Simulating Elastomer Seal Mechanics for a Low Impact Docking System

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The application of computational modeling to design can greatly reduce the expense and development time of engineered components. The success of a computational model in representing the correct behavior of components is contingent on the accuracy of the material models used. In this work, the material constitutive behavior of three space-grade silicone elastomers, Esterline ELA-SA-401, and Parker Hannifin S0383-70 and S0899-50, is fit to a hyperelastic material model from experimental data. The hyperelastic properties of these materials are presented along with friction, thermal, and other bulk properties. Simplifying approximations are proposed that greatly reduce the computational expense and complexity of the models along with a discussion on when such approximations are valid. Several benchmark problems are compared with experimental data, and more complicated examples demonstrate the application of the model to more complex loading/thermal conditions that are difficult to reproduce experimentally.

I. Introduction

Computational models of the nonlinear mechanics of engineered components, such as seals, can be of tremendous value when the manufacturing of prototypes is expensive or time consuming, or when the expected operating conditions are difficult to reproduce experimentally. In the development of space flight hardware, all of these difficulties are often encountered.

NASA is currently developing a Low Impact Docking System† (LIDS) to expand the docking and berthing capability of future space vehicles. This system is to become the agency standard for docking systems of next generation space vehicles and structures included in Project Constellation. One of the LIDS design requirements is that the seals are to function both in seal-on-seal and seal-on-plate configurations. The seals must function under conditions of radial misalignment and without full axial compression. Additionally, the temperature of the seal is expected to vary between -50 and 50 degrees Celsius during operation. Another challenge is that the design calls for a redundant, i.e. two seals, design that must fit on a small 3.81 cm wide flange.

Computational models of seal mechanics have been studied previously. Recent works by Green et al. computed stresses in O-ring seals with a finite element method‡, but this used only a linear combination of the principal strain invariants with a Mooney-Rivlin strain energy density function for a problem that was predominately plane strain (i.e. only two of the invariants were independent). In addition, reduced

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integration was employed to reduce shear locking and the amount of compression was limited to 30% by the conditioning of the discretized equations of motion. Recent advances in finite element technology including mixed displacement-pressure (u-P) formulations have enabled modeling of incompressible materials with much larger strains.

In this study, a third-order, two-invariant, Yeoh strain energy density function is employed for problems where the strain state is primarily plane strain. A u-P formulation is employed to greatly increase the accuracy of the analysis for nearly incompressible deformation. In the u-P method, the hydrostatic pressure is interpolated by internal nodes in each element at one order lower than the displacement interpolation. This method enables the system of equations to remain well-conditioned as the strain exceeds 50%.

The paper is organized as follows: derivations of the hyperelastic stress-strain relationship and engineering approximations are given in Section II, the experimental tests to measure the material response under various strain states and the method of fitting the material test data to the hyperelastic constitutive law is given in Section III, the material models are verified for various deformations in Section IV, and some numerical examples of more complicated thermal/loading conditions are presented in Section V. Conclusions are presented in Section VI, and the material properties of the three elastomers are tabulated in the appendix.

II. Approach

A. Hyperelastic materials

A key engineering assumption in the analysis of elastomers is that the material is hyperelastic, that the deformation is elastic and the work done is independent of the load path. The second Piola-Kirchoff stress tensor, $S$, in such a material is given by the derivative of the stored strain energy, $\psi(E)$, which is a function of the Green-Lagrange strain $\mathbf{E}$:

$$S = \frac{\partial \psi(E)}{\partial \mathbf{E}} = 2 \frac{\partial W(C)}{\partial C}$$  \hspace{1cm} (1)

where $W(C)$ is the strain energy as a function of the right Cauchy-Green deformation tensor, $C = \mathbf{F}^T \cdot \mathbf{F}$, and $\mathbf{F}$ is the deformation gradient tensor. Tensors and vectors are distinguished from scalars by bold face type.

The stored energy of an isotropic hyperelastic material can be expressed as a function of the principal invariants $(I_1, I_2, I_3)$ of the right Cauchy-Green deformation tensor. As a result (1) can be written as:

$$S = 2 \left( \frac{\partial W}{\partial I_1} \frac{\partial I_1}{\partial C} + \frac{\partial W}{\partial I_2} \frac{\partial I_2}{\partial C} + \frac{\partial W}{\partial I_3} \frac{\partial I_3}{\partial C} \right) = 2 \left( \frac{\partial W}{\partial I_1} + I_1 \frac{\partial W}{\partial I_2} \right) \mathbf{I} - 2 \frac{\partial W}{\partial I_1} \mathbf{C} + 2I_3 \frac{\partial W}{\partial I_3} \mathbf{C}^{-1}$$  \hspace{1cm} (2)

where $\mathbf{I}$ is the identity tensor. The Cauchy (true) stress tensor is given by:

$$\sigma = \mathbf{F} \cdot S \cdot \mathbf{F}^T J^{-1} = 2J^{-1} \left( \left( \frac{\partial W}{\partial I_1} + I_1 \frac{\partial W}{\partial I_2} \right) \mathbf{B} - \frac{\partial W}{\partial I_2} \mathbf{B}^2 + I_3 \frac{\partial W}{\partial I_3} \mathbf{I} \right)$$  \hspace{1cm} (3)

where $\mathbf{B} = \mathbf{F} \cdot \mathbf{F}^T$ is the left Cauchy-Green deformation tensor, and $J = \det \mathbf{F}$ is the Jacobian. In the case where the material is fully or nearly incompressible, i.e. $I_3 = J^2 \approx 1$, then the expression for the Cauchy stress can be reduced to:

$$\sigma = 2 \left( \frac{\partial W}{\partial I_1} + I_1 \frac{\partial W}{\partial I_2} \right) \mathbf{B} - \frac{\partial W}{\partial I_2} \mathbf{B}^2 + \frac{\partial W}{\partial I_3} \mathbf{I}$$  \hspace{1cm} (4)

The strain invariants can be expressed in terms of the principal stress ratios as shown below:

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$$
$$I_2 = \lambda_1^2 \lambda_2^2 + \lambda_1^2 \lambda_3^2 + \lambda_2^2 \lambda_3^2$$
$$I_3 = \lambda_1^2 \lambda_2^2 \lambda_3^2 = J^2$$

where $\lambda_I$ are the principal stretch ratios defined by $\lambda_I = 1 + \epsilon_I$ and $\epsilon_I$ are the principal engineering strains.
B. Engineering approximations

It is not practical to attempt to simulate every aspect of elastomer behavior, particularly if doing so adds unnecessary complication to the analysis method. In the present application of docking seals, it is only necessary to consider the loading behavior of a cross section of a seal that will be primarily in plane strain. Additionally the material can be said to be nearly incompressible and will have undergone a break-in period of many loading cycles before flight.

C. Behavior of elastomeric materials

The hyperelastic model described previously represents the equilibrium behavior of elastomers, but it fails to predict rate-dependence, hysteresis, and the response to cyclic loading. Although methods have been recently introduced to deal with such behavior, such a detailed analysis is not warranted in this preliminary design application. The speed of docking and berthing operations is slow enough that viscoelastic effects are negligible. Hysteresis is not a concern because the loading during docking will be monotonic and only the behavior at the docked configuration is of importance. Finally the seals will undergo extensive checkout and “break-in” so any softening due to the Mullins effect will have already diminished. As a result, we will consider herein only the stabilized, increasing load, quasi-static response.

D. Simplification of the work function

When choosing a form of the work function, it is important to consider the mode of deformation that is to be modeled. Assuming a very nearly incompressible material, \( I_3 \approx 1 \), all forms of deformation can be plotted on a plane with \( I_1 \) and \( I_2 \) as the axes, (see Fig. 1).

![Figure 1. Plot of the relationship between \( I_1 \) and \( I_2 \) for different modes of deformation for an incompressible solid. All possible deformation must fall between uniaxial tension and biaxial tension.](image)

If the principal directions are chosen such that \( \lambda_1 > \lambda_2 > \lambda_3 \) then it must be that for any non-zero deformation \( \lambda_1 > 1 \) and \( \lambda_3 < 1 \) or else the incompressibility requirement \( \lambda_1 \lambda_2 \lambda_3 = 1 \) can not be met. Thus the character of the strain state is determined by the value of \( \lambda_2 \). The limiting cases are defined as follows: \( \lambda_2 = \lambda_1 \) (equibiaxial tension), \( \lambda_2 = 1 \) (planar tension or plane strain), \( \lambda_2 = \lambda_3 \) (uniaxial tension).

Since the seals will be subjected to axisymmetric loads and have a large radius compared to the width of their cross section, the strain state will be very nearly plane strain, \( \lambda_2 \approx 1 \), and it can be seen from (5) that \( I_1 \approx I_2 \). This suggests that an appropriate simplification is \( \frac{\partial W}{\partial I_2} = 0 \), i.e. the form of \( W \) is not dependant on \( I_2 \). This also implies that the material property tests should mimic as closely as possible the state of strain in the application; in this case, the plane strain response should be measured.

1. Form of the work function

The selection of a hyperelastic constitutive model should be driven by the material being modeling and the loading under consideration. In the case of seals with large radii and axisymmetric symmetry in geometry and loading, it does not make sense to choose a three invariant model because the strain state will be predominately plane strain for which the first and second strain invariants are the same. For this case a
Yeoh formulation is appropriate where the strain energy is defined as a function of the first strain invariant and the Jacobian. The Yeoh model and its derivatives with respect to the strain invariants are:

\[ W = \sum_{i=1}^{N} c_i (\bar{I}_1 - 3)^i + \sum_{k=1}^{N} \frac{1}{2k} (J - 1)^{2k} \]

\[ \frac{\partial W}{\partial I_1} = \sum_{i=1}^{N} ic_i (\bar{I}_1 - 3)^{i-1} J^{-2/3} \]

\[ \frac{\partial W}{\partial I_2} = 0 \]

\[ \frac{\partial W}{\partial I_3} = \sum_{k=1}^{N} \frac{k}{2k} J (J - 1)^{2k-1} \]  \hspace{1cm} (6)

where \( \bar{I}_1 = I_1 J^{-2/3} \) is a modified invariant, and \( N \) is the order of the polynomial fit, which in this study is chosen to be cubic so that the large strain behavior can be captured and the material response remains stable at all strains.

The choice of the order of the work function is driven by several considerations. The linear term, \( c_1 \), captures the initial slope of the work function and is equal to half the shear modulus at zero deformation. A necessary condition for stability is \( c_1 > 0 \). The quadratic term, \( c_2 \), usually captures the softening that elastomers show at moderate deformation, and as a result \( c_2 < 0 \). The cubic term, \( c_3 \), represents a hardening at higher strain, and if \( c_2 < 0 \), then \( c_3 \) must be greater than zero to guarantee stability at the limit \( I_1 \to \infty \).

To guarantee material stability for all \( I_1 \), then \( \frac{\partial W}{\partial I_1} > 0 \ \forall \ I_1 \). Including higher orders complicates the stability analysis and usually does not substantially improve the accuracy of the fit.

### III. Procedure

#### A. Experimental material testing

The goal in testing materials for fitting hyperelastic constitutive models is to achieve states of stress that allow simplification of the stress-strain relationships derived in the previous section. The most common types of tests are planar, uniaxial, and biaxial tension, and volumetric compression. Achieving pure states of stress is difficult and often requires the use of optical measures of deformation where the stress is uniform. Sketches of three of the four basic material tests are shown in Figs. 2a-c. Further details on the testing methodology are reported by Miller.\(^{11}\)

![Figure 2](image)

**Figure 2.** (a) Uniaxial tension test - stretched in \( e_1 \) direction, free in \( e_2 \) and \( e_3 \) directions with equal compliance. (b) - Planar tension test - stretched in \( e_1 \) direction, free in \( e_2 \) and \( e_3 \) directions with compliance in \( e_3 \) direction much greater than \( e_2 \) direction. (c) Biaxial tension test - stretched in \( e_1 \) and \( e_2 \) directions, free in \( e_3 \) direction.

1. **Uniaxial tension**

In a uniaxial tension test a long thin specimen is stretched such that its length increases and the cross sectional area decreases. For incompressible materials the relationship between the stretch ratios is \( \lambda_2 = \lambda_3 = \lambda_1^{-\frac{1}{2}} \).
2. Planar tension

For plane strain or axisymmetric configurations with large radii the planar tension test is the most appropriate for determining hyperelastic properties. In this test a very wide strip of material is loaded in tension. Due to the difference in compliance between the thickness and width dimensions, and the incompressibility of the material a state of nearly pure shear exists in the specimen at a 45 degree angle to the stretching direction. The relationship between the stretch ratios with incompressible deformation is $\lambda_1 = \lambda_3^{-1}$, $\lambda_2 = 1$.

3. Biaxial tension

In a biaxial tension test a thin sheet of material is stretched such that there is an isotropic tensile strain in the plane of the material. This can be accomplished by pulling on all four sides of a square material or stretching a circular sheet of material uniformly around the circumference. For incompressible materials, the stretch ratios are related by: $\lambda_1 = \lambda_2$ and $\lambda_3 = \lambda_1^{-2}$.

4. Volumetric compression

The volumetric compression test determines the resistance of the material to a change in volume when a hydrostatic pressure is applied. In this test a plug of material is compressed by a plunger while constrained in all directions. For the materials considered in this study the bulk modulus of the material was measured to be three to four orders of magnitude greater than the shear modulus, which validates the assumption of incompressibility.

B. Data analysis

Once the test data is collected, the next step is processing the engineering stress and strain data and fitting parameters for the chosen work function. Figure 3 shows the basic method of preparing data for fitting.

Data from repeated planar tension tests were selected from loading cycles after the stress-strain curve stabilized. The seals under development will be assumed to be in a “broken-in” state before they are flown, so softening due to the Mullins effect is neglected.

![Figure 3. Data analysis method: (a) load segments from different specimens of the same material are combined. (b) Any offset strain and stress are subtracted from each segment so that all segments begin at the origin. A number of strain points are selected, $e_i$ that span the load segment with the smallest range. (c) At each strain point $e_i$ the average stress is computed and the constitutive law is fit to $\bar{P}_i$. The uncertainty is computed from the Student’s t distribution of the averaged points and the error due to the fit.]

1. Fitting the Yeoh work function to plane strain data

Once the data are averaged, the parameters $c_i$ from the work function in (6) are determined with a least squares fit by minimizing:

$$\sum_k \left( P_k^{exp} - P^{fit} (\lambda_k) \right)^2$$  \hspace{1cm} (7)

where $P_k^{exp}$ is the average nominal stress from the experimental material tests, $\lambda_k$ is the experimental stretch ratio, and $P^{fit}$ is the nominal stress computed for the case of incompressible planar tension by:
\[ P^{fit}(\lambda_k) = 2 \left( \lambda_k - \lambda_k^{-3} \right) \sum_i i c_i \left( \lambda_i^2 + \lambda_i^{-2} - 2 \right)^{i-1} \] (8)

where the subscript, \( k \), on \( \lambda \) refers to the specific experimental data point rather than the dimension, and the first invariant of the right Cauchy-Green tensor is computed for planar tension and incompressibility by \( I_1 = \lambda^2 + \lambda^{-2} + 1 \).

To fit the experimental data with a least squares approach, the following vectors are defined:

\[
\begin{align*}
A_k &= 2 \left( \lambda_k - \lambda_k^{-3} \right) \\
B_k &= 4 \left( \lambda_k - \lambda_k^{-3} \right) (I_{1k} - 3) \\
C_k &= 6 \left( \lambda_k - \lambda_k^{-3} \right) (I_{1k} - 3)^2
\end{align*}
\] (9)

The values of \( c_i \) are then the solution of the linear system:

\[
\begin{bmatrix}
\sum A_k A_k & \sum B_k A_k & \sum C_k A_k \\
\sum A_k B_k & \sum B_k B_k & \sum C_k B_k \\
\sum A_k C_k & \sum B_k C_k & \sum C_k C_k
\end{bmatrix}
\begin{bmatrix}
c_1 \\
c_2 \\
c_3
\end{bmatrix}
= 
\begin{bmatrix}
\sum A_k P_k^{exp} \\
\sum B_k P_k^{exp} \\
\sum C_k P_k^{exp}
\end{bmatrix}
\] (10)

For all the materials and temperatures analyzed, the application of the Yeoh strain energy function to compute stress from uniaxial or equibiaxial deformations fell within the experimental variation for non-planar strains of up to 10\%. In the case of an axisymmetric loading, such as the docking seals considered here, the only non-planar strain is a result of displacement in the radial direction that creates a hoop strain. The hoop stress is coaxial with planar strain because it is by definition perpendicular to the two principal plane strains. Thus the stretch ratios can be superimposed multiplicatively. This means that for displacement of the material towards the radius the strain state will tend towards uniaxial tension (two stretch ratios less than unity), while displacement away from the centerline will push the strain state towards biaxial tension, (two stretch ratios greater than unity).

In the smallest seals considered, (radius 129 mm), the distance from the seal centerline to the inner edge of the seal is about 3 mm. Therefore the maximum amount of hoop strain possible is only about 2.3\%, well below the 10\% that the Yeoh model fits accurately. Thus the Yeoh model is well-suited for axisymmetric seals analysis.

2. Fitting the work function for volumetric compression data

The volumetric deformation is defined as \( \lambda_1 = \lambda_2 = \lambda_3 \). Since the material is very nearly incompressible, it also can be said that \( \lambda_1 \approx 1 \). Given these approximations the pressure is directly related to the Jacobian by:

\[ p = \frac{\partial W}{\partial J} \] (11)

This is equivalent to \( \frac{\partial W}{\partial J} \frac{\partial J}{\partial J} \) where \( \frac{\partial J}{\partial J} = \frac{1}{2\sqrt{J}} \) and \( \frac{\partial W}{\partial J} \) is defined in (6).

It is important to note that in the volumetric tests the pressure is measured with respect to the original cross section, i.e. it is proportional to the trace of the first Piola-Kirchhoff stress. To convert to the correct pressure it should be multiplied by \( J^{-2/3} \), although this quantity should be very nearly unity. The fitting procedure is the same as it was for fitting the deviatoric constants in the work density function. In this case the following vectors are defined.

\[
\begin{align*}
A_k &= 2 (J - 1) \\
B_k &= 4 (J - 1)^3 \\
C_k &= 6 (J - 1)^5
\end{align*}
\] (12)

The values of \( d_k \) are then the solution of the linear system:

\[
\begin{bmatrix}
\sum A_k A_k & \sum B_k A_k & \sum C_k A_k \\
\sum A_k B_k & \sum B_k B_k & \sum C_k B_k \\
\sum A_k C_k & \sum B_k C_k & \sum C_k C_k
\end{bmatrix}
\begin{bmatrix}
d_1^{-1} \\
d_2^{-1} \\
d_3^{-1}
\end{bmatrix}
= 
\begin{bmatrix}
\sum A_k P_k^{exp} \\
\sum B_k P_k^{exp} \\
\sum C_k P_k^{exp}
\end{bmatrix}
\] (13)
An example result of the post processing of experimental data is shown in Figure 4, where the deviatoric pure strain states are fitted to the planar tension data (Fig. 4a), and the volumetric compression is fit up to a 300 MPa hydrostatic stress (Fig. 4b). The colored bands around each experimental plot indicate the amount of variance in the experimental data computed by the Student’s t distribution with 95% confidence.

Figure 4. Least squares fit of room temperature data from ELA-SA-401 specimens in (a) Deviatoric deformation (uniaxial tension, equibiaxial tension, planar tension) and (b) volumetric compression. The shaded regions indicate the fit to the data. Note that the fit for uniaxial tension and equibiaxial tension is within the experimental variation for strains of up to 14%.

IV. Verification Tests

To test the accuracy of the fitted work function, seals were compressed in a load fixture in a seal-on-seal configuration and the required force to compress the seals was compared to the computational predictions. The test specimens were Gask-O-Seals™, manufactured by Parker Hannifin Corporation, Composite Sealing Systems Division. The specimens consist of single-bead elastomer seals vacuum-molded into an aluminum ring. During the test the seals were aligned co-axially and compressed until the surfaces of the two aluminum rings came into contact. The seal materials that were tested were S0383-70 or S099-50. Further details of the testing can be found in Daniels et al.12

<table>
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<th>FEA (N)</th>
<th>% diff</th>
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<td>S0899-50</td>
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<td>1125</td>
<td>885</td>
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<td></td>
<td>75%</td>
<td>2108</td>
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<td></td>
<td>100%</td>
<td>3688</td>
<td>3986</td>
<td>8.1</td>
</tr>
<tr>
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<td>1700</td>
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<td></td>
<td>75%</td>
<td>3554</td>
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<td></td>
<td>100%</td>
<td>7819</td>
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</table>

Table 1. Comparison of experimental seal (Exp) load to finite element predictions (FEA), load is measured in experimental compression tests. The nominal diameter of the seal was 25.7 cm.

Table 1 compares the predicted and experimental load values as a function of compression. For reference purposes, percent compression defines the amount the free height of the seal bulb is compressed and the free height is defined as the height above the aluminum retainer (nominally 1.0 mm) the seal protrudes. The seals were found to have a significant amount of waviness around their circumference. The height of the
seal bulb varies by as much as 17% of the free height. Additionally, the mean free height of the seal was measured to be 16 to 20% less than nominal. Due to the very large aspect ratio between the circumference of the seal and its thickness, it is only practical to model the seal in an axisymmetric configuration assuming the mean value of the inspected dimensions. As a consequence the force-displacement curve predicted by the analysis does not match the beginning of the experimental data well, but the final loads agree to within 10% (as shown in Table 1, where 100% compression indicates metal to metal contact of the aluminum rings). The quality of fit is quite remarkable given the waviness of the seal and the amount of variation between different specimens in the material property tests.

Figure 5. $\sigma_{22}$ axial stress contours at different stages of compression for (top) S0899-50 and (bottom) S0383-70 materials. While the nominal initial seal free height is 1.0 mm, the actual free height was measured to be 16-20% less.

V. Numerical Examples

The true advantage in computational modeling of components is to allow designers to predict performance without requiring development of prototypes and running tests. The following two examples illustrate conditions that cannot yet be accurately tested experimentally, but are straightforward to analyze computationally with modest computation time (both examples ran in less than 20 seconds on a dual-core workstation requiring less than 100 MB of RAM).

A. Effect of a modest rise in temperature

Due to the temperature range (-50 to 50°C) the seals must operate in, seal designers need to be able to assess seal contact pressures and unit loads to ensure proper seal performance. The coefficient of thermal expansion of the seals is quite large, as much as 15-20 times as high as the aluminum the seals are molded into. Additionally the seal is molded into its retainer ring and it is not free to expand in all dimensions, which amplifies the thermal expansion. A key point in the design of incompressible elastomeric seals is to ensure that in the most extreme condition, the amount of volume the seal occupies is always less than the space available for the seal to deform. To illustrate this point the seal geometry modeled in the verification tests noted above is considered with the S0383-70, S0899-50, and ELA-SA-401 material properties. In these analyses, the nominal dimensions are used instead of the measured seal dimensions so that valid comparisons between materials can be made.

The analyses take place in two steps. In the first step a uniform temperature is prescribed to all nodes and the seal is allowed to expand or contract from its initial shape at 23°C. The resulting expansion or contraction leads to a very small change in the height of the seal, generally 5-6% of the free height, and at first glance it appears that very little has changed. Next the seal is compressed until the bulb is completely
within the retainer groove, i.e. 100% compression. Figure 6 shows the deformed state of a seal made from the S0383-70 material. As can be seen from the figure, the amount of free volume after compression varies dramatically across the operating temperature range of the seal and the peak stress varies from 5440-9190 kPa as a result of the large hydrostatic pressure generated as the seal becomes more volume constrained.

Figure 6. Plot of deformed configurations after at three different temperatures for S0383-70 material. (a) -50°C (b) 23°C (c) 50°C. At 50°C the free volume after compression has nearly vanished.

Figure 7 compares the unit loads of the three materials at -50, 23, and 50°C. For both the S0383-70 and ELA-SA-401 materials the load increases by over 60% at 50°C from the nominal load at room temperature. The consequences of this change would be quite destructive in the situation where a spacecraft was docked and then exposed to direct sunlight where the seals would be heated and expand. The increase in load could damage the latch mechanisms that hold the docking craft together and possibly cause the two flanges to separate.

B. Contact pressure profile of a misaligned seal

One specification for the LIDS seal design is that the seals must accommodate radial misalignments when used in a seal-on-seal configuration. While available test facilities can measure the leakage rate of misaligned seals experimentally, there is no method of determining what the contact pressure is across the seal when misaligned. With moderate normal force, the coefficient of friction between two seals is approximately 0.5, which means that the seals are not expected to slide past each other as they are deformed; however there is no way to observe this experimentally.

The next example considers the same geometry and S0383-70 material fully compressed at room temperature with a radial offset of 0.5 mm. The purposes of this analysis are to determine whether the two seal surfaces in contact slipped, and investigate the resulting contact pressure profile between the seals.

The results of the analysis are presented in Figure 8. As seen from the pressure contour plot, the distribution appears to be smooth without any sharp peaks that might result in damage to the surface of the
seal (Fig. 8a). The plot of radial displacement at full compression, (Fig. 8b), suggests that the top seal is not sliding with respect to the bottom, as the radial displacement is nearly continuous across the interface. This analysis supports the assumption that with the large coefficient of friction between the materials they will not slide while compressed in a misaligned configuration.

VI. Summary

A method of fitting a constitutive law to elastomer materials subjected to deformation that is mainly plane strain has been developed to aid the design of docking seals operating in space environments. The method of extracting and averaging data from materials tests and least squares fitting to the Yeoh strain energy density function has been shown to be very effective at providing a remarkably accurate computational tool in the development of seals to meet NASA’s challenging design goals. This study focused on three space-capable materials under consideration for use in the LIDS seal.

Several key assumptions allowed the simplification of the computations, limiting the run time to well under a minute. This fast computation allows for the exploration of many design variables to facilitate understanding the behavior of the seals. The key simplications were:

1. If a monotonic load path is to be followed with a small strain rate, and the material stress-strain response is stabilized after several loading cycles, then a time-dependent material model is not required. Unlike elastomers, hyperelastic materials are load-path independent, however if the load path is monotonic, then it is only necessary to fit the hyperelastic model to that specific load path.

2. Most seals with axisymmetric geometry and loading will be very nearly in plane strain, where the first and second strain invariants are equivalent, and a two invariant function such as the Yeoh model is sufficient.

3. The seal material is very nearly incompressible, i.e. \( J = I_3 = 1 \). The only case where this should not be assumed is for a volumetric test, where the load is hydrostatic. For this test the strain energy is assumed to be only a function of the Jacobian, \( J \).

Computational analysis helped avoid designs where combined thermal expansion and compression could cause enormous increases in load due to the material incompressibility. In the reference seal design studied in this work, the seal load was shown to increase by two-thirds of its nominal value with a temperature rise of only 27°C due to the large thermal expansion coefficient and incompressibility of the seal material.

A second example showed the deformation of seals with coaxial misalignment. The results suggest that the contact friction between seals is large enough to prevent sliding contact, and that the contact pressure will remain smooth between the seals. The computational analysis allowed the mechanics and kinematics of misaligned seals under compression to be shown in considerably more detail than is possible experimentally.
References

Appendix: Experimentally Measured Elastomer Properties

Constants for the Yeoh strain energy function at different temperatures

\( c_i \) in MPa, \( d_i \) in MPa\(^{-1}\)

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature (°C)</th>
<th>( c_1 )</th>
<th>( c_2 )</th>
<th>( c_3 )</th>
<th>( d_1 )</th>
<th>( d_2 )</th>
<th>( d_3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0899-50</td>
<td>-50</td>
<td>0.2839</td>
<td>-0.0735</td>
<td>0.0385</td>
<td>0.00114</td>
<td>2.51e-5</td>
<td>-1.44e-6</td>
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<tr>
<td></td>
<td>23</td>
<td>0.2693</td>
<td>-0.0644</td>
<td>0.0278</td>
<td>0.00112</td>
<td>8.38e-5</td>
<td>6.43e-6</td>
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<td></td>
<td>50</td>
<td>0.2505</td>
<td>-0.0391</td>
<td>0.0157</td>
<td>0.00138</td>
<td>3.52e-5</td>
<td>-2.97e-6</td>
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<td>125</td>
<td>0.2688</td>
<td>-0.0491</td>
<td>0.0185</td>
<td>0.00162</td>
<td>4.7e-5</td>
<td>-6.93e-6</td>
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<tr>
<td>S0383-70</td>
<td>-50</td>
<td>0.6494</td>
<td>-0.3435</td>
<td>0.4189</td>
<td>0.00092</td>
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<td></td>
<td>23</td>
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<td>-0.1630</td>
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<tr>
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<td>-0.0446</td>
<td>0.0347</td>
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<td>23</td>
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<td>-3.3e-6</td>
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Static and dynamic coefficients of friction (same material) at different temperatures

<table>
<thead>
<tr>
<th>Temperature(°C)</th>
<th>Normal pressure kPa</th>
<th>S0899-50</th>
<th>S0383-70</th>
<th>ELA-SA-401</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Static</td>
<td>Dynamic</td>
<td>Static</td>
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<tr>
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<td>1.92</td>
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<td>70</td>
<td>1.35</td>
<td>0.96</td>
<td>1.39</td>
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<td>700</td>
<td>0.80</td>
<td>0.61</td>
<td>0.85</td>
</tr>
<tr>
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<td>14</td>
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<td>1.04</td>
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<td>1.25</td>
<td>0.73</td>
<td>0.76</td>
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<td>700</td>
<td>0.53</td>
<td>0.37</td>
<td>0.64</td>
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<tr>
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<td>14</td>
<td>1.64</td>
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<td>1.10</td>
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<tr>
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<td>1.16</td>
<td>0.82</td>
<td>0.85</td>
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<tr>
<td></td>
<td>700</td>
<td>0.67</td>
<td>0.48</td>
<td>0.61</td>
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<tr>
<td>125</td>
<td>14</td>
<td>1.25</td>
<td>0.87</td>
<td>0.85</td>
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<tr>
<td></td>
<td>70</td>
<td>0.96</td>
<td>0.77</td>
<td>0.68</td>
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<tr>
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<td>700</td>
<td>0.51</td>
<td>0.43</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Coefficient of thermal expansion at different temperatures

\( °C^{-1} \times 10^{-6} \)

<table>
<thead>
<tr>
<th>Material</th>
<th>-50°C</th>
<th>23°C</th>
<th>50°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0899-50</td>
<td>317</td>
<td>330</td>
<td>321</td>
</tr>
<tr>
<td>S0383-70</td>
<td>371</td>
<td>355</td>
<td>348</td>
</tr>
<tr>
<td>ELA-SA-401</td>
<td>430</td>
<td>389</td>
<td>374</td>
</tr>
</tbody>
</table>

Bulk properties at 23°C

(\( \kappa \) - thermal conductivity, \( \alpha \) - thermal diffusivity, \( c \) - heat capacity, \( \rho \) - density)

<table>
<thead>
<tr>
<th>Material</th>
<th>( \kappa ) (W/mK)</th>
<th>( \alpha ) (mm(^2)/s)</th>
<th>( c ) (MJ/m(^3)K)</th>
<th>( \rho ) (g/cm(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0899-50</td>
<td>0.332</td>
<td>0.229</td>
<td>1.45</td>
<td>1.13</td>
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<tr>
<td>S0383-70</td>
<td>0.334</td>
<td>0.237</td>
<td>1.41</td>
<td>1.24</td>
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<tr>
<td>ELA-SA-401</td>
<td>0.241</td>
<td>0.161</td>
<td>1.50</td>
<td>1.17</td>
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