ISSN : 2321-9416

Indo - American Journal of Mechanical Engineering

www.iajme.org

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Indo-American Journal of Mechanical Engineering
ISSN 2321–9416www.iajme.org
Vol 15, Issue 2, 2026

LARGE DEFORMATION ANALYSIS OF A RUBBER BOOT SEAL USING NONLINEAR STATIC FINITE ELEMENT METHODS

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Abstract

Rubber boot seals are critical components in mechanical and automotive systems, where they must accommodate large axial and torsional deformations while maintaining reliable sealing performance. This study presents a nonlinear static finite element analysis of a rubber boot seal assembled over a cylindrical shaft. A half-symmetry three-dimensional model is developed in ANSYS Mechanical to capture geometric, material, and contact nonlinearities. The rubber material is modeled using a Neo-Hookean hyperelastic formulation to represent large elastic strains, while the shaft is idealized as a rigid body. Three contact regions are defined: a rigid–flexible frictional interface between the boot and shaft, and two self-contact regions on the inner and outer boot surfaces. The analysis is conducted in three sequential load steps: interference fit, axial compression, and combined axial compression with shaft rotation. Results demonstrate significant nonlinear deformation, stress concentration near geometric transitions and contact regions, and strong coupling between frictional contact and hyperelastic material response. The study confirms the necessity of advanced nonlinear modeling techniques for realistic prediction of rubber sealing performance.

1. Introduction

Rubber boot seals are widely used in applications such as constant-velocity joint assemblies, steering systems, and protective bellows. Their primary function is to maintain environmental isolation while permitting substantial relative motion between a shaft and housing. Unlike metallic components, rubber seals operate under large strains—often exceeding 100%—requiring nonlinear material modeling and large-deformation kinematics.

The mechanical response of such systems is governed by three interacting nonlinearities:

1. **Geometric nonlinearity** due to large strains and rotations.
2. **Material nonlinearity** associated with hyperelastic behavior.
3. **Contact nonlinearity** resulting from evolving frictional interfaces and self-contact.

Analytical approaches are inadequate for capturing these coupled effects. Therefore, finite element analysis (FEA) becomes essential for evaluating deformation, stress distribution, and contact pressure under realistic loading conditions.

This work presents a nonlinear static structural analysis of a rubber boot seal using ANSYS Mechanical. The objective is to establish a robust modeling framework capable of simulating large deformation, hyperelastic behavior, and complex contact interactions under combined axial and torsional loading.

2. Literature Review

2.1 Hyperelastic Modeling of Rubber

Rubber materials exhibit nonlinear elastic behavior that cannot be described using linear elasticity. Hyperelastic models derive stress from a strain energy density function and are suitable for large deformation analysis.

Common hyperelastic formulations include:

- Neo-Hookean
- Mooney–Rivlin
- Yeoh
- Ogden
- Arruda–Boyce

For moderate strain levels and numerical robustness, the Neo-Hookean model provides an effective balance between simplicity and physical accuracy. It assumes isotropy and near-incompressibility—characteristics consistent with elastomeric sealing materials.

2.2 Finite Element Analysis of Rubber Seals

Nonlinear FEA has become the standard approach for analyzing rubber seals and boot components. Previous benchmark studies have demonstrated the importance of:

- Accurate contact definitions
- Proper hyperelastic material calibration
- Incremental load application
- Symmetry exploitation for computational efficiency

Classical APDL-based boot seal examples have been widely referenced for demonstrating nonlinear solution capabilities. Modern workflow-based environments allow similar analyses with improved model organization and transparency.

2.3 Contact Algorithms for Large Deformation

Contact modeling is a dominant source of nonlinearity in seal analysis. In this study, a surface-projection-based contact method is used to evaluate contact constraints at integration points, improving pressure smoothness and numerical stability during large sliding.

Frictional behavior with a coefficient of 0.2 is incorporated to simulate rubber–metal interaction under torsional loading. Self-contact is also defined to prevent nonphysical self-penetration during folding of the boot.

3. Materials and Methods

3.1 Geometry and Symmetry

To improve computational efficiency without compromising physical accuracy, half symmetry is exploited in the present model. The geometry of the boot seal and the cylindrical shaft, as well as the applied loading conditions, are symmetric about a longitudinal plane. Under these conditions, the deformation and stress fields in one half of the structure are mirror images of those in the other half. Therefore, only half of the geometry needs to be modeled explicitly.

The model consists of:

- A hyperelastic rubber boot
- A cylindrical shaft (rigid body)

Half symmetry is applied along the longitudinal plane to reduce computational expense while preserving physical behavior.

4 The shaft is modeled as rigid due to its significantly higher stiffness relative to rubber, eliminating unnecessary degrees of freedom.

3.2 Material Modeling

The rubber boot is modeled using a compressible Neo-Hookean formulation with:

- Shear modulus $\mu = 1.5$ MPa
- Incompressibility parameter $D_1 = 0.026$ MPa^{-1}

This formulation captures large elastic deformation while maintaining numerical stability.

The shaft is assigned rigid stiffness behavior, focusing computation on the deformable rubber component.

Shear Modulus (μ)

The shear modulus controls the material's resistance to distortional (shape-changing) deformation. A value of 1.5 MPa is typical for soft rubber compounds used in sealing applications and governs how easily the boot can flex, bend, and twist under applied loads.

Incompressibility Parameter (D_1)

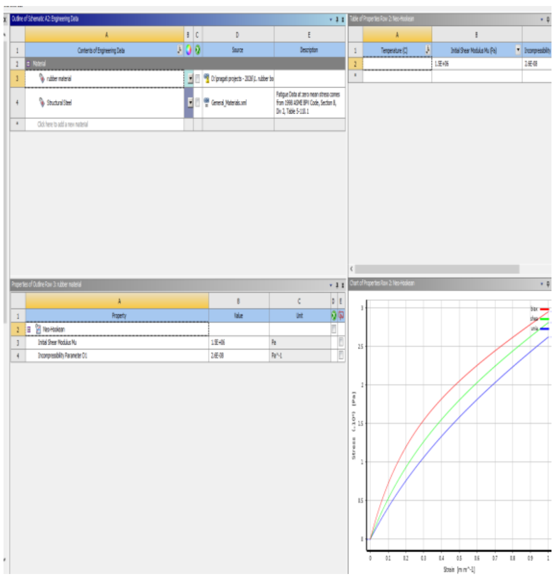
The parameter D_1 controls the volumetric response of the material. Rubber is nearly incompressible, meaning that its volume remains almost constant even under large deformation. A small value of D_1 enforces this behavior numerically by penalizing volumetric strain.

This near-incompressibility is essential for accurately predicting:

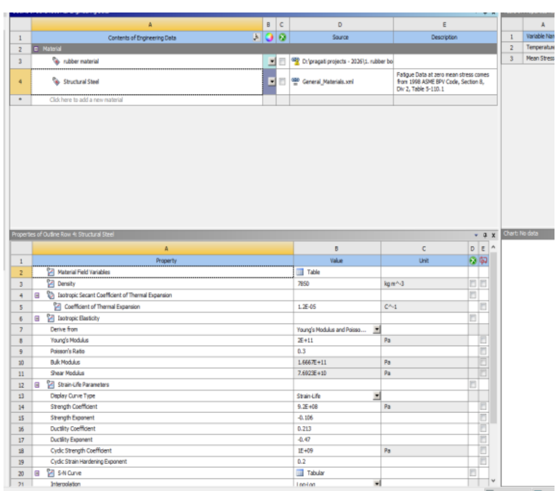
- Contact pressure distribution
- Stress localization
- Folding and wrinkling behavior of the boot

Inadequate representation of incompressibility can lead to unrealistic volume changes and incorrect stress results.

Material Assignment to the Boot Geometry



Rubber material



Structural steel

3.3 Mesh Generation

After defining the hyperelastic material, it is assigned to the rubber boot geometry within ANSYS Mechanical. This is done by selecting the Part object in the model tree and choosing “Rubber Material” from the Material Assignment property.

A structured finite element mesh is generated with:

- Linear solid elements
- Face meshing on the cylinder contact surface
- Local sizing (2 mm) on critical contact and curvature regions

Role of the Mesh in Nonlinear Rubber Analysis

In nonlinear finite element simulations involving large deformation, hyperelastic materials, and frictional contact, the quality of the mesh plays a decisive role in both numerical convergence and physical accuracy. Unlike linear elastic problems, where coarse meshes may still provide acceptable global results, rubber seal analyses require careful meshing to:

- Accurately represent large strains and rotations
- Capture evolving contact areas and pressure distributions
- Avoid excessive element distortion
- Maintain stable and efficient convergence of the nonlinear solver

The meshing strategy adopted in this tutorial reflects a balance between computational efficiency and the level of accuracy required for instructional and preliminary engineering evaluation.

Face Meshing on the Cylinder Surface

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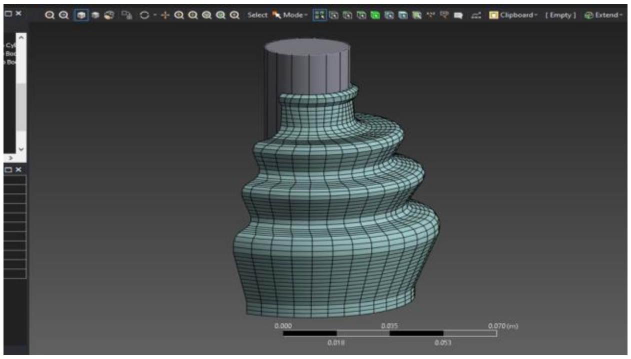
Purpose of Face Meshing



A Face Meshing control is applied to the exterior surface of the cylindrical shaft. This control enforces a more structured and uniform mesh on the contact surface, which is critical for stable and accurate contact detection.

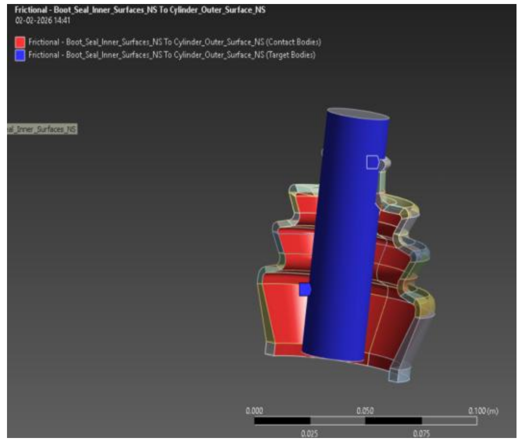
Face Meshing Parameters

- Geometry: Exterior surface of the cylinder
- Internal Number of Divisions: 1

Setting the Internal Number of Divisions to 1 produces a simple mapped mesh across the face without excessive subdivision. This is sufficient because the shaft is modeled as rigid and does not require stress resolution. The primary goal is to provide a clean, consistent target surface for contact with the rubber boot.

Sizing Control on Critical Surfaces

Need for Local Mesh Refinement



The rubber boot experiences:

- High strain gradients near contact interfaces
- Localized stress concentrations
- Significant deformation during compression and rotation

To capture these effects accurately, local mesh refinement is introduced using a Sizing control.

Mesh Sensitivity and Best Practice Considerations

While the mesh used in this tutorial is adequate for demonstrating the modeling workflow and capturing overall behavior, best engineering practice requires mesh refinement studies. Such studies involve systematically reducing element size and comparing key results such as:

- Maximum equivalent stress
- Contact pressure distribution
- Total deformation
- Reaction forces at the remote point

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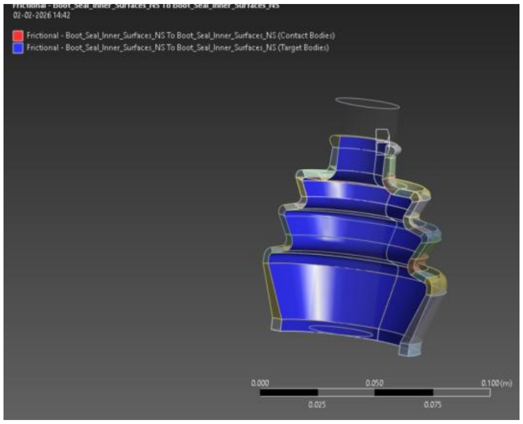
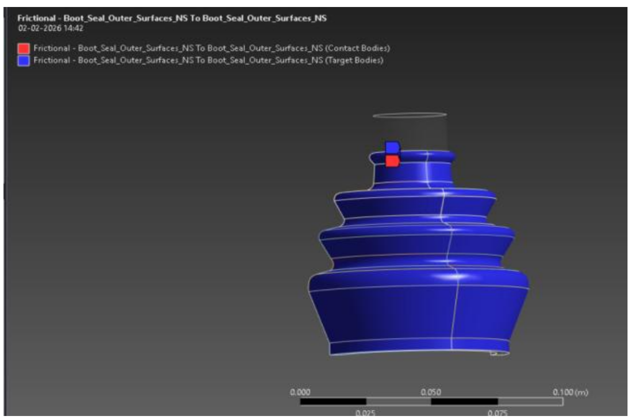


This process helps assess the sensitivity of results to mesh density and establishes confidence in the numerical predictions.



Differences Between Workbench and APDL Meshes

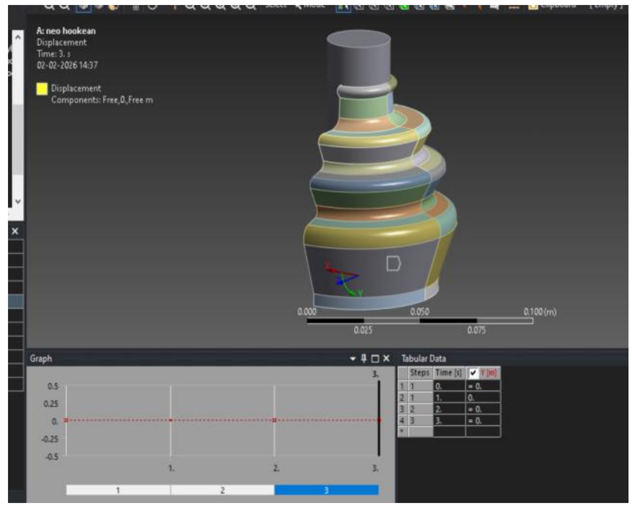
Physical Interpretation:

In the defined cylindrical coordinate system, the Y direction corresponds to the axial direction of the shaft. By constraining the Y component of displacement on the symmetry plane, the model enforces the requirement that:

- No axial motion occurs across the plane of symmetry
- Deformation remains symmetric throughout the analysis

This condition ensures that the half-model behaves exactly as if the full boot were present, preserving physical realism while reducing computational cost.

Axial Constraint on the Bottom Portion of the Boot



A second Displacement boundary condition is applied to two faces at the bottom of the boot, which represent regions that are effectively fixed in the axial direction in the real assembly.

Mesh refinement is concentrated in regions expected to experience high strain gradients and contact pressure variation.

3.4 Contact Definitions

Three frictional contact regions are defined:

1. Boot inner surface → Shaft outer surface (rigid–flexible contact)
2. Inner surface self-contact
3. Outer surface self-contact

Detection methods:

- Gauss-point-based detection for boot–shaft contact

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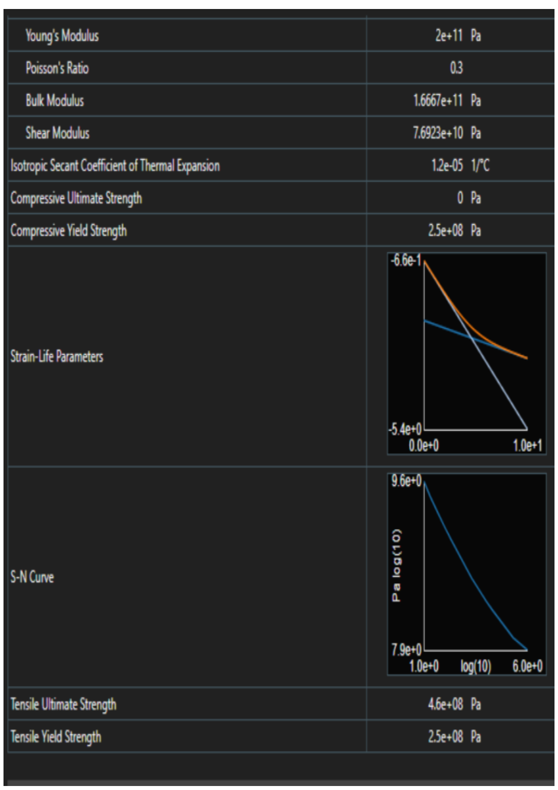
- Nodal-projected normal detection for self-contact

Interface treatment includes ramped offset effects to stabilize the initial interference condition.

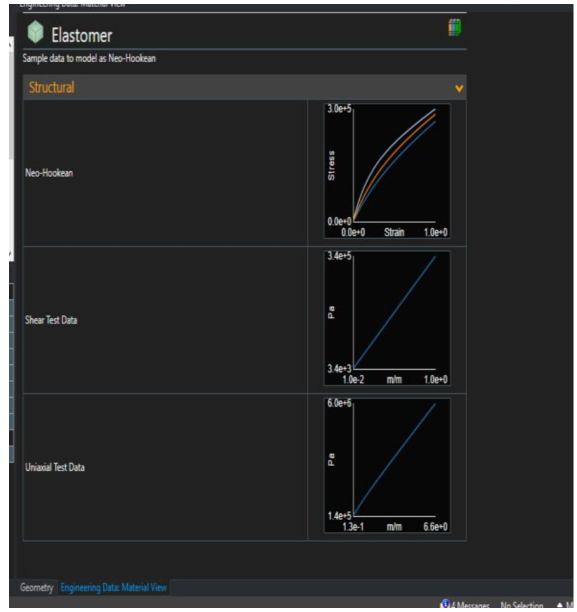
Definition Details

- Scope: Named Selection
- Contact: Boot_Seal_Inner_Surfaces_NS
- Target: Boot_Seal_Inner_Surfaces_NS
- Type: Frictional
- Frictional Coefficient: 0.2

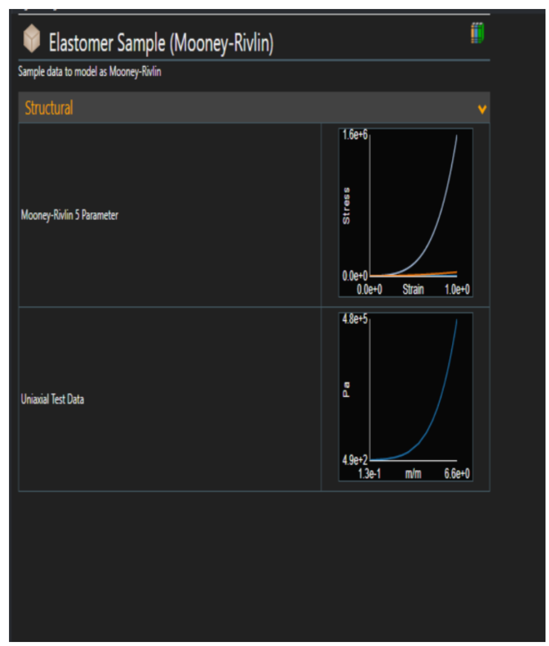
Using the same surface as both contact and target enables the solver to detect when different regions of the inner surface approach or touch each other.



Young's Modulus	2e+11	Pa
Poisson's Ratio	0.3	
Bulk Modulus	1.6667e+11	Pa
Shear Modulus	7.6923e+10	Pa
Isotropic Secant Coefficient of Thermal Expansion	1.2e-05	1/°C
Compressive Ultimate Strength	0	Pa
Compressive Yield Strength	2.5e+08	Pa
Strain-Life Parameters		
S-N Curve		
Tensile Ultimate Strength	4.6e+08	Pa
Tensile Yield Strength	2.5e+08	Pa



Elastomer



Mooney Rivlin

3.5 Boundary Conditions and Loading

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Role of Boundary Conditions in Nonlinear Rubber Boot Analysis

In nonlinear finite element analysis, boundary conditions do more than merely "hold" the model in place—they define the physical experiment being simulated. For rubber boot seals, improper constraints can easily lead to:

- Artificial stiffening
- Nonphysical stress concentrations
- Loss of convergence
- Incorrect deformation modes

The present model uses a carefully designed combination of displacement constraints and a remote displacement, applied in both global and cylindrical coordinate systems, to accurately represent real assembly and operating conditions of a boot–shaft system.

A cylindrical coordinate system is defined to align with the shaft axis.

A remote point controls shaft motion using tabular displacement data across three load steps:

Step	Axial Displacement	Rotation
1	0 mm	0 rad
2	−10 mm	0 rad
3	−10 mm	0.55 rad

Large deflection is enabled. Automatic substepping is used to ensure convergence:

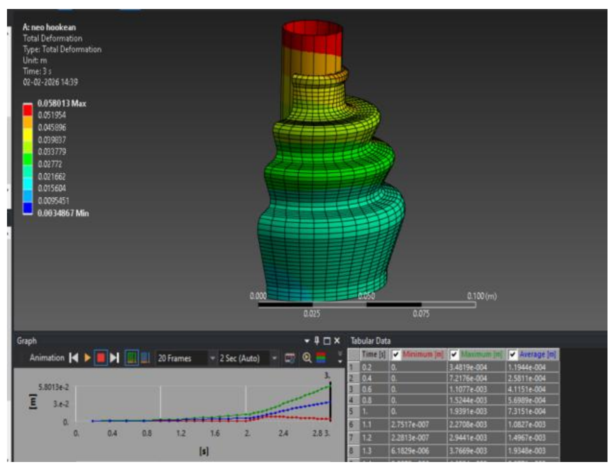
- Step 1: 5–1000 substeps
- Step 2: 10–1000 substeps
- Step 3: 20–1000 substeps

4. Results and Discussion

4.1 Deformation Behavior

The final load step shows substantial global deformation due to combined axial compression and torsion.

The Total Deformation result at the maximum shaft angle (i.e., at the end of Step 3) shows the global deformation of the rubber boot under combined axial compression and torsion. The boot folds and bends in response to the −10 mm axial displacement and 0.55 rad rotation of the shaft, with the largest deformations occurring near the convolutions and in regions where the boot wall is relatively thin. The interference fit and frictional contact with the shaft restrain motion at the inner surfaces, while the outer surfaces undergo significant bending and stretching.



Rubber Material – def 1

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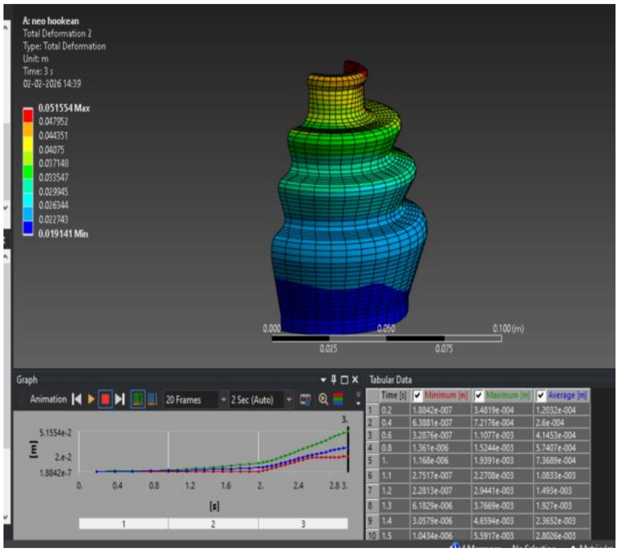
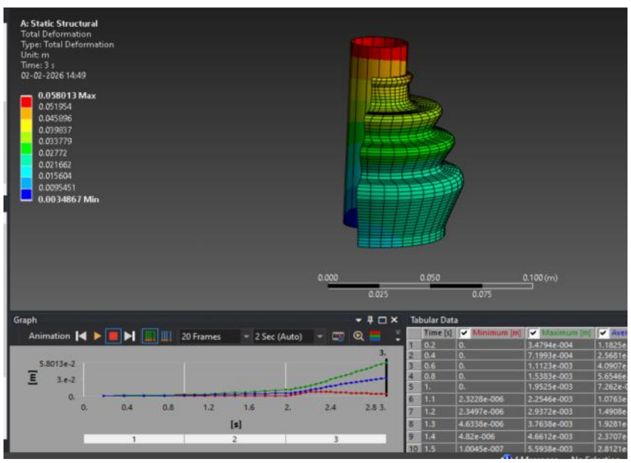
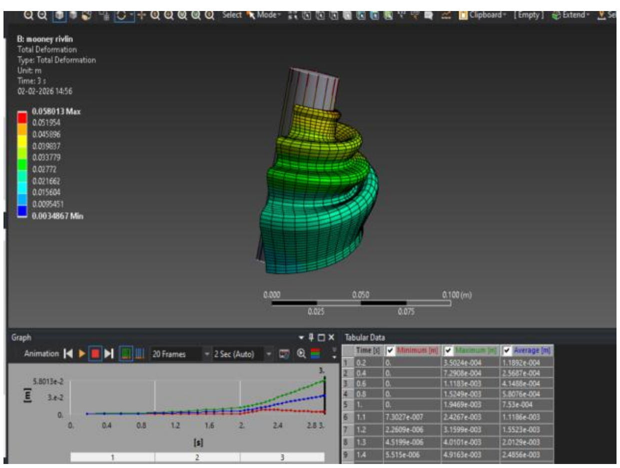


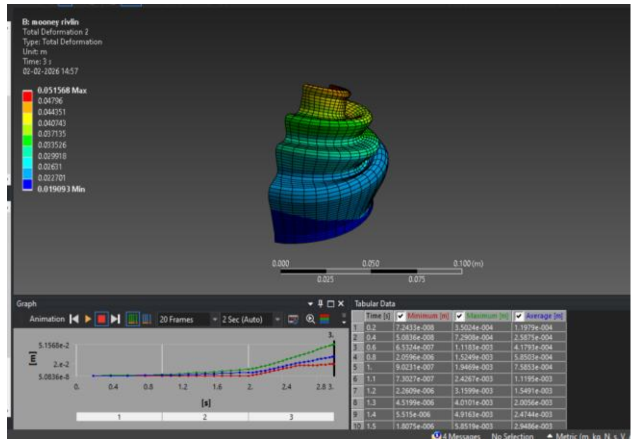
Rubber material def- 2



Elastomer



Mooney Rivlin def 1



Mooney Rivlin def 2

Key observations:

- Folding near convolutions
- Maximum displacement near thin wall sections
- Contact constraints preventing self-penetration

The deformation confirms strong geometric nonlinearity.

4.2 Stress Distribution

Equivalent (von Mises) stress concentrations occur at:

- Thickness transitions
- Contact interfaces
- Regions of combined bending and torsion

The Equivalent (von-Mises) Stress plot for the final load step highlights the regions of highest stress within the rubber boot. Elevated stress zones typically occur near geometric discontinuities, such as transitions between thick and thin sections, grooves, and

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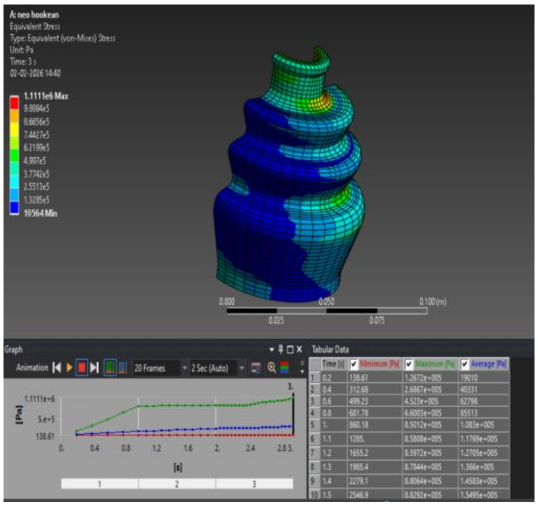
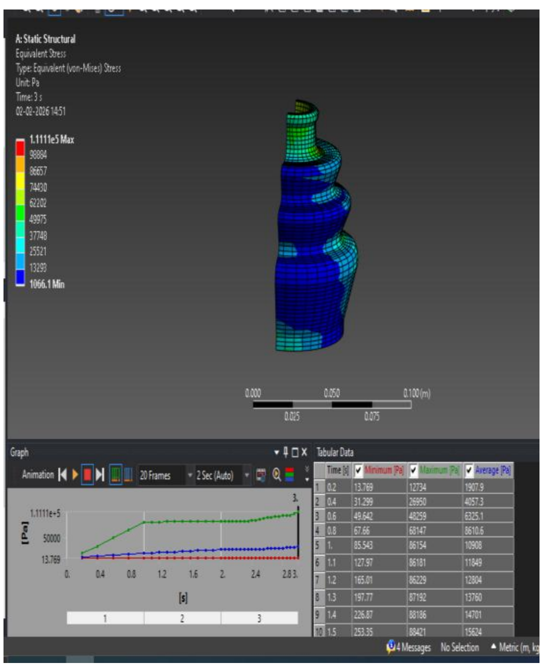
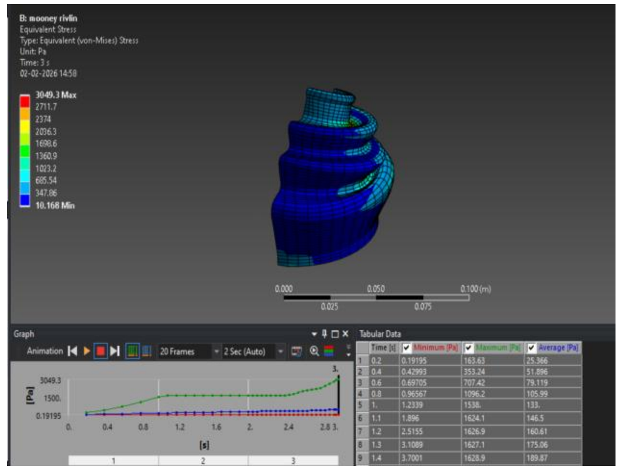
fillets, as well as in areas where the boot experiences significant bending due to shaft rotation. Contact with the shaft contributes to localized stresses on the inner surfaces, particularly at the locations of interference fit and frictional sliding.



Rubber material stress



Elastomer stress



Mooney Rivlin stress

Although von Mises stress is traditionally associated with metals, it provides a useful scalar measure for identifying critical regions in elastomers.

Maximum equivalent stress observed (Neo-Hookean model):≈ 6.2 × 10^5 Pa.

4.3 Strain Distribution

The Equivalent Elastic Strain (von-Mises) plot provides insight into the strain distribution in the boot at the maximum shaft angle. As expected for a hyperelastic rubber, large strains are present in regions of significant curvature and bending, especially near the convolutions of the boot and along the interfaces where the boot folds onto itself. These high-strain regions often coincide with the high-stress areas, but the strain plot can reveal additional details about stretch and compression in the material that are not evident from stress alone.

Large equivalent elastic strains are observed near:

- Convolution folds

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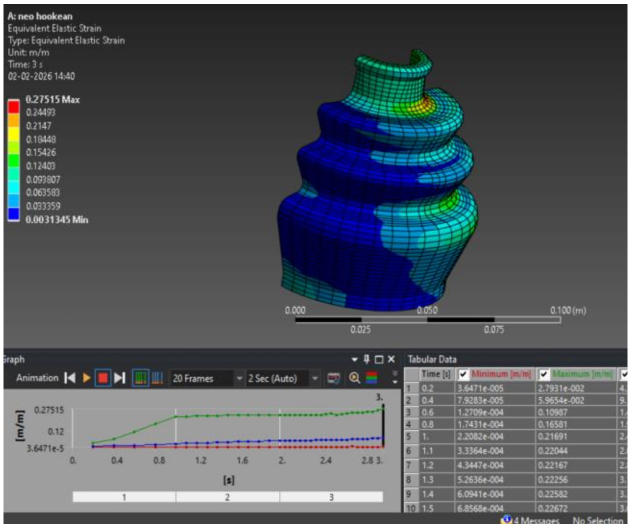
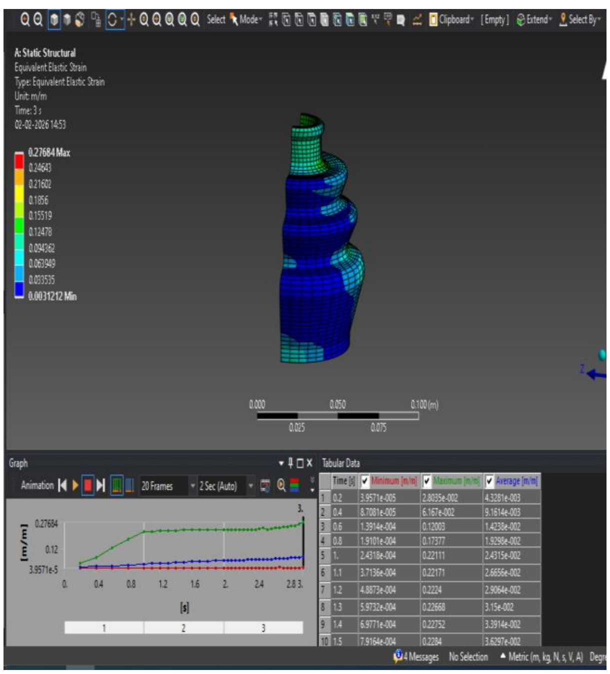
- Contact tightening zones
- Regions undergoing torsional shear

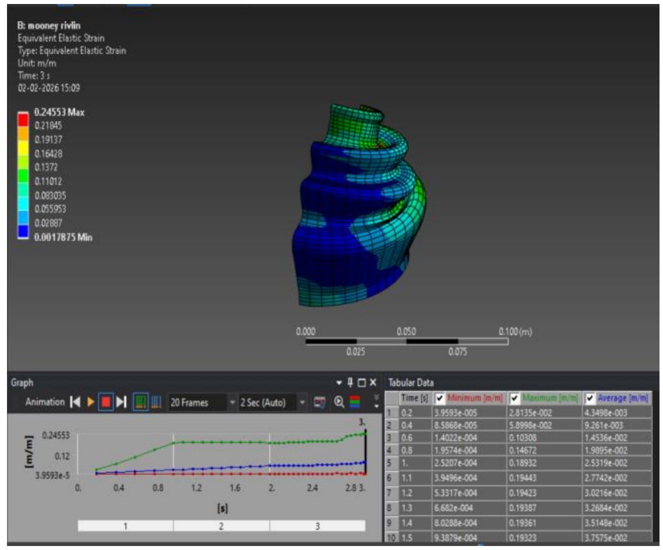
Maximum strain levels approach 0.2 (20%), validating the need for hyperelastic modeling.



Rubber Material



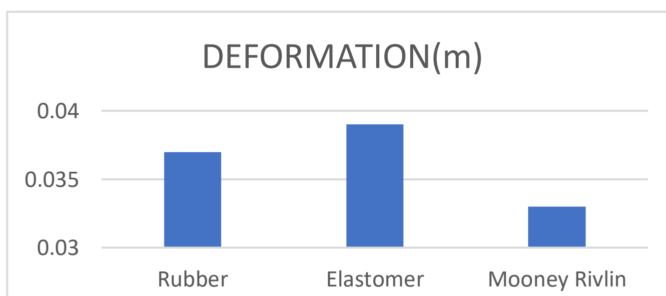
Elastomer



Mooney Rivlin

4.4 Material Model Comparison

S.NO	MATERIAL	DEFORMATION (m)	EQUIVALENT STRESS(pa)	ELASTIC STRAIN(m/m)
1	Rubber	0.037	6.2*10^5	0.2
2	Elastomer	0.039	1*10^5	0.19
3	Mooney Rivlin	0.033	3000	0.16



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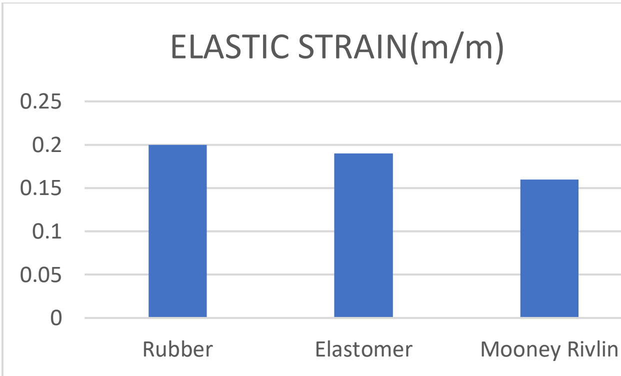

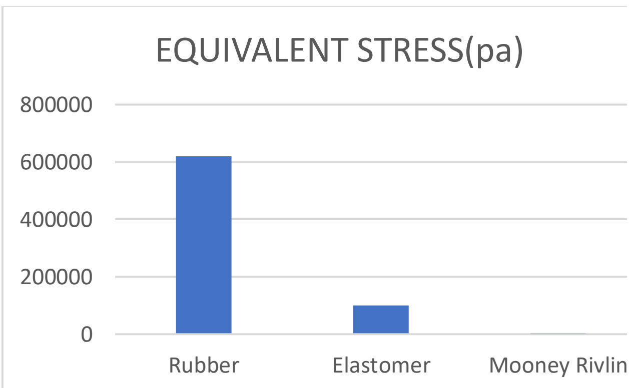

The Neo-Hookean model provides realistic stiffness and stress prediction while maintaining numerical stability.

5. Conclusion

This study presents a comprehensive nonlinear finite element analysis of a rubber boot seal subjected to interference, axial compression, and torsional loading. The combined effects of geometric nonlinearity, hyperelastic material behavior, and frictional contact significantly influence deformation and stress distribution.

Key findings include:

- Large deformation concentrated in convoluted regions.
- Stress localization at geometric transitions and contact interfaces.
- Strong influence of friction and contact detection methods on solution stability.
- Necessity of incremental load application for convergence.

The modeling framework—incorporating hyperelastic material definitions, surface-projection-based contact, symmetry reduction, and staged loading—provides a reliable template for analyzing elastomeric sealing components. Future work may extend this approach to fatigue analysis, parametric optimization, and experimental validation.

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