

### Simulation of rubber materials for seals in use in nuclear power plants

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# Abstract

## **Simulation of rubber materials for seals in use in nuclear power plants**

Finite element (FE) simulations of how rubber materials for seals behave over time is performed. The application is seals for nuclear power plants where seals are exposed to elevated levels of ionizing radiation and temperature.

A major challenge for the simulations is to find an appropriate material model for the rubber materials and how to calibrate it to experiments. Here is a material model proposed that can include effects like creep, permanent set, and temperature dependence. Calibration of material models for relaxation tests on EPDM rubber is performed and presented with good results. Simulations of leak and tightness of seals are evaluated and some initial observations on the effects temperature and ageing on the tightness are made.

Key words: Seals, Calibration, Hyper-elasticity, Visco-elasticity, Rubber, Nuclear Power

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# 1 Introduction

This report is about simulation of seals in nuclear power plants. It is a continuation of the report [1] that is part of the COMRADE project [2]. The purpose of the project, which this work is part of, is to evaluate how materials for seals degrade in a nuclear power-plant environment and how to measure this degradation. The permanent set test is a common way to evaluate the state of seals in nuclear applications. It is the expectation that the findings and results of this report can be of aid to nuclear power plant maintenance to understand the behaviour of the seals and develop new methods for the analysis of seals.

The particular aim of this report is the development of simulation methods that can be used to evaluate test methods of aged seals e.g. compression set and how they perform in service i.e. provide leak tightness. The developed methods should both be models that are of direct use and lay a basis for more advanced development on both numerical simulations techniques and materials modelling. Further information on the project and testing is available in [3].

Seals are typically made of a rubber material e.g. EPDM and have, for instance, the form of O-rings. An issue with rubber materials is their creep behaviour i.e. they deform over time at constant load and can also retain a permanent deformation – permanent set. This can reduce the sealing function since the compressive force on the seal decreases which can cause penetration of the pressurized fluid to be contained by the seal. A further complication in nuclear power applications is elevated temperatures and ionizing radiation levels which can accelerate or initiate degradation like creep in polymers such as rubbers.

The simulation is performed with finite element (FE) modelling. The advantage of FE modelling is that complex geometry and material behaviour can be handled. In this case the complicated behaviour of the rubber becomes the major difficulty to address here.

## 1.1 Outline

In this report, some parts of [1] are here re-given while in other parts, a reference to [1] is made. The continuation from report [1] is use of better relaxation tests for material model calibration and also incorporating temperature effects. The calibrated material model is then used to simulate compression set tests which are a standardized test to evaluate seal materials in this application. Results from performed compressions set testing are compared to the simulated results. This comparison can be seen as a validation of the calibrated material model. Finally, the capability of simulation of leak tightness is tested and evaluated.

## 2 Material modelling

Rubber is a material that compared to most other engineering materials can undergo extreme deformation and after loading (nearly) go back to the undeformed shape. This property makes rubber suitable for seals when assembled in pipe joints. This is because the rubber material is heavily deformed compared to the surrounding materials e.g. steel, which causes it to maintain the sealing pressure all times at. This type of extreme deformation is modelled with hyper-elasticity material models which is a generalization of linear elasticity (Hooke's law) that is only valid for small strains. Rubber also exhibits other behaviours like creep and permanent set. For further reading refer to e.g. [4].

### 2.1 Elasticity

The constitutive theory of hyper-elasticity is based on an energy density potential from which the relation between strain and stress is derived. The use of an energy potential leads to that the deformation is reversible causing the material to go back to the original shape (a property of elasticity). Many choices of energy potentials exist that can be used to model rubber, e.g. Neo-Hookean, Mooney-Rivlin, Arruda-Boyce, Ogden, and Yeoh.

An O-ring in a normal application is subjected to compressive strain of moderate magnitude (stretch 0.5 or engineering strain -50 %). In such conditions where the strains are compressive together with moderate shear strains, the Neo-Hookean type material is fully adequate [5], [6] and is here chosen for the elastic part of the material modelling. The more advanced hyper-elastic models are more suitable and needed for cases with large tensile strains where the polymer molecular-chains get heavily stretched.

The Neo-Hookean energy potential is the most simple and is

$$\phi = C_{10}(J^{-2/3}I_1 - 3) + \frac{1}{D_1}(J - 1)^2 \quad (1)$$

where  $I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$  is the first invariant,  $J = \lambda_1\lambda_2\lambda_3$  is the volume ratio and  $\lambda_i$  are principal stretches. It can be regarded as an extension of the linear elastic material model (Hooke's generalized law) and is valid for large strains. Like the linear elastic model, it has only two material parameters:  $C_{10}$  and  $D_1$  that govern elasticity similarly as Young's modulus  $E$  and the bulk modulus respectively in linear elasticity. In linear elasticity one often defines the behaviour with the parameter Poisson's ratio  $\nu$  which relates to the compressibility. In the small strain limit, hyper-elastic material models approach the linear elastic behaviour where expressions for  $E$  and  $\nu$  can be formed. For the Neo-Hookean model the relations are

$$C_{10} = \frac{E}{4(1 + \nu)} \quad (2)$$

$$D_1 = \frac{6(1 - 2\nu)}{E} \quad (3)$$

## 2.2 Creep

The creep and permanent set behaviours of the rubber are combined with hyper-elasticity in a rheological model. The modelling here is composed of parallel chains with an elastic component and a viscous component apart from one chain which instead have a plasticity component to include permanent set. The rheological network is portrayed in Figure 1 and is in the numerical FE-implementation generalized to 3 dimensions. All elasticity (springs in Figure 1) are modelled with the same hyper-elastic model while each chain (dash-pots) has different viscous behaviours. Furthermore, the stress in each chain is scaled with an individual factor  $S_i$  (index  $i$  representing chain number starting from zero for the elastic(plastic)-part) so they add with different amounts to the total response. The sum of all  $S_i$  adds up to 1.

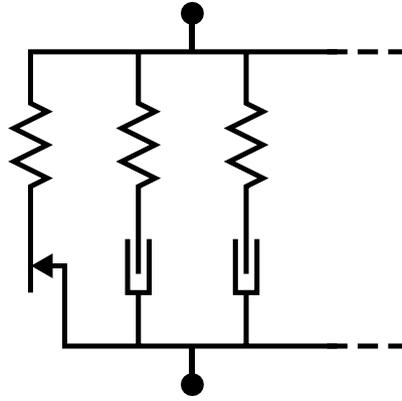


Figure 1 Rheological network with multiple chains where the springs model hyper-elasticity, dash-pots model viscoelasticity and one slider models plasticity.

The viscoelastic behaviour gives effects like creep and relaxation. The dash-pots in Figure 1 represent viscoelastic behaviour given by a creep law – a differential equation governing the creep rate  $\dot{\epsilon}_{cr}$  of the form

$$\dot{\epsilon}_{cr} = \frac{d\epsilon_{cr}}{dt} = f(\sigma, \epsilon, t; \mathbf{P}) \quad (4)$$

where  $\sigma$  is stress,  $\epsilon$  is strain,  $t$  is time and  $\mathbf{P}$  are material parameters. Various creep laws exist that can be used in the rheological network. Mixing of different creep laws in one rheological network is possible. Two examples of creep laws that are tried here are given below.

One is of strain hardening type and is used in a similar application [6] and given by

$$\dot{\epsilon}_{cr} = (A\sigma_e^n [(m+1)\epsilon_{cr}]^m)^{\frac{1}{m+1}} \quad (5)$$

where  $A, n, m$  are material parameters and  $\sigma_e$  is the von Mises effective stress.

Another creep law developed specifically for hysteresis in rubbers is the Bergstrom-Boyce model [7] which is given by

$$\dot{\epsilon}_{cr} = A(\lambda_{cr} - 1 + H)^C \sigma_e^m \quad (6)$$

where  $A, C, m$  are material parameters and  $\lambda_{cr}$  is a stretch measure.  $H$  is a constant to regularize the creep strain rate near the undeformed state, the value  $H = 0.01$  is used here. The parameter  $C$  is restricted to the interval -1 to 0 while typically it has the value  $C = -1$  for common rubbers. The parameter  $m$  is generally greater than 1.

## 2.3 Plasticity

The plasticity that gives the permanent set behaviour is included with the slider as depicted in Figure 1. Various models exist for plasticity. Either is a regular method for plasticity modelling with a von Mises yield surface and linear isotropic hardening, or more advanced plasticity models, used.

## 2.4 Temperature effects

Temperature dependence can also be included for the creep behaviour by applying Arrhenius shift factors to the creep rate. Each chain can have an individual temperature dependence. The temperature ( $T$ ) dependent  $\dot{\epsilon}_{cr,T}$  is thus implemented so that the reference creep rate  $\dot{\epsilon}_{cr}$  is multiplied by a temperature dependent factor  $a(T)$ , i.e.

$$\dot{\epsilon}_{cr,T} = a(T)\dot{\epsilon}_{cr} \quad (7)$$

Arrhenius equation can be written in various but equivalent ways. Here it is written in the form

$$a(T) = \exp\left(-\frac{E_0}{R}\left(\frac{1}{T - T_z} - \frac{1}{T_0 - T_z}\right)\right) \quad (8)$$

where  $E_0$  is the activation energy,  $R$  is the universal gas constant,  $T_z$  is the absolute zero in the temperature scale being used and  $T_0$  is the reference temperature at which  $\dot{\epsilon}_{cr}$  is given for. This formulation of Arrhenius equation is convenient because it is easy implemented for a case when the creep rate is defined at  $T_0$  and is known at another temperature.

### 3 Calibration to relaxation tests

The material-model calibration is performed for a relaxation test. A relaxation test is performed by constant compression of a specimen while the force required to hold compression is monitored.

In such a test the stress and strain in the material cannot be calculated directly due to non-uniform deformation. Instead, and as previously discussed, the specimen is modelled with a FE model that handles the complicated deformation. The resulting quantities, total compressive displacement and compressive force are then available from the FE calculation and can then be compared to the experiments. The FE software package Abaqus/Standard version 2018 [8] is used for simulations.

The specific behaviour of material models is determined by the parameters in the model. In an engineering application, the parameters are calibrated to the materials in use. The process of calibration takes place by adjusting the parameters, so the response of the model matches a test with a material sample. When the material model is complex, advanced methods for fitting the parameters to test data are usually needed. The method for this fitting is referred to as an optimization and is typically conducted so an error measure between test data and predicted values from simulation is minimized.

An introduction of the optimization methodology is given in [1]. The optimization method that is used here is the quasi-Newton method with the Hessian approximated with the BFGS method and gradient approximated with finite differences. The software Dakota [9] is here used to perform the optimization. Dakota is a free open source software that includes all the methods described here and is developed by National Technology and Engineering Solutions of Sandia.

### 3.1 Test data

Test data of relaxation type is available in [10]. The tests are on circular disc-shaped specimens of EPDM rubber with diameter 28 mm and the two thicknesses 6.49 mm and 6.68mm. The specimens are compressed by 25 %. This compression is then kept and the temperature held at 140 °C while the compressive force is monitored. The test data is presented in Figure 2.

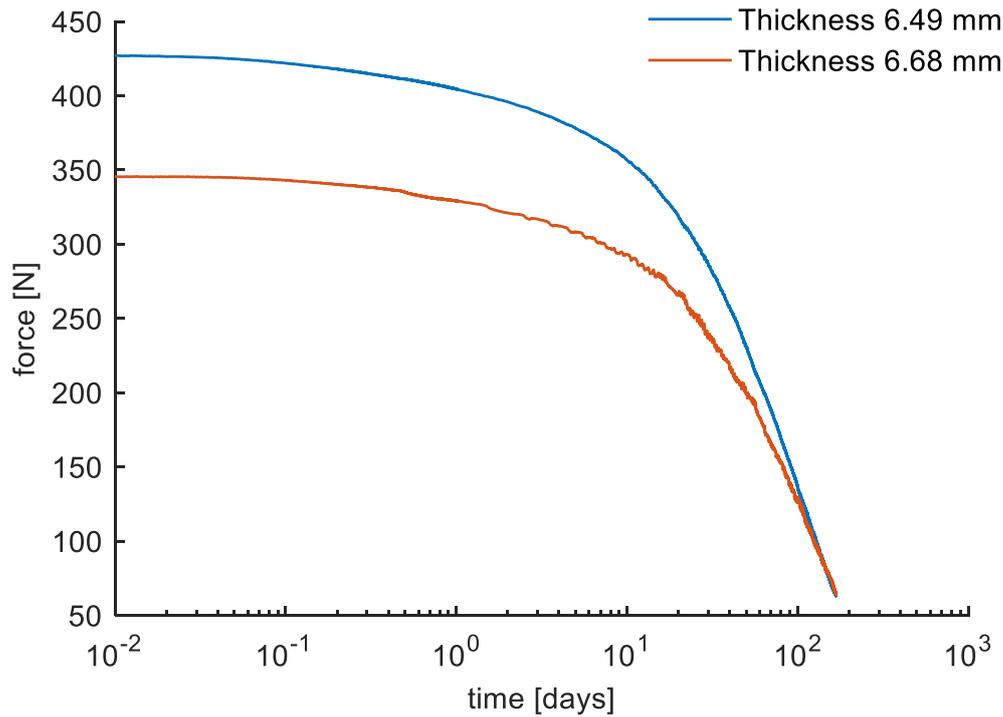


Figure 2 Relaxation test data on two specimens with thicknesses as indicated. The temperature is 140°C.

## 3.2 Simulation

The simulation of relaxation is performed by modelling a rubber body that is compressed between rigid planes. Since the specimens are circular, a 2D axi-symmetric geometry can be used. Symmetry is also used in the vertical z-direction in the middle of body. Hence only a 2D simulation of a quarter of the body cross section is explicitly modelled. The geometry is depicted in Figure 3.

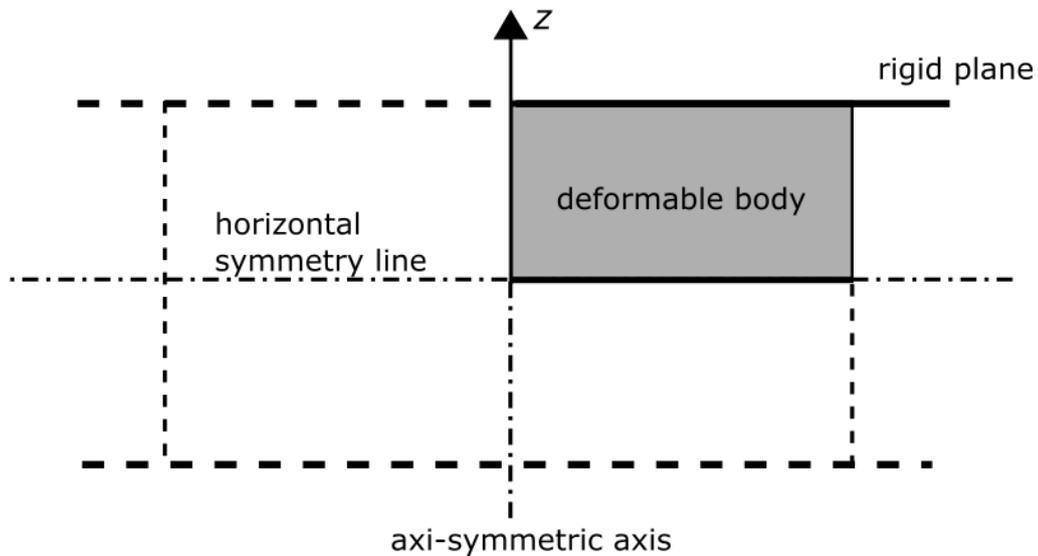


Figure 3 Geometry in the model. Dashed lines represent the boundaries of the part that are not used in the model due to symmetry. Symmetry lines and axes are represented by dash-dot lines.

The solving is performed with implicit quasi-static time integration, i.e. no inertia forces are taken into account. The elements used are linear 2D axi-symmetric elements with a hybrid formulation (Abaqus designation “CAX4RH”). Since rubber is nearly incompressible, the hybrid formulation is needed since it treats the pressure in the element as a separate degree of freedom. Without it, the pressure is un-determinate for fully incompressible materials or causing numerical difficulties for nearly incompressible materials. In Figure 4 is the FE mesh and rigid plane depicted. The mesh in the right-hand side is deliberately made unstructured in a specific way that makes the shape of the elements to get better quality when the rubber deforms heavily.

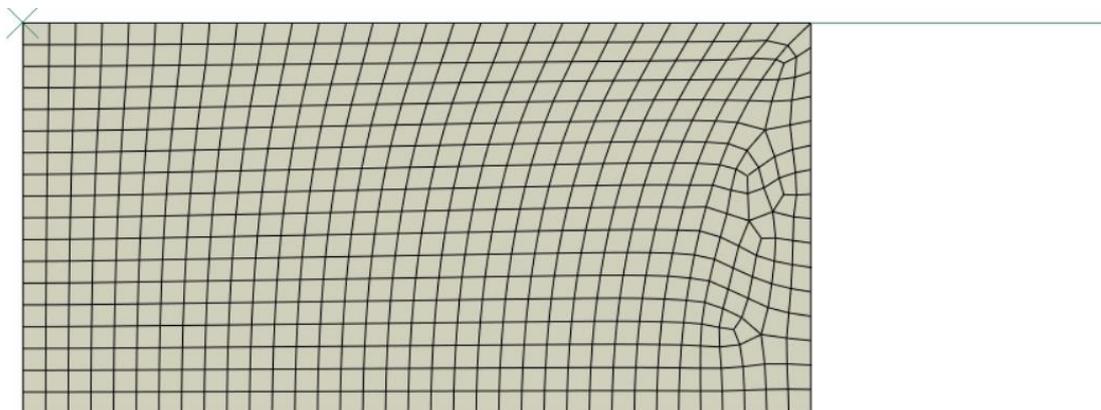


Figure 4 FE mesh and rigid plane (upper line).

The horizontal symmetry is achieved by setting the vertical displacements to zero along the horizontal symmetry line. The axi-symmetry is achieved by using axi-symmetric elements. The rigid plane is constrained in all degrees of freedom including rotational. The rigid plane interacts with the body through contact using 0.5 as coefficient of maximum friction.

The loading takes place by forcing the rigid plane down towards the horizontal symmetry line. To model the relaxation loading, the plane is in a first step moved half (to account for vertical symmetry) the distance of the total compression. Then in a second step the displacement of the rigid plane is fixed while the reaction force is monitored as resulting force to be compared to relaxation tests. In Figure 5 are FE simulation results given before and after relaxation starts, using the material parameters from calibration in the results section 3.3.

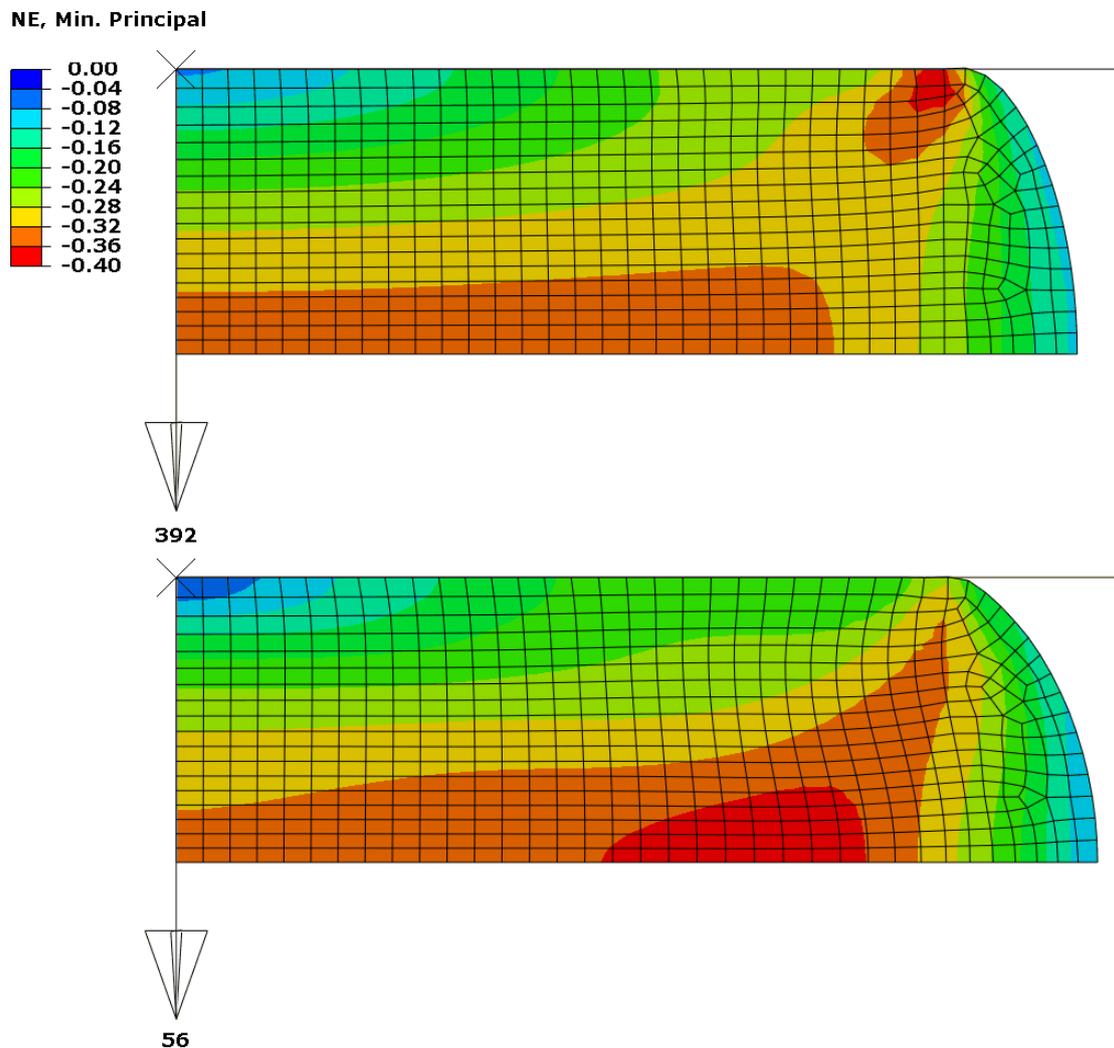


Figure 5 FE simulation results before relaxation (upper) and at end of relaxation simulation (lower). The color contour is minimum (compressive) principal strain and the arrows are the reaction force in Newtons.

### 3.3 Results

Different material models have been investigated for calibration to relaxation testing as described previously. In the preceding work in project, as described in [1], the strain hardening creep model (equation (5)) was used to model the relaxation. Here, instead the Bergstrom-Boyce creep model (equation (6)) is used. This model has been found to be advantageous due to better convergence in the nonlinear solving of the FE problem. The strain hardening creep model have difficulties to solve the very long relaxation times of more than 10 million seconds. This manifests in small time steps that makes the simulation too long to complete. The Bergstrom-Boyce creep model did not suffer from this in any significant way.

The elastic parts in the rheological network have the same hyper-elastic model. Since the Neo Hookean model is used, only two parameters are needed for the elastic part. In [6] where similar simulations and calibrations were performed for EPDM rubber, Neo-Hookean parameters corresponding to Poisson's ratio 0.48 for the small-strains linear-elastic limit were found to be suitable. Therefore, the elastic parameters are also here chosen to similarly match Poisson's ratio 0.48. Then the elastic parameters also need to be adjusted to match the stiffness seen in the test. This can be performed simply by manually adjusting one of the material constants in the Neo-Hookean model and calculating the other keeping Poisson's ratio fixed at 0.48 using equations (2) and (3) so the simulated response matches the initial measurements using the first evaluation point as described later. The resulting parameters are  $C_{10} = 1.0389$  MPa and  $D_1 = 0.039024$  MPa<sup>-1</sup> which correspond to Young' modulus 6.15 MPa in the small strain linear elastic limit.

The calibration for the creep model is performed as described here for the tests in Figure 2 and one viscous component in the rheological model (Figure 1). The resulting comparison between tests and simulation with the calibrated model is presented in Figure 6 and resulting FE-results are given in Figure 5. The difference between simulated values for different thicknesses is indistinguishable. Consequently, only one simulated curve is used. This is due to that the compression is relative (25 %) to the thickness.

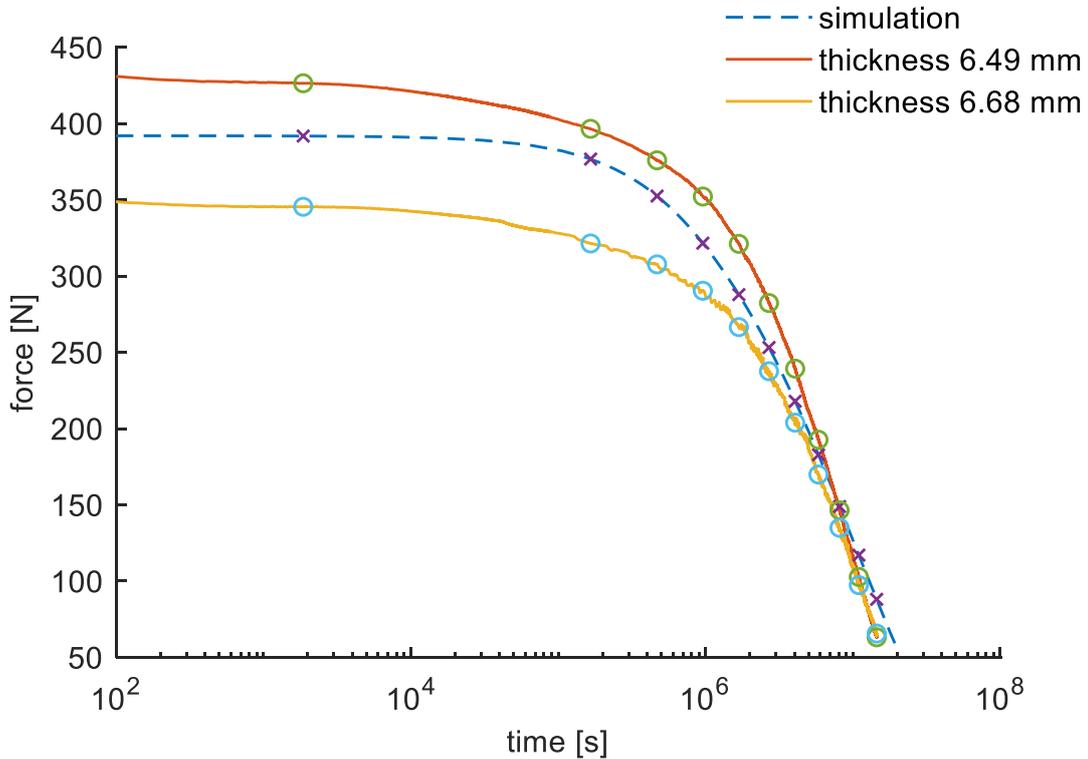


Figure 6 Relaxation forces from the tests (solid lines) and the simulation (dashed line) with the material model and calibrated material parameters. The circles are evaluation points from the testing data and the x-markers are evaluation points from the simulations.

The resulting calibrated parameters are given in Table 1. It is noted that the parameter  $S$  is 1.0 implicating that the rheological mode becomes a simple one-chain model without any pure elastic part. The optimization procedure has been conducted with the constraint  $m \geq 1$ . Here it is noted that the optimization gives the smallest allowed value. Values lower than  $m = 1$  are not typical [7] and the effect of this have not been further explored here.

Table 1 Calibrated parameters for the material model.

Parameter	Calibrated value
$A$ [ $\text{MPa} \cdot \text{m} \cdot \text{s}^{-1}$ ]	$1.0233 \cdot 10^{-9}$
$C$	-1.0
$m$	1.0
$S_1$	1.0

Inclusion of a plasticity part in the material model has not been successfully performed here. This is in large part probably due to that for a single relaxation test it is difficult to distinguish between the effects of elasticity, plasticity and creep. The consequence will be difficulty to perform the optimization due to an ill-posed mathematical problem.

### 3.4 Temperature effects

Relaxation tests from the project are available in [10]. These are conducted for the temperatures 90 °C, 120 °C and 140 °C and given in Figure 7. It is noted that the data for 90 °C is deviating from what is expected since it does not start at the same force value. The cause of this is not known, consequently the 90 °C data is not used here.

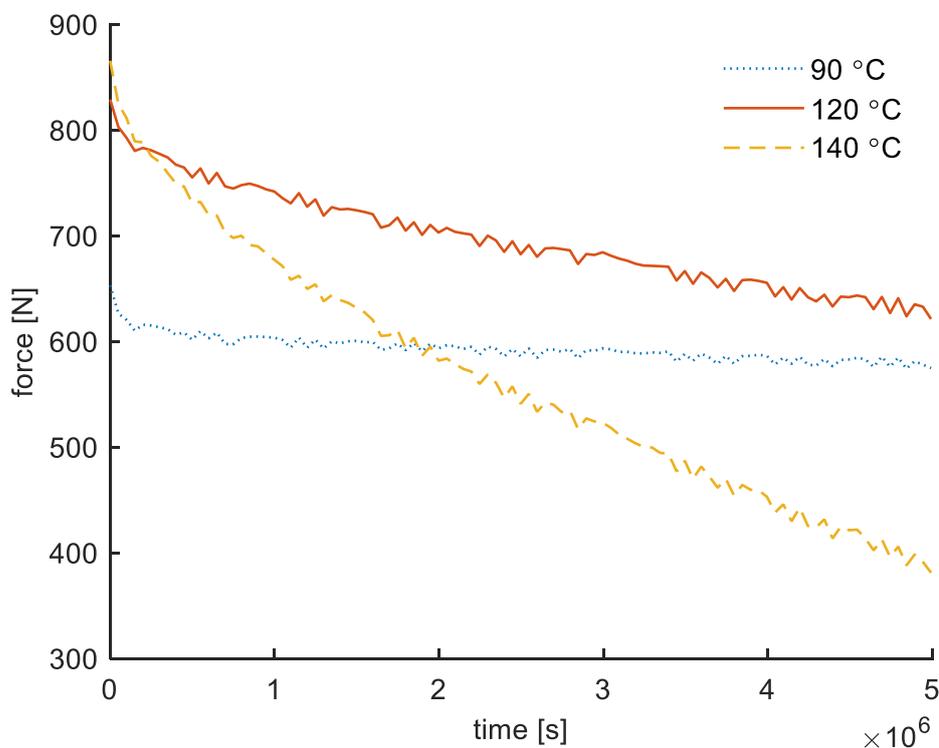


Figure 7 Relaxation for different temperatures.

If the amount of relaxation is taken as the decreasing change in force, it is seen that the 90 °C test have little relaxation while the 120 °C test relaxes about half the amount of the 140 °C test. To better quantify and illustrate this, the measure *relative relaxation* is defined here and calculated as follows.

1. Each relaxation test is normalized to its initial (and maximum) force
2. The normalized 90 °C data and 120 °C data are each subtracted from the normalized 140 °C data. The resulting quantity is then the here defined *relative relaxation* (to the 140 °C test)

This relative relaxation is presented in Figure 8.

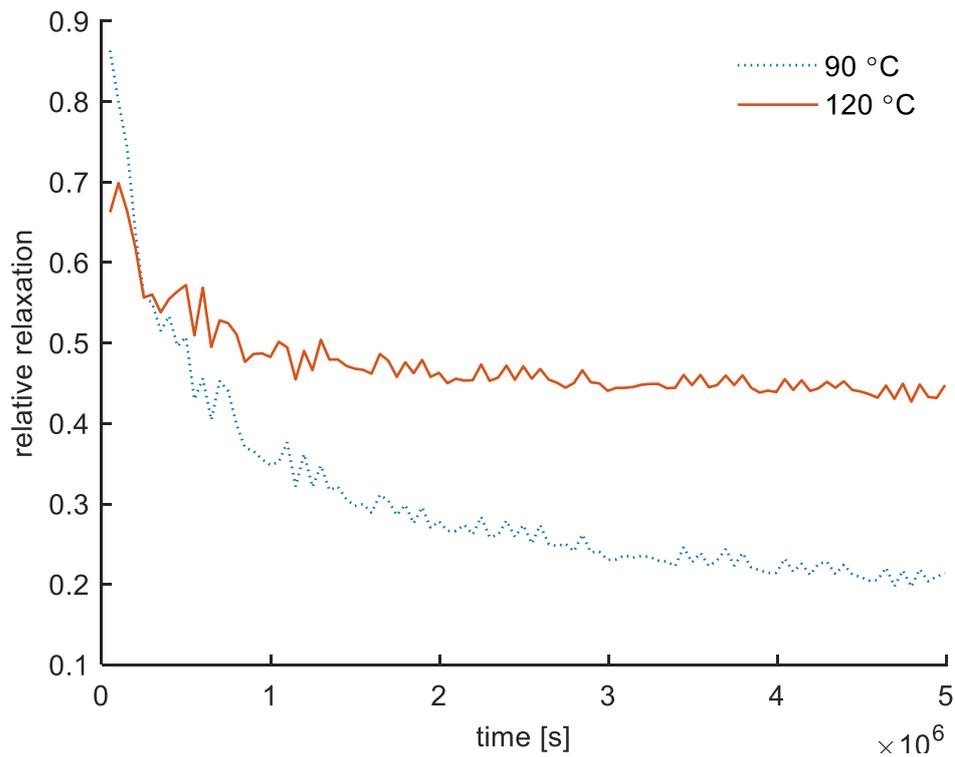


Figure 8 Relative relaxation compared to the 140 °C test.

It is possible to make a calibration of the thermo-effects modelling with the optimization methods used previously. To simplify the work another, much simpler, procedure is instead attempted. It is realized that since the 120 °C test relaxes about half as much as the 140 °C test (except in the beginning) the creep rate is about a factor of 0.5 between the 120 °C and 140 °C temperatures. Accordingly, it can further be realized, for the temperature dependent factor defined by equation (8), that  $a(120) = 0.5$  when  $T_0 = 140$  °C. The activation energy  $E_0$  in Arrhenius equation (8) can then be solved for since  $R$  and  $T_z$  are known constants in equation (8). The resulting activation energy then becomes  $E_0 = 46805$  J/mol.

This will be further used for analysing the compression set testing in the next section.

## 4 Compressive set and validation

The compressive set test measures the permanent deformation of a rubber seal and is described in the standard ISO 815 [11]. It is conducted by compression of the seal for a certain ageing time. The compression is then released and the height of the seal is measured. The permanent set is then defined as

$$\frac{h_0 - h_1}{h_0 - h_s} 100\% \quad (9)$$

with

$h_0$  – original height of the seal

$h_s$  – height of the seal during the compression

$h_1$  – height of the seal after the release

The test rig used here also has a cylindrical outer wall that acts as a confinement on the outer perimeter of O-ring.

The compression set data will here be used for validation of the simulation model. This means that the model calibrated from the relaxation test is used to simulate the compression set test as a validation. If the simulation results matches the validation test, the model is said to be validated.

## 4.1 Test data

Test data is available for compression test for various ageing times and temperatures in [10]. The O-rings have the following dimensions 6.99 mm in cord diameter and 43.65 mm in ring diameter. The ageing times are 60, 88, 140 and 180 days. The temperatures are 90, 120 and 140 °C. The measurement results are given in Figure 9.

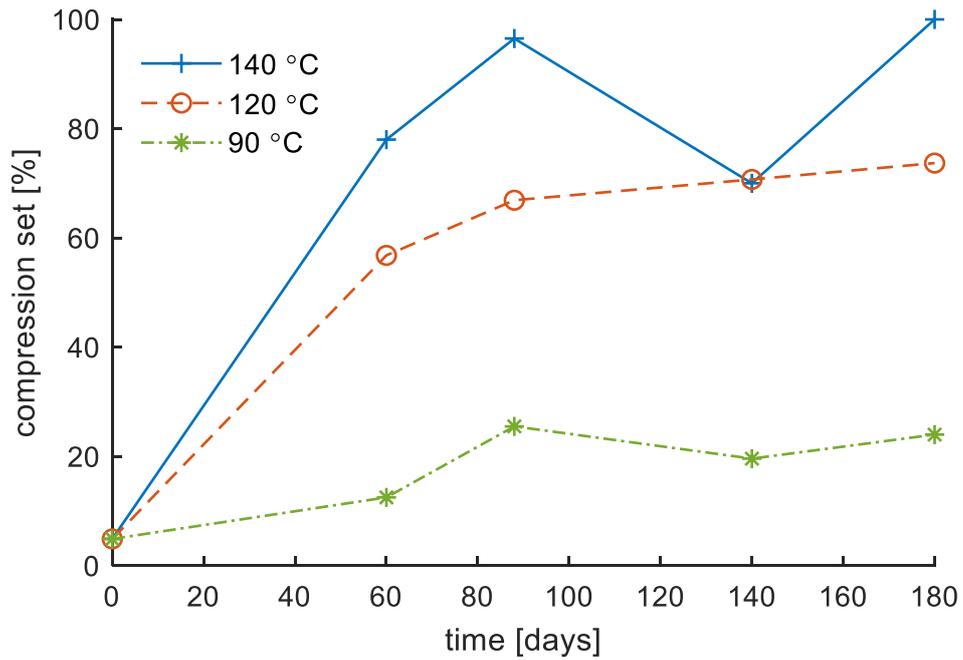


Figure 9 Compression set test results.

## 4.2 Simulation

Simulation of compressive set testing can be performed according to the same principle as for relaxation by adding an un-loading step after the relaxation step. In addition to the horizontal rigid plane is also a vertical and fixed rigid surface placed at outer perimeter of the undeformed O-ring to represent the cylindrical wall. In the un-loading step, the horizontal rigid plane is released so the contact is lost and the seal can expand. The seal will then over time further expand though creep and the difference between the partially expanded deformation and original shape is used to calculate the compressive set with equation (9). The time after release when the compressive set is determined from the simulation can either be a predetermined time corresponding to a test or sufficiently long to correspond to a permanent set.

In Figure 10 are results presented for the temperature 140 °C and ageing time 60 days. It is seen how the strain after the release decreases so only the residual strains remains and that a permanent deformation has occurred.

To see and account for the possibility of reversed creep after the release, a creep stage of 1000 seconds is added after the release. The relative difference in strain between immediately after the release and an additional 1000 second is less than  $10^{-5}$ . It can therefore be concluded that no gradual recovering towards the original shape after unloading occurs on the time scales that the permanent set test is ended and measured. This is expected since when considering the relaxation rate in Figure 2 it is seen that substantial relaxation does not occurs until after several days.

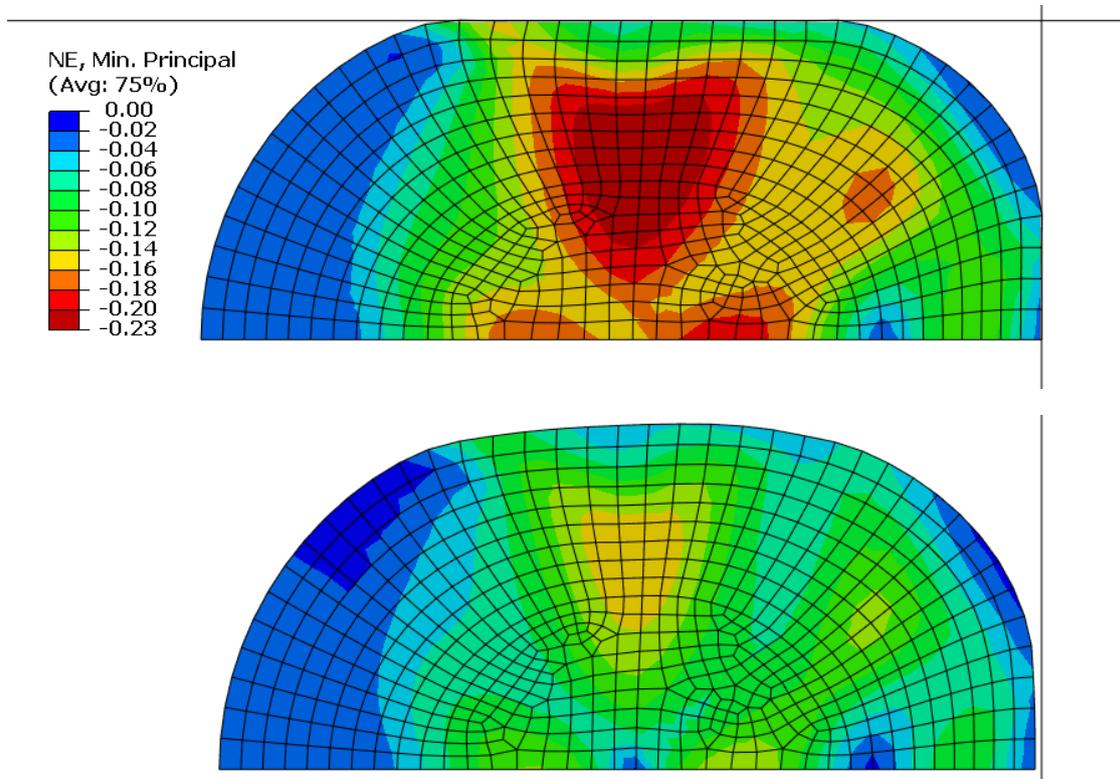


Figure 10 FE simulation results at end of ageing for 60 days in compression, immediately before release of compression (upper) and 1000 seconds after the release (lower). The color contour is minimum principal (compressive) strain. Temperature is 140 °C. The lines are rigid bodies representing the permanent set fixture.

In Figure 11 are the results compared for measured compression set values and simulated compression set at equivalent ageing times. This comparison serves as validation and moderate deviations are noted. Considering that Arrhenius equation here is used for the rather complicated physical phenomenon of creep and the crude and simple way it was calibrated in section 2.4, the deviation is not that unsatisfactory. It should also be mentioned that the compression set test appears to have considerable scatter as some results, like lower compression set for longer ageing time is not reasonable and probably caused by scatter or measurement uncertainty.

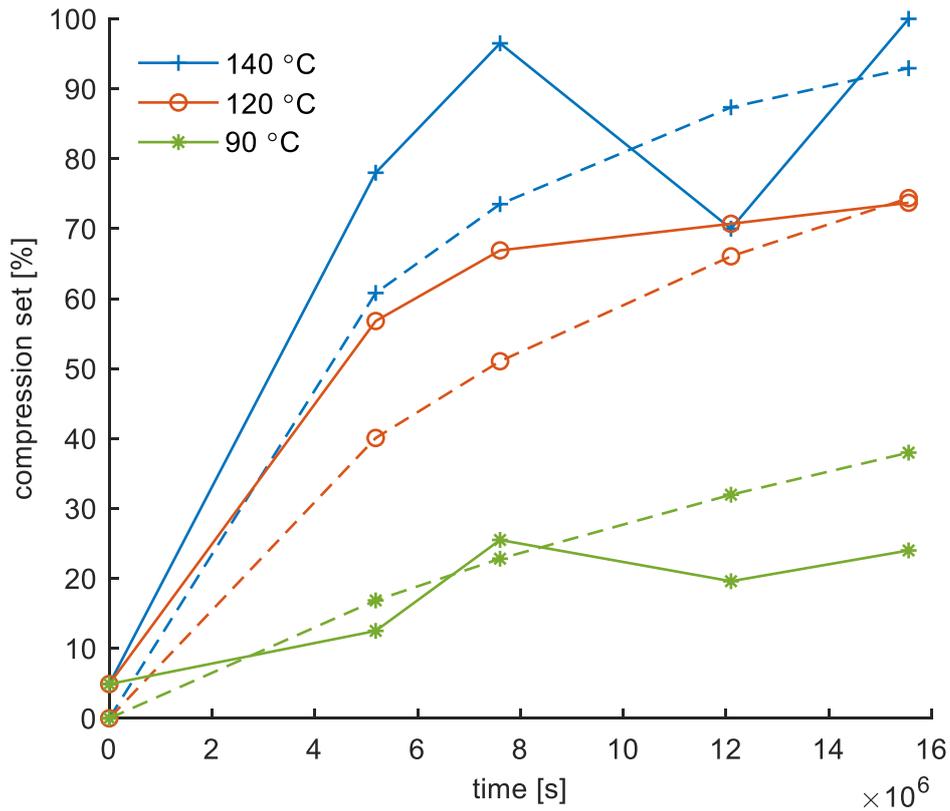


Figure 11 Comparison between compression set for measured values (solid lines) and simulated values (dashed lines) at different temperatures and ageing times.

## 5 Leak and tightness

Leaking and tightness of a compressed seal containing a pressurized fluid can be simulated with FE modelling. This was performed in [6] for polyethylene flange joints. The modelling of an O-ring is setup with contacts similarly to what is described for the relaxation simulation. In addition, a feature called pressure penetration is added [8].

This pressure penetration functionality works by adding the fluid pressure to the surface of the seals that is exposed to the fluid but not to the surfaces that are in contact with the surrounding solid (e.g. the pipe flanges of the joint). If the pressure is high enough, the contacting surfaces can separate. Then the pressure penetration functionality adds the fluid pressure to surfaces that lost contact. This can then if circumstances are correct further separate the contacting surfaces until the pressure penetrates all way the between the contacting surfaces which is to be interpreted as leak in the simulation.

The pressure penetration functionality is here tried and implemented for seals that are considered in this project. The simulation is setup in the same way as compression set is implemented in section 4.2 with the addition of the pressure penetration functionality.

The seals that are modelled have the following dimensions, 3.53 mm in cord diameter and 29.7 mm in ring diameter. The material is modelled with the same model as calibrated in section 3. The seals are simulated with following steps

1. Compression to reduce the O-ring thickness by 20 %
2. Ageing for 1 million seconds (11.6 days)
3. Increase of inner pressure from 0 to 200 bar in a short duration of time with no creeping active

Ageing is performed for the three temperatures 90 °C, 120 °C and 140 °C.

When the simulation is performed, the contacting surfaces become partially separated as the pressure is increased. At a certain pressure, convergence problems (difficulties to find numerical solutions in simulation) occur that force the simulation to be terminated. This is not the preferred outcome of the simulation. Instead it would have been desired that the contacting surfaces further separated to form a complete leak or that the simulation completed to the full pressure (200 bar) without leaking or convergence problem. Whether the convergence problems occur just prior to a rapid event such as a sudden complete full penetration and leakage or is due to other instabilities (mechanical or numerical) is not known at this stage. To be able use pressure penetration simulations to predict leakage, more work is required to develop the method and its implementation so credible results can be acquired.

In Figure 12 are two results presented for the temperature 90 °C, one at the end of the ageing time 1 million seconds (before pressurization) and one for the point just before the termination of simulation due to the convergence problems. It is noticed the compressive strains are high near the part of the seal where the pressure is penetrating the contact. The pressure at which the simulation terminates due to convergence problems depends on the ageing temperature. The pressure at which this occurs is given in Table 2. It is noticed that higher temperatures result in lower pressures at which the simulation terminates. It can be suspected that the convergence problem is related to the point in time where leakage is imminent so in some respect this is an indication of the effect of temperature on leakage although no certain or quantitative conclusions can be drawn.

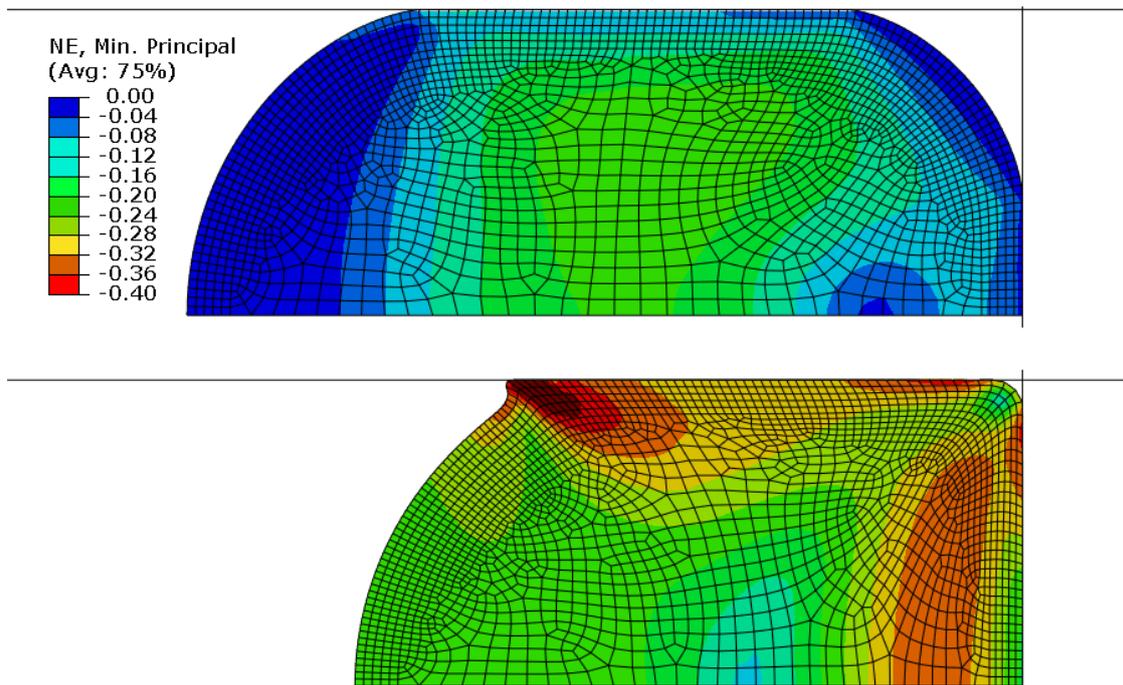


Figure 12 FE simulation results for the temperature 90 °C at end of the ageing time 1 million seconds and before pressurization (upper). Results just before the termination of simulation due to the convergence problems (lower).

Table 2 Fluid pressure when the leak simulation terminates at various temperatures.

Temperature [°C]	Pressure [bar]
90	96
120	83
140	59

## 6 Conclusions and discussion

It is shown how the relaxation tests can be used together with simulations to calibrate rubber material behaviour in seal applications. The visco-elastic (creep) behaviour is the most important in this respect. The creep model that was shown to be most suitable is the Bergstrom-Boyce model. When compared to the strain-hardening model from the previous report, the Bergstrom-Boyce model has better efficiency and more stability which allows for larger time increments in the simulations. The material model can also include a plasticity part in the rheological network. Since only one type of relaxation test is used there is not enough data to distinguish the plasticity from the creep and elasticity leading to that plasticity is not included in the model. A possible way to include and calibrate a plasticity part could be to also use the compression set test data. Here it is chosen not to use the compression set in this way. Instead this data is used in a validation process. A validation process here means that the calibration is done without the validation data. The validation data is instead used to test if the calibrated model can match results from the different validation test. The result is thus a more credible material model.

The effect of temperature is included with calibration of relaxation tests at different temperatures. It would have been possible to also perform a thorough calibration to this data. The resources in this project do not allow this. Instead, a simple observation is made on how much relaxation roughly occurs. With this observation the activation energy in Arrhenius equation can be determined. This modelling of the temperature effect is also validated with the compression test data. In the validation, the match between the test and simulated results is reasonably good when considering the rather crude and simple way the temperature effects calibration is performed. Furthermore, the Arrhenius equation is derived for one well defined chemical reaction while creep in rubbers is a complex process. Considering also this, the thermo-effects modelling seems good. This successful use of the Arrhenius equation for more complex effects is an experience that is often seen in various applications. Although not attempted here, it could also be possible to use the Arrhenius equation for ionizing radiation together with temperature.

The material models are used in a leak and tightness simulation attempt. This work is not fully completed. Although such simulations were successfully used in work such as [6], it does not work to full extent here. Numerical difficulties occur that prevent the simulations to be used to simulate leakage with confidence. From the leak and tightness simulations performed here it is shown that the increased creep for higher ageing temperatures seems to have a detrimental effect on the tightness, although one cannot assure or quantify the effect.

Further work that can improve and build on the findings in this report is:

- More detailed calibration and modelling of temperature and ionizing radiation effects
- Use of O-rings also in the calibration stage instead of flat specimens. This would be better as the deformed state then better matches the reality. Currently, the used coefficient of maximum friction has some uncertainty. The effect of this would have less impact for O-rings specimens compared to flat specimens.
- Use of more chains in the rheological network to get better accuracy in the calibrations

Another possibility could also be to use radically more advanced material modelling in the FE-simulation framework when such modelling becomes available. An example is to use molecular dynamics as a creep law. Such work is also part of the COMRADE project. This would allow to explicitly include e.g. temperature, radiation and other chemical degradation effects.

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