Proceedings of the Canadian Society for Mechanical Engineering International Congress 2020
CSME Congress 2020
June 21-24, 2020, Charlottetown, PE, Canada

Finite Element Simulation on Squeeze-off of Polyethylene Pipes

A. Ebrahimian*, P.-Y. B. Jar
Department of Mechanical Engineering, University of Alberta, Edmonton, AB, Canada
*eb1@ualberta.ca

Abstract Squeeze-off is a widely used industrial procedure to block or reduce fluid flow in polyethylene (PE) pipes. In this study, squeeze-off of PE pipe is simulated using finite element modelling. A set of experimental testing data was used to tune and extract an elastic-plastic and creep material properties of a model which consists of a pipe specimen and a squeezing bar. Squeezing speeds of 0.01, 1, and 50mm/min that cover common speeds used during the pipe repair or maintenance were used to model the squeeze-off process. A material sensitivity analysis was performed to identify parameters in the constitutive equations for which change of values yields sensitive response of the deformation behaviour of PE. This study shows that identifying these parameters improves agreement between experimental data and finite element simulation. The finite element model was then used to determine stress and strain distribution in the pipe specimen during the squeezed off process.

Keywords*: *Finite element; pipeline; squeeze-off; polyethylene

I. INTRODUCTION

Employing polyethylene (PE) pipes for natural gas transportation has been significantly increased in recent years due to its desirable physical and mechanical properties and superior corrosion resistance. A large portion of the natural gas distribution lines are made of PE pipes. One main advantage of PE pipes over the metallic counterparts is that a relatively straightforward and quick procedure, known as squeeze-off process, can be utilized to shut off or reduce gas flow when the pipeline requires maintenance or repair. Such a procedure is used more than half million times every year. Therefore, it is very important to investigate the influence of parameters that may affect mechanical properties of PE pipe after being subjected to this procedure.

Some researches have conducted experimental studies to investigate the effect of squeeze-off on the mechanical behaviour of PE pipe. A study showed that failure behaviour in the PE pipe after the squeeze-off process [1] involves two failure modes, brittle fracture and slow crack growth (SCG). Although the latter was known to start from defects or third part impingement, the former could be generated without the presence of any defect in the material. The squeeze-off increases compressive stress across the pipe wall thickness, which is believed to induce the SCG development. That study concludes that by controlling the squeeze and release rates, failure could be avoided. Another experimental study designed a squeeze-off tool that could be used in a proper keyhole for squeezing by a single operator [2]. For this purpose, equations were developed to predict the required squeeze-off forces under different conditions, such as temperature, tool dimensions, and squeeze-off rate. In studies of long-term performance of PF pipe, lifetime of PE materials was analyzed at their in-ground temperature and pressure based on external loading modes, including rock impingement and pipe bending as the primary load, and squeezing load as the secondary load [3,4]. The SCG was regarded as a long-term failure mode for PE pipe in service. For damage initiation, results from of pipe testing suggest that the main parameters that govern damage formation are pipe wall compression, squeeze tool size, pipe thickness, and pipe material [5]. Some studies [6,7] investigated PE pipes of different wall thickness and pipe diameters to understand the effect of pipe wall thickness on damage generated in the squeeze-off process.

Numerical studies were also conducted on squeeze-off of PE pipes. One of the studies investigated stress and strain distribution in high-density PE (HDPE) pipes when they are subjected a squeeze-off load [8]. Another study [9] used a numerical model to quantify the influence of squeeze-off on degradation of mechanical properties for PE pipe. This study considered three squeezing speeds of 0.01, 1 and 50 mm/min to cover the full range of possible squeeze-off scenarios that may be encountered during pipe repair or maintenance. Key outcomes from the simulation are reproduced in Fig. 1. Although the simulation results show a reasonable agreement with the experimental data, some discrepancy exists, especially for the load drop during the stress relaxation stage. Such discrepancy leads to concerns about accuracy of the simulation and conclusions drawn from the study, that is, decrease of squeeze-off speed has no effect on the extent of mechanical property degradation of PE pipe. This conclusion is contradictory to the common belief that decrease of the squeezing speed should reduce the extent of degradation of mechanical properties for PE pipe [9].

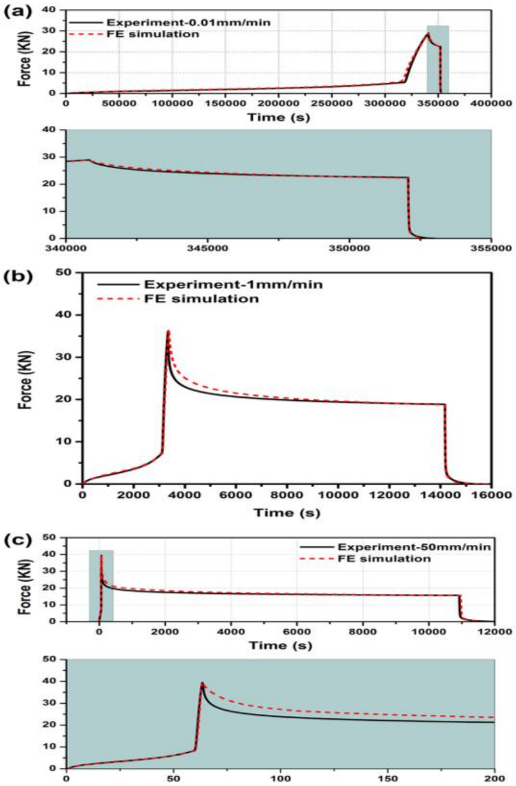

Figure 1. Comparison between FE simulation and experimental testing at squeezing speeds of 0.01 (a), 1 (b) and 50 mm/min (c) [9].

The squeeze-off process considered in the present work follows that used in ref. [9]. That is, the pipe samples were squeezed to the squeezing ratio of 30% at one of the crosshead speeds considered and kept at this squeezing ratio for 10,000 sec to mimic the maintenance procedure. Then the load was released at a constant crosshead speed of 0.1 mm/min. Fig. 2 presents plots of force versus displacement for the three squeeze-off speeds considered in the previous study, in which points A to B is the first part of the squeezing process, till the inner pipe walls touch each other. The pipe is further squeezed until wall compression (WC) reaches 30%, which corresponds to point C in Fig. 2. From points C to D, the squeezing tool is maintained at the same position for 10,000 seconds. Then, the squeezing bar is unloaded to point E [9].

One of the challenges for quantifying the effect of squeeze-off speed on the PE pipe performance is the viscous behaviour of PE. In the previous work [9], performed in our research group, the squeeze-off process was simulated using finite element modelling (FEM), but the simulation results were not close enough to the experimental data, especially at squeeze-off speeds of 1 and 50 mm/min.

Work presented in this paper is to examine possibility of reducing the difference between FEM simulation results and experimental measurements. For this purpose, the FEM simulation is based on the same experimental data as those used previously. The main difference between the current simulation approach and that used previously is that instead of the simple try-and-error approach, sensitivity of parameters

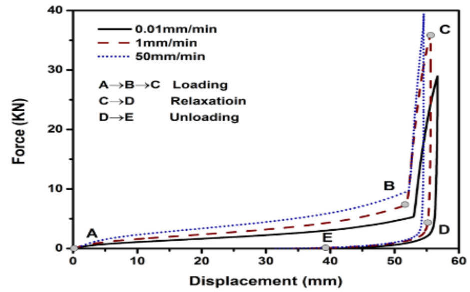

Figure 2. Variation of force with displacement at squeezing speeds of 0.01, 1, and 50 mm/min [9]

used to prescribe material properties was first analyzed using a simple model under tensile loading. Parameters that have the most sensitive control of load-displacement profile were identified and then used in the squeeze-off model to mimic the experimental measurements.

II. Finite Element Simulation

FEM was performed using ABAQUS to establish complex strain distribution generated in the PE pipe during the squeeze-off process. As mentioned in the previous section, in addition to the model for the squeeze-off process, a simple cylindrical model with constant cross section, under tensile loading, was performed to evaluate sensitivity of deformation to material parameters used to establish the stress-strain relationship for FEM of the squeeze-off process.

A. *Squeeze-off Process*

Geometry and Mesh Assignement

The model includes three parts, a PE pipe specimen, a squeeze-off bar and a rigid plane, as shown in Fig. 3. Due to the geometric symmetry, the model consists of only half of the pipe length and quarter of the cross section, and the squeeze-off bar and the rigid plane were constructed as a rigid body. The rigid plane was to avoid extrusion passing the plane of symmetry. The pipe model consists of 27,000 C3D8R elements (10 elements through the wall thickness direction and 30 elements along the quarter of the circumference. Size of the elements was chosen to be small enough to ensure convergence of the simulation results, based on a common mesh sensitivity analysis.

Solution Steps

Four steps were defined in the model to simulate the experimental tests. The 1st and 2nd steps were for the loading at a constant crosshead speed of 0.01, 1, or 50 mm/min, till a squeezing ratio of 30% was reached. The 1st step contained a significant portion of the loading and was purely based on the static behavior of the model, but the 2nd step involved creep deformation to take into account viscous behavior of the model. The 3rd step was for stress relaxation under constant displacement, which also included the creep deformation used in the 2nd step and lasted for 10,000 seconds. The 4th step is for unloading, again purely based on the static deformation.

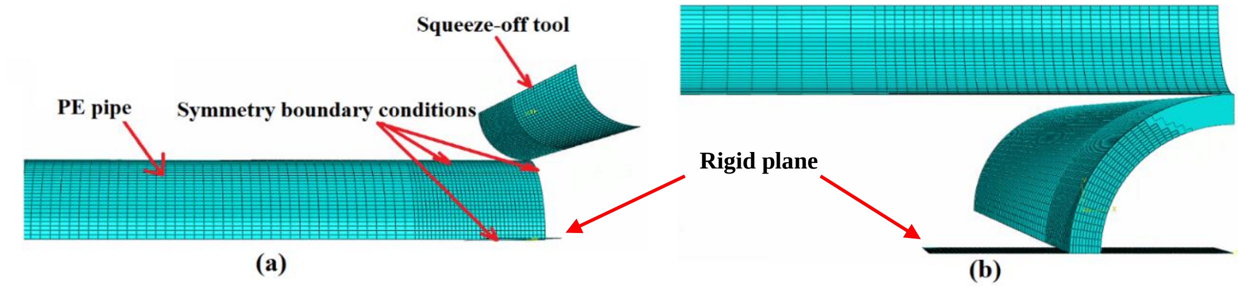

Figure 3. The front view (a) and side view (b) of a 3-D FE model for the squeeze-off process.

Contact conditions

Two contact conditions have been defined in the model:
(i) Between the outer surface of the PE pipe and the squeeze-off bar: This contact is considered to be a hard contact in the normal direction, and frictional contact in the tangential direction with a friction coefficient of 0.08, based on results from an experimental study [10].
(ii) Between the inner surface of the PE pipe and the rigid plane: This contact is defined to avoid extrusion over the plane of symmetry.

Loading and Boundary Conditions

Boundary conditions for the model (as shown in Fig. 3) are as follows:
(i) Planes of symmetry were defined on x-y, y-z and x-z planes.
(ii) For the loading step, a total displacement in y-direction was assigned to the reference point of the loading bar. The bar moved at the desired speed to achieve a squeezing ratio of 30% at the end of the loading step. In the stress relaxation step, the loading bar was kept stationary without any additional displacement. Finally, in the unloading step the bar returned back to its initial position.
(iii) The rigid plane was fixed and without any displacement and rotation.

Establishment of Input Material Properties

The constitutive equations proposed by Kwon and Jar [11] and later extended by Muhammad and Jar [12] were used to simulate deformation introduced by the squeeze-off process. The constitutive equation is based on the classical J_2 flow theory, and as shown in Eq. 1 below, is expressed through a set of stress-strain relationships. Eq. 1 consists of four expressions in four different strain ranges that cover both elastic and plastic deformation.

$$\sigma(\varepsilon)=\begin{cases} \dfrac{3}{2(1+\upsilon)}E\varepsilon & \varepsilon\le\varepsilon_y \quad \text{(a)} \\ d\left\{\left[a\left(\varepsilon+b\right)\right]^{(c-1)}-\left[a\left(\varepsilon+b\right)\right]^{(-c)}\right\}+e & \varepsilon_y\le\varepsilon\le\varepsilon_n \quad \text{(b)} \\ \alpha k\varepsilon^N & \varepsilon_n\le\varepsilon\le\varepsilon_t \quad \text{(c)} \\ k\exp\left(M\varepsilon^{\beta}\right) & \varepsilon\ge\varepsilon_t \quad \text{(d)} \end{cases} \qquad (1)$$

where σ and ε are equivalent stress and equivalent strain, respectively, ε_y the transitional strain from linear to nonlinear deformation, ε_n the critical strain for the on-set of necking, and ε_t the strain at the beginning of the exponential hardening. The other parameters (a, b, c, d, e, α, k, N, M, and β) are user-defined variables for which the values were determined from an iterative process until the time function of the reaction force in the loading bar from the FEM simulation, matched that from the experimental testing. In addition to Eq. 1, a simple power-law creep function, as described in Eq. 2, was introduced to increase strain under the same loading level in order to reproduce the experimental measurements.

$$\dot{\bar{\varepsilon}}^{cr}=A\sigma^n t^m \qquad (2)$$

where $\dot{\bar{\varepsilon}}^{cr}$ is the equivalent creep strain rate, t time measured from the start of the deformation process, and *A*, *m*, and *n* user-defined fitting parameters.

B. Sensivity of FEM to Material Parameters

To identify fitting parameters that have a bigger influence on the output results than the other parameters, an axisymmetric cylinder model of constant cross section was developed, subjected to tensile displacement.

As explained earlier, there are totally 5 mathematical expressions to describe the stress-strain relationship. Four expressions in Eq. 1 describe the elastic-plastic behavior, and the expression in Eq.2 describes the creep (time-dependent) behaviour.

Note that Eq. 1(d), for the exponential hardening, covers the widest strain range introduced in the squeeze-off process, from 0.3 to 1.1. Therefore, Eq. 1(d) is further divided into 4 stages, with different sets of *k*, *M*, and β values. Because exponential hardening has a high rate of stress increase with the increase of strain, these parameters are expected to have the most effect on the deformation behaviour of the model. Therefore, these parameters were investigated for their influence on the output stress from the model. In addition, variables in Eq. 2 (i.e. *A*, *n*, and *m*) were also included in the sensitivity analysis, as they have been reported to have a considerable influence on the output strain at a given stress level [12].

In total, six parameters (three from the Eq. 1(d) and three from Eq. 2) were considered for their influence on the output from the FEM model. This part of the simulation was conducted using a simple cylindrical mode with constant cross-sectional area. Fig. 4 depicts this model and boundary conditions. As shown in the figure, the model is fixed at the bottom and subjected to upward displacement at the top. Input material properties are similar to those used for the squeeze-off simulation.

The cylindrical model was first based on parameter values that were used in the previous study on the squeeze-off process [9]. Then, values for the 6 parameters, as mentioned above, were increased or decreased by 10%, one parameter each time while keeping values for the other five parameters unchanged. The corresponding output stress for the same element in the cylindrical model was recorded and compared to the output stress from the original model. Since the stress distribution was uniform in the model, each time an arbitrary element in the middle of the model was selected to record the stress output.

Information from the above study could reveal the parameters that showed the most influence on the output stresses, which were then the focus in the tuning process for the squeeze-off model in order to better fit the experimental measurements.

III. RESULTS AND DISCUSSION

Results are presented in the following order: sensitivity analysis, material and model development, and stress and strain contours.

A. Sensitivity Analysis in the Cylindrical model

As discussed, sensitivity of the stress output to the change of parameter values was analyzed to determine the most sensitive parameters. Table 1 shows results of the parameter sensitivity analysis. In both cases, results by either increasing or decreasing the parameter values by 10% suggest that parameter n in the exponential hardening equation and N in the creep equation caused a bigger difference than the other parameters with the same percentage change of the value in the output stress. Therefore, these two parameters should be the most influential parameters for adjusting the output stress, and thus were tuned in the squeeze-off model in order to improve the closeness of the simulation results with the experimental measurements. Other parameters in Eqs. 1(a-c) were changed based on the updated parameters in Eq. 1(d) in order to establish a smooth stress-strain curve.

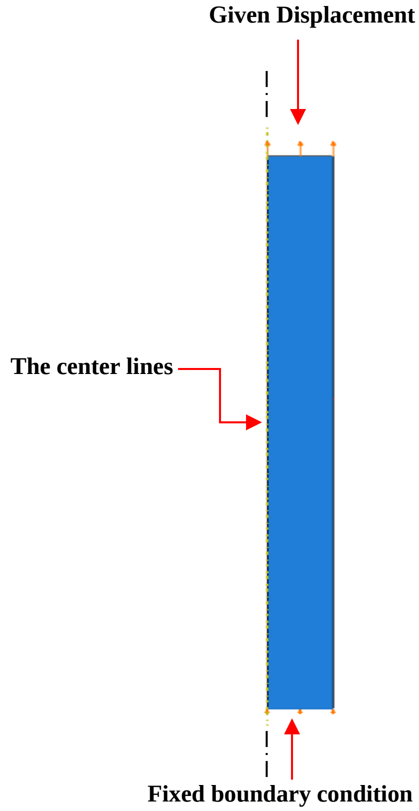

Figure 4. The simple tensile model and boundary conditions

B. Material and Model Development

As explained in section II. Finite Element Simulation, material parameters in the Eq. 1 were tuned in an iterative

Table 1. Results from the parameters sensitivity analysis

	Increase of parameter values by 10%					Decrease of parameter values by 10%				
	A	n	m	αk	N	A	n	m	αk	N
Initial Value	$6.6E-20$	10	-0.61	18.1	0.07	$6.6E-20$	10	-0.61	18.1	0.07
New Value	$7.26E-20$	11	-0.67	19.9	0.77	$5.94E-20$	9	-0.549	16.33	0.063
Equivalent stress for the initial value (MPa)	17.227	17.227	17.227	17.227	17.227	17.227	17.227	17.227	17.227	17.227
Equivalent stress for the new value (MPa)	17.226	24.556	17.226	23.495	17.236	17.227	12.534	17.227	17.834	15.784
Stress change (%)	0.0058	42.54	0.0058	36.38	5.22	0.00	27.242	0.00	25.495	-8.376

process to achieve a good agreement between the reaction force results from simulation and the experimental load-time data. Table 2 lists the final values for parameters in Eq. 1. Fig. 5 shows an example of the stress-strain curve obtained by replacing the parameters in the Table 2 in the constitutive equation at the cross-head speed of 1 mm/min. Fig. 5 shows the stress-strain input curve in ABAQUS in which the elastic parameters (the Young's modulus and the Poisson's ratio), plastic material behavior (the relationship between yield stress and plastic strain) and time-hardening creep parameters are defined. After running the model, the reaction force versus time in the squeezing bar were obtained from ABAQUS.

Fig. 6 compares reaction force obtained from the FEM simulation with the experimental data at the same squeeze-off speeds. As shown in this figure, there is a good agreement between reaction force obtained from the FEM simulation and the experimental results.

Table 2. Values for parameters and strain range in Eqs.6 and 7, determined from the FE simulation.

FE model			Squeeze-off process		
Crosshead speed (mm/min)			0.01	1	50
Equation (3a)		ε_y	0.05	0.005	0.005
		E	900	950	1100
		ν	0.4	0.4	0.4
Equation (3b)		ε_n	0.02	0.02	0.02
		a	20	20	29.5
		b	0.025	0.0354	0.018
		c	0.05	0.07	0.004
		d	-16.5	-50.3	-23.8
		e	14.3	15.5	20.62
Equation (3c)		ε_t	0.3	0.3	0.3
		αk	16.64	25.93	30.14
		N	0.07	0.07	0.07
Equation (3d)	Section 1	ε_{t1}	0.6	0.6	0.6
		K_1	14.3	22.281	26.35
		M_1	0.59	0.59	0.44
		β_1	1.8	1.8	1.8
	Section 2	ε_{t2}	0.8	0.8	0.8
		K_2	13.52	21.06	25.58
		M_2	0.71	0.71	0.5
		β_2	1.8	1.8	1.8
	Section 3	ε_{t3}	1.2	1.2	1.2
		K_3	11.43	17.924	23.55
		M_3	0.94	0.93	0.61
		β_3	1.8	1.8	1.8
	Section 4	ε_{t4}	2	2	2
		K_4	7.77	12.2	20.2
		M_4	1.2	1.2	0.71
		β_4	1.8	1.8	1.8
Equation (4)		$A\times10^{15}$	6.6	6.6	9.6
		n	10	10	10
		m	-0.72	-0.96	-0.98

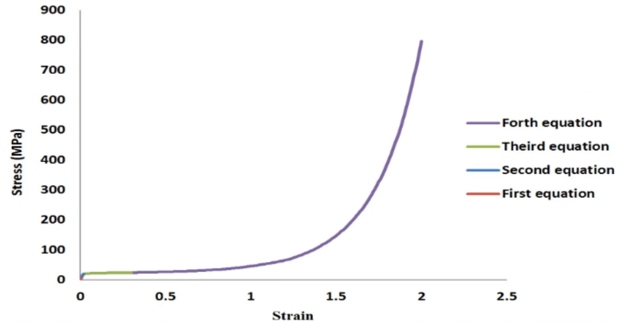

Figure 5. Stress-strain curves obtained by adjusting the parameters in the material behavior equation with the experimental data.

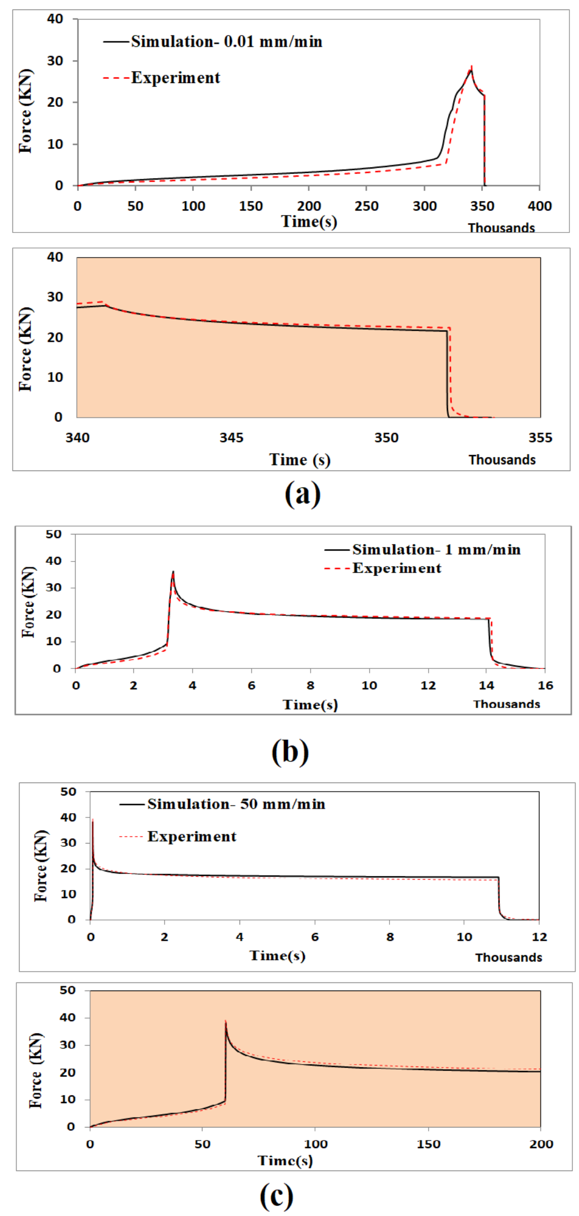

Figure 6. Comparison of FE simulation and experimental testing at squeezing speeds of 0.01(a), 1(b), and 50 mm/min (c).

C. *Stress and Strain Development During Squeeze-off Process*

As discussed earlier, squeeze-off process includes three main steps: loading, relaxation and unloading. Fig. 7 shows the equivalent stress contours in the specimen at the beginning of the loading step, at the beginning of the relaxation step, and at the end of unloading step, respectively. Due to plastic deformation introduced in the squeeze-off process, the bar does not return back to its initial position.

IV. SUMMERY AND CONCLUTIONS

Work presented in this paper is to use a set of squeeze-off test results that were conducted in a previous study to explore the possibilities of determining the stress-strain relationship to improve the simulation accuracy. A three-dimensional finite element model was developed to mimic the squeeze-off process. This model includes a PE pipe specimen, squeeze-off bar and a rigid plane. Linear quadrilateral elements were assigned to the model parts. An elastic-plastic constitutive equation and a creep model were used to tune the model to match the experimental measurements. Furthermore, proper contacts, loads and boundary conditions were assigned to the model assembly to mimic the actual conditions in the squeeze-off process. Three steps were defined to load the model, including loading, relaxation and unloading steps. The results indicate that the constitutive equation can provide suitable stress-strain relationship to mimic closely the squeeze-off process. Moreover, the results suggest that due to plastic deformation, the pipe cannot return completely to its initial dimensions. As a result, significant degradation could be introduced by the squeeze-off process.

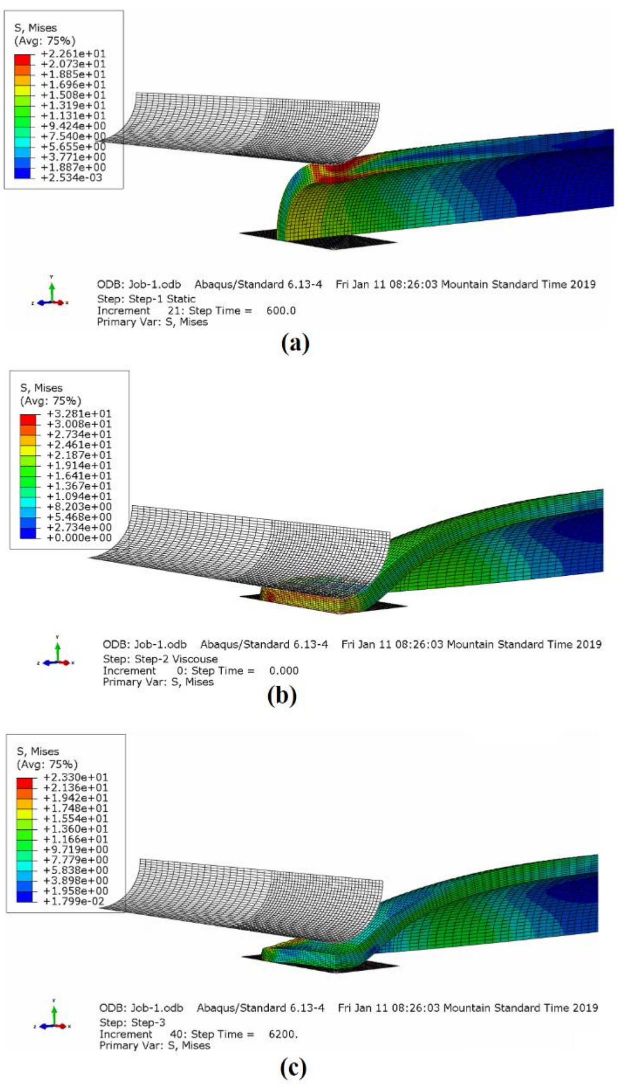

Figure 7. Equivalent stress contours (a)at the beginning of the loading step, (b) at the beginning of the relaxation steps, and (c) at the end of the unloading step.

ACKNOWLEDGEMENT

The work was sponsored by Natural Sciences and Engineering Research Council of Canada (NSERC), and Imperial Oil-the University Research Awards program.

REFERENCES

[1] N. Brown and J.M. Crate, "Analysis of a Failure in a Polyethylene Gas Pipe Caused by Squeeze off Resulting in an Explosion," Fail. Anal. and Preven. J. Pennsylvania. USA, vol. 12, pp. 30–36, December 2011.

[2] K.E. Harris, "Squeeze-off& gel patch repair methods for polyethylene pipe in natural gas distribution lines", Corvallis.USA: Organ State University, 2007.

[3] G. Palermo, " Correlating Aldyl "A" and Century PE Pipe Rate Process Method Projections with Actual Field Performance", 2004, Milan. Italy.[Plastics Pipes XII Conference].

[4] D.R. Stephens, M.J. Cassady, B.N. Leis, "Progress report on preliminary screening tests on squeeze-off of polyethylene gas pipes", Battelle, Columbus, OH (United States), January 1987-December 1989.

[5] D.R. Stephens, B.N. Leis, R.B. Francini, M.J. Cassady, "Users' guide on squeeze-off of polyethylene gas pipes", vol.1, August 1989-February 1992. Battelle, Columbus, OH (United States).

[6] D.Uzelac, S. Bikiae, M. Durdeviae, I. Bordeasu, "Change of Polyethylene Pipe Wall Thickness after Squeezing Using Squeeze off-Tool", Materiale Plastice .J, vol.47, pp.461–466, December 2010.

[7] P. Yayla, Y. Bilgin, "Squeeze-off of polyethylene pressure pipes: Experimental analysis", Polymer Testing. J, vol. 26, pp.132–141, 2007.

[8] A. Egugen and O.M. Emilia, "Determining the Forces in the Polyethylen Pipes after Squeeezing Them off with Specific Equipments," AEECE, 2015 [International Conference on Advances in Energy, Environment and Chemical Engineering].

[9] Y. Zhang, P.-Y, Jar, "Effect of squeeze-off on mechanical properties of polyethylene pipes". International Journal of Solids and Structures.J, vol. 135, pp. 61–73, November 2017.

[10] S. Dhouibi, M. Boujelbene, M, Kharrat, M, Dammak, A, Maalej, "Friction Behavior of High-Density Polyethylene (HDPE) Against 304L Steel: An Experimental Investigation of the Effects of Sliding Direction, Sliding History and Sliding Speed", Journal of Surfaces and Interfaces of Materials.J, vol. 1, pp. 71–76, March 2013.

[11] H.J. Kwon, P.-Y. Jar, P.-Y.B, "On the application of FEM to deformation of high-density polyethylene.", International Journal of Solids and Structures.J , vol. 45, pp. 3521–3543, June 2008.

[12] S. Muhammad, P.-Y.B. Jar" Determining stress–strain relationship for necking in polymers based on macro deformation behavior", Finite Elements in Analysis and Design.J, vol. 70–71, pp. 36–43, September 2013.

[13] P.-Y. Ben Jar, S. Muhammad, "Cavitation-induced rupture in high-density polyethylene copolymers", Polymer Engineering & Science. J vol. 52, pp. 1005–1014, November 2011.