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Numerical tool to model collapse of polymeric liners in pipelines

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ABSTRACT

Polymeric liners are widely used in the gas and oil transportation industry. They provide improved corrosion resistance to metallic tubes and they also are used in rehabilitation of deteriorated pipelines. Oil derived gases permeate across the liner wall; which during rapid depressurization produce external pressure that in many cases lead to buckling collapse of the liner. A number of simple models to calculate critical pressure for buckling collapse are available, but these models do not account for surface or geometrical defects that are usually present in liners under service conditions. The non-linear characteristics of the problem generate convergence issues that make it difficult for classical FEM to reproduce the actual behavior of experimental curves. This paper is concerned with simulation of the buckling collapse of HDPE liners. Three ways to raise and resolve the issue of liner collapse have been used in this study. Two of them, the General Static Model and the Riks Static Method have been used before for similar simulations. Innovatively in this work, a non-conventional approach to finite element analysis (FEA) which makes use of hydrostatic elements has been tried for the first time. This approach has the inherent advantage of allowing the use of time-dependent material constitutive models. Three types of constitutive models were considered to model HDPE stress–strain behavior: elastic, ideal elastic–plastic and an elastic-strain hardening plastic model that takes into account the complete deformation curve determined from uniaxial tensile experiments. Validation of the simulations are made by comparing the results with analytical, or semi-analytical models and with results from previous publications. The collapse of polymeric liners in the presence of external pressure is adequately reproduced by the finite elements method (FEM) models developed.

1. Introduction

Liners used for internal protection of pipes have had two main engineering applications: as a method of corrosion protection in transport of aggressive chemical agents and rehabilitation of damaged pipes. The rehabilitation technique known as relining was first developed in Europe and North America for the rehabilitation of water pipes [1]. Liners can fail after a certain time in service, causing major economic losses. Of these failures, those occurring during rapid decompression of pipelines are of interest for this study. Sudden decompression could occur with certain frequency, either due to service stoppages or shut downs for inspection or maintenance [2].

Avoiding failures of liners led to recent studies aimed to elucidate mechanisms and root causes of liner failures [3–6]. Some organic components in oil are capable of penetrating plastic materials, preferably in their amorphous phases. This interaction can be seen as an effect of physical swelling, caused by the rupture of the attraction of the intermolecular link due to the presence of migratory species.

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Polymers in high pressure operation dissolve CO_2 and CH_4 gases which are dissolved in oil. They permeate through the wall of the thermoplastic material, to balance the internal pressure of the pipe with that of the outer annulus or gap between the liner and the pipe wall. Permeation rate increases with the severity of swelling of the liner material, a relevant in-service degradation mechanism when the liner is in contact with hydrocarbons. According to these considerations, after a depressurization liners are subject to stresses generated by excessive pressure on the annular cavity which can lead to the collapse of the liner by radial buckling. Fig. 1 shows a section of a failed liner. It shows how a liner can collapse. There are also other types of failures [7–9] related with thermoformed joints in certain host pipe geometries that represent potential failure sources. These could generate micro-cracks and brittle fracture of the liner [10]. These types of failures are not considered in this work.

Although annular pressure from gas migration from the bore is the base case investigated here, it is worth noting that the base design case in subsea water injection flowlines is that the liner must be resistant to vacuum collapse. A vacuum could arise if the pressure in the reservoir is lower than a column of injection water of the same depth and the injection pumps shut down without wellhead valves closing. This would enable injection water to flow down into the reservoir pulling a vacuum behind it.

Analytic models allow calculating the critical pressure which causes the elastic collapse by buckling of a restrained tube under external pressure. The Glock model [11] is based in the principle of minimal potential energy and the non-linear deformation theory:

$$P_{cr} = \frac{E}{1-\upsilon^2} \cdot \left(\frac{t}{D}\right)^{2,2} \tag{1}$$

where E is the elastic Young's modulus for the material, v is the coefficient of Poisson, and t and D are pipe thickness and diameter respectively. This elastic model does not consider that the material can deform plastically; this model is useful in thin walled pipes that fail by elastic buckling before yielding. Jacobsen [12] developed a semi-analytical model which considers yielding, according to the following system of equations:

$$\frac{R}{t} = \sqrt{\frac{\left(\frac{9\pi}{4\beta^2}\right) \cdot \left[\pi - \alpha + \beta \cdot \left(\frac{sen\ \alpha}{sen\ \beta}\right)^2\right]}{12 \cdot \left(\frac{sen\ \alpha}{sen\ \beta}\right)^3 \cdot \left[\alpha - pi \cdot K - \beta \cdot \frac{sen\ \alpha}{sen\ \beta} \cdot \left(1 + \frac{\tan^2(\alpha-\beta)}{4}\right)\right]}} \tag{2}$$

$$\frac{P}{E'} = \frac{\frac{9\pi^2}{4\beta^2} - 1}{12\left(\frac{R}{t}\right)^3 \cdot \left(\frac{sen\ \alpha}{sen\ \beta}\right)^3} \tag{3}$$

$$\frac{\sigma}{E'} = \frac{t}{2 \cdot R}\left(1 - \frac{sen\ \beta}{sen\ \alpha}\right) + \frac{P \cdot R \cdot sen\ \alpha}{E' \cdot t \cdot sen\ \beta} \cdot \left[1 + \frac{4\alpha\ Rsen\ \alpha\ \tan(\alpha-\beta)}{\pi\ tsen\ \beta}\right] \tag{4}$$

where E' is Young's modulus in plane strain deformation $E/(1-\upsilon^2)$, R is pipe thickness radius. Σ is yield strain, P is the collapse pressure and A and B are geometric parameters defined in Fig. 2.

This model considers the critical pressure in which a liner reaches the material yield stress at some point [13]. The model is recommended for the design of metallic liners [14]. In the case of thick pipes, for which yielding occurs before reaching the buckling pressure, the collapse pressure predicted by the model can be lower than the actual failure pressure. But, thin pipes

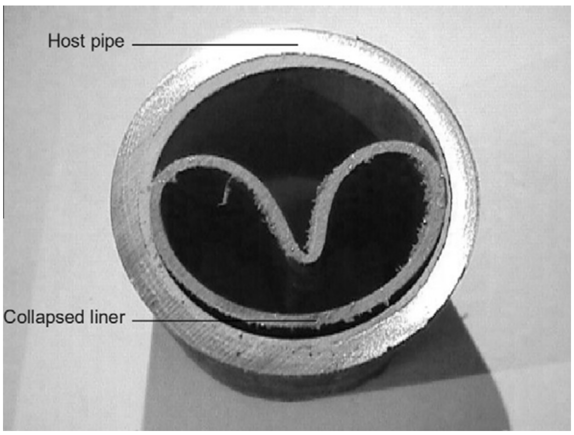

Fig. 1. Section of a collapse failed liner.

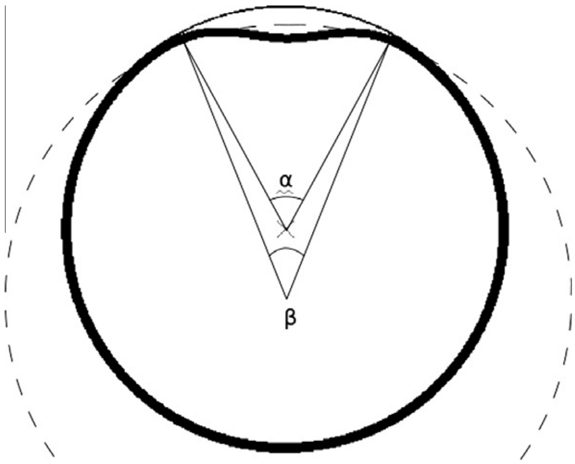

Fig. 2. Schematic of buckling of a liner with a single lobe.

tend to fail by buckling before reaching yield stress, and models could predict a larger critical pressure than the actual failure pressure.

El-Sawy [13] based his FEM analysis in determining whether the liner collapses elastically or plastically:

$$\frac{\sigma_y}{E} = 1.45\left(\frac{t}{D}\right) + 3.93\left(\frac{t}{D}\right)^2 \quad (5)$$

Eq. (5) determines the limit between both collapse types, and depends upon t/D and σ_y/E. Both Glock and Jacobsen models consider the shape of the final cross section of the collapsed tube as a single lobe shape. This failure mode is the most critical and is shown in an actual case in Fig. 1. These models are limited to considering the material as elastic – ideally plastic; they are not able to model the mechanical behavior with constitutive equations. Aside from the limitations described, these analytical models are not able to analyze the influence of geometrical or surface defects present in a real situation.

The purpose of this study is the development of a FEM model of liners which allows introducing experimental data relating to the in-service mechanical behavior of the liner material and specific geometric and surface conditions. The model developed in this work is intended to be used as a general tool, not only in failure analyses but also in the design stage. This article describes a specific model developed with FEM to assess the incidence of common geometric defects in an HDPE liner. A very small out of roundness is introduced in the FEM mesh to nucleate buckling; validation of the model is carried out by contrasting results with analytical predictions.

2. Numerical and testing procedures

2.1. Purpose and methods

At this stage, the developed model is not intended to predict the actual values of collapse pressure of a real component. The material was modeled as elastic–plastic with strain-hardening, from data obtained in HDPE tensile tests. This behavior was introduced into the Abaqus software environment using a table with stress and plastic strain data. It must be borne in mind that the mechanical behavior of a polymeric component is highly dependent on temperature, time, applied stresses, and strain rate. These are strongly influenced by prolonged contact with oil or other fluids transported by the pipeline.

The collapse of polymeric liners in the presence of external pressure is reproduced in this study by finite element modeling. Different types of constitutive models for the HDPE material and various FEM analysis approaches were applied. Validation of the method was carried out by comparison with analytical and semi-analytic models previously described; numerical results were also compared with results from previous publications.

Frost et al. modeled the collapse behavior of liners confined within rigid steel pipes [15]. They studied the axial stability of collapse under different loading conditions and the effect of restraint at the liner ends. They found that the effect of end restraint can be neglected, except in the case of short liners, where buckling collapse can be inhibited. Their work demonstrated that the effect of restraint at the liner ends can be neglected for long liners, with length to radius L/R values greater than about 2. This is indeed the normal case in practical applications. Liners are installed in lengths ranging from 200 to 1200 m, so that longitudinal deformations are heavily constrained, and axial strains are practically null. This allows considering a section of pipe of a certain length L under plane strain. In this study, $L = 2D$, as also done in previous works [13,16]. The full 360° profile of the liner was originally modeled in order to visualize the shape of the collapse; afterwards symmetry was used to model only half the cross section.

A small degree of ovalization was introduced to induce buckling collapse. The ratio between larger and smaller diameters was kept at 1.0005; that is, ovalization is only 0.05%. The lengths of the two radii within the smallest diameter were kept identical; thus imposing a symmetric figure. This symmetry induced a single-lobe buckling.

2.2. Tensile testing and constitutive model of liner material

Bone-shaped test pieces were machined from a 2 mm thick compression molded HDPE plate. Tensile tests were conducted with an extensometer to characterize elastic Young's module. A Poisson's ratio of 0.35 was initially defined, which represents an average for measured values in liner materials.

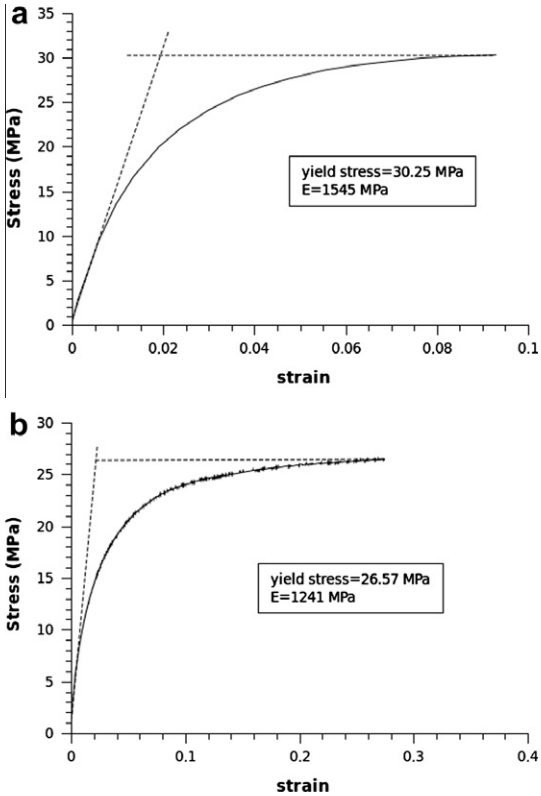

Fig. 3. HDPE tensile tests at two different strain rates. Fig 3a – 50 mm/min. Fig. 3b – 1 mm/min.

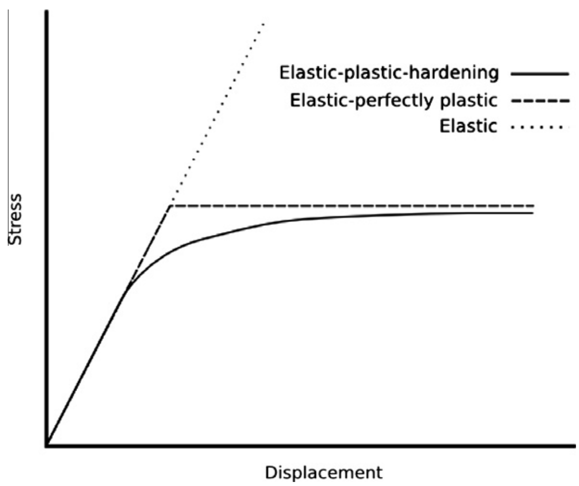

Fig. 4. Constitutive models for liner material.

Three basic constitutive models were considered to assess their influence in the collapse behavior. These are elastic, elastic-ideal plastic, and elastic plastic with strain hardening as illustrated in Fig. 4.

2.3. FEM models

Three ways to raise and resolve the issue of modeling liner collapse have been used in this study. All three cases involve a static analysis, although in different ways. This means that the complete collapse is considered as a series of successive equilibrium steps. The absence of time as a variable would in principle not allow coupling a visco-elastic constitutive equation. The static analysis is valid for the constitutive models so far considered (Fig. 4) [13,16]. Three methods are considered, these are called general static, static with hydrostatic elements, and Riks general static.

When loading has a large bending component it is advisable to use linear and quadratic functions. In this study the liner is modeled with quadratic 8-node quadrilateral elements in plane strain (CPE8R) using the Abaqus 6.9 software. The host tube was modeled in certain cases as an analytical rigid surface or a discrete rigid. The host is considered to be a buried steel tube, which has a practically infinite rigidity compared with that of the HDPE. Contact between the outer surface of the liner and the host is modeled considering normal and tangential behaviors. To comply with the rigid tube assumption, the tangential behavior is modeled as a system without friction, and the linear elastic normal stiffness is taken as 10 times larger than that of the liner.

Since collapse represents a limit for linearity, the resolution of the finite element problem consists of the incremental application of load. The General Static Model was first used due to its simplicity [16]. A uniform and linearly increasing pressure was applied on the external surface of the liner profile. The host tube was modeled as an analytical surface. As the applied load grows, the profile is deformed up to collapse leading to pressure versus displacement curves according to the one shown in Fig. 5. The two main emerging disadvantages are the instability of calculation in post buckling, and that the model can never reproduce correctly a complete pressure versus actual deformation curve. The model imposes a linearly growing pressure, but in the actual case pressure is a function of the volume of gas contained in the annulus between liner and tube. Actual experimental pressure versus deformation curves (Fig. 6) present a fall at the time of the collapse, when the volume of

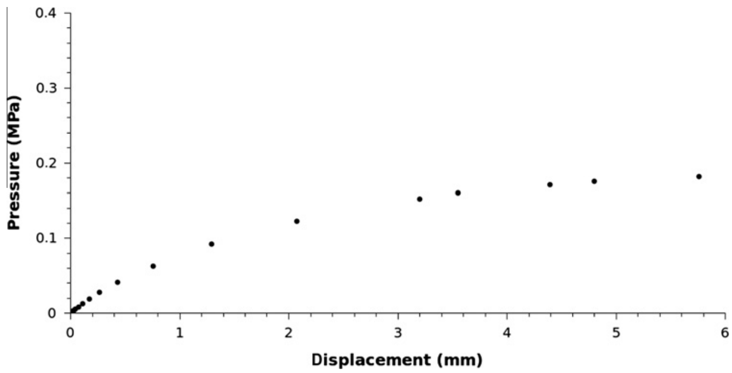

Fig. 5. FEM curve for pressure versus radial deformation of HDPE liner.

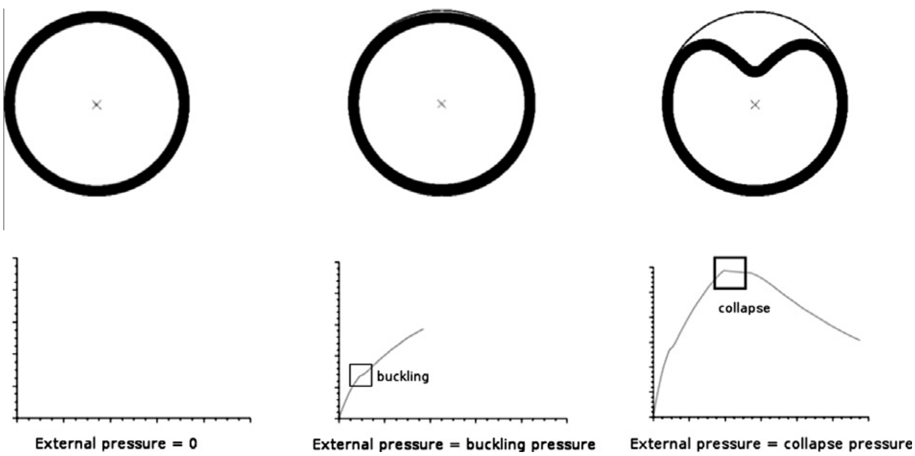

Fig. 6. Schematic representation of liner collapse under external pressure according to Pinel et al. [19].

the annulus suddenly grows. The imposition of increased pressure after collapse generates problems of convergence in the calculation.

The Riks Static Method uses iterative solutions to each increase of load to approximate the movement of the structure to a condition of equilibrium [17]. This condition is often expressed through the system of equations:

$$r = \lambda q - f(u) = 0 \tag{6}$$

where u is the nodal displacement vector, f is the vector of internal forces depending of u, q is the vector of external nodal forces, λ is a multiplier factor of vector q and r is the vector of residual or unbalanced forces. In classical procedures, a solution is sought iteratively at each load increase to reduce the factor r, the factor λ remains constant. This solution process, which specifies load jumps for which λ is constant, is called Load Control Method.

In structures with critical response conditions the system of equilibrium Eq. (4) might not have a solution if the factor λ remains constant in the calculation process. In these cases it is impossible to know the value of the loads λq corresponding to such critical points, or the behavior of the structure in post-critical states. One way to avoid this drawback is to treat the factor λ as another variable of the problem, so that the system (4) has a solution [17]. This method is recommended by Abaqus for behaviors with a high degree of non-linearity, as is the case of buckling collapse. This technique was applied and results were compared with similar works [13] and analytical results.

The Static Model with hydrostatic elements is used to represent fluid-filled cavities, in this case the gap or annulus between the host pipeline and the liner. The fluid can be modeled as (compressible) pneumatic or (incompressible) hydraulic. These elements share the nodes with the cavity filled with fluid; and represent an internal shell in a three-dimensional cavity or a one-dimensional perimeter in a two-dimensional profile (Fig. 7).

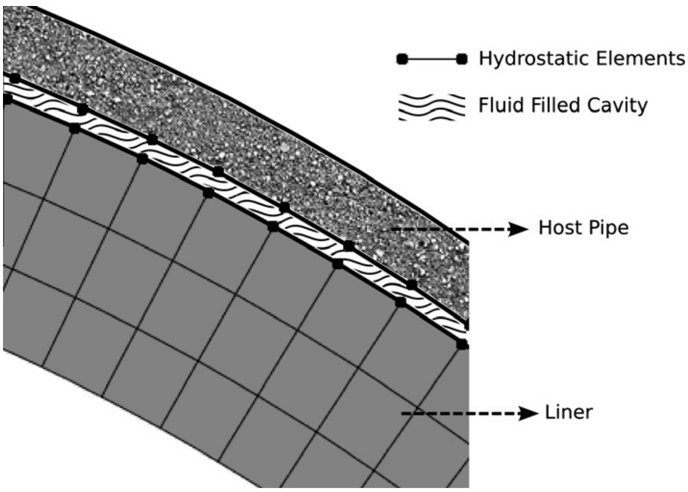

Fig. 7. Cavity with fluid elements.

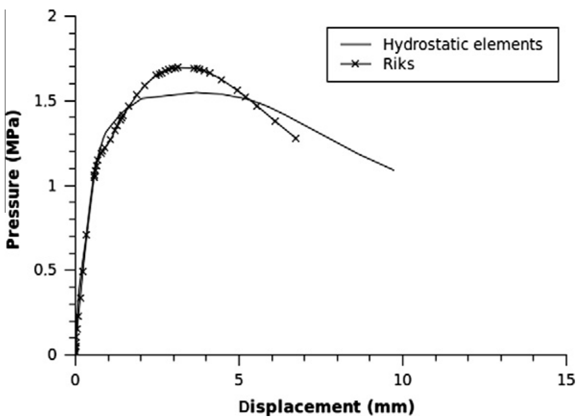

Fig. 8. Comparison between pressure versus displacement curves obtained with hydrostatic elements and Riks method for HDPE tube with t/D = 0.05 and an elastic–plastic model.

Temperature and pressure conditions are initially imposed. The amount of fluid retained in the annulus is progressively augmented with a constant flow. The increasing amount of fluid in the cavity increases pressure, which gradually deforms the cavity (the liner in this case). The quantity of retained fluid is increased with a defined flow. Volume and pressure of the annulus are consistently calculated by a node reference, both as a function of applied fluid flow. In this way the pressure suddenly drops at the time of the collapse, as happens in an actual collapse due to external pressure.

The difficulty of applying such elements lies in that they are not part of the graphic environment of Abaqus. In this work these elements are added directly in the analysis file as user-defined code; a software to build meshes with these elements was developed in Fortran 90. An advantage of this method over Riks method is that it can be used in a dynamic analysis. This is useful when implementing a visco-elastic constitutive equation. Such elements were not used in any previous works to model collapse. The great potential of this method is related to the capability of use a time dependent constitutive equation or a dynamic load. This is not possible using Riks method.

2.4. Analytical solutions

The analytical solutions by Glock (1) and Jacobsen (2–4) where considered for a comparison with FEM results. A routine in SciLab (numerically oriented programming software) was programmed for the resolution of the Jacobsen system of Eqs. (2)–(4) applying Genetic Algorithms.

3. Results

The mesh size used in the FEM model was approximately 1/4 of pipe thickness. A convergence analysis was conducted to prove its viability, by comparing the results of models with mesh/pipe wall thickness relationships of 1/10 and 1/4. Then, a 1/4 mesh was used for all work. For the verification of methods, pressure–displacement curves obtained with hydrostatic elements were compared with results using Riks method (Fig. 13). Two representative pressure curves corresponding to each method are depicted in Fig. 8.

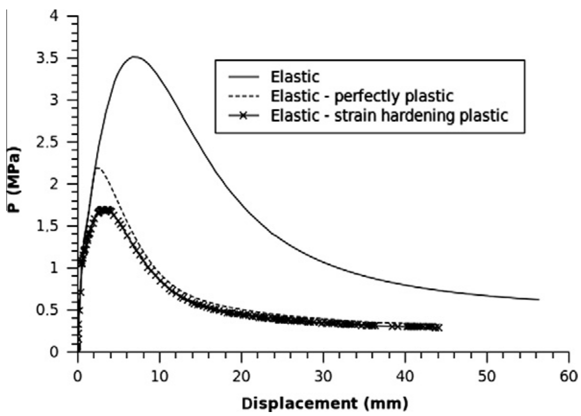

Fig. 9. Pressure curves for a $t/D = 0.05$ pipe with the three constitutive models (Riks method was used).

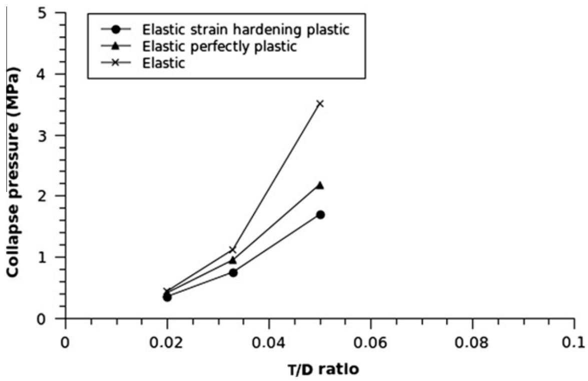

Fig. 10. Collapse pressures converge when decreasing t/D.

Predicted shapes of the collapsed section were also analyzed. The profiles were drawn in such a way as to induce buckling in a single lobe. These are the most critical since they occur in real structures at the lowest pressure. As mentioned in earlier work [18], even in the case of a single lobe collapse there is a trend that begins with the formation of two lobes.

Simulations based on the three proposed models were conducted for different t/D ratios, using Riks method. According to experimental data from the left curve in Fig. 3 the elastic model considered an elastic module of 1545 MPa. The same elastic module and 30.25 MPa yield stress were used for the ideal elastoplastic model. The whole curve in Fig. 4 was used for the elastoplastic with strain hardening model. When applying these different models, results differ mostly after bucking or in the linear first part of the pressure versus displacement curve (Fig. 9).

It can be seen that the largest collapse pressure is predicted by the elastic model, while the smallest corresponds to the elastoplastic case with hardening model. These differences would decrease if the ratio t/D decreases. At lower t/D ratios, the probability of elastic collapse increases, while at larger t/D ratios the collapse tends to be inelastic [13]. This behavior is associated with the relationship between the pressures for elastic collapse and the onset of plastic deformation. The lower of the two will define the type of collapse. It is noted in Fig. 10 that the collapse pressures converge with decreasing t/D, and diverge for larger t/D ratios. This is in line with the fact that the elastic character of the collapse increases with decreasing t/D.

Fig. 11 represents Eq. (5) for the relationship $\sigma_y/E' = 0.017$ corresponding to HDPE. The lowest value of t/D falls in the area of elastic collapse, while the other values are within the inelastic zone.

The most important difference in the final form of the collapsed tube is seen between the elastic model and the other two (Fig. 12). The ideal elastoplastic and elastoplastic with hardening models more adequately resemble the actual final shape shown in Fig. 1.

The model of Jacobsen considers only the elastic modulus and the yield strength of the material, so the FEM model used to contrast the results with Jacobsen was the ideal elastoplastic model with $E = 1545$ and $\sigma y = 30.25$. FEM simulations were carried out with Riks method including hydrostatic elements with different t/D ratios. These are compared with the results of the equations by Jacobsen and Glock in Fig. 13.

Percent differences are plotted in Fig. 13a. FEM results with Riks method and hydrostatic elements differ less than 10%. When compared with Jacobsen equations, the largest difference occurs for the lowest t/D ratios. This positive difference of almost 50% further indicates that Jacobsen may overestimate the collapse pressure for low t/D. The Jacobsen model considers the critical pressure as the pressure for which first yielding in the line material occurs.

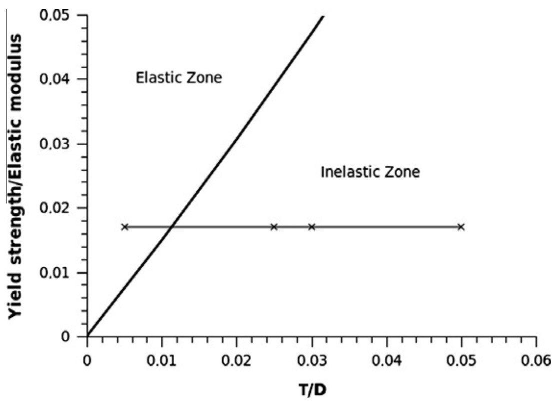

Fig. 11. Limit between both collapse types (Eq. (5)), for $\sigma_y/E' = 0.017$.

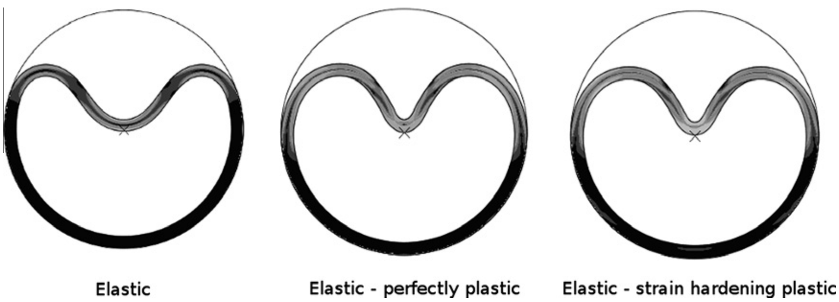

Fig. 12. Final collapse shape for pipes with $t/D = 0.05$.

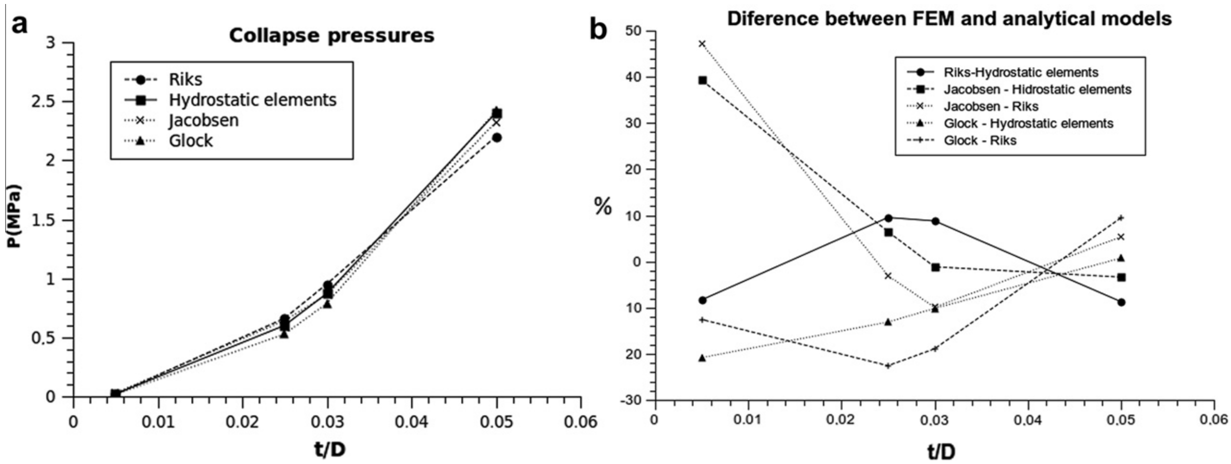

Fig. 13. (a) FEM predictions of collapse pressure and (b) Compared with results by Jacobsen and Glock.

Considering from Fig. 11 that for $t/D = 0.005$ collapse is elastic, these results are logical since buckling collapse precedes plastic deformation. In this case, the Glock model is more efficient. Increasing t/D the difference between FEM and Jacobsen is reduced. However, no great improvement is seen with respect to the model of Glock for the cases under consideration. Therefore, this method, which is easily solved, might be a good way for immediate calculation.

4. Conclusions

Polymeric liners are widely used in the gas and oil transportation industry. At high operation pressures, some oil derived gases permeate the liner wall. During rapid depressurization these gases produce an external pressure that in some cases leads to the buckling collapse of the liner. A number of models to calculate critical collapse pressure are available, which assume elastic or elastic perfectly plastic behavior of liner material. But these models do not account for surface or geometrical defects.

The difficulty to reproduce buckling collapse is related to the non-linear characteristics of the problem. In this work, a non-conventional approach to finite element analysis is used, in order to simulate buckling collapse of HDPE liners. Three constitutive models are considered for HDPE stress–strain behavior: elastic, elastic–plastic with strain hardening and data matching uniaxial tensile experiments.

Previous numerical models show that the effect of restraint at the liner ends can be neglected in all practical applications [15]. Semi-analytical and analytical methods such as those by Jacobsen and Glock have been developed to model the collapse induced by external pressure. However, they are unable to describe the whole process as they only give a critical value of pressure. In order to fully describe the problem it is necessary to use FEM simulation. Previous attempts to deal with the problem did not simulate the post-collapse pressure drop. Recent publications have shown the pertinence of FEM based simulations with the Riks method to solve the issue [13]. Riks method has the advantage of being a numerically stable and simple procedure to solve this problem. However, it cannot be used in dynamic conditions, that is, it would be impossible to apply to viscoelastic constitutive equations.

The hydrostatic elements introduced by the authors enabled FEM modeling of the whole process of elastic and inelastic collapse of polymer liners, under dynamic or static conditions. Maximum differences between FEM results using Riks model and hydrostatic elements is 10%.

Results also show that for HDPE liners, given their σ_y/E' relationship, the application of the method of Jacobsen is not justified. While Jacobsen is more effective for some t/D ratios, the implementation of Glock method is much simpler, yet maximum differences with FEM are 22% over the entire range. On the other hand, very low t/D ratios lead to mostly elastic collapses; here Jacobsen method over-predicts critical pressures for up to 60%.

From these results it emerges that hydrostatic elements may be a suitable tool for time-dependent problems. Further work is in progress in order to experimentally reproduce the collapse of a plastic liner and to check the prediction capacity of the proposed methodology.

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