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MODELING OF PIPE COLD BENDING: A FINITE ELEMENT APPROACH

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Abstract*. Cold bending of pipes is an important operation regularly used for in situ pipeline route adjustments during on-shore pipeline construction. The operation consists of curving permanently a straight pipe by cold bending using a rotary type of field pipe-bending machine. During the process problems as excessive ovalization and the development of local ripples must be avoided. In this work a nonlinear finite element model is developed to study pipe cold bending. The model considers plastic behavior, large displacements and large rotations. Numerical simulations for high-strength steel pipes with high diameter to thickness ratio are developed to estimate the conditions for the development of excessive ovalization and ripples.*

Keywords: *Finite Element Method, Cold Bending, Pipes, Modeling, Numerical Simulation*

1. INTRODUCTION

Nowadays fuel transportation can be done through several ways: by trucks, trains, ships and pipelines. The last one offers several advantages, especially when large quantities of fuel must be delivery to long distances. Pipes are regularly manufactured with 12 m length and a pipeline construction involves the welding of pipes *in situ*. In several situations the terrain offers geographic occurrences, as large rocks and differences of altitude. The use of curved pipes is the solution regularly used to implement pipeline path adjustment. To accelerate the pipeline installation process usually pipes are curved *in situ* with the utilization of a rotary type of field pipe-bending machine.

Pipe cold bending is a complex operation that can present some problems as excessive ovalization and the development of local ripples. Several authors have developed experimental and modeling studies of pipe cold bending (PRCI, 1996; Damslet *et al.*, 1999; Fukuda *et al.*, 2003; Sen *et al.*, 2006; Riagusoff, 2008).

This work utilizes a simple numerical model based on the Finite Element Method to study cold bending of pipes and assess important information that can affect pipe structural integrity as residual stresses and ovalization. The finite element model considers plastic behavior, large displacements and large rotations. Also a simple analytic model is presented to introduce the variables that are important in cold bending and estimate them. Numerical and analytic results are compared.

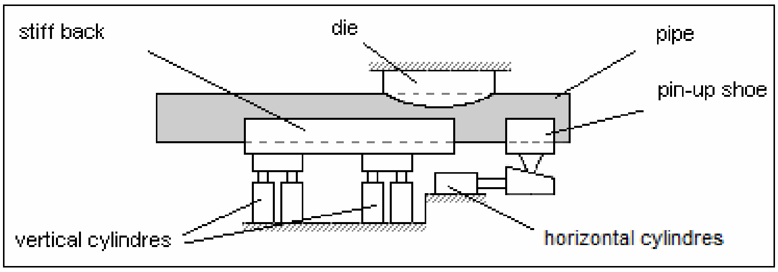
2. COLD BENDING PROCESS

Figure 1*a* shows a rotary type of field pipe-bending machine whereas Figure 1*b* shows a schematic representation of the main components. This type of machine uses pressurized hydraulic cylinders to apply the loads necessary to promote the cold bending of pipes in the field. To fix the pipe in the machine, the pin-up shoe and the stiff back, actuated by horizontals and vertical cylinders respectively, pushes the pipe against the die. Before the pipe cold bending operation take place a mandrel is positioned and expanded inside the pipe. Vertical cylinders are then actuated to promote the pipe bending at a determined pipe cross section. The operation is repeated at various cross sections until the pipe reach the required curvature.

3. ANALYTIC MODEL

A simple analytic model is used to estimate the main variables of the cold bending process. The following hypotheses are adopted: small displacements and rotations, elastic-perfectly plastic material, annular pipe cross section and a pure bending loading. This model does not consider complex phenomena as wrinkle formation or ovalization.

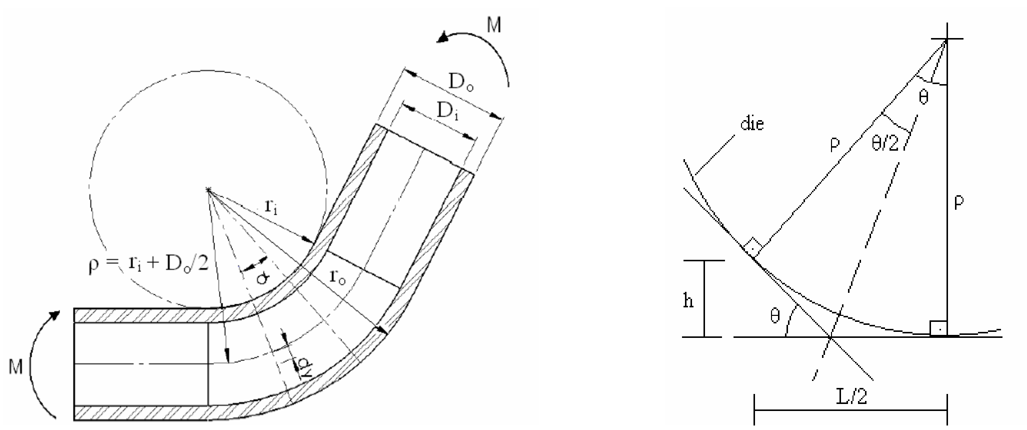
(*a*)



(*b*)

Figure 1. (*a*) Rotary type of field pipe-bending machine (CRC, 2009) and (*b*) a schematic representation of the main components (mandrel is not represented).

Figure 2*a* shows a schematic drawing of a pipe submitted to a bending moment, *M*, applied at both ends (the bending angle is exaggerated for clarity). Figure 2*b* shows the main variables used to estimate strains with the analytic model.



(*a*) (*b*)

Figure 2. Analytic Model - Cold bending process parameters: (*a*) loading and (*b*) geometry.

A linear axial strain ε distribution is observed through the pipe cross section:

$$\varepsilon = -\frac{y}{\rho} \qquad \text{and} \qquad \rho = \frac{L/2}{\left(1+\cos(\theta)\right)\tan\left(\frac{\theta}{2}\right)} \tag{1}$$

where, y is a distance from the neutral axis to the chosen point (in figure 2*a* y at intrados is negative), ρ is the radius of curvature, L is the pipe length submitted to moment M and θ is the pipe angle at curved cross section.

Equilibrium requirements states that during the loading stage:

$$\int \sigma dA = 0 \qquad \text{and} \qquad -\int y\sigma dA = M \tag{2}$$

$$M = 2\left[-\int_0^{y_y} y\left(\frac{y}{y_y}\sigma_y\right)dA_1 - \int_{y_y}^{r_i} y\sigma_y dA_1 - \int_{r_i}^{r_o} y\sigma_y dA_2\right] \tag{3}$$

$$dA_1 = \left(\sqrt{r_o^2 - y^2} - \sqrt{r_i^2 - y^2}\right)dy\,, \qquad dA_2 = \sqrt{r_o^2 - y^2}\,dy \quad \text{and} \quad y_y = \frac{\sigma_y}{E}\rho \tag{4}$$

where A_1 is a annular area, A_2 is a solid area, dA is a differential area, r_i and r_o are, respectively, the internal and external radius and y_y is the distance from neutral axis to the interface between elastic and plastic regions. Substituting (4) in (3), the applied moment M can be estimated by:

$$M = 4\sigma_y\left\{\frac{1}{\left(\frac{\sigma_y}{E}\rho\right)}\int_0^{\left(\frac{\sigma_y}{E}\rho\right)} y^2\left(\sqrt{r_o^2 - y^2} - \sqrt{r_i^2 - y^2}\right)dy + \int_{\left(\frac{\sigma_y}{E}\rho\right)}^{r_i} y\left(\sqrt{r_o^2 - y^2} - \sqrt{r_i^2 - y^2}\right)dy + \int_{r_i}^{r_o} y\sqrt{r_o^2 - y^2}\,dy\right\} \tag{5}$$

Note that in (5) there are three integrals to deal with two different areas dA_1 and dA_2 and to stresses σ at the elastic core and at plastic region (gray colored at Fig. 3). The residual stress σ_{res} and strain ε_{res} can be estimated, respectively, by:

$$\sigma_{res} = -\sigma_y + \sigma_m \text{ (for intrados)} \qquad \text{and} \qquad \sigma_m = \frac{M\,y}{I} \tag{6}$$

$$\varepsilon_{res} = -\varepsilon + \Delta\varepsilon \text{ (for intrados)} \qquad \text{and} \qquad \Delta\varepsilon = \frac{\sigma_m}{\left(\frac{\sigma_y}{\varepsilon_y}\right)} \tag{7}$$

where, σ_m is the restoring stress, I is the area moment of inertia, σ_y and ε_y are respectively the yield stress and yield strain. E is the Young modulus.

Figure 3 shows a partially yielded cross section (xy plane), showing the main variables and a representation of material behavior during loading and unloading (spring back). During the loading stage the stress is null at neutral axis, tensile at extrados and compressive at intrados and has a linear distribution on the elastic region and a constant distribution on the plastic region, where its value equals to material yield stress σ_y.

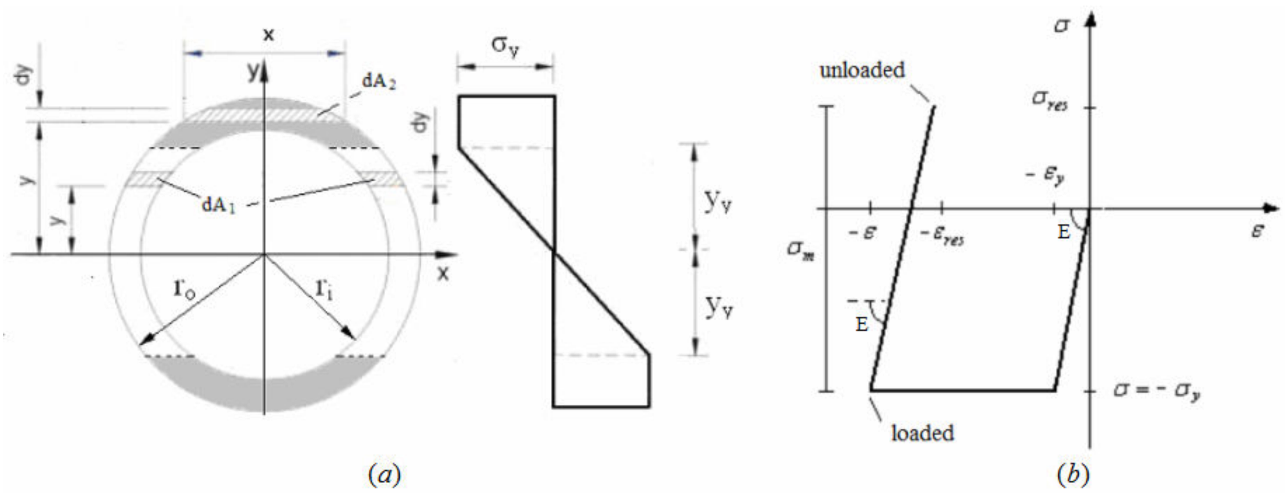


Figure 3. (*a*) Partial yielding of a pipe cross section with stress distribution for an elastic-perfectly plastic material and (*b*) Analytic model material behavior.

Figure 3*a* shows the stress distribution (in the *z* direction) at the end of the loading step and Figure 3*b* shows the material behavior at intrados: first submitted to a compressive stress state at loading step and then a tensile stress state at the end of the unloading step (spring back).

4. NUMERICAL MODEL

A non-linear finite element model is presented to study the cold bending of pipes. Numerical simulations are performed with commercial finite element code ANSYS Workbench 12.1 (ANSYS, 2009). A bilinear kinematic hardening model BKIN (ANSYS, 2009) is used to represent the material elastoplastic behavior.

Elements SOLID 186 were used for spatial discretization. This element type is a higher order 3-D 20-node solid element that exhibits quadratic displacement behavior and is defined by 20 nodes with three degrees of freedom per node: translations in the nodal x, y, and z directions. SOLID186 element supports plasticity, hyperelasticity, creep, stress stiffening, large deflection, and large strain.

The proposed model is applied to the bending of API 5L X70 steel pipe with a 38” external diameter, a thickness of 3/4” and a 12 m length (API, 2007). The material properties are presented in Table 1 and Figure 4 presents the stress-strain curve used in the numerical simulations.

Table 1. Material properties for API 5L X70 steel pipe (API, 2007).

Material Parameter	Value
Young modulus - E (GPa)	210
Yield stress - S_Y (MPa)	483
Ultimate strength - S_{ut} (MPa)	565
Ultimate strain - ε_{ut} (%)	11
Poisson ratio - v	0.30
Plastic modulus - H (GPa)	1402

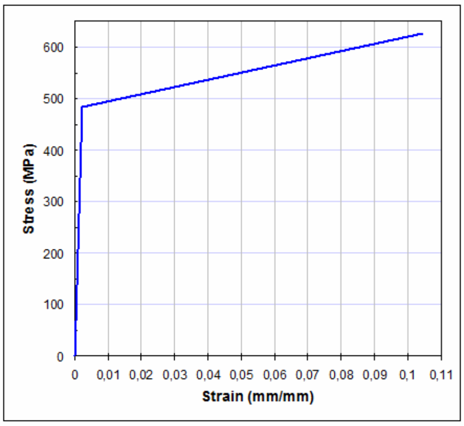
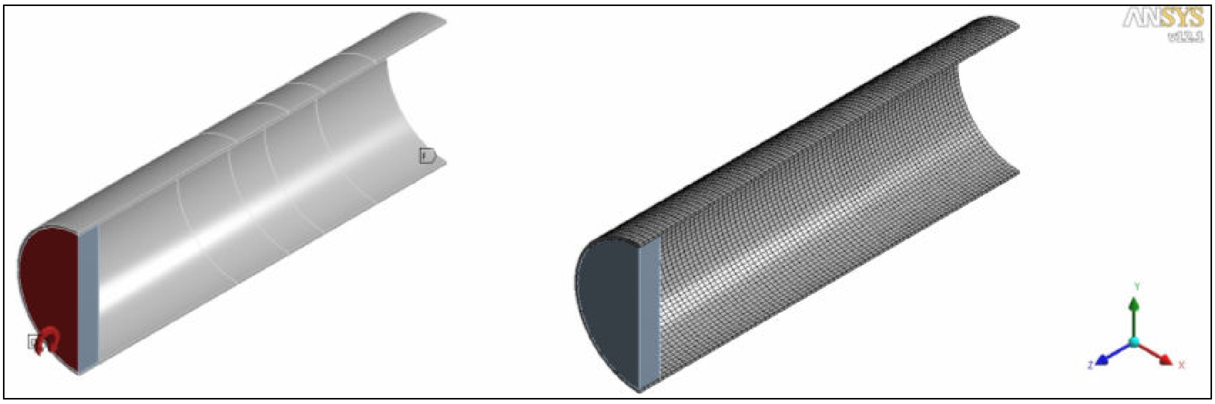


Figure 4. Stress-strain curve. Bilinear kinematic hardening model.

Numerical model considers a 2.85 m length part of a straight pipe submitted to pure bending at one end. Figure 5*a* shows boundary conditions and the applied loading. A bending moment is applied at one of the pipe ends *D* and then removed while a null prescribed displacement, in all directions, is applied to the other pipe end *F*. The final mesh is defined after a convergence analysis and is shown in Fig. 5*b*. Symmetry conditions are applied in the *yz* plane and geometric nonlinearity associated to large displacement is considered in the analysis.



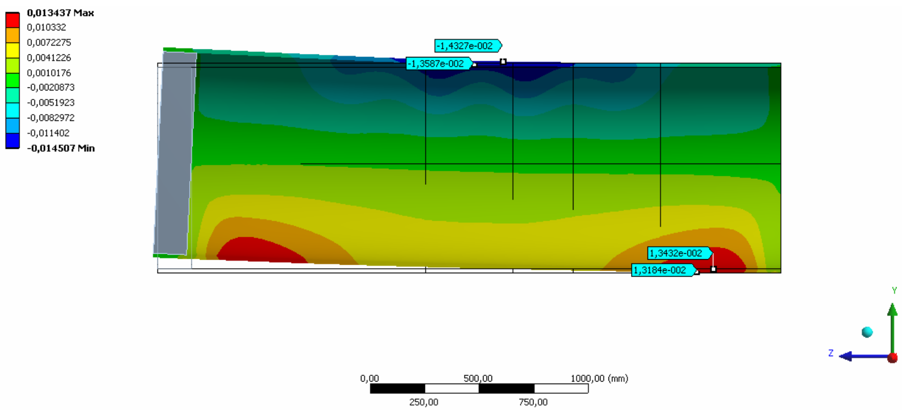
(*a*) (*b*)

Figure 5. (*a*) Boundary conditions and loadings. (*b*) Finite element mesh.

5. NUMERICAL SIMULATIONS

The cold bending process model considers two stages: *loading* and *unloading*. In the *loading stage* a bending moment is applied to one of the pipe ends promoting the development of plastic strain. In the *unloading stage* the bending moment is removed and a residual stress is observed due to the presence of gradients of plastic strain.

Figures 6, 7 and 8 show, respectively, longitudinal total strain, longitudinal stress and *von Mises* equivalent stress distribution for *loading* and *unloading* stages.



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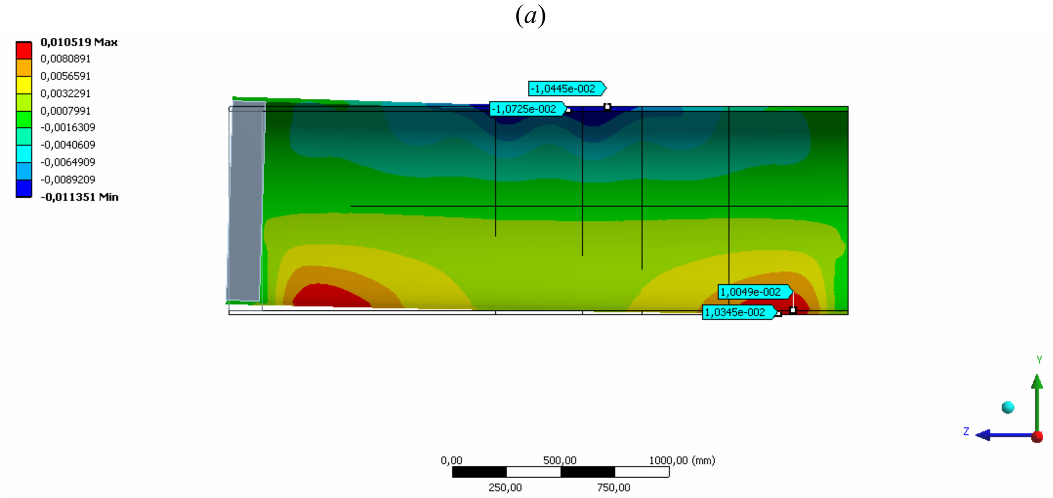

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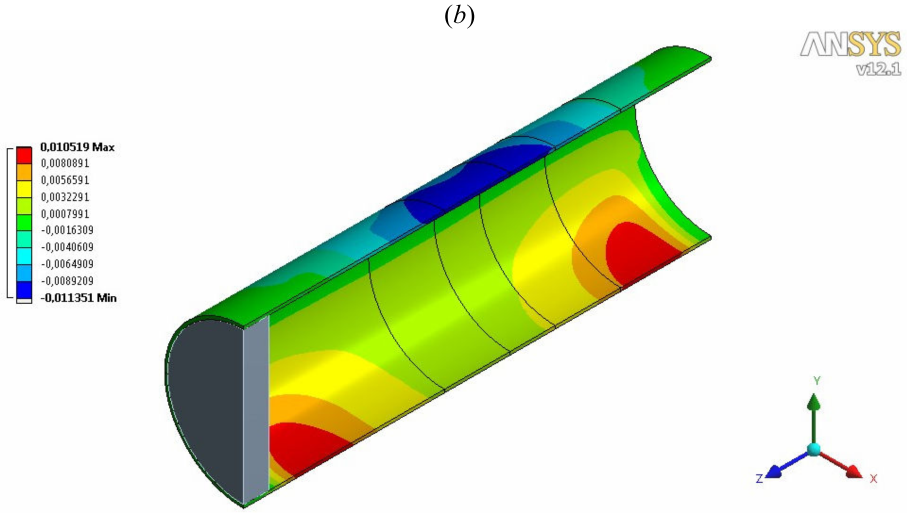
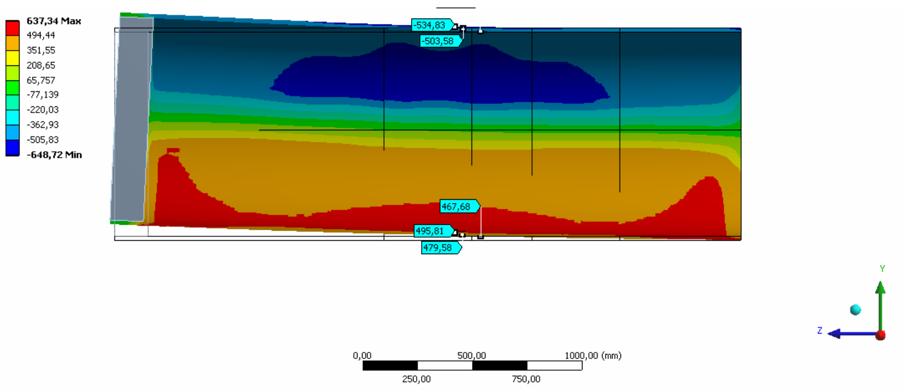


(*c*)

Figure 6. Longitudinal strain distribution for *loading stage* (*a*) and *unloading stage*: (*b*) side view and (*c*) perspective view.



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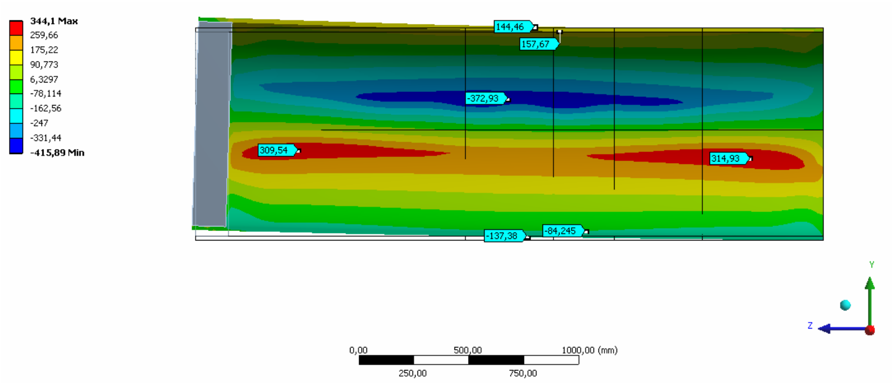

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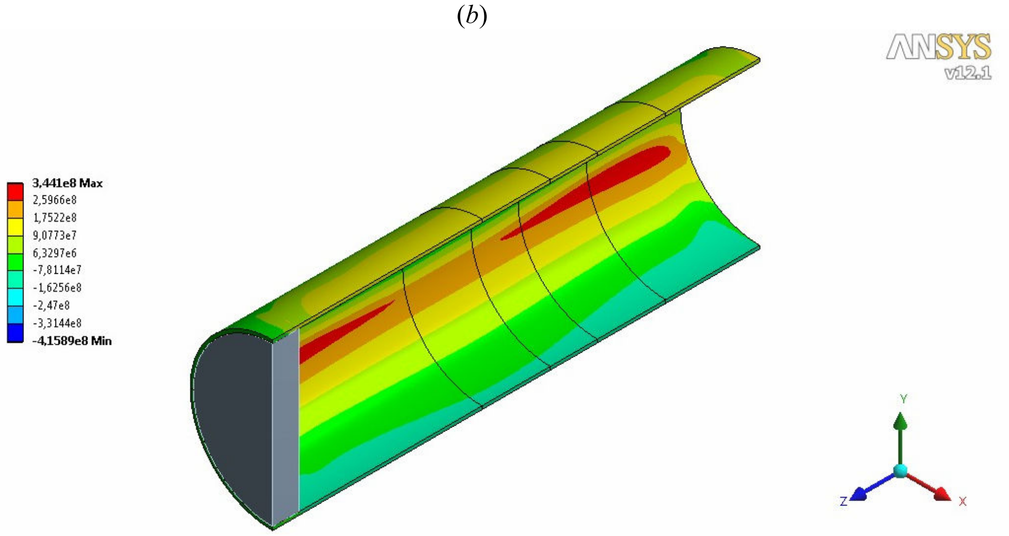

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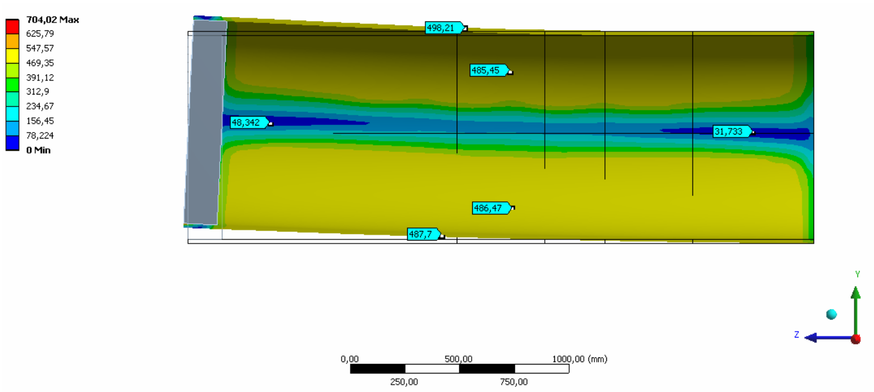
Figure 7. Longitudinal stress distribution for *loading stage* (*a*) and *unloading stage*: (*b*) side view and (*c*) perspective view.



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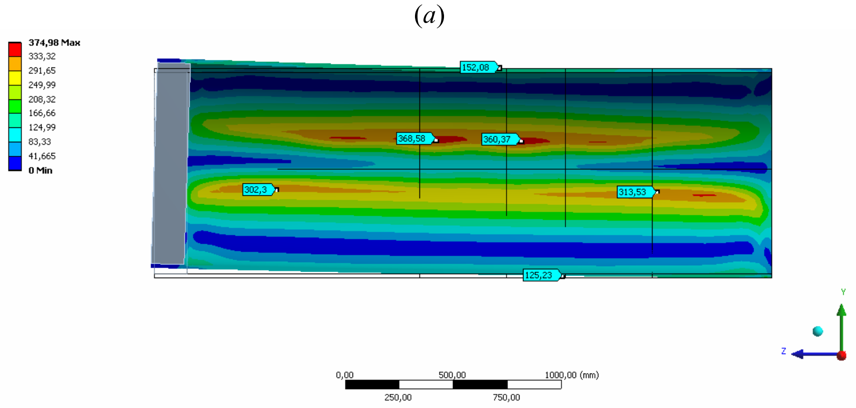

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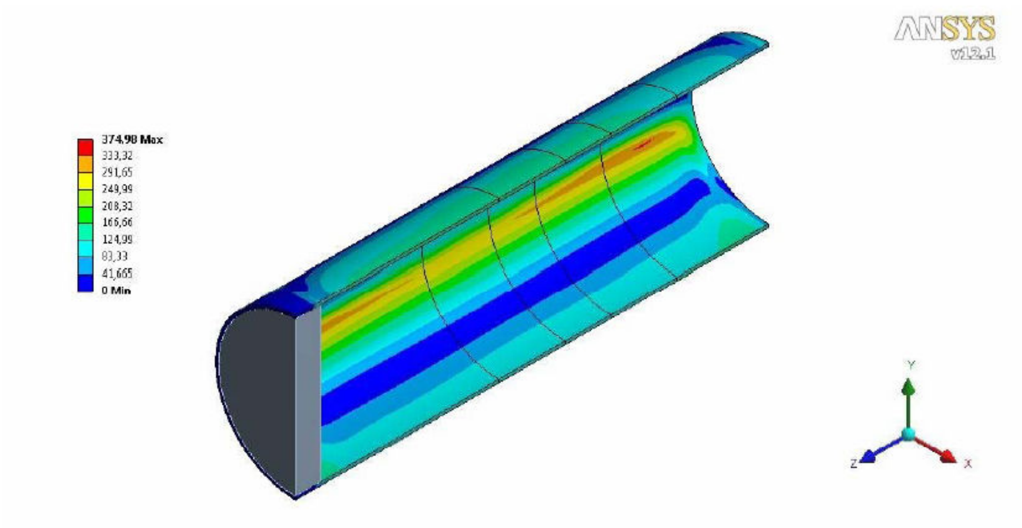


(*c*)

Figure 8. ***Von Mises*** **equivalent stress distribution for** ***loading stage*** **(a) and** ***unloading stage*****: (*****b*****) side view (*****c*****) perspective view.**

Numerical results show that the cold bending process promotes high levels of residual stresses. Values near yield stress are observed. Figure 8 shows a maximum value of *von Mises* residual stresses of 375 MPa which represents 78% of the yield stress.

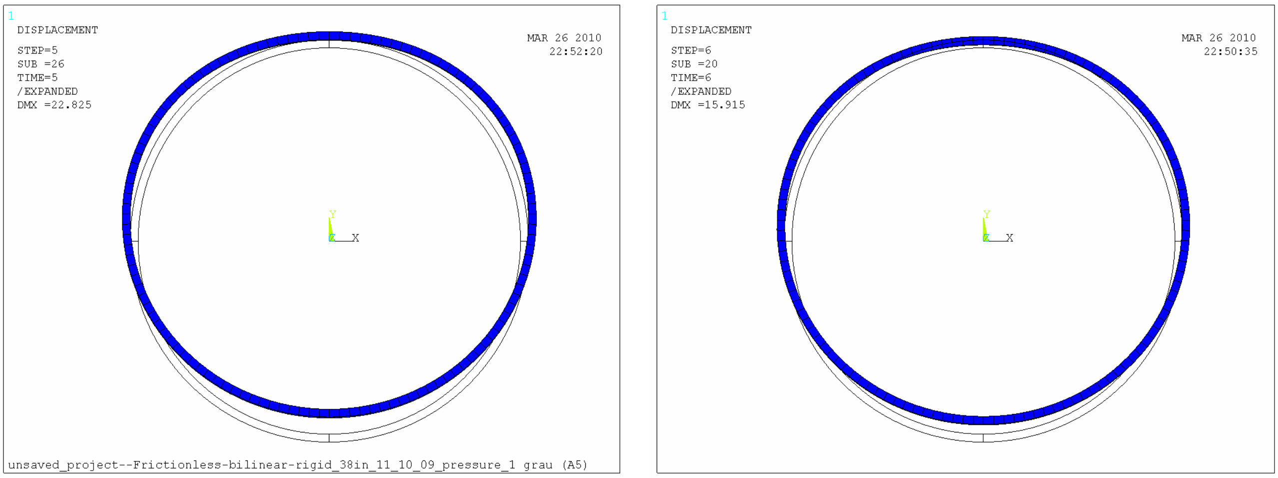
At this point results obtained from numerical and analytic models are compared. Table 2 shows a comparative study between analytic and numeric models.

Table 2. Comparative performance between analytic and numeric models.

	Analytic model	Numeric model	Percentual error
σ	-483 MPa	-534 MPa	-10 %
ε	-13,700 με	-13,870 με	-1.2 %
σ_{res}	117 Mpa	144 MPa	-23 %
ε_{res}	-10,800 με	-10,725 με	+0.7 %
M	8.2 MN	4.1 MN (symmetry conditions)	-

The numeric model was used as reference. Very good results were obtained by the analytic model for strains while for stresses the results were only reasonable. The use of elastic-perfectly plastic material for the analytic model and a bilinear hardening material for the numeric model explains the differences of behavior, since in analytic model the stresses were limited to yield stress. Also the analytic model does not consider the ovalization produced by the cold bending of pipe.

Figure 9 shows the cross section ovalization at *loading* and *unloading stages* in a cross section localized at the half length of the pipe obtained from the numerical analysis. An amplification factor of 3 is used to represent the deformed configuration (filled blue line) and help the deformed geometry visualization. The undeformed cross section is also represented in the figure. The spring-back effect due load removal can be observed.



(*a*) (*b*)

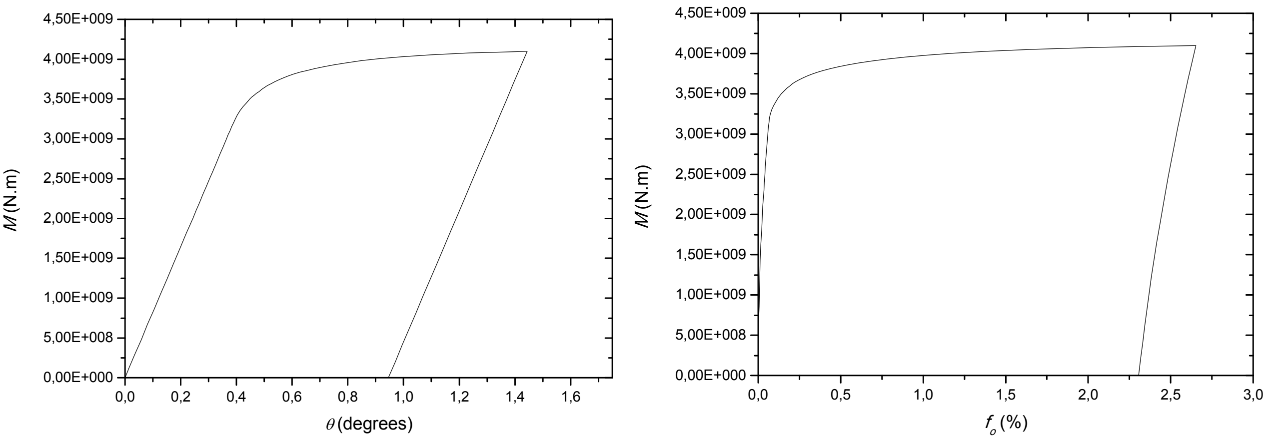
Figure 9. Cross section ovalization. (*a*) *loading* and (*b*) *unloading stages*.

Cross section ovalization criterions are defined by different standards (Petrobras, 2008; API, 2007; DNV, 2003). Petrobras N-464 Standard (2008) defines the ovalization factor, f_0, as:

$$f_0 = \frac{D_{\max} - D_{\min}}{D_{nom}} 100\ \% \tag{8}$$

where, $D_{\max}$ is the maximum outer diameter, $D_{\min}$ is the minimum outer diameter and D_{nom} is the nominal outer diameter (before loading). N-464 standard (Petrobras, 2008) establishes that the ovalization factor after the pipe curve bending must not exceed 2.5%. In this work it is assumed that the pipe initial cross section before loading has no ovalization and ovalization factor is estimated from results of numeric model measuring the horizontal and vertical distance in a cross section localized at the half length of the pipe using (8).

Figure 10*a* and 10*b* shows, respectively, the applied bending moment as a function of the bending angle and the ovalization factor. At the end of *loading stage* a bending angle of 1.44° and an ovalization factor of 2.65% are observed whereas at the end of *unloading stage* a bending angle of 0.95° and an ovalization factor of 2.31% are observed.



(*a*) (*b*)

Figure 10. (*a*) Bending moment *versus* bending angle. (*b*) Bending moment *versus* ovalization factor.

Results show that the applied loading promotes a final bending angle of near 1° and a final ovalization below the allowed maximum value stated by N-464 standard (Petrobras, 2008).

6. CONCLUSIONS

A nonlinear elastoplastic finite element model was developed to study pipe cold bending. The proposed model is applied to the bending of 38” API 5L X70 steel pipe. Numerical results indicate that large values of residual stresses can be obtained. A comparison between results obtained from the analytic simple model and the numerical model indicates a very good agreement between strain results and reasonable relationship between stresses results. Numerical results furnish ovalization data. The numeric model also shows large strains in positions that ripples could appear.

The proposed methodology can be used as a tool to study the effects of the process parameters, like bending angle, residual stresses, strains and ovalization promoted by the process. Moreover, an experimental program must be established to validate the proposed model.

7. ACKNOWLEDGEMENTS

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