined to biaxial testing procedures for X70 Steel.

In addition, erosion element as per ANSYS® (2018) was adopted. It is a simple criterion in that, when element strain reaches material strain fracture it is deleted. Allowing new stiffness matrix creation and accounting the accumulated other elements plastic strain to be considered in the failure criteria for deletions, until the complete pipe cutting.

Adopted Failure Criteria

The failure criteria adopted in this work is the same criteria used by Green *et al.* (2017), the material model used is Johnson & Cook (1983) JC constitutive law, that represents satisfactorily a ductile material. In the JC material model, the plasticity model basis itself on the von Mises material yield equation, composed of five constants varying as strain and temperature function to calculate the equivalent plastic stress, according to Eq. (5). Where A is the Yield Stress, B represents strain hardening effects, C is the strain hat constant, m is the material thermal softening constant and n is the strain exponent. Additionally, $T^* = \frac{T-T_{room}}{T_{melt}-T_{room}}$, is the homologous with T as test temperature.. In addition, $\dot{\epsilon}^* = \frac{\dot{\epsilon}}{\dot{\epsilon}_0}$ is the equivalent plastic strain rate, where, ϵ is the current strain given by Eq. (8) and reference strain rate and $\dot{\epsilon}_0 = 1/s$.

$$\sigma = [A + B\epsilon^n][1 + C\ln\dot{\epsilon}^*][1 - T^{*m}] \quad (5)$$

The material failure criterion for fracture model adopted is Johnson & Cook (1985). In this case, the element damage is defined as Eq. (6), with $\Delta\epsilon$ as the equivalent plastic strain increment and ϵ_f is the fracture strain.

The general expression for fracture strain is given by Eq. (7), where σ_m is the average normal stress, $\bar{\sigma}$ is the equivalent von Mises stress and $\sigma^* = \sigma_m/\bar{\sigma}$ is the pressure stress ratio. The constants D_1 is the void nucleation strain, as in Hancock (1976), D_2 and D_3 are material constants, determined experimentally in order to guarantee the relation that strain to fracture decreases as equivalent hydrostatic stress σ_m increases, as in Johnson & Cook (1985). D_4 constant represents the strain rate effect and D_5 represents the temperature effect.

$$D = \sum \frac{\Delta\epsilon}{\epsilon_f} \quad (6)$$

$$\epsilon_f = [D_1 + D_2e^{D_3\sigma^*}][1 + D_4\ln\dot{\epsilon}^*][1 + D_5T^*] \quad (7)$$

Then, Eq. (8) can give the accumulated current strain as stated by Eqs. (8) - (9). .

$$\epsilon = \sum \dot{\epsilon} \Delta t \quad (8)$$

$$\dot{\epsilon} = \sqrt{\frac{2}{9} [(\dot{\epsilon}_1 - \dot{\epsilon}_2)^2 + (\dot{\epsilon}_2 - \dot{\epsilon}_3)^2 + (\dot{\epsilon}_3 - \dot{\epsilon}_1)^2]} \quad (9)$$

Where Δt is the time step increment and $\dot{\epsilon}$ is the strain rate in the time increment, $\dot{\epsilon}_1$, $\dot{\epsilon}_2$ and $\dot{\epsilon}_3$, are the principal strain rates. Then, when the element strain ϵ is equal to fracture strain ϵ_f , $D=1$, within consecutively elements must be deleted until pipe wall shearing.

Material Properties

Based on the argument that materials failure, ductile fracture occurs by shear and ductile damage, DNV(2011), the material used in this pipe model is AISI 4340 as Johnson & Cook (1983, 1985). The RAM material was ordinary structural steel with stress strength, deformations and JC hardening constants presented in Table 1.

Table 1. - Material Properties

Parameters		Constants	AISI4340
Yield Limit		A(MPa)	792
Hardening Modulus		B(MPa)	510
Hardening Exponent		n	0.18
Hardening Sensitizing		C	0.12
Damage Factors	Equiv. Stress	D ₁	0.05
		D ₂	3.44
		D ₃	-2.12
	Strain ratio	D ₄	0.002
Thermal Factor		D ₅	0.61
Reference Strain ratio		ϵ_0	1
Ultimate Stress		σ_u	1422
Ultimate Strain		ϵ_u	0.5

Numerical Model

A 3D CAD – Computer Aided Design – Model, as Fig. 5, is the Finite Element Model basis. It considers rams and pipe alignment to Cartesian axes, including small offset form pipe surface to ram edges, with model dimensions as Table 2.

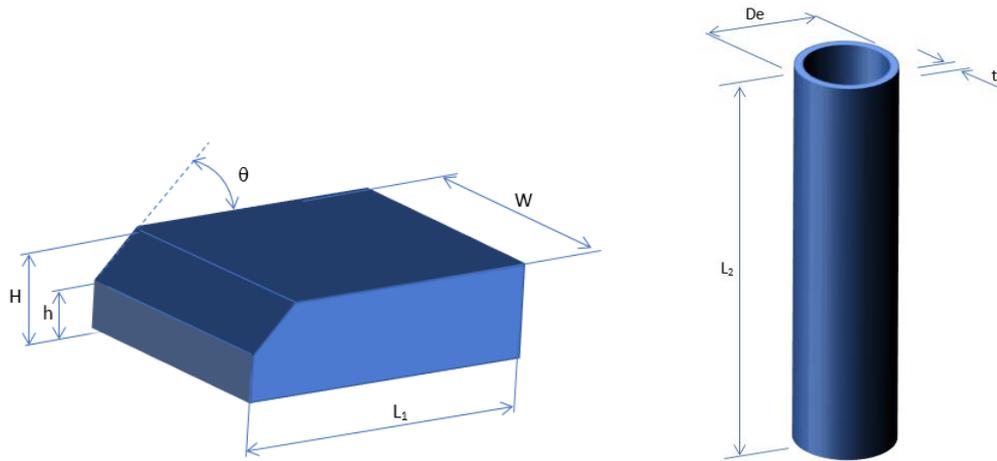


Figure 5. - CAD Models

Another important assumption is that RAMS submitted to no kind of plastic strain, which can change sharp edge and consequently the shear force during pipe cutting.

Table 1. CAD model dimensions (mm)

H	h	W	θ	L ₁	De	t	L ₂
50	10	200	30	200	114.3	5.21	866

The hexahedral linear element with reduced integration was adopted to obtain the finite element model, as Fig. 6, (mesh with more than 200,000 nodes). Including element erosion control based on element fracture strain as JC in Eq. (7), element geometric strain limit, ANSYS® (2018) and Hour Glass Damping control Flanagan Belytschko. Assuming quasi-static model, with 1s (one second) as total cutting time. Applying 70mm as rams displacements to cut the pipe.

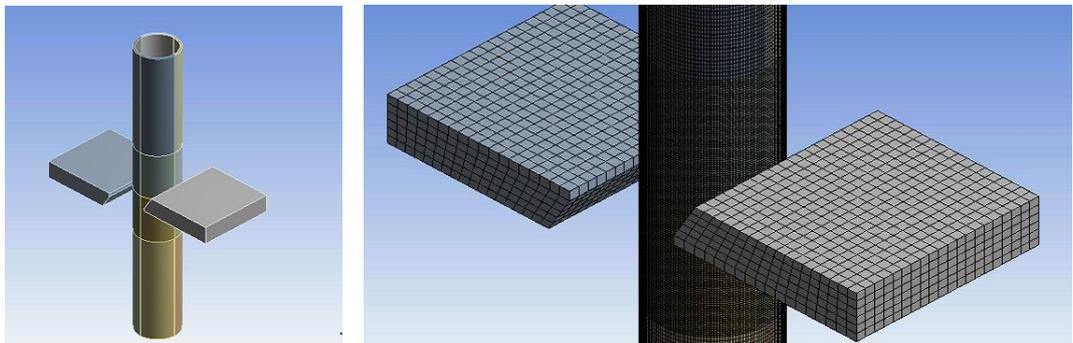


Figure 6. – Finite Element Model

RESULTS AND DISCUSSIONS

The finite element model results in Fig. 7, presents the pipe cross-section change according to rams displacements on time. It is possible to identify from this results, the phases crushing, denting and buckling beginning of the pipe, followed by cross-section forming, that is the shape changing from circular to oblong and as of the last phase, the wall shear. From this picture is possible to see that highest cutting force occur in shear wall phase giving 2.26MN as the max force at ~56mm (~0.8s) in ram displacement.

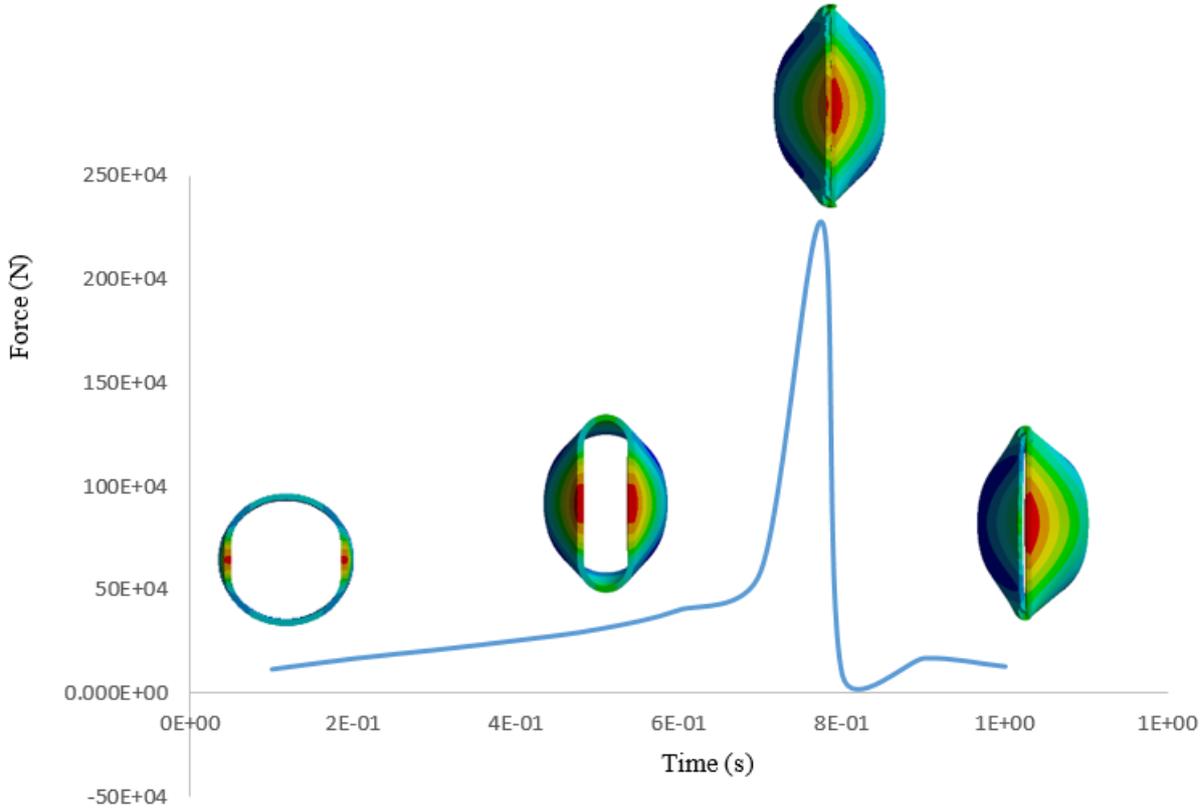


Figure 7. – Finite Element Model

Analyzing stress levels during the cutting process in Fig. 8, it is possible to note high stresses levels on oblong inner pipe corner surface, with peak stress value under K_S , Schuler (1998), 995MPa. When the analysis comes to plastic strains, Fig. 9, reveals maximum values at the same place with strain peaks under the ultimate strain limit.

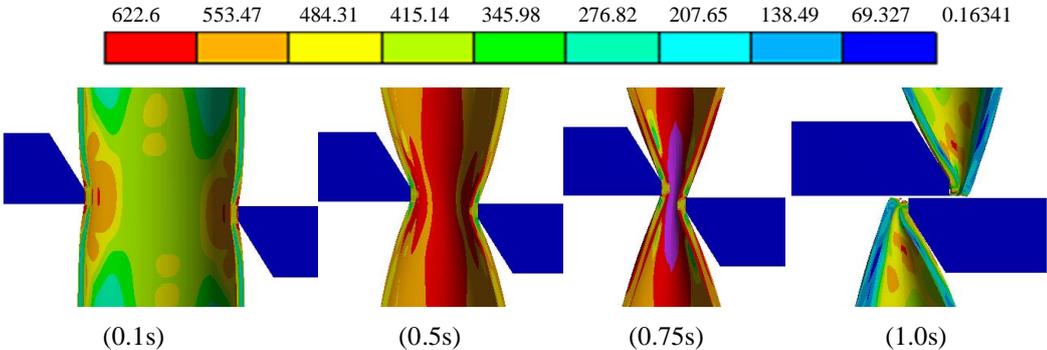


Figure 8. – Finite Element Model: Maximum Shear Stress (MPa)

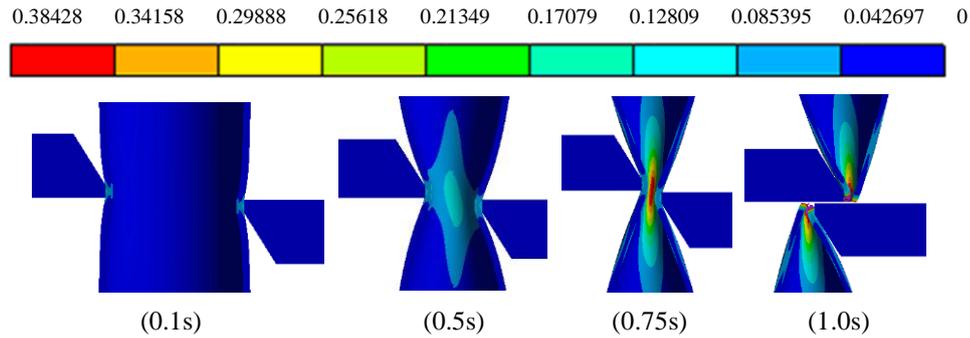


Figure 9. – Finite Element Model: Equivalent Plastic Strain (%)

Observing continuity stress levels, on the noticeable area with magenta color, on Fig. 8 and the plastic strain area, with cyan color at Fig. 9, it is possible to conclude that it is a reasonable result, considering that all this area is plastically deformed. However, FEM Max Shear Stress is considerably smaller than K_S . In addition, FEM Equivalent Plastic Strain maximum value is also smaller than ϵ_1 .

On analytical approach to estimate pipe cutting force, it was considered S_u as 205ksi, pipe linear weight as 12.25lb/ft, C1 as 37, C3 as 0.23, K_s as $0.8 \cdot S_u$ and Plunger diameter as 6". Then, it was possible to estimate Shear force by Eq. (1) to Eq. (4) as Table 3 below, where force values are smaller than FEM prediction.

Table 3. Analytical Shear Force Estimative

Estimate Formula Equation	Result (MN)	FEM comparison (%)
(1)	2.16	95.5
(2)	1.96	86.7
(3)	1.74	76.9
(4)	2.14	94.6

Observing all results, there are some important convergences, the statistic formula, Eq. (1), and forming formula, Eq. (4), results converge around 99%, OME formulas, Eq. (2) and Eq. (3), results converge around 88%. The average value among them is 2.052MN, representing 90% of FEM prediction, that is the highest value among all, as the same behavior as found by Liu et al. (2017).

CONCLUSIONS

Theoretical approaches, even empirical or numerical, give conservative load estimate. In this way, the adopted methodology, to do a FEM model, adopting a quasi-static load, Johnson Cook material behavior for ductile pipe material and cross-check force response with the Statistical approach, as BSEE (2014), or empirical, as Schuler (1998), can give a conservative way to predict pipe cutting force for flat ram blades. And this value reliability can be reinforced if those approaches give higher values than OME formulas, which can be applied also, but carefully, because it depends on linear actuator, pipe, rams and other important information, which is commonly available for explorers or manufacturers. For further works, there are many suggestions to be investigated as different ram shape, pipe sizes, materials models, boundary conditions and loads.

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REFERENCES

- ANSYS ©19, Manual 2018
- API SPEC 5D 5th Edition, October 2001
- API, 2012, Std 53: Blowout Prevention Equipment Systems for Drilling Wells, 4th edition, November 2012;
- API, 2017, Spec 16A: Specification for Drill-Through Equipment, 4th edition, April 2017;
- Bai Y., Wierzbicki T., Application of extended Mohr-Coulomb criterion to ductile fracture, *Int. J. Fract.* 161 (2010) 1–20.
- Bathe k. J., *Finite Element Procedures*, Second Edition, K. J. Bathe, Watertown Inc., fourth print 2016, USA
- Budynas R. G., Nisbett K. J. 2011 *Shigley's Mechanical Engineering Design*, Ninth Edition. MacGrawHill
- BSEE – Bureau of Safety and Environmental Enforcement, Shear Ram capabilities study for U.S. Minerals management Service, requisition No. 3-402-1001, September 2004 – WEST Engineering Services. Disponível em: <<https://www.bsee.gov/sites/bsee.gov/files/tap-technical-assessment-program//463aa.pdf>> Acesso em 28 de November de 2017
- Cameron, Schlumberger 2017 Product catalog, Drilling Rams. Disponível em: <https://www.products.slb.com/-/media/cam/resources/2017/09/19/18/48/drilling-rams-brochure.ashx>, Acesso em 11 de Novembro de 2018;
- CSB, U.S. 2014, Chemical Safety Board, Investigation Report volume 2 – “Explosion and fire at the Macondo well - U.S. Chemical Safety and Hazard Investigation Board, Report no. 2010-10-I-OS 6/5/2014”, Disponível em: <http://www.csb.gov/assets/1/7/Vol_2_Final_Version.pdf> Acesso em: 27 de Novembro de 2017;
- DNV, Det Norske Veritas.(2011) "Forensic examination of deepwater horizon blowout preventer. Volume I Final Report" Washington DC: US DOI, Bureau of Ocean Energy Management, Regulation, and Enforcement. EP030842.
- Green S. T., Mueschke N., McCleney A., Chocron S., 2017, “Subsea bop stack shear/seal capability modeling tool, Final Report”, Southwest Research Institute , Prepared for: Department of Interior, Bureau of Safety and Environmental Enforcement (BSEE), Acquisition Operations Branch, 45600 Woodland Road, Mailstop VAE-AMD, Sterling, Virginia 20166, USA. Disponível em: < <https://www.bsee.gov/research-record/tap-764-subsea-bop-stack-shearseal-capability-modeling-tool>>. Acesso em 08 de Marco de 2018.
- Han C. , Yang X., Zhang J., Huang X., 2015, “Study of the damage and failure of the shear ram of the blowout preventer in the shearing process”, *Engineering Failure Analysis* 58 (2015) 83–95, ScienceDirect, 2015
- Hancock J. W., and Mackenzie A. C., “On the mechanism of ductile failure in high-strength steels subjected to multi-axial stress-states”. *J. Mech. Phys. Sol.* 147-175 (1976).
- Johnson, G.R. and Cook, W.H. ,1983 A Constitutive Model and Data for Metals Subjected to Large Strains, High Strain Rates, and High Temperatures. *Proceedings 7th International Symposium on Ballistics*, The Hague, 19-21 April 1983, 541-547.
- Johnson G. R., Cook W. H., 1985, “Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures” *Engineering Fracture Mechanics* Vol. 21, No. I, pp. 3148. 1985, U.S.A. 0013-7944/85;
- Koutsolelos E., Wierzbicki T. Numerical analysis of a shear ram and experimental determination of fracture parameters, Massachusetts Institute of Technology. Dept. of Mechanical Engineering. 2012.
- Liu Z.G., Guo J. Y., Guo T.F., Cole T., Sridhara N., Force prediction in blow-out preventer shearing of drill pipes, *Engineering Failure Analysis* Volume 74, April 2017, Pages 159-171
- Mackowsky, R. M., Kende, C. B., Benett, R. C. & Ziemianski, J. A., 2010. *The Deepwater Horizon Catastrophe: A Factual Overview and Preliminary First-Party Analysis*, U.S.A.: Cozen O'Conor.
- MCS Kenny, 2013 Assesment of BOP Stack;, Sequencing monitoring and kick detection technology; Final Report 01 – BOP Stack, Sequencing and shear ram design, Report Number 12-1841-DG-RPT-0001; Report for BSEE – Bureau of Safety and Enviromental Enforcement.
- Niemeyer P., São Paulo, Janeiro de 2011. “O Estádio – Os riscos do Pré-Sal”. Disponível em: <<http://economia.estadao.com.br/noticias/geral,os-riscos-do-pre-sal-imp-,670213>> Acesso em: 27 de Novembro de 2017.
- Petrobras, 2015, Rio de Janeiro, 2015 – “Fatos e dados, 06 de Janeiro de 2015”. Disponível em: <<http://www.petrobras.com.br/fatos-e-dados/esclarecimento-viabilidade-de-producao-no-pre-sal.htm>>. Acesso em: 28 de Novembro de 2017.

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Read J., Shilling R., Frontier Deepwater Solutions LLC, Legacy BOP technology could be approaching design limitations. 2016 Disponível em: <<http://www.offshore-mag.com/articles/print/volume-76/issue-2/drilling-and-completion/legacy-bop-technology-could-be-approaching-design-limitations.html>> Acesso em: 27 de Novembro de 2017.

Rungrujirat N., Nergaard A., Syse H., Master's Thesis, Basic Design of Subsea BOP Stack with RCD for Riser less Drilling, Master's Programme in Offshore Technology Stavanger University June 17th, 2013

Tulimilli B. R., Naik P., Chakraborty A., Sawant S., Whooley A., Weiss R., Experimental And Numerical Investigation Of Bop Shear Ram Performance Proceedings of the ASME 2014 33rd International Conference on Ocean, Offshore and Arctic Engineering OMAE2014 June 8-13, 2014, San Francisco, California, USA

Schuler, Metal Forming Handbook“, Springer-Verlag Berlin Heidelberg 1998

Wierzbicki T., Hardt D. E., Koutsolelos E. , 2012, “Numerical analysis of a shear ram and Experimental determination of fracture parameters”, Master Thesis Massachusetts Institute of Technology, June, 2012;

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