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FINITE ELEMENT MODELING OF THE CUTTING PROCESS OF DRILLPIPES USING A BLOWOUT PREVENTER

Fábio Vinicius Castilho
Pedro Manuel Calas Lopes Pacheco
Paulo Pedro Kenedi
PPEMM – Graduate Program in Mechanical Engineering and Technology of Materials
CEFET/RJ – Centro Federal de Educação Tecnológica Celso Suckow da Fonseca
20.271.110 - Rio de Janeiro - RJ – Brazil
fvcastilho@yahoo.com.br, calas@cefet-rj.br, paulo.kenedi@cefet-rj.br

Abstract. *The exploitation of oil and gas in deepwater has introduced several operational difficulties and the necessity for the development of new technologies. The drilling of oil wells should avoid accidents with damage to persons, environment and materials. In this context, various equipment in drilling of wells are essential to maintain the safety of the operation. The Blowout Preventer (BOP) is a device that has the function of closing the well in an emergency to prevent the fluid leakage from the well to the environment. An important component of the BOP is the blind-shear ram whose function is to cut the pipe and provide sealing. In an emergency, BOP is the last safety barrier and the shear ram is essential to allow the closure of the well safely. The cutting process is composed by a pipe crushing stage followed by a blanking process stage. Although some simple analytic models based on metal cutting and blanking are used to estimate the main parameters of the process as the cutting force, more complete analysis using numerical models must be used to obtain a more complete understanding of the whole process and to estimate the main parameters with greater accuracy. In this work a tridimensional elastoplastic finite element model with contact and large displacements is used to access the stress distribution and the load-displacement behavior developed during the cutting process. An erosion parameter is used to model the separation process of the drillpipe during the cutting stage. Numerical results show a good agreement with experimental data indicating that the numerical model captures the main characteristics of the process.*

Keywords: *Blowout Preventer, Drillpipes, Finite Element Method, Numerical Simulation, Modeling*

1. INTRODUCTION

The increasing exploitation of oil and gas in the Brazilian deep-water scenario introduced higher operational and technological difficulties, and the drilling of oil wells should be done in the best possible way to avoid accidents with damage to people, environment and materials. The success of well control, depends on a fast response for influx detection and a system capable to deliver the application of corrective efficient measures. After the detection a device called Blowout Preventer (BOP) installed on the wellhead on the seabed is activated to close the well.

The BOP consists basically of a series of hydraulic valves divided into two major structures: BOP Stack, composed of ram valves, and Lower Marine Riser Package (LMRP), that contains valves responsible for sealing the annular space between the pipe and the body of the BOP. One of the valves on the BOP Stack is the blind-shear or shear ram. Generally, this ram is on top of the BOP stack and is intended to cut the tubular in case of a need for emergency disconnection, providing the possibility of closing the well safely. According to the studies made by West Engineering Services request from US Minerals Management Service (Childs *et al.*, 2004), 30 % of the tests performed in real situations with shear ram achieve success. Two of the three main BOP manufacturers estimate the force required to cut drill pipes using a basic equation based on distortion energy theory. The new requirements found in the exploration of oil in ever deeper waters, increases the need for a reliable estimation of the required cutting force, as this parameter is essential for the correct operation of the system.

In this work a tridimensional elastoplastic finite element model with large displacements is used to access the stress distribution and the load-displacement behavior developed during the cutting process. An erosion parameter is used to model the separation process of the drill pipe during the cutting stage. The finite element method can be used to provide a more accurate estimate of the cutting force and the displacement shear rams, improving both safety and reliability.

2. BLOWOUT PREVENTER (BOP)

The traditional process of drilling an oil well involves the use of a drill rig. In rotary drilling, the rock is drilled by rotating and weight imposed on the bit at the end of the drill string. The drill string consists mainly of commands, heavy weights and drill pipes. The fragmented rock is continuously drawn through the drilling fluid that is injected by the pumps inside the drill string and back to the surface by the annular space between the well and the column.

One of the main functions of drilling fluid is exert a hydrostatic pressure larger than the pressure of the fluid contained in the pores of rocks drilled. If for any reason the pressure of the drilling fluid becomes lower than the fluid pressure in the rock pores, there could be a flow of the pores of rocks into the well. This flow is called kick. A blowout, as Fig. 1, is defined as an uncontrolled gas flow from the reservoir to the well and from the well into the atmosphere or the seafloor. A kick must be identified quickly and kept under control.

The equipment that allows you to close the well safely is called Blowout Preventer (BOP). In a simplistic way, the BOP can be defined as a set of valves. The subsea BOP can be divided into two distinct parts: Lower BOP Stack (LBS) and the Low Marine Riser Package (LMRP). Figure 2 shows a schematic representation of a BOP and the BOP Stack elements directly associated to the pipe cutting operation: pipe rams, shear rams and blindshear rams.

Figure 1. Macondo blowout in the Gulf of Mexico.(USCSH, 2014)

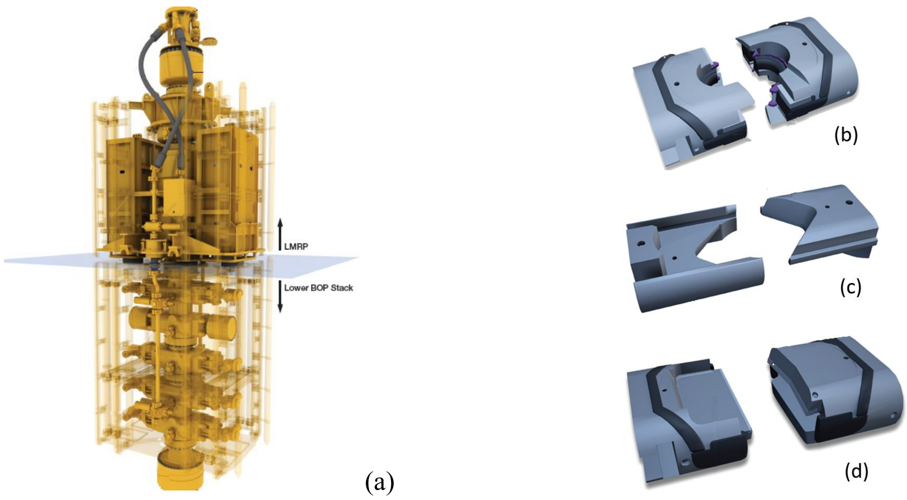


Figure 2. (a) Blowout Preventer (BOP) (Rungrujirat, 2013). Lower BOP stack elements: (b) Pipe ram, (c) Shear ram, (d) Blind shear ram. (Transocean, 2011)

The cutting process of the drill pipe, shown in Fig. 3, actually involves two phases: (1) pipe crushing process and (2) pipe cutting process. Figure 4 shows two pipes after the BOP cutting process.

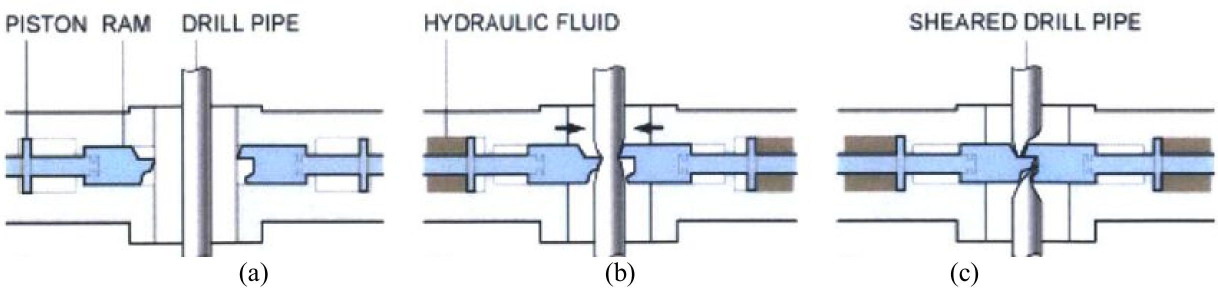


Figure 3. Blind shear ram shearing process: (a) Shear rams open, (b) shear rams closing, and (c) shear rams closed and sealed the wellbore.

Figure 4. Two pipes after the BOP cutting process (Childs *et al.*, 2004).

3. ANALYTICAL MODELS

BOP cutting process involves a stage of pipe crushing followed by a stage of pipe cutting. Simple analytical models can be used to assess the cutting force developed during the operation.

DeRuntz and Hodge (1963) analyzed the force-displacement relationship for the crushing of a tube carried by two rigid plates by a perfectly-plastic rigid model. The failure mode consists of four plastic hinges, as shown in Fig. 5.

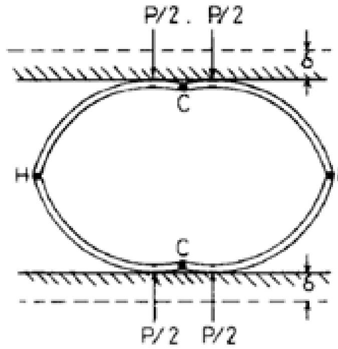


Figure 5. Crushing model (DeRuntz and Hodge, 1963)

Such hinges are considered stationary in relation to other parts of the tube, the separation occurring between the tube and the rigid plate in the center of the contact zone. The crushing load, *P*, is evaluated as:

$$P = \frac{4\frac{\sigma_0 t^2}{4}}{R(1-\left(\frac{\delta}{R}\right)^2)^{1/2}} \tag{1}$$

where σ_o is the material yield stress limit, *t* is thickness, *R* is the pipe radius and δ is the vertical plate displacement.

Cutting process is a mechanical forming process widely used in mechanical engineering for the production of equipment and structures. During this process the material is subjected to loading conditions that promote a quite complex state of stresses and strains, with the presence of geometrical nonlinearities (large displacements) and material nonlinearities (as plastic deformation). Several authors have developed models to estimate parameters for several cutting processes (Ghosh *et al.*, 1985; Farzin *et al.*, 2006; Hambli, 2001; Yu *et al.*, 2007; Atkins, 1980, 1990).

Atkins (1980) proposed a pure shear model. Disregarding the friction in the process, the required cutting force, *F*, can be evaluated as:

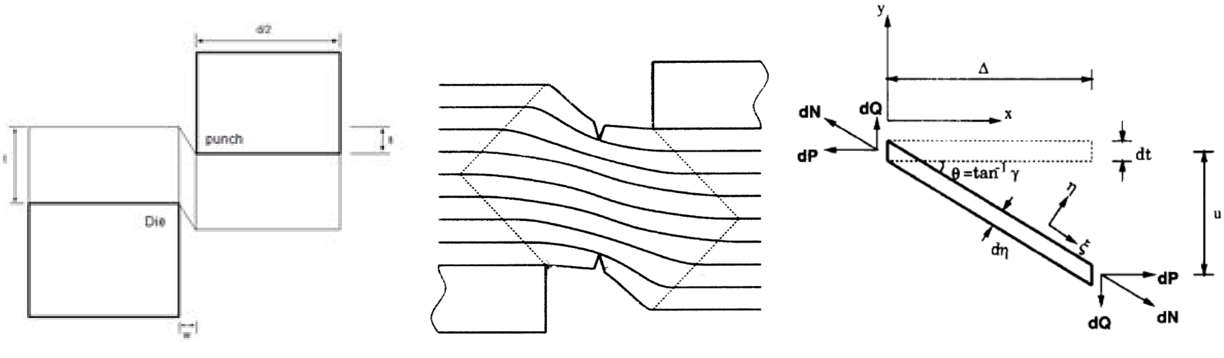
$$F = \pi.d.[t-\delta]\tau_0 \left(\frac{\delta}{w}\right)^n] \tag{2}$$

where, *n* is the strain hardening exponent, τ_0 is the shear strength coefficient, *w* is the deformation zone width, *d* is the punch diameter, δ is the punch penetration and *t* is the plate thickness. Figure 6a shows parameters used for Atkins

(1980) model. Zhou and Wierzbicki (1996) proposed a model in which during the cutting the fibers are elongated in accordance with the geometry shown at Fig. 6b. They adopted a simplified representation of the region in which plastic deformation occurs, considering it as a parallelogram. Considering a representative element thickness *dt* undergoes a pair of shear forces *dQ*, where the thickness of the sheared area is constant and equal to Δ, as shown at Fig. 6b. Considering a material power law stress-strain constitutive model, large deformation and a *von Mises* equivalent stress and strain criterion, the shear force *Q* can be obtained as:

$$Q = \left(\frac{2}{\sqrt{3}}\right)^{n+1} \frac{Ku}{\left(\frac{2(u_f-u_i)}{\gamma_f t_0}\right)} \int \int_{\gamma_0}^{\gamma_f} \left(ln\sqrt{1+\gamma^2}\right)^n \frac{1}{\gamma(1+\gamma^2)} d\gamma \tag{3}$$

where, *K* and *n* are parameters of the constitutive material model, γ is the shear strain, γ_0, γ_f and γ_c are, respectively, the current shear strain of the center layer, the fracture shear strain of material and the critical shear strain. u_f and u_i are, respectively, the final and initial penetration, and t_o is the initial thickness.



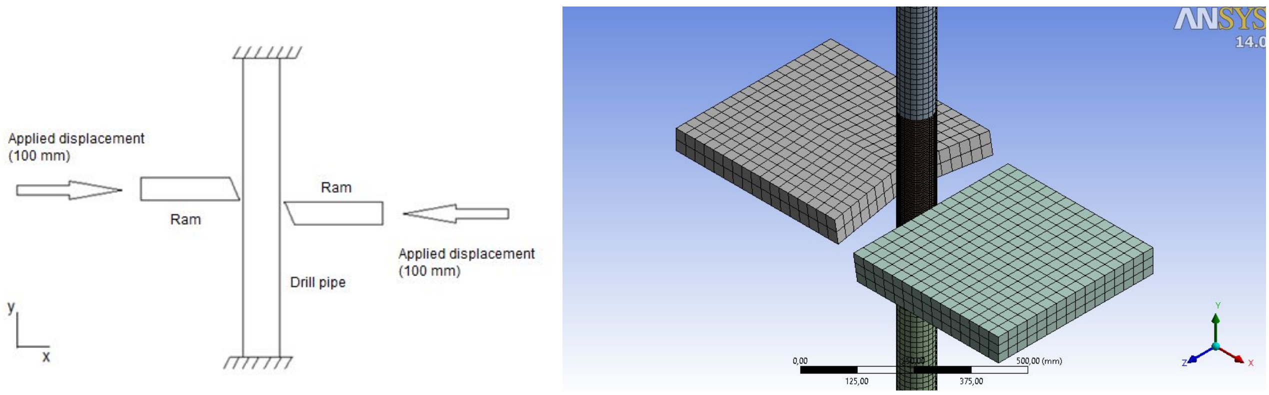
(a) (b)

Figure 6. (a) Atkins (1980) pure shear model and (b) Zhou and Wierzbicki (1996) tension model parameters.

4. NUMERICAL MODEL

A tridimensional elastoplastic finite element model with contact and large displacements is used to access the stress distribution and the load-displacement behavior developed during the cutting process. A commercial finite element code ANSYS (Ansys, 2015) considering explicit dynamics analysis is employed for spatial discretization. Explicit dynamics integration methods are an efficient approach to solve highly nonlinear problems involving large displacement, large plastic strains and material failure.

Figure 7a shows the geometric model with the boundary conditions and the prescribed displacement loading. The model considers a 2 m length pipe clamped at both ends. Figure 7b shows the finite element mesh obtained after a convergence analysis based on the maximum load.



(a) (b)

Figure 7. (a) Drill pipe cut process model and (b) Finite element model mesh.

The numerical model considers that the tube to be cut is fixed in the *x*, *y* and *z* directions at both ends. A prescribed displacement of 100 mm is applied at both rams in the *x* direction, with null displacements in *y* and *z* directions. Rams are considerable stiffer than the pipe and are modeled as rigid elements. According to Lee (2014) a uniform mesh size is desirable for improved accuracy in simulations using the dynamic explicit method. For these reasons a mesh was chosen with solid 3- D hexahedral elements with 8-nodes, that according Hallquist (2006) is suitable to simulate metal forming processes. For purpose of computational time reduction, the pipe was divided into three zones. In zones 1 and 3 were used a mesh with 30 mm element size (represented in Fig. 7b in light green) and in zone 2, the region where the cut was made is a refinement in the mesh with 3 mm section (represented in Fig. 7b in dark green).

The rupture of the material is modeled through the adoption of an erosion criterion approach where the material rupture occurs after a certain threshold limit is reached. This limit may be based on the strain or on stress (Luccioni and Araoz, 2011). Erosion criterion based on strain is useful for metals but not adequate to model frictional materials response characterized by a great difference between tension and compression behavior like concrete, that is more adequate to use erosion criterion based on stress. In this work the adopted erosion criterion is based on a strain limit defined by:

$$\varepsilon_{\text{eff}} = \frac{2}{3}\sqrt{|(\varepsilon_{11}^2 + \varepsilon_{22}^2 + \varepsilon_{33}^2) - (\varepsilon_{11}\varepsilon_{22} + \varepsilon_{22}\varepsilon_{33} + \varepsilon_{33}\varepsilon_{11}) + 3(\varepsilon_{12}^2 + \varepsilon_{23}^2 + \varepsilon_{31}^2)|} \tag{4}$$

where, ε_{eff} is the effective strain and ε_{ij} (i =1,2,3; j =1,2,3) are the strain tensor components. The erosion control is a failure criterion that is implemented in finite element codes as a numeric mechanism of removal elements during simulation, allowing the solution to remain stable until its end. This method has been used successfully by other authors (Luccioni and Araoz, 2011; Abdel-Kader and Fouda, 2014). It is important to understand that erosion is not a physical concept but a numeric criterion to solve real problems and should always be used with caution. This criterion can be used in several problems involving fracture, cutting and penetration and is considering in ANSYS (2015) by adopting an empirical parameter called erosion control factor. In this work the default value of 1.5 for erosion control factor is adopted.

5. RESULTS

In this paper the developed analytical and numerical models are applied to the study of two drill pipes configurations. Geometric (*OD*: outer diameter; *t*: thickness) and material properties are shown in Table 1. The BOD process is model using analytical models to assess crushing behavior and shear loads. Two stages are considered: a crushing stage followed by a cutting stage. The crushing behavior is obtained using the DeRuntz and Hodge (1963) model, whereas the shear load is obtained considering the pure shear model (Atkins, 1980) and tension model (Zhou and Wierzbicki, 1996). The numerical model considers a tridimensional elastoplastic finite element model with contact and large displacements. Values obtained from the presented models are compared with experimental data obtained by Childs *et al*. (2004), presented in Table 1. Analytical models parameters are shown in Table 2.

Table 1 – Drill Pipe Geometric and Material Properties.

Pipe	*OD* (in)	*t* (in)	*OD*/*t*	Yield Stress (MPa)	Ultimate Tensile Strength (MPa)	Experimental Cutting Force (kN)
01	3.5	0.368	9.5	605	735	1260
02	5	0.5	10	832	934	1377

Table 2 – Parameters for analytical models.

Pipe	n	K (MPa)	e_f	u_i (mm)	u_f (mm)	w (mm)	τ_0 (MPa)	t (mm)
01	0.17	1800	7	0	13	0.9	800	18.7
02	0.15	2150	8	0	16	2	969	25.4

Figure 8 shows the load-displacement curves for Pipe 01 obtained from crushing analytical model based on DeRuntz and Hodge (1963), pure shear (Atkins, 1990) and tension (Zhou and Wierzbicki, 1996) cutting analytical models and the proposed finite element model. Pipe crushing analytical model curve shows a crushing end displacement of near 35 mm. Pure shear model and tension models presents maximum load values of 2154 kN and 1459 kN, respectively. Finite element model results show that a maximum force of 1810 kN develops at the upper shear ram, while the experimental test obtained by Childs *et al*. (2004) presents a value of 1260 kN, representing a percentage difference of 43%. Cutting models presents maximum load values that represent a difference to experimental results of 71% (pure shear model) and 16% (tension model). Figure 8 shows that the analytic model, composed by the crushing and cutting stages, is capable to represent adequately the main aspects observed during the process.

Figure 9a shows the total deformation distribution observed at the final cutting stage obtained from the finite element model, with upper and lower shear rams. In Fig. 9b the rams were removed for better viewing of the cut drill pipes rupture region. For this pipe characteristics, the cutting final stage occurs when the pipe is almost crushed, associated to a configuration similar to Fig 4-left.

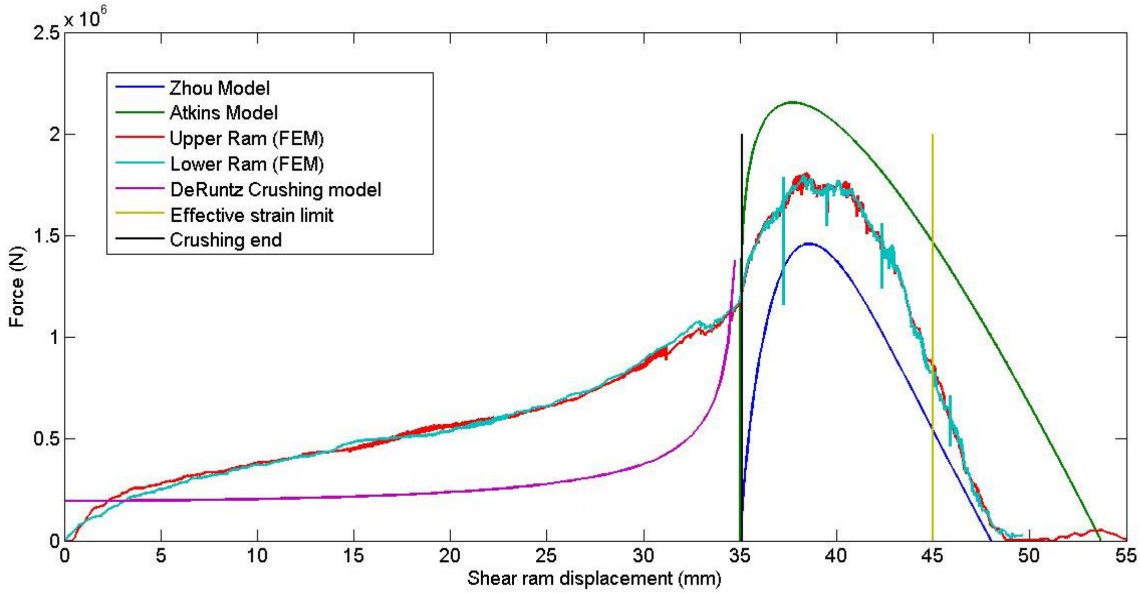
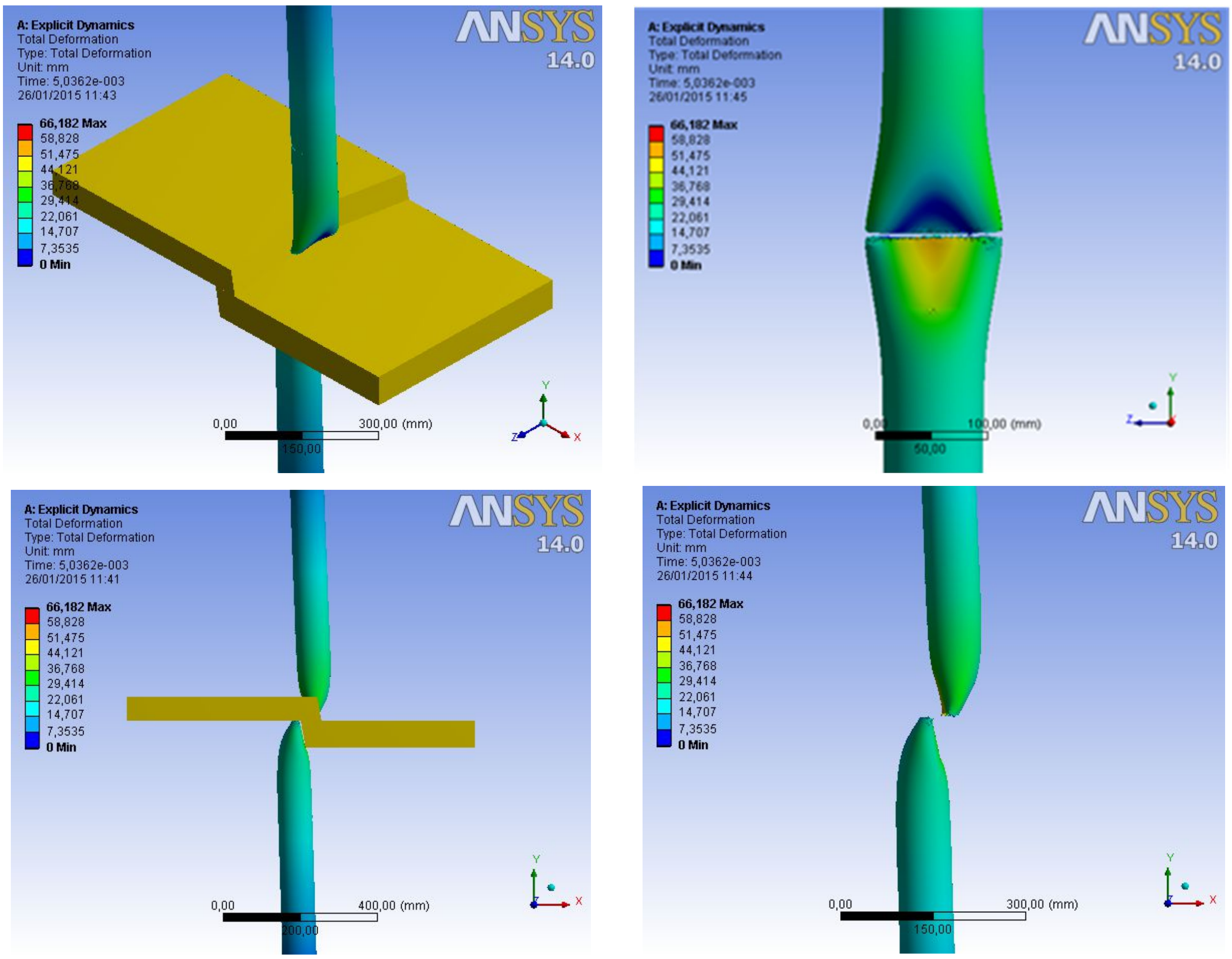


Figure 8. Load displacement curves for Pipe 01 obtained from pure shear (Atkins, 1990) and tension (Zhou and Wierzbicki, 1996) cutting analytical models, crushing analytical model (DeRuntz and Hodge, 1963) and the proposed finite element model.



(a) (b)

Figure 9. Finite Element Model total deformation distribution observed at the final cutting stage: (a) with shear rams and (b) without shear rams.

Figure 10 shows the load-displacement curves for Pipe 02 obtained from crushing analytical model based on DeRuntz and Hodge (1963), pure shear (Atkins, 1990) and tension (Zhou and Wierzbicki, 1996) cutting analytical models and the proposed finite element model. Pipe crushing analytical model curve shows a crushing end displacement of near 50 mm. Pure shear model and tension models presents maximum load values of 4605 kN and 3522 kN, respectively. Finite element model results show that a maximum force of 1660 kN develops at the upper shear ram, while the experimental test obtained by Childs *et al*. (2004) presents a value of 1377 kN, representing a percentage difference of 21%. %. Cutting models presents maximum load values that represent a difference to experimental results of 239% (pure shear model) and 160% (tension model). Figure 10 shows a large horizontal load-displacement offset between analytic and numerical predicted curves and also a large maximum load difference. This behavior is not observed for Pipe 01 that presents a good agreement between analytic e numeric models. For Pipe 02, the cutting final stage occurs before the pipe is totally crushed, a situation similar to the configuration presented in Fig 4-rigth.

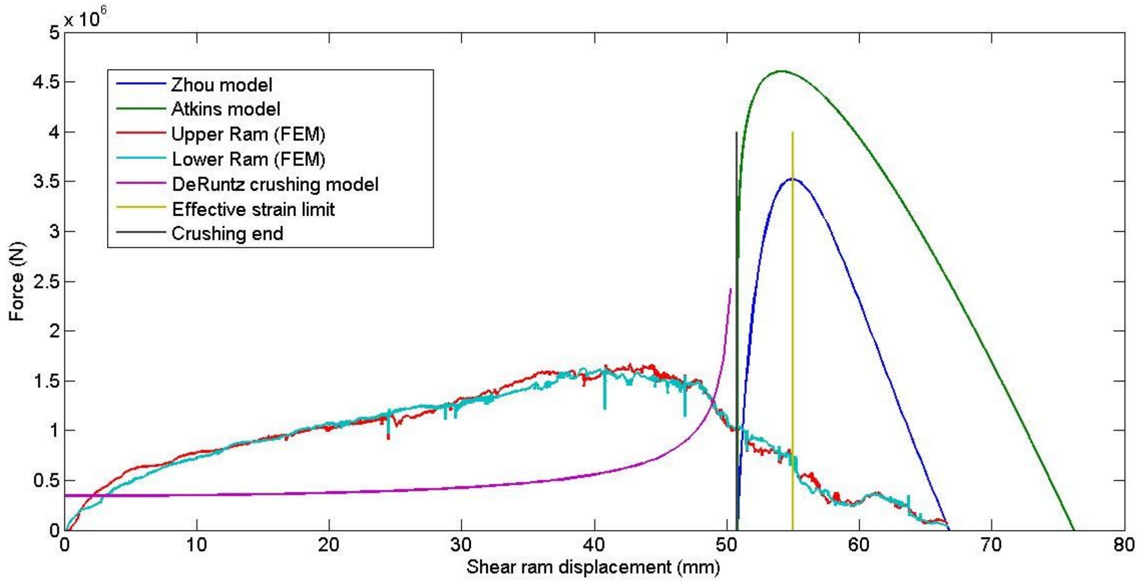


Figure 10. Load displacement curves for Pipe 02 obtained from pure shear (Atkins, 1990) and tension (Zhou and Wierzbicki, 1996) cutting analytical models, crushing analytical model (DeRuntz and Hodge, 1963) and the proposed finite element model.

Table 3 presents a comparison between the obtained analytical and numerical results with the experimental data. Analytical models can furnish simple assessments. However, as the BOP process is very complex involving nonlinear effects as contact, large displacements, large plastic strains and material separation, which reiterates the importance of numerical modeling to solve such complex problems. Results indicate that for the two cases studied, the proposed numerical model furnish a good agreement with experimental results for the required BOP load. Whereas the proposed finite element model presents a maximum difference from experimental results of 43 %, analytical models present a maximum difference of 239%. However, an experimental program must be developed before the proposed finite element model can be used as an effective design methodology.

Table 3. Comparison of Analytical, Numerical and Experimental Results.

Pipe	Experimental (Childs *et al*., 2004) (kN)	Pure Shear Analytical Model (Atkins, 1980)		Tension Analytical Model (Zhou and Wierzbicki, 1996)		Numerical Model	
		Value (kN)	Δ(%)	Value (kN)	Δ(%)	Value (kN)	Δ(%)
01	1260	2154	71	1459	16	1810	43
02	1377	4605	239	3522	160	1660	21

6. CONCLUSIONS

Deep-water oil and gas exploitation scenario introduces new and more severe operational and technological difficulties for the equipment. The Blowout Preventer (BOP) is a safety equipment whose adequate operation is essential to avoid accidents with damage to people, environment and materials. Therefore, the development of new and more precise design tools can contribute to rise the confidence levels of these equipment.

In this work a tridimensional elastoplastic finite element model with contact, large displacements and large strains is used to access the stress distribution, the load-displacement behavior developed during the cutting process and the maximum ram force developed. An erosion parameter is used to model the separation process of the drill pipe during the cutting stage. Numerical results are compared with simple analytical models and experimental data. Numerical results show a good agreement with experimental data indicating that the numerical model captures the main characteristics of the process. Results indicate that the proposed model can be used to assess important parameters of the BOP, as the cutting force and the shear rams displacements. However, an experimental program must be developed before the proposed finite element model can be used as an effective design methodology.

7. ACKNOWLEDGEMENTS

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9. RESPONSIBILITY NOTICE