

COMPARISON OF SINGLE-SOLVER FSI TECHNIQUES FOR THE FE- PREDICTION OF A BLOW-OFF PRESSURE FOR AN ELASTOMERIC SEAL

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Summary: *Assessment of leakage performance is a fundamental aspect in the design of elastomeric fluid seals. The key characteristic of the leakage performance is the blow-off pressure, which when it is reached, the leakage rate through the seal is no longer acceptable and the seal no longer performs its function. Prediction of the blow-off pressure under different operating conditions such as the amount of preload, pressure build-up rate, etc., would facilitate improvement in the seal design methodology and would allow subsequent efficient optimisation of a seal design. For an accurate prediction of the blow-off pressure, any computational methodology should ideally include Fluid-Structure Interaction (FSI), since the geometrical disposition of the seal, its deformation and its contact conditions with respect to the main structure are adversely affected by the fluid pressure. Two FSI single-solver techniques, available in the commercial FE-code Abaqus, are investigated in this study with application to the simulation of leakage. The first technique is Pressure Penetration Interaction, available for general structural analysis using a static implicit solver, which propagates the applied fluid pressure into contact openings. The second, more advanced FSI technique, is the Coupled Eulerian-Lagrangian (CEL) approach which is available for coupled fluid-structural analysis in a dynamic explicit solver. The CEL approach is the most versatile and can be applied to a wide range of FSI problems, e.g. simulation of a seal blow-off and fluid leakage through the resulting contact gap [1]. When trying to develop the art and science involved in the simulation of leakage phenomenon, a robust FSI technique has the potential to be a critically important design tool which could be applied to a wide range of more complex sealing geometries. This paper addresses a typical hollow rubber seal and investigates how the amount of initial compression and initial stretching affect the leak tightness of the seal using two different FSI techniques. The complexity of problem setup, the efficiency of the solver and the robustness of obtained solution will be compared and discussed.*

1 INTRODUCTION

1.1 Problem introduction

Accurate simulation of fluid structure interaction is a long running problem in the world of fluid sealing. This report will attempt to address the difficulties associated with this type of problem by employing the coupled Eulerian-Lagrangian (CEL) approach to facilitate computationally efficient, and accurate, prediction of the blow off pressure for a seal of typical geometry [2] and material properties.

The simulation work was completed using ABAQUS 2018, the CEL approach provided in this package allows for simultaneous computation of the fluid, and structure interaction effects, within one environment. This technique is a more advanced version of the arbitrary Eulerian-Lagrangian (AEL) [3] approach which utilises adaptive re-meshing and transfers results taken at the solid boundary of a fluid problem, to the solid boundary of a solid problem, for each individual time step. This transferring of results leads to interpolation between the time steps which can give rise to an erroneous result. By using the CEL technique these errors can be eliminated, making it an attractive choice. However, it is not without its disadvantages; the improved accuracy over AEL comes with a substantial increase in computational time.

The geometry of the seal and the corresponding pressurisation model have been purposefully kept simple to increase computational efficiency and aid in the speed of analysis. This study is interested in evaluating the performance of the technique and not the specific seal to which it is applied.

In order to gain a comprehensive understanding of the performance of the technique, a sensitivity study was conducted for the compression of the typical seal geometry, therefore the shape of the seal will not be varied during the various analysis attempts. Investigated parameters are the level of circumferential pre-stretch and radial compression. These different configurations were pressurised by a solid piston which pushed a body of fluid. The corresponding leakage pressures for different compression levels have been obtained, and evaluated to determine if the CEL technique provides effective and robust results.

1.2 Background

More traditional FEA simulations use a purely Lagrangian mesh to monitor the deformation of solids from their reference position. This approach leads to inaccuracies, when applied to problems subject to large deformations, due to distortion of the shape of individual elements. As the simulation considered in this project is expected to undergo severe deformation of the fluid as it deforms to the shape of the solid seal, a Lagrangian mesh for this component is not appropriate.

The coupled Eulerian-Lagrangian approach is extremely useful for simulation of multi-physics problems in which there are large deformation of the fluid-solid interface. This is due to the ability to track the position of the fluid when the solid boundary undergoes large deformations, without creating severe distortion of the mesh associated with the fluid domain. Having a fixed (Eulerian) mesh allows the fluid to move freely through the stationary mesh and make contact with solid boundaries. Further benefits of using an Eulerian mesh for the fluid domain is the capability for the creation and vanishing of the free boundary contacts in a realistic manner. Coupling this behaviour, with that of the seal finite elements, creates an

accurate simulation of fluid structure interaction.

As the model is arranged with the Eulerian domain extending further than the seal (see figure 2) the fluid can be allowed to deform, pressurise the seal and simulate a leak past the sealing surface into the free space. Due to the possibility of seal re-contact with the counter surface after leakage, CEL allows for the prediction of the sustained pressure during leakage and the secondary sealing pressure which defines the seal's ability to recover after unloading – phenomena that can only be investigated with this technique or experimental methods.

1.3 Limitations

A significant limitation of the CEL approach for fluid leakage problems is the time taken to complete the analysis. CEL is only available as a dynamic explicit analysis, therefore, in the case of this study, the computation time for a three second simulation is of the order of 480 CPU hours (120 hours on a typical 4 core processor). For this reason, the mesh of the fluid element and the solid boundaries are kept reasonably coarse in an effort to reduce the solution time. Large computational time arises from the need to carry out the analysis in small, stable, time steps. The duration of the stable time increment is defined as the time taken for a pressure wave to propagate across any element in the analysis [4].

1.4 Literature review

A large quantity of information is available on using the CEL technique with many papers focusing on the applications to multi-physics problems involving geophysics and material joining [5, 6]. Additionally a small portion of the literature focuses on the modelling of structure interaction with a solid body of hyperelastic material. One such paper by L Foucard [7], proved particularly useful for contextualising the project by providing a detailed background on the technique. Foucard also illustrated the accuracy of the CEL technique when applied to problems involving large deformations of hyperelastic media by comparing simulated results to experiment. This is valuable information for this study as similar materials are being considered that will experience large deformation. Based on the available literature this technique is most effective when applied to problems which are likely to experience severe mesh deformation such as the problem considered in this study. Further evidence to support the use of this technique for fluid-structure interaction problems is provided by S Morlacchi [8] in his paper which models the fluid-structure interaction between the rigid structure of a boat and an Eulerian fluid. Morlacchi provides a detailed specification of the analysis setup which proved valuable when constructing the model considered in this report

This project considered a combination of methods from these papers and applied them to a problem which involved large deformation of solid boundaries in hyperelastic media considering fluid-structure interaction.

The hyperelastic material model considered in this paper is presented in Treloar's "Stress-strain data for vulcanised rubber under various types of deformation" [9]. This quantifies the non-linear stress strain relationship of the material, validates the material models against experimental data and is widely regarded as the baseline for hyperelastic material models.

2 METHODOLOGY

2.1 Geometry

The geometry used for the simulation was created in Solidworks and is based on a simplified arrangement of a fracking well with a pipe which is statically sealed inside a cylindrical borehole. Figure 1 shows a revolved view of the geometry to illustrate the scale of the problem in a typical arrangement.

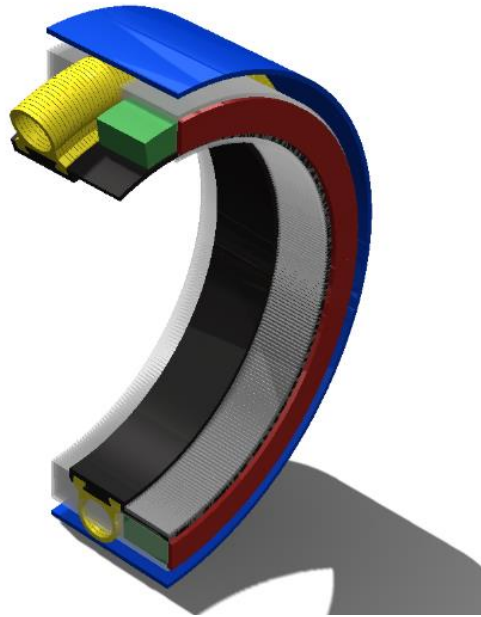


Figure 1: Revolved geometry

The internal radius of the elastomeric seal is 200mm and it is assembled inside a housing which anchors it to the pipe. Figure 2 presents a view of the model geometry which was used for the analysis. This is an axisymmetric 1 degree segment and the seal is 60mm tall.

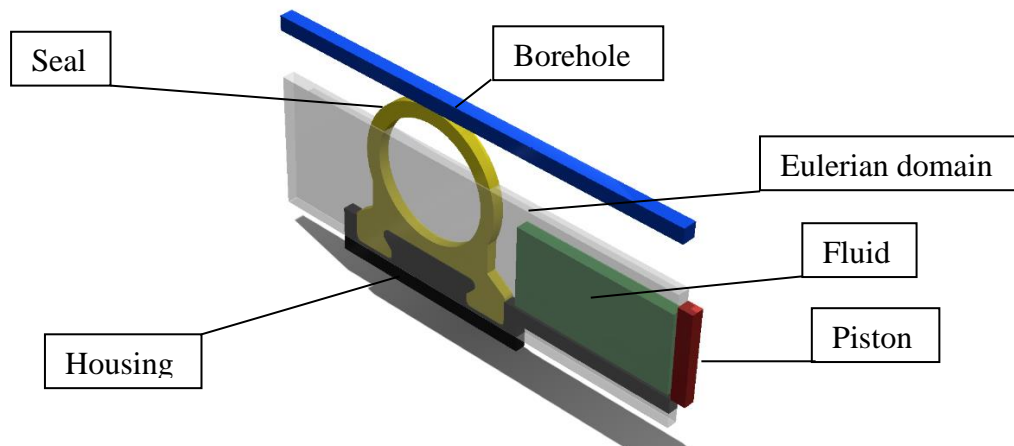


Figure 2: Axisymmetric 1 degree segment geometry

All of the components pictured are revolved around a common axis by 1 degree. The transparent “Eulerian domain” component houses the Eulerian mesh and the fluid component contained within the Eulerian specifies the initial position of the fluid. The fluid is coupled to the rest of the model through general contact definitions allowing the fluid structure effects to be analysed.

2.2 Analysis setup

Water

In accordance with the ABAQUS documentation [10] the “fluid” is assigned the properties of water using the Us-Up (Linear Mie–Grüneisen) equation of state [10]. This setup defines the wave propagation speed, dynamic viscosity and density of the fluid and enables realistic simulation of the dynamic behaviour of fluid.

Elastomers

Elastomers exhibit non-linear hyperelastic stress-strain relationships during experimental testing. There are many models available to replicate this behaviour in FEA, however, in this study coefficients for a third order Ogden model were used. This was chosen based on the experience of the academics involved and the results of a previous research project [11]. Figure 3 shows the stress-strain relationship for the chosen material model

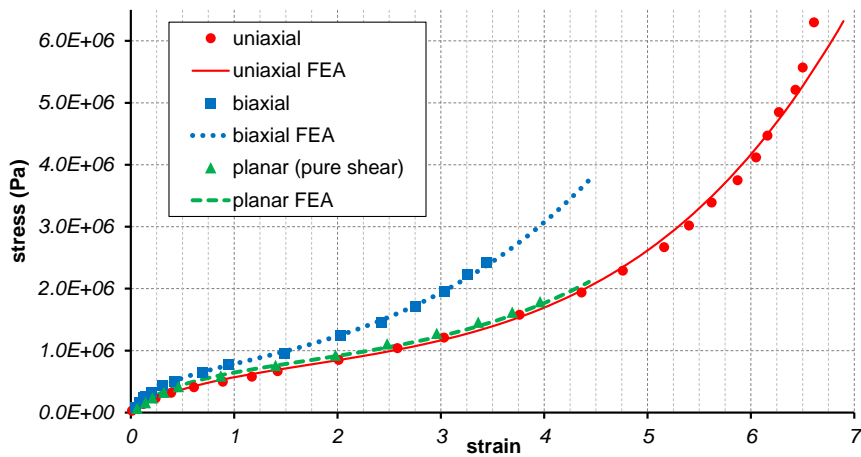


Figure 3: Stress-strain relationship for hyperelastic material

The constants that define the material behaviour are listed in table 1 and describe a near incompressible material with a Poisson’s ratio of 0.499995.

Table 1: Coefficients for 3rd order Ogden model

i	MU i	Alpha i	D i
1	371784.209	1.45175070	5.147674720E-10
2	1308.62521	5.48862619	0.00000000
3	15445.0545	-1.87467855	0.00000000

Contact

A general (surface to surface) contact was defined between the seal and the borehole with a coefficient of friction of 0.3. This is an approximation of friction taken from experimental results [12] as the analysis considered in this report is loosely based on similar material and contact conditions.

2.3 Simulation

The simulation work for this study was carried out in ABAQUS 2018 using the Coupled Eulerian-Lagrangian approach. The model considered in this study was created in two steps. Firstly, the seal was compressed in the radial direction and stretched in the circumferential direction in a general implicit analysis. The second step was to model the pressurisation of the fluid in a dynamic explicit analysis.

2.3 Implicit analysis

The purpose of the initial analysis was to radially compress and circumferentially stretch the seal. To simplify the analysis, all simulations were carried out at 10% strain in the circumferential direction. The value of compression was varied between 10mm and 20mm in 2.5mm increments to observe the consistency of the analysis technique in different configurations.

Creating an implicit model for this step reduced the computational time of the full analysis by approximately 4 hours. To use the results from this analysis, restart output requests were enabled in ABAQUS which allowed the displacements and reaction forces in the seal elements to be recorded and imported into an explicit analysis.

Model setup

Boundary conditions were specified to fix the position of the housing and move the borehole surface down vertically. A datum co-ordinate system was placed on one cut face of the seal segment to fix its position flush with the cut face of the housing. On the axis of the revolved components (centre axis of pipe in figure 1) a cylindrical co-ordinate system was defined to allow the second cut face of the seal geometry to be stretched around its circumference of revolution until a strain of 10% was reached. Only the 'Housing', 'Seal' and 'Borehole' components were used for initial pre-stretch.

2.4 Dynamic explicit analysis

The main portion of the project work was defining an appropriate model for the explicit analysis. The model was analysed over a duration of three seconds to minimise the effect of fluid momentum on sealing pressure.

Model setup

An initial state was defined in the explicit analysis to import the final nodal positions and strains of the elastomeric seal from the last step of the implicit analysis. Implicit import required an identical mesh to be used in both analyses.

In addition to the components used in the implicit analysis, the ‘Piston’, ‘Eulerian’ and ‘Fluid’ components were used to create the CEL simulation.

The same boundary conditions were applied and modified to fix the position of the ‘Housing’, ‘Seal’ and ‘Borehole’ components in their final position from the implicit analysis. The Eulerian domain was conditioned to be stationary with no fluid flow out of the cut faces and free movement of fluid within the domain. The ‘Piston’ (see figure 2) was defined to move 55mm towards the seal, compressing the fluid in the process. In order to minimise displacement jumps and violent wave propagation through the analysis, a smooth step distribution was used over the 3 second analysis.

The same contact conditions were applied, with the addition of contact between the fluid and solid. Fluid-solid contact is defined by an explicit ‘all with self’ contact condition which allows no slip once fluid is in contact, consistent with common boundary layer theory.

3 RESULTS

Results were obtained at 10% strain circumferentially, and a range of compression levels radially from 10 to 20mm. To illustrate the analysis and post processing of the CEL technique, one scenario has been presented in detail at 12.5mm compression. An overview of the full range of results is also presented to describe the behaviour of the seal as compression level changes. Figure 4 shows the distribution of strain in the seal and illustrates its deformation during leakage.



Figure 4: Maximum principle strain of seal under 12.5mm compression during leakage

Figure 5 shows the value of sealing pressure obtained for a range of compression levels, this is the pressure at first leak, see Table 2 for individual values. The first leak moment can be identified visually in the post processing stage. The field output delivers images every 0.001s during the analysis allowing accurate prediction and visualisation of the leakage point, see Figure 4. However, an alternative method was also identified to locate the position of first leak in time and to quantify the pressure at that point, shown in section 3.1.

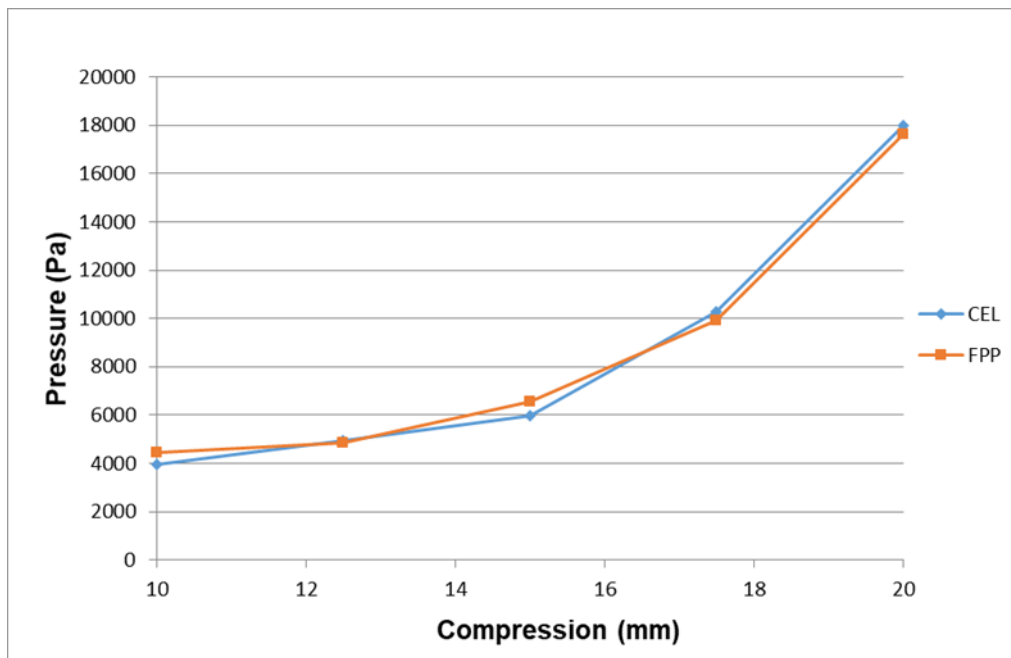


Figure 5: Graph showing comparison between leakage pressure vs compression level for CEL and FPP techniques

Table 2: Leakage pressures for both CEL and FPP techniques, and their difference

Compression (mm)	Pressure (Pa)		Δ (%)
	CEL	FPP	
10	3950	4453	12.7
12.5	4950	4850	2.0
15	5980	6550	9.5
17.5	10250	9910	3.3
20	18000	17610	2.2
	average:		6.0

3.1 Post processing

ABAQUS is capable of producing a field output for averaged pressure in the elements of the Eulerian domain but it is difficult to quantify the pressure of the fluid as there is large variations in pressure between different elements. A solution to this issue is to average the pressure across the entire domain, however, there are approximately 11000 elements in the Eulerian domain, and each element has a value of averaged pressure for each of the 3000 output steps. ABAQUS is not capable of executing the post processing required. As a solution, the xy-plot data was exported for all Eulerian elements in the analysis and processed in Microsoft Excel.

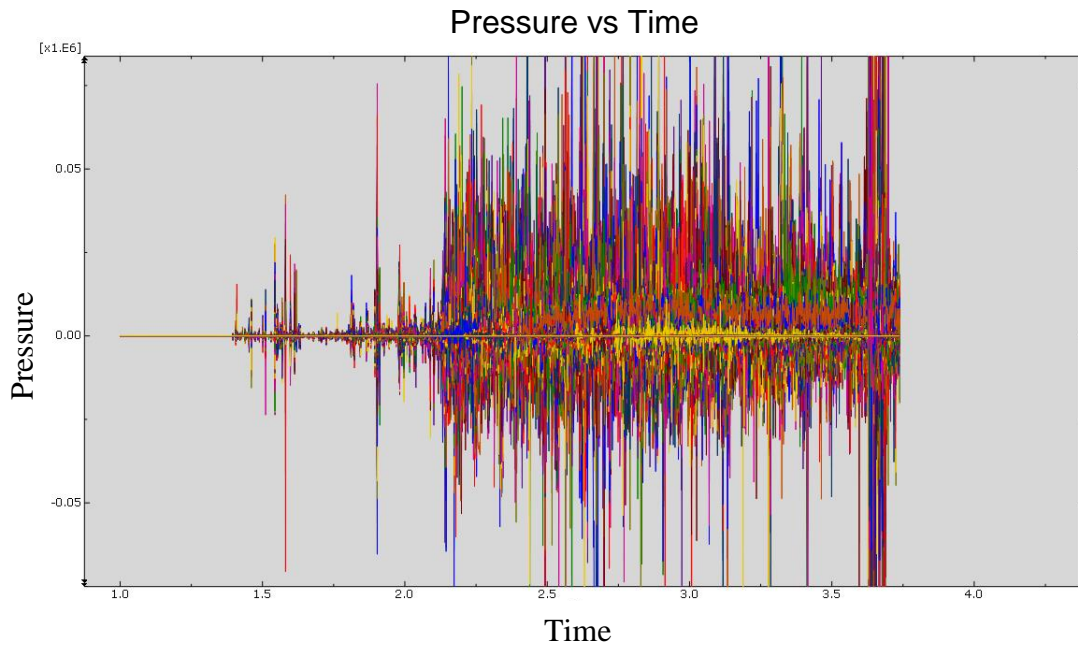


Figure 6: Element pressures versus time from ABAQUS

Figure 6 shows fluid pressure vs time with each line on the graph representing the pressure-time history for one individual element. In this form, the solution has too much noise to be valuable in determining the leakage pressure, however, Figure 7 shows the same graph with only one line representing the fully averaged pressure in the fluid throughout the analysis after processing in Excel.

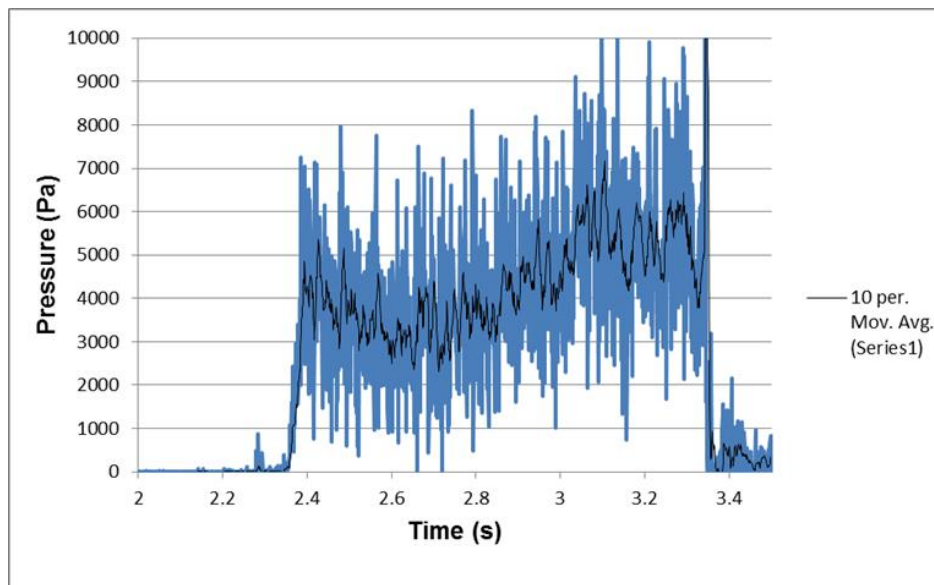


Figure 7: Graph of averaged fluid pressure vs time for 15mm compression

The results presented in figure 7 allow for evaluation of the pressure-time behaviour of the seal and quantify the pressure. At approximately 2.4 seconds the seal experiences an elastic leak at a pressure of 4950 Pa followed by a continuous cycle of: Leak – Pressure drop – re-seal – leak, which continues at a reduced pressure until the velocity of the piston increases, ramping up the pressure to a point where the seal is lost from its housing at time approximately 3.3 seconds, See figure 8. This behaviour is consistent with experimental results obtained by Q Liu [13] which act as an initial form of validation for the current results.

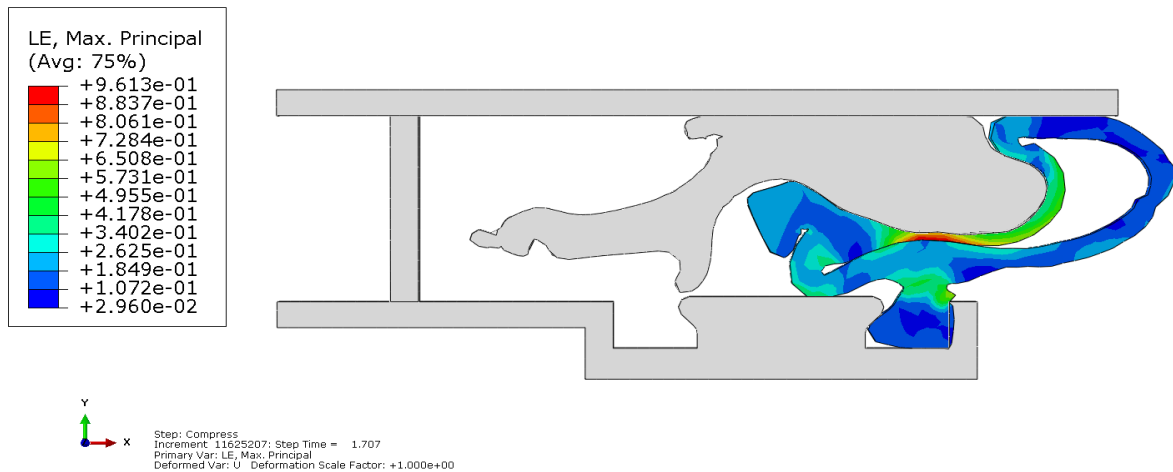


Figure 8: Loss of anchor points in seal at 15mm compression

3.2 Validation

Validation is essential for FE techniques as it relates the simulated model to the real world and must be carried out to develop confidence in simulation results. One way of carrying out basic validation is to compare results with, alternative, well validated FE techniques. As experimental validation is expensive, a comparative study was chosen for this report.

The CEL results shown in Figure 5 were validated against a well-established leakage prediction technique – Fluid Pressure Penetration interaction (FPP). FPP works by propagating fluid pressure into the contact region to simulate leakage. The technique was used and successfully validated by W Dearman for a similar application [14]. Figure 5 shows a comparison of both analysis techniques and validates the accuracy of the CEL technique for the range of compression levels resulting in average difference between the techniques of about 6%. Individual leakage prediction pressures for FPP can be found in Table 2.

The FPP simulation was carried out using an identical setup to the implicit pre-stretch analysis to give the same initial configurations and contact conditions. An additional analysis step was then added to accommodate the use of the fluid pressure penetration interaction which is coupled to each of the surface contacts. FPP then applied the applied the fluid pressure to the outer surface of the seal causing deformation until leakage. One advantage of this technique is the reduced computational time when compared with CEL, implicit FPP simulations have a duration of less than 10 minutes in the case presented here.

4 DISCUSSION

The results obtained show that blow off pressure will increase with increasing compression and that the increase is not linear. These results are expected and prove that the CEL technique is capable of analysing leakage of an elastomeric seal and will provide realistic results given the correct boundary conditions. The results from different compression levels show a variety of leakage mechanisms when analysed individually, such as continuous leakage, loss of one anchor point in the housing and more violent loss of both anchor points at the higher end of the compression scale.

The validation carried out confirms the accuracy of the technique when compared with an alternative, well established, leakage pressure prediction technique (FPP).

8 CONCLUSION

The findings of this project suggest that the future of leakage prediction may lie in the use of the Coupled Eulerian-Lagrangian technique as it has many benefits over the alternatives. Not only does this technique allow prediction of critical leakage pressure or blow off pressure, it also allows for observation of the behaviour of seals after leakage occurs which will allow for more efficient optimisation of seal design. CEL offers valuable visualisation of leakage mechanisms which enables designers to identify target areas for improvement. Applying this design methodology to the seal considered here, the designer may observe the extrusion of the seal through the gap and solve this issue with more robust anchor points or seal retention rings.

There are limitations to this technique such as large computational time and solution noise. Therefore, future work will aim to improve post processing and investigate techniques to reduce noise in the solution such as slightly compressible material models for the operating fluid. Alternatively, both analysis methods considered in this project may be used in conjunction to accurately describe the initial leak pressure and the post leak behaviour of the seal. The FPP technique is more efficient at predicting initial leakage pressure but does not provide any indication of post-leak behaviour, whereas CEL is not as effective at prediction of initial leakage pressure but is very effective in analysing post-leak behaviour. The use of both techniques provides a more comprehensive view of seal behaviour under all operating conditions.

Additionally, experimental validation of this technique would be extremely valuable when considering the accuracy of the simulated results before application to more costly and complex applications.

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