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Finite element stress analysis of squeeze-off of polyethylene pressure pipes

Pasa Yayla*
Mechanical Engineering Department Marmara University RTE Campus, Istanbul 34840 Maltepe /, Türkiye

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In this study, the stress analysis of PE 100 grade high-density polyethylene pressure pipe squeeze-off has been carried out using ABAQUS, a general-purpose finite element code. The squeeze-off phenomenon has been investigated for the single and double squeeze-off pipes. In the finite element analysis, the true stress-strain curve of the material has been adopted. The stress distributions in the squeezed pipe have been obtained. Special attention has been paid to the axial and von Mises stress distributions along the pipe axis and around the squeeze-off ear. Finally, the practical implications of the axial stress and von Misses stress distributions resulting from the squeeze-off phenomenon have been discussed and correlated with the minimum distance away from the pipe welds, mechanical connections, local saddle joints, or nearest squeeze-off locations imposed by related standards.

Keywords: Polyethylene pipes, Squeeze-off, Finite element modelling, Pipe stresses, Pipe failure

1 Introduction

Polyethylene (PE) pressure pipes have been widely used in gas and water distribution networks, provide maximum corrosion resistance and long service life and are compatible with conventional electro-fusion and butt-fusion jointing techniques. Despite these excellent performance records, various abnormal loading conditions can result in the failure of these pipes[1-4]. One problem with PE pipes' performance is their suspected performance after the squeeze-off operation, which is widely used to stop the flow of fluid or gas in emergency cases. Squeeze-off is a relatively simple procedure that involves temporarily controlling or stopping gas or liquid flow in a polyethylene pipe by compressing the PE pipe between two parallel solid metallic bars with a mechanically or hydraulically controlled squeeze-off tool until the inside surfaces of the polyethylene pipe make contact with each other. This is commonly performed to take a branch from the main pipe for maintenance tasks and to replace or repair damaged pipe sections without shutting down the whole system. After the squeeze-off is completed, the PE pipe recovers much of its original shape, allowing liquid or gas flow to resume. The squeeze-off process is a very effective procedure as it can be undertaken at almost any point in the pipeline[5]. Because the pipe undergoes an extensive shape change during the squeeze-off, resulting in considerable stresses as the pipe becomes flattened, it is crucial to determine whether this practice has any detrimental effect on the remaining lifetime of the pipeline. Furthermore, inappropriate squeeze-off procedures can cause damage to the pipe, create a safety hazard, or do both. As the pipe is squeezed-off, the stresses are not uniformly distributed, and thus peak values are bound to occur, depending on the pipe dimensions, the geometry of the squeeze-off tool, and the pipe squeeze-off ratio. Due to these complications and uncertainties, the finite element stress analysis of the PE squeeze-off phenomenon has yet to be studied. The other significant complication to be considered in the analysis is the non-linear and visco-elastic, even elasto-viscoplastic response of the pipe material. On the other hand, the deformation behaviour of materials at different strain rates is also important because the mechanical properties and the deformation mechanisms are strongly dependent on the applied strain rate[5]. Rate-dependent deformation mechanisms are well known to characterise the behaviour of polymeric materials, in particular semi-crystalline polymers such as polyethylene[6-7]. This strain rate sensitivity of PE is also important in the squeeze-off PE pipes as loading and unloading in the squeeze-off tests are performed at a certain velocity, which may also influence the post-squeeze-off behaviour[8]. A significant number of studies have been dedicated to understanding the roles of various loading parameters at the macroscopic scale, such as temperature[9-10], strain rate[9,11], and stress triaxiality[12,13]on the mechanical behaviour of PE material.

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*Corresponding author (E-mail: pasa.yayla@marmara.edu.tr)

Despite the widespread use of squeeze-off methods in pressure pipe applications of PE pipelines, the limitations of detailed experimental work and the lack of any data on the stress distribution in the squeeze pipe are well known by the relevant academia and industry. Thus, the present work's main aim is to use the results of numerical solutions, such as the finite element (FE) technique for the polyethylene squeeze-off. FE analysis is a rather informative and worthwhile numerical tool to perform this analysis to understand the nature of the pipe squeeze-off phenomenon. In the FE analysis, the simplest material model is the linear elastic material model. However, it is well known that due to material non-linearity, geometric non-linearities, and contact conditions, it is crucial to consider the non-linearity in the FE analysis. Taking these three sources of non-linearities into account in the stress analysis adds significant complexities to the model, and the non-linear model can arise in some problems, making the model much more difficult and time-consuming to solve[14-17]. Accurate experimental data is essential for achieving better results. Unfortunately, the data provided by resin suppliers is insufficient to calculate how the material performs under various real-life scenarios.

To the author's knowledge, there is no study on numerical analysis of the squeeze-off of PE pressure pipes at the aforementioned points. Thus, this investigation aims to analyse the distribution of surface stress in PE pipe when subjected to the squeeze-off process. The stress state created in the pipe could enable us to understand the associated damage mechanisms resulting from the squeeze-off practices. Furthermore, the variation of surface stresses around the circumference and axial directions is investigated and studied in detail to re-evaluate the minimum distances from squeeze-off locations to the nearest weld or mechanical connection regions and the following potential future squeeze-off points set by the related standards and code of practices. The main concern is that a failure may be triggered during or after the squeeze-off process if an adequate distance is not left between the squeeze-off location and local saddles, mechanical or weld joints.

2 Materials and Methods

2.1 Finite element analysis

In the FE analysis of the squeeze-off problem, a three-dimensional (3D) model of the problem is set up. Due to the symmetry, only a quarter section of the system is considered in the FE model. Details of the finite element model and boundary conditions are presented in Fig. 1 and Fig. 2. In this study, a general-purpose finite element package, ABAQUS6.14, was used for the computational scheme. Special attention was devoted to the finer meshing scheme of the pipe under the squeeze bars to enable the simulation to analyse the extensive deformations encountered when the pipe is fully squeezed-off. Thus, to increase the accuracy of the calculation and reduce CPU time, a finer mesh is used around the squeeze-off regions and a coarser mesh for other regions. Fourteen elements along the thickness are used. The element size along the thickness is not constant: 0.62 mm at the inner radius and gradually (linearly) increased to 1.24 mm at the outer radius. 1.41 mm along the pipe axis. In the analysis, Abaqus element type C3D8R, a first-order reduced integration hexahedral element, which is the most suitable element type for the highly deformed plastic analysis, is utilised. The total element number used in the model is 197976. All

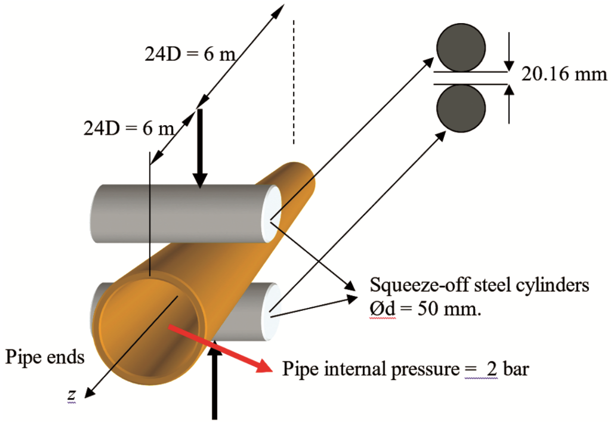

Fig. 1 — Single squeeze-off analysis parameters: PE pipe has outside diameter of 250 mm, 12.6 mm thickness, total length 12 m (48D), Scope A.

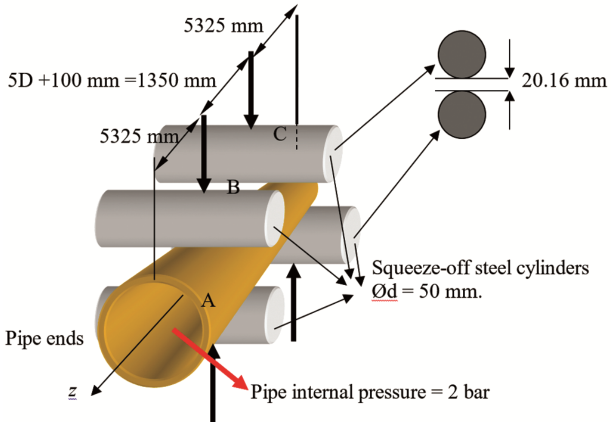

Fig. 2 — Double squeeze-off analysis parameters: PE pipe has outside diameter of 250 mm, total length 12 m (48D), Scope B.

calculations were done using Abaqus/Standard, which uses an implicit solver. In the current study, the pipe is squeezed-off until the predefined squeezing ratio is reached, which is 80% of the total pipe wall thickness, as dictated by the *ASTM* F1734 standard[18]. This ratio is given in Eq. 1.

$$WC[\%] = \left(1-\frac{L}{2t}\right)x100 \qquad \ldots(1)$$

where;

L: Distance between the squeeze toolbars

t: Uncompressed pipe wall thickness, expressed in the same units as L.

The additional aim of the FE analysis is to model the shape of the PE pipe when the squeezed-off tools are at various separation distances. The most important part is the external and internal shape between the two squeeze-off tools. However, the overall distorted shape is required for a distance of approximately four times the pipe diameter (4D) beyond the two squeeze-off tools so that the pipe becomes essentially undistorted, e.g., if the separation distance is 1D, the total length in the FE model would be 9D.

Although PE pressure pipes can be used in a wide range of diameters, ranging from 16 to 630 mm, in the current work, 250 mm outside diameter with a standard dimensional ratio (D/t) SDR 21 PE 100 pipe is taken into account. This is mainly due to the fact that this size of the pipe is one of the most widely used pipes in the main PE gas and water distribution networks. The total pipe length is 12 m (48D), squeeze-off bar diameters = 50 mm, and the temperature is 20 °C.

The current work has two main scopes: Scope A and Scope B. To simulate the real-life condition, both pipe ends are restrained, and 2 bar internal pressure is applied for both scopes.

Scope A

In this scope, a 250 mm SDR 21 PE100 pipe with a single squeeze-off is analysed. From this fundamental FEA analysis of single squeeze-off, axial surface stresses along the pipe will be plotted at 0°, 45°, and 90° positions from the top, as depicted in Fig. 3 with locations a, b and c, respectively. After loading, the distance between squeeze-off steel cylinders is 20.16 mm (80% total thickness of PE pipe), as depicted in Fig. 1.

Scope B

Multiple squeeze-offs may be needed to ensure 100% shut-off during the squeeze-off process. This is normally conducted with double squeeze-off units simultaneously, Fig. 2. Thus, the deformation of the squeezed pipe between the two consecutive squeezed locations has special importance. Particular attention has to be paid to the distance between squeeze-off tools. Furthermore, consideration must be given to the distance between the squeeze-off tool and the neighbouring fitting and weld. Therefore, it is of interest to study the double squeeze-off PE pipe, as indicated in Fig. 2. In this scope, s 250 mm SDR 21 PE 100 pipe having a wall thickness of 12.6 mm with the double squeeze-off tool at 5D+100 mm in-between distance is analysed. The 100 mm is added as it's the length of the tapping tees saddle base, which is placed mid-way between the squeeze-offs to act as a gas vent. Following site practice, the squeeze-offs are done sequentially. The double squeeze-off is to be in the middle of the 12 m (48D) pipe length. To simulate the real-life condition, both ends of the pipe are restrained and 2 bar internal pressure is applied. As depicted in Fig. 3, the distance between squeeze-off steel cylinders is 20.16 mm (80% total thickness of PE pipe) after loading.

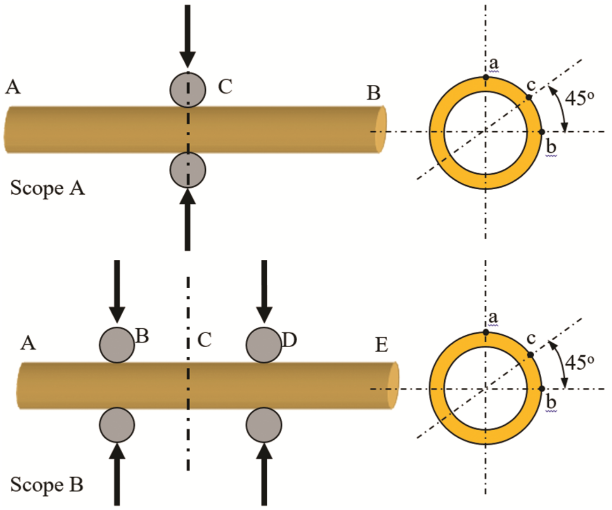

Fig. 3 — Calculated and tabulated stress locations for Scopes A and B, respectively. Points (a) are for 12 o'clock, points (b) are for 3 o'clock, and points (c) are mid-way between (1:30 o'clock) positions.

From this FEA analysis of double squeeze-off, the axial stresses between and away from the squeeze-off positions will be obtained at 12 o'clock, 3 o'clock, and mid-way between (1:30 o'clock) positions, as depicted in Fig. 3.

2.2 Material modelling

The mechanical response of PE is highly non-linear and time-dependent. The plastic flow starts to develop when there is a small strain, and the material behaves in both a visco-elastic and visco-plastic manner[17,19-21]. Due to this visco-elastic and the visco-plastic nature of PE materials, it is not an easy task to perform an accurate finite element (FE) stress analysis from the material point of view. The problem gets more complicated due to the fact that during the squeeze-off operation, the deformation at the most critical regions, namely at the squeeze-off ears, exceeds far beyond the yield stress of the material. These two hurdles in the material modelling overcomplicate the FE analysis of the problem. Additionally, the triaxial stress state around the squeeze-off ears complicates the problem further. Despite these difficulties, it would be worthwhile to investigate the problem with the uniaxial true stress-strain curve obtained for the material.

The material considered in the analysis was high-density pressure pipe-grade polyethylene, having a minimum required strength (MRS) of 10 MPa, also known as PE 100. This pipe-grade PE material has been extensively used in natural gas and potable water distribution networks. Figure 4 represents the experimentally determined uniaxial tensile stress-strain response for this grade of PE carried out at 0.025 s^{-1} strain rate test. This curve was obtained from samples extracted from the pipe, extruded from PE 100 material. The material was tested at 20 ^{o}C and a crosshead speed of 50 mm/min[21]. From the stress-strain curve of PE material shown in Fig. 4, it could be seen that the initial slope is only valid for strains up to yield, or about 10%. Beyond this point, non-linear visco-elastic and visco-plastic material models must be considered for the material characterisation, where the modulus is allowed to change as a function of strain. Considering this type of modelling adds additional complexity to the FE analysis. Since the strain at break for PE 100 material is over 600% and above 30% of strain, the graph remains relatively the same; thus; for the sake of convenience, only a small portion of the stress-strain curve is presented here.

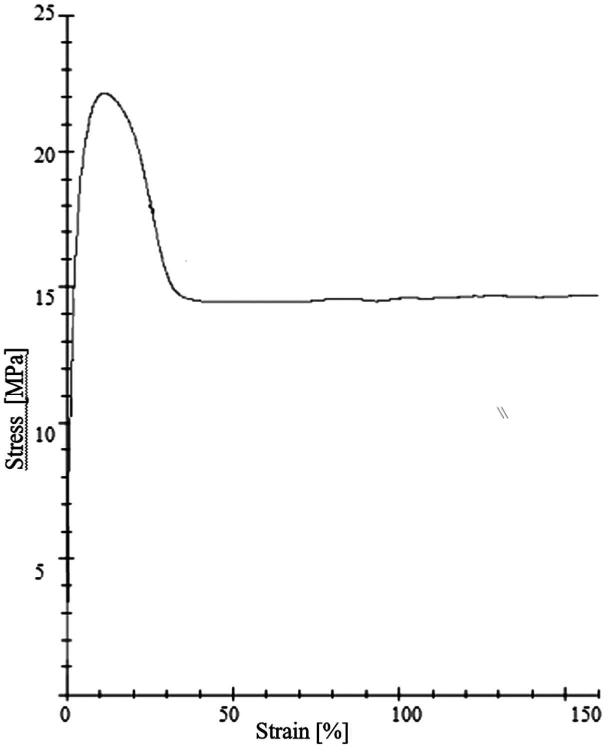

Fig. 4 — Engineering stress-strain curve of HDPE PE100 pipe-grade polyethylene.

In the squeeze-off phenomenon, the stresses are relatively high, particularly those that occur in the squeeze-off ears. Therefore, instead of nominal (engineering) strains and stresses, using true (logarithmic) strains and stresses in FE analysis would be more convenient. Thus, Eqs. 2 and 3 are used to convert the nominal stains and nominal stresses to true strains and true stresses, respectively. The true stress-strain curve, given by Eqs. 2 and 3, has been considered for finite element analysis. The engineering stress-strain curve of the PE material obtained during the tensile tests has been converted to true stress-true strain by using Eqs. 2 and 3 and loaded to ABAQUS.

$$\varepsilon_T = ln(1 + \varepsilon_N) \qquad \ldots(2)$$

$$\sigma_T = \sigma_N(1 + \varepsilon_N) \qquad \ldots(3)$$

where;

ε_T =True strain
ε_N =Nominal strain
σ_T =True stress
σ_N =Nominal stress

In the FE analysis, Poisson's ratio of 0.43 is used[14,19]. Due to the symmetry, only the quarter section of the pipe was considered in the FE model.

3 Results and Discussion

The validation of the FE analysis results with experimental results is essential for the rest of the current work. This is done with the single squeeze-off of PE 100 pipe with 180 mm outside diameter having SDR 17.6. In this validation test, given in Fig. 5, the vertical deflection results of a single squeezed-off pipe obtained numerically and experimentally with the Faro coordinate measurement machine (CMM) are given in Fig. 6, showing relatively a good

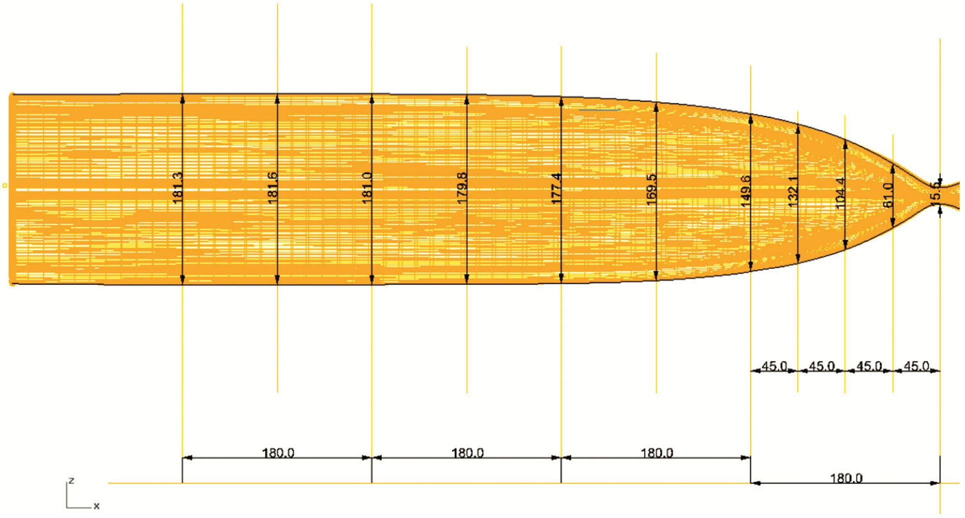

Fig. 5 — Measurements of the pipe external heights of an axial half-section (black lines)

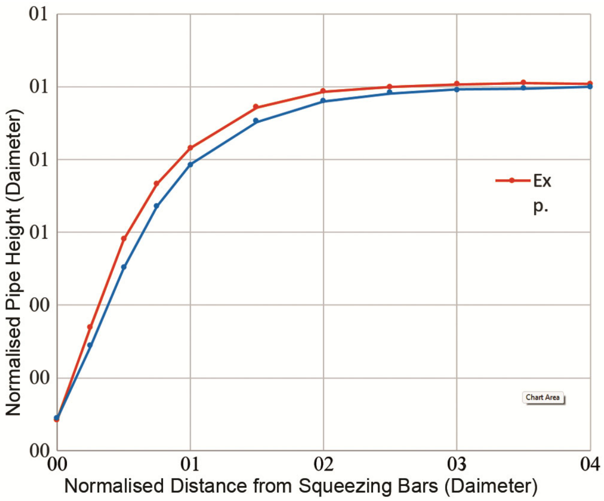

Fig. 6 — Shape of the pipe away from the squeeze-off unit. At 2D the pipe shape is relatively unaffected by the adjacent squeeze-off (98.6%)

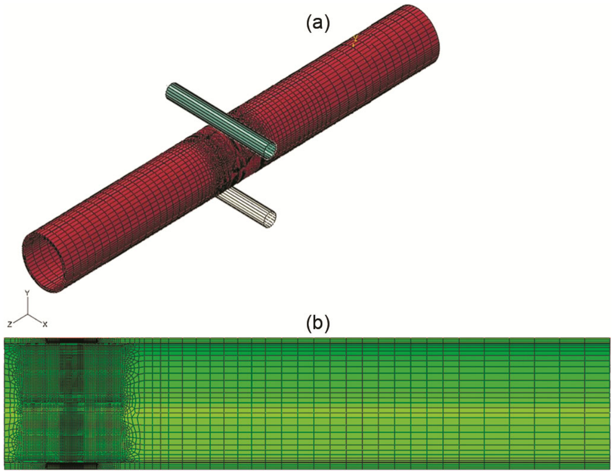

Fig. 7 — FEM models and meshing in single squeezed-off PE pipe. (a) is the perspective, and (b) is the front view of the pipe

agreement in between, with a maximum difference of around 15%. Furthermore, the force-displacement results of the squeeze-off test obtained experimentally[21] and numerically are in good agreement with each other. These two good compatibilities of numerical and experimental results reinforce the reliability of the current FE results.

3. Results of scope A

For Scope A condition, the FEM model and meshing in a single squeezed-off PE pipe are given in Fig. 7, showing finer meshes around the squeezed region. The distorted geometry of the pipe with von Mises stress is given in Fig. 8. As expected, the highest stresses are generated on each side of the squeeze-off ears. These are the locations where the squeezed pipes suffer dramatically. The hydrostatic pressure test results on squeezed pipes have also failed at these locations[21].

Figures (9-12) show the variations of outer axial surface stress and von Mises stress at locations (a) and (c) along the pipe length. Stress variations along the pipe for points (a) and (c) are very similar but stresses at point (b) along the pipe axis are almost three times higher than those at points (a) and (c). The maximum axial and von Misses stresses along the pipe length are created at the squeeze-off centre. Then, a sudden drop is observed at each side of the squeeze-off bar. It is also worth noting that the second peak axial stresses are generated at approximately 160 mm axial distance (0.64xD) from the squeeze-off centre, after which they begin to diminish and reach their asymptotic minimum values at approximately 1000 mm (4xD)

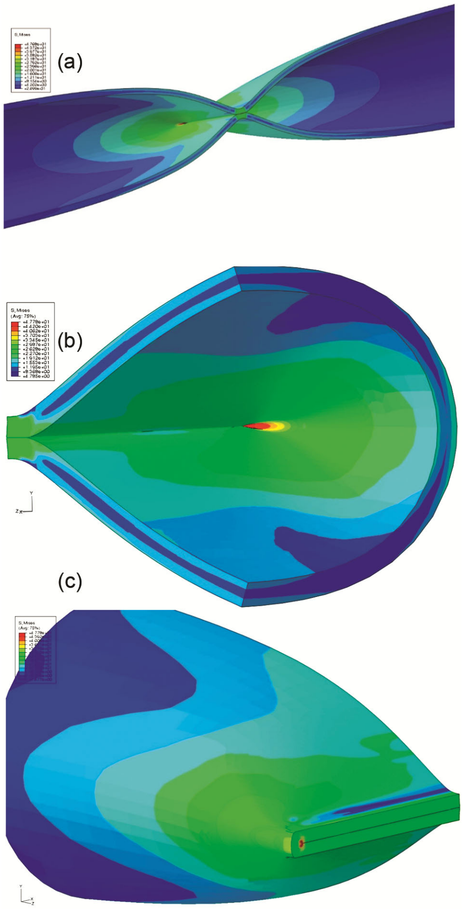

Fig. 8 — Single squeezed pipe deformation with von Mises stress distribution. (a) is the half view cut of squeezed pipe, (b) isone-quarter cut of squeezed pipe, and (c) is the one-quarter cut of the squeezed pipe ear.

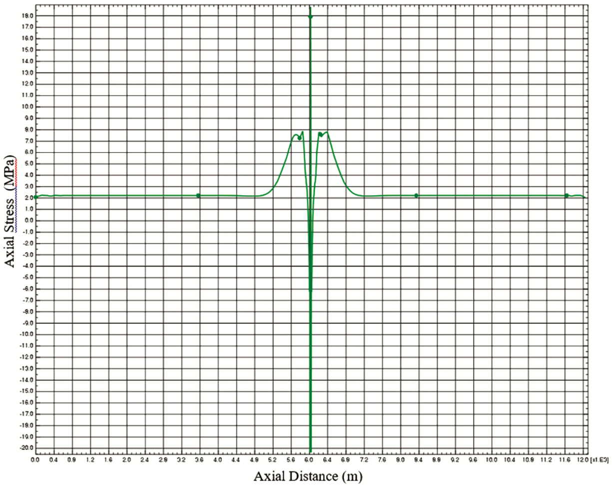

Fig. 9 — Variation of axial stress along the pipe axis at points (a).

from the squeeze-off centre. Thus, after the 4D distance from the squeeze-off centre, the pipe does not feel that it is being squeezed.

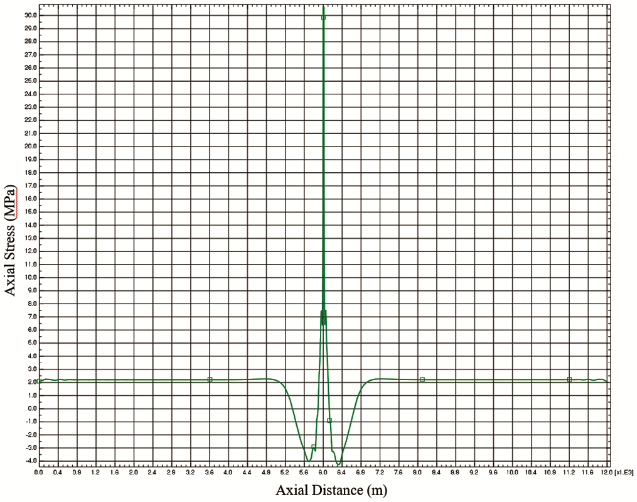

Fig. 10 — Variation of axial stress along the pipe axis at points (b).

3.2 Results of Scope B

For Scope B condition, the FEM models and meshing in double squeezed-off PE pipe are given in Fig. 13, showing finer meshes around the squeezed region. The distorted geometry of the double squeeze-off pipe with von Mises stress is given in Fig. 14. Maximum stresses are generated at each side of the squeeze-off ears, as in a single squeeze-off pipe.

Figures (15-18) show the variations of axial (membrane) surface stress and von Mises surface stresses at locations a and b along the pipe length. It is clear from these figures that the stresses remain relatively unchanged along the pipe up to the start of the squeeze-off region. However, all the stress components change their variations around the squeezing cylinders and attain their maximum values at the centres. Thus, similar to the single squeeze-off pipe, the maximum stresses are created at the squeeze-off centres. The maximum von Mises stress exceeds the uniaxial yield stress of the material, causing wrinkling at the squeeze of ears and the pipe wall thinning[22]. Thus, if any short or long-term failure occur due to the pipe squeeze-off, the failure will originate from these ears and extend along the pipe in the axial direction. A sudden drop in stress is observed at each side of the squeeze-off bars. The stress variation patterns beyond the squeezed zone are very similar to the single squeezed-off pipe in general. The main difference is in the region between the two squeeze-off toolbars.

It might be of interest to investigate the effect of internal pressure and squeezed PE pipe end conditions on the numerical results. In addition to the 2 bar

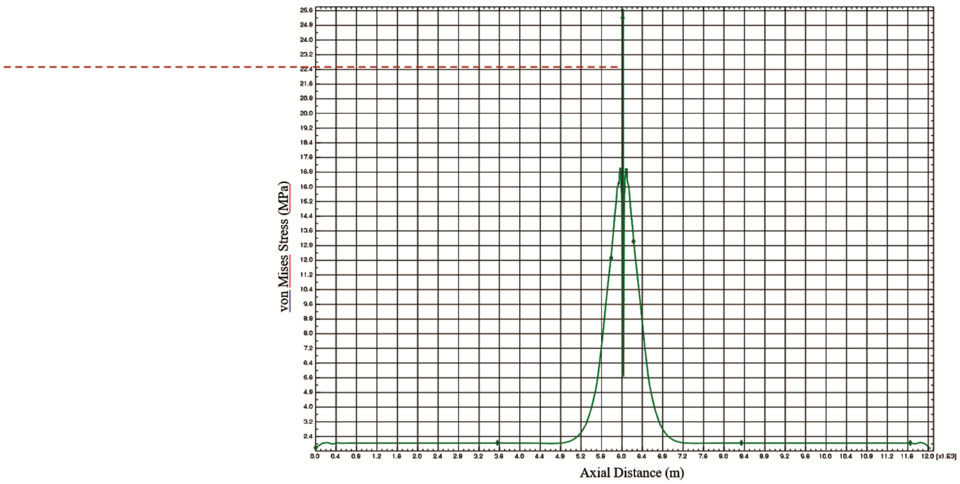

Fig. 11 — Variation of von Mises stress along the pipe axis at points (a).

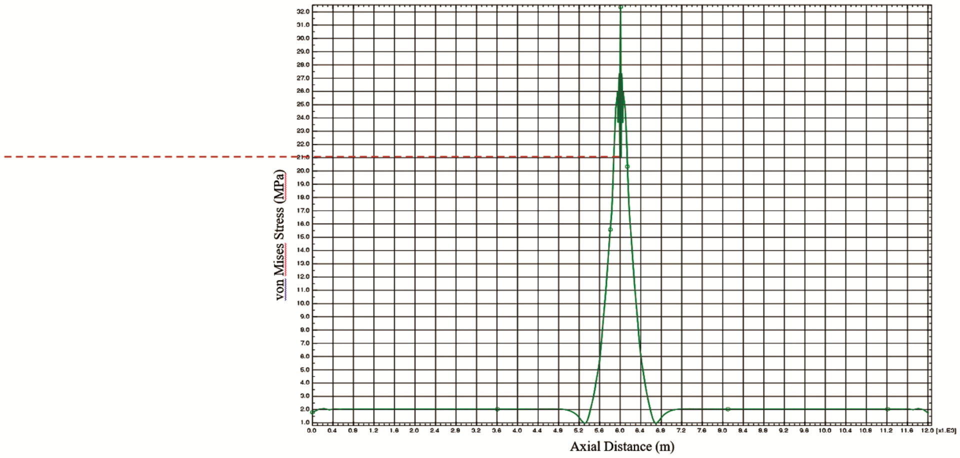

Fig. 12 — Variation of von Mises stress along the pipe axis at points (b).

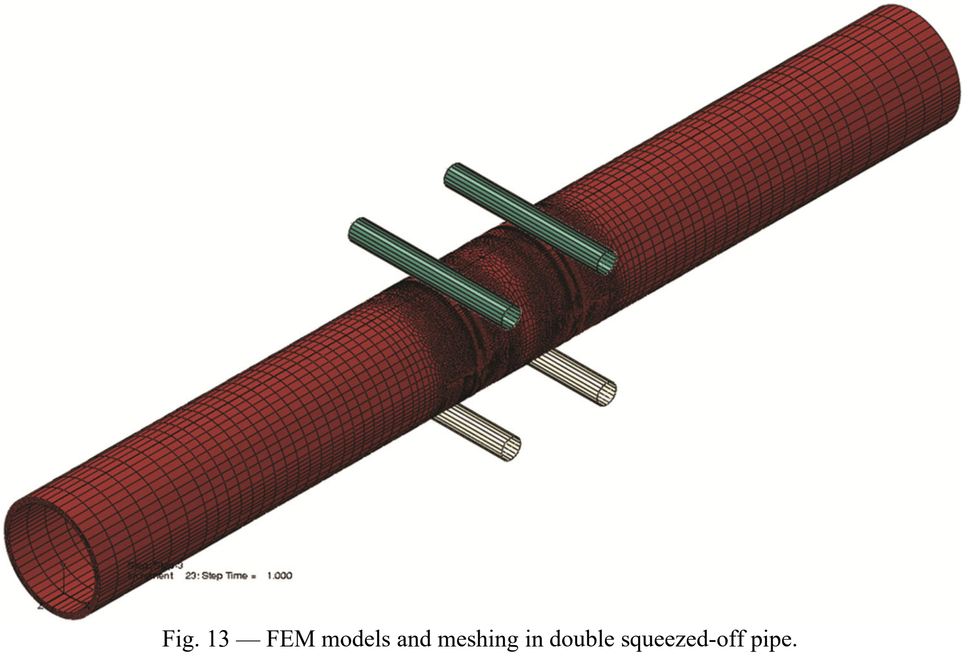

Fig. 13 — FEM models and meshing in double squeezed-off pipe.

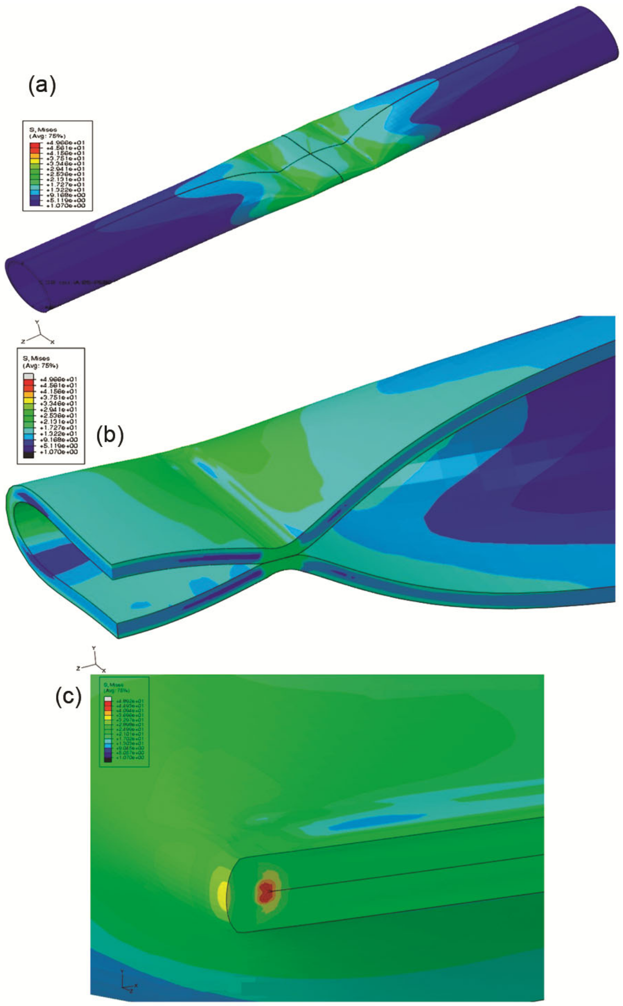

Fig. 14 — Double squeezed-off pipe deformation with von Mises stress. (a) is the full view of squeezed pipe, (b) isone-quarter cut of squeezed pipe, and (c) is the one-quarter cut of the squeezed pipe ear.

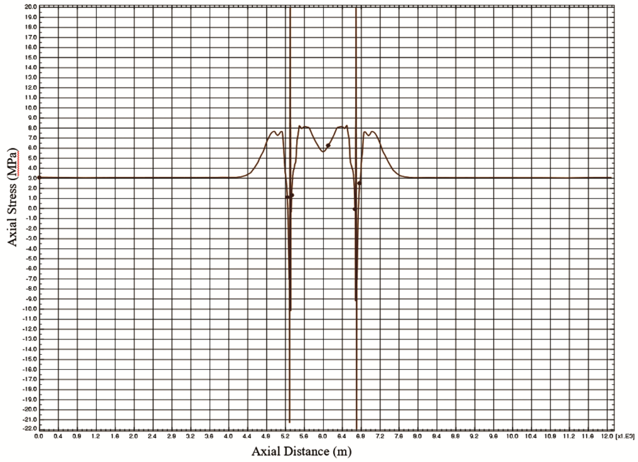

Fig. 15 — Variation of axial stress along the double squeezed-off pipe axis at points (a).

internal pressure and both pipe ends restrained, two additional test runs, one with only one PE pipe-end restrained and one with two PE pipe-ends restrained, were analysed. In these additional analyses, no internal pressure is applied. These additional analyses revealed that the peak stress values and overall stress distributions are affected by less than 1% with these two different boundary conditions and internal pressure.

It is clear from the FEM results that the stresses created at the pipe during the squeeze-off region, particularly at the ears, are well above the uniaxial yield stress of the PE material. Thus, if failure is to occur as a result of the squeeze-off process, it is most likely to take place at the squeeze-off ears. The short-term as well as long-term pressure tests on the squeezed pipes have also verified that failure always occurs at these excessively deformed and thinned squeezed pipe ears[21].

Standards such as ASTM F1734[18] and ASTM F1041[23], or some other code of conduct, code of practice, or regulations must be followed during the squeeze-off procedure to avoid damage to the short- and long-term performance of a PE piping system. Currently, those regulations impose a minimum distance of 3D, or 12 inch (305 mm), whichever is greater, from any butt-fusion or electro-fusion joints, mechanical connection, previous squeeze-off location, or second or multiple squeeze-off tools. Failure to comply with these limitations could lead to severe damage to the pipe and may result in catastrophic failure. Despite this limitation, pipeline operators are interested in shortening this 12 inches or 3D distance further to reduce time and effort.

It is worth pointing out that additional works are required before a complete understanding of the stress state in real squeeze-off tests. Furthermore, it is not possible to realistically model all the important aspects of squeeze-off behaviour unless the triaxial stress-strain response of the material is effectively modelled; presumably, in this situation, plastic deformations dominate and some form of the elasto-viscoplastic model is required. It is also worth mentioning that no effects of the frozen-residual stress state in the pipe wall[7] and any anisotropic effects resulting from the extrusion process of the PE pipe[24] were considered in this investigation, which is mainly due to the fact that residual stresses are small and may not make a significant contribution to squeezed pipe stress fields.

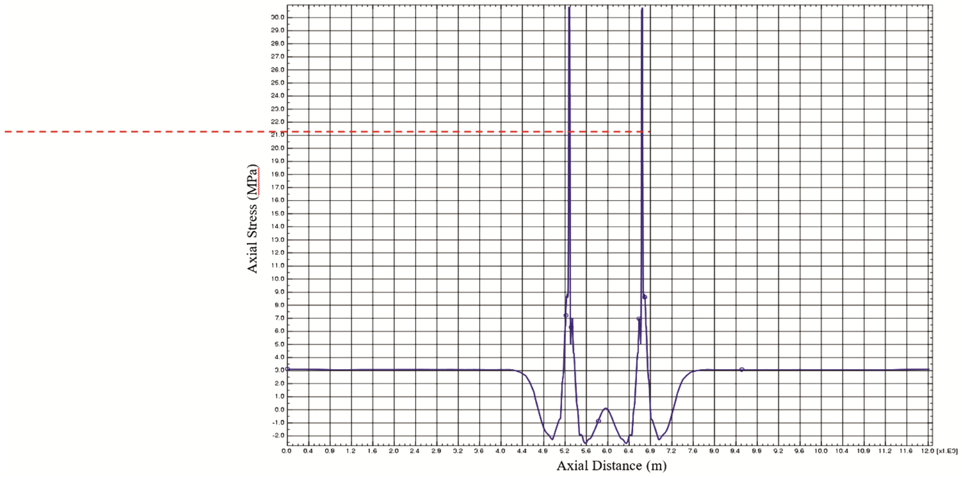

Fig. 16 — Variation of axial stress along the double squeezed-off pipe axis at points (b).

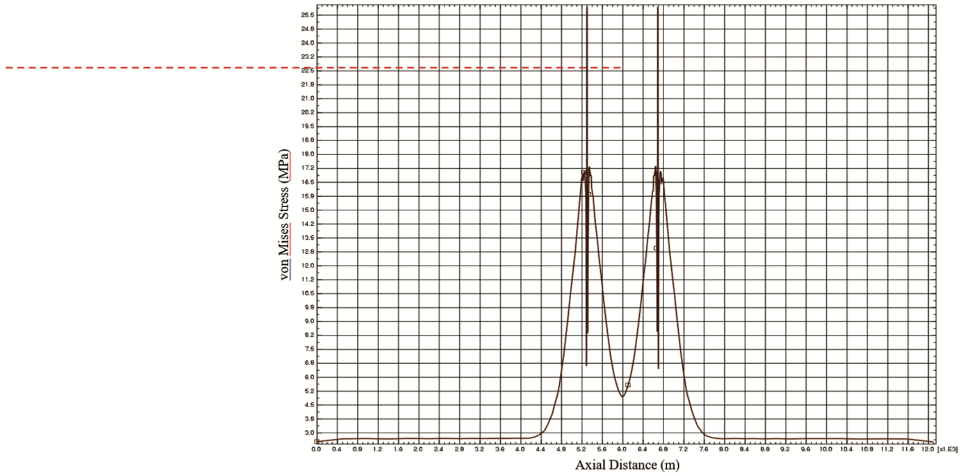

Fig. 17 — Variation of von Mises stress along the double squeezed-off pipe axis at points (a).

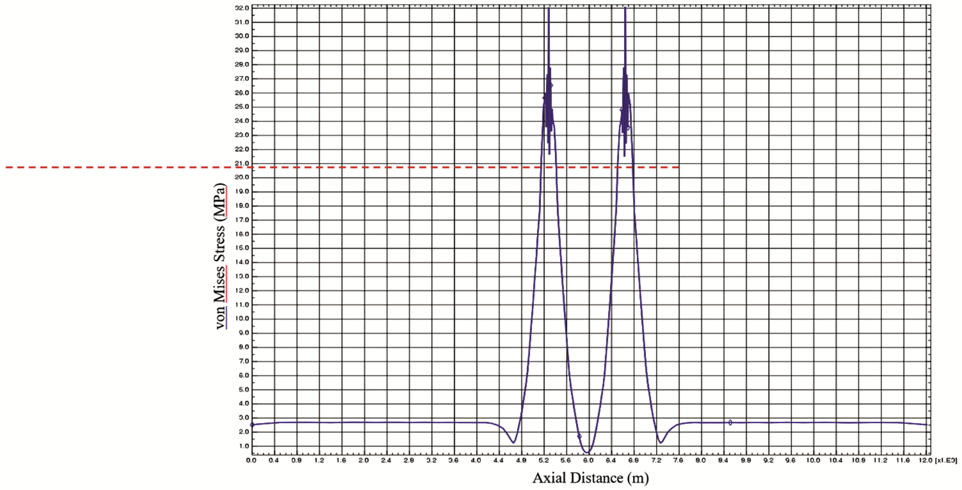

Fig. 18 — Variation of von Mises stress along the double squeezed-off pipe axis at points (b).

4 Conclusion

This article has touched on the most general features of finite element stress analysis of the squeeze-off of PE 100 pressure pipe. The three-dimensional finite element analysis results presented here have highlighted the following essential features and conclusions.

1) The FE calculated stress distribution of the squeezed-off pipe indicates very high stresses at the squeezed-off PE pipe ears. The stresses in these regions are of interest regarding the general effect of squeeze-off on PE pipe connections and the remaining lifetime of the pipe after squeeze-off.

2) All stress components, including von Mises stress, at the squeeze-off-ears are well above the uniaxial yield stress of the PE material.

3) The very high values for the 3D stress state at the ears reflect themselves on real pipe squeeze-off tests with a change in colour, such as stress-whitening and crazing at the squeeze-off ears, evidencing damage imposed on the squeezed pipe. The location of the damage in the hydrostatic pressure performance tests[21,25] on these ears is also another important verification of these higher stresses. Thus, reinforcement clamps or fittings at the squeeze-off location are highly recommended as a failure-preventing guideline in related governing codes and project specifications.

4) The material model used in the FE analysis considerably affects the stress and strain gradients throughout the pipe thickness at the squeeze-off ears. To predict the stresses in the squeezed pipe, the non-linear effects arising from the PE material response and large displacements must also be taken into consideration. This type of analysis may require further effort, but the results are always more realistic.

5) The findings and observations presented in this work investigated whether ASTM F 1041[23] requires a minimum of three pipe diameters or 12 inches (305 mm) distance from any electro fusion joint (1.5 diameters for butt-fusion joints) or mechanical fitting. As the stresses created around squeezed-off pipes are considered, the squeeze-off locations on pipes may be shortened further compared with the current minimum distance level imposed by the related ASTM standards, code of conducts, or practices.

Acknowledgment

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Nomenclature

ASTM	American Society for Testing and Materials
CMM	Coordinate measurement machine
D	Pipe outer diameter
FEA	Finite element analysis
L	Distance between the squeeze toolbars
SDR	Standard dimensional ratio
WC	Total compresses wall thickness
t	Uncompressed pipe wall thickness

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