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# Numerical Simulation of Weather-Strip Wrinkle

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**ABSTRACT:** The automotive door system's weather-strip seals play a crucial role in determining the degree of door closure, sealing the passenger cabin from water, and reducing wind noise inside the vehicle. Wrinkles often occur when installing weather-strips on door surfaces with bent or twisted profiles, affecting both the closure tightness and the noise insulation properties of the car door system. This study characterizes the wrinkling of Ethylene Propylene Diene Monomer (EPDM) automotive weather-strip seals during bending and identifies critical conditions for wrinkle formation. The hyper elastic behaviour of the seal's EPDM sponge and dense EPDM rubber was modeled using the Foam and Mooney-Rivlin models, respectively. A Finite Element Analysis (FEA) model of the automotive weather-strip seal was then developed and analysed using the linear FEA software Abaqus to determine the deformation and thickness reduction in areas prone to wrinkling. Finally, the critical criteria for wrinkle formation were determined through reaction force analysis in these areas. The proposed analytical method significantly reduces the product design cycle and cuts down on design and prototype costs.

**KEYWORDS:** automobile weather-strip seal; wrinkling; finite element analysis (FEA); hyper elastic constitutive model;

## I. INTRODUCTION

Automotive weather-strip seals are typically made from dense rubber and sponge, forming a dual-extruded tube that is attached to doors or the body of the vehicle to seal the passenger cabin from water and external air, thereby reducing interior wind noise. These seals are crucial for improving the ride comfort and for controlling noise, vibration, and harshness (NVH) characteristics in the cabin. The manufacturing process involves extruding the seals in straight sections with a metal framework and then bending them at corners. These seals are installed at specific points on both the door seal and the door frame. During installation, especially when bent around corners, the seals may twist, frequently leading to wrinkling. This wrinkling can impact the seal's effectiveness and the operational integrity of the door system when assembled on the car body [1].

Today, numerical simulations based on Finite Element Analysis (FEA) methods are established tools in product development for evaluating vehicle body design performance. For instance, they enable reliable results in automotive crashworthiness analysis. By utilizing these tools, designers can reduce the number of prototypes needed, significantly cutting down both time and costs involved in the design process.

Several scholars have conducted studies using Finite Element Analysis (FEA) methods on weather-strip seals. Wagner et al utilized nonlinear Finite Element Method (FEM) techniques to analyse the cross-sections of seals, determining behaviours such as Compression Load Deflection (CLD), contact pressure distribution, and suction forces due to pressure differentials across the seal [2]. Moona et al proposed a method to theoretically predict the minimum speed required for door closure using back forces and the blueprint dimensions of the automobile body [3]. They experimentally measured the door seal back force and mathematically calculated the changes in cabin air pressure when air flows in and out. Kim et al suggested a method for indirectly calculating the total reaction force generated solely by the seal components assembled on the automobile body and door, multiplying the two-dimensional Finite Element results of each seal's cross-section by its length [4].

However, the report does not explicitly discuss the wrinkles that occur when weather-strips are assembled on door surfaces with bent or twisted profiles.

In this study, we considered a weather-strip seal used in passenger cars, as depicted in Figure 1. The seal is manufactured using Ethylene Propylene Diene Monomer (EPDM) material is extruded and coated. This process involves vulcanizing both EPDM sponge and dense EPDM rubber. The study focused on examining the wrinkling of the weather-strip seal using Finite Element Analysis (FEA) methods, from which critical criteria for wrinkle formation were inferred. Figure 2 shows the Finite element model of Weather-strip seal.

## II. MATERIAL PROPERTIES

Automotive weather-strip seals are commonly dual-extruded tubes made from sponge and dense rubber, attached to doors or the vehicle body to seal the passenger compartment. For quasi-static analysis, understanding the static material behaviour of both the sponge and dense rubber is essential.

### THE HYPER ELASTIC CONSTITUTIVE MODEL OF THE SPONGE RUBBER MATERIAL

Sponge rubber can be considered a hyper elastic material because it exhibits highly compressible, nonlinear, elastic, and isotropic behaviour [5]. Typically, the relationship between stress and strain in hyper elastic materials, which is characterized by the strain energy potential, is essential for the Finite Element Analysis (FEA) of rubber components. Defining the constitutive relations of hyper elastic materials requires experimental test data to determine the material parameters of the strain energy potential. In this study, the Foam function was chosen to specify the constitutive model for sponge rubber material. The strain energy potential of the Foam model is expressed as shown in Equation-1 [6, 7]

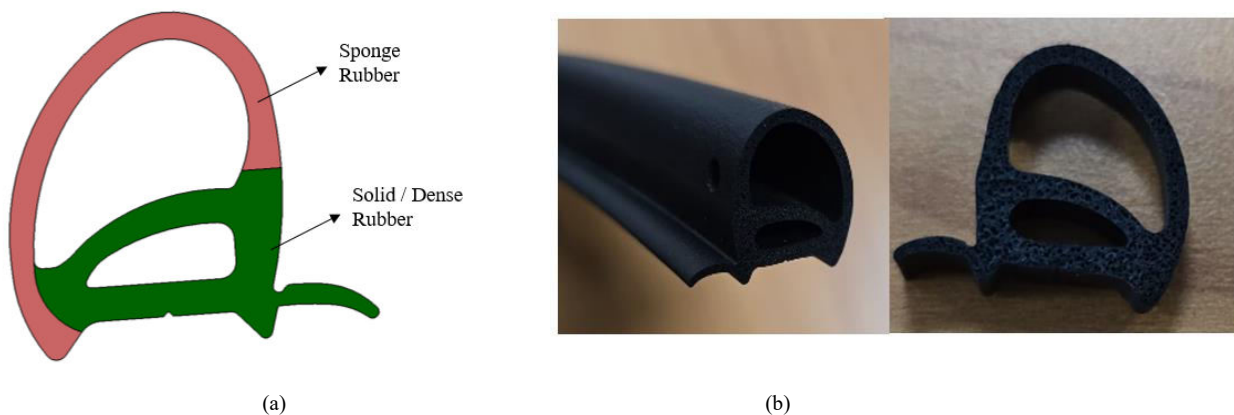


Figure 1. a. Cross section of weather strip seal – CAD, b. Cross section of weather strip seal – manufactured part



Figure 2. Weather strip seal – 3D mesh

$$W = W_s + W_b \tag{1}$$

The strain potential energy associated with an incompressible material  $W_s$ , is outlined in Equation 2, while Equation 3 details the strain potential energy  $W_b$ , resulting from volume changes.

$$W_s = \sum_{n=1}^N \frac{\mu_n}{\alpha_n} (\lambda_1^{\alpha_n} + \lambda_2^{\alpha_n} + \lambda_3^{\alpha_n} - 3) \tag{2}$$

$$W_b = \sum_{n=1}^N \frac{\mu_n}{\beta_n} (1 - J^{\beta_n}) \tag{3}$$

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \tag{4}$$

$$I_2 = (\lambda_1 \lambda_2)^2 + (\lambda_2 \lambda_3)^2 + (\lambda_1 \lambda_3)^2 \tag{5}$$

$$I_3 = (\lambda_1 \lambda_2 \lambda_3)^2 \tag{6}$$

The material parameters  $\alpha_n$ ,  $\beta_n$ , and  $\mu_n$  are defined based on results from material testing.  $J$  represents the change in volume of the material as observed in mechanical tests. The invariant strain values of the first, second, and third orders, designated as  $I_1$ ,  $I_2$ , and  $I_3$ , are derived from the principal stretch ratios  $\lambda_1$ ,  $\lambda_2$ , and  $\lambda_3$ . These ratios are defined as the proportion of a specimen's elongated length to its original length in the three principal directions of stress. For a uniaxial stress state, the principal stretch ratios  $\lambda_1$ ,  $\lambda_2$ , and  $\lambda_3$  are specified in Equation 7.

$$\lambda_1 = \lambda_u, \lambda_2 = \lambda_3 = 1/\sqrt{\lambda_1} \tag{7}$$

$\lambda_u$  is defined as the principal stretch ratio along the loading direction, while  $\lambda_2$  and  $\lambda_3$  are the principal stretch ratios along the planes perpendicular to this direction. Subsequently, the strain potential energy for a compressible material is reformulated in Equation 8.

$$W = \sum_{n=1}^N \frac{\mu_n}{\alpha_n} (\lambda_1^{\alpha_n} + \lambda_2^{\alpha_n} + \lambda_3^{\alpha_n} - 3) + \sum_{n=1}^N \frac{\mu_n}{\beta_n} (1 - J^{\beta_n}) \tag{8}$$

In this study,  $N$  is an integer typically less than 3, although it can be as high as 10. For our purposes, we set  $N$  to 3. The material parameters  $\alpha_n$ ,  $\beta_n$ , and  $\mu_n$  were calibrated using data from Figs. 3-5, which includes results from uniaxial tensile tests, uniaxial compression tests, and volumetric tests.

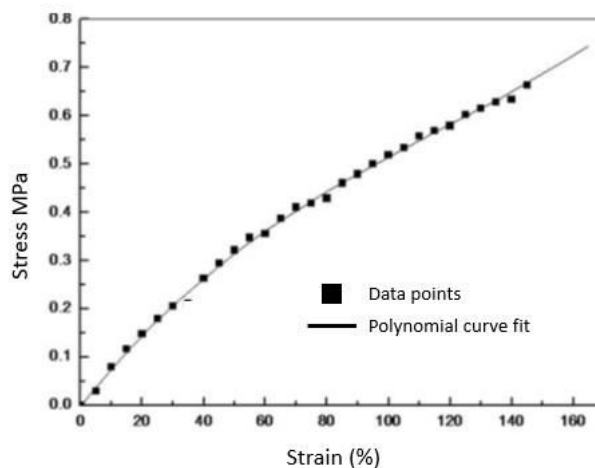


Figure 3. Fitted curve of stress vs. strain in uniaxial tensile test

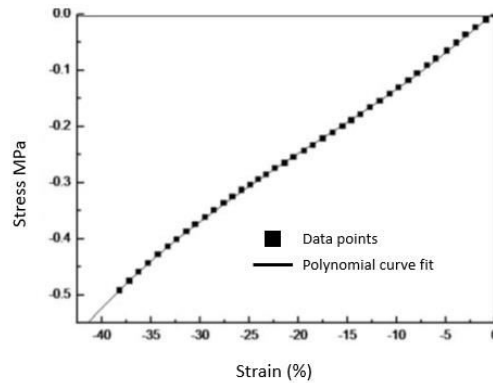


Figure 4. Fitted curve of stress vs. strain in uniaxial compression test.

### THE HYPER ELASTIC CONSTITUTIVE MODEL OF THE DENSE RUBBER MATERIAL

Dense rubber exhibits the characteristics of a hyper elastic material, demonstrating a highly nonlinear, isotropic, and incompressible elastic behaviour. The Mooney–Rivlin model is commonly applied to describe the constitutive behaviour of such incompressible rubber materials. The strain potential energy for this model is detailed in Equation 9.

$$W = \sum_{n=1}^N C_{ij} (I_1 - 3)^i (I_2 - 3)^j + \frac{1}{2} (\sqrt{I_3} - 3)^2 \quad 9$$

$C_{ij}$  is a material parameter established through material testing. The three-parameter Mooney–Rivlin model, detailed in Equation 10, was chosen to define the constitutive model for dense rubber.

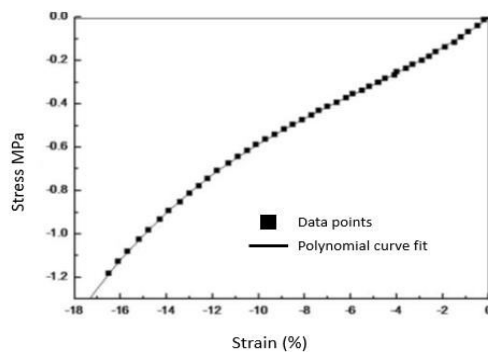


Figure 5. Fitted curve of stress-strain of volumetric test.

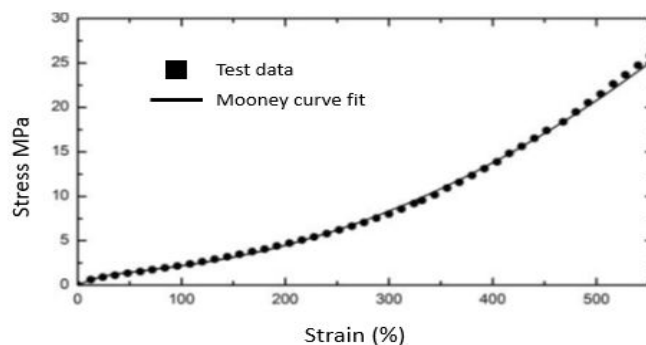


Figure 6. The stress vs. strain curves of the dense rubber material and Mooney model fitted

$$W = C_{10}(I_1 - 3) + C_{01}(I_1 - 3) + C_{11}(I_1 - 3)(I_2 - 3) \quad 10$$

The parameters  $C_{10}$ ,  $C_{01}$ , and  $C_{11}$  for the dense rubber material were calculated based on uniaxial tensile test data. Through data fitting procedures using this experimental data, the values for  $C_{10}$ ,  $C_{01}$ , and  $C_{11}$  were established as - 0.438, 1.537, and 0.132, respectively. Figure 6 illustrates the stress versus strain curves, comparing the experimental results with those predicted by the Mooney model.

### III. BOUNDARY CONDITION



Figure 7. shows the finite element model of the weather-strip seal for a 3D analysis.

Analysis was done using the commercial program Abaqus, a nonlinear simulation program. The hexahedral element with Herrmann integration was adopted to mesh the dense rubber and the 8-node hexahedral element was adopted to mesh the sponge rubber in this analysis [10].

The boundary conditions to simulate the deformation of the weather-strip seal assembled on the door surfaces which have bent or twisted profiles were set as follows:

- (1) A nodal force of 200N in the reverse direction of the Y axis acted as shown Figure 7.
- (2) In order to prevent the seal from moving in the direction of the X & Z axis, the displacement in the direction of the X axis on the symmetry plane of the seal was set as 0 at load location.
- (3) The displacement on the Left fixed point fully fixed on all DOF.

### IV. RESULTS OF THE WEATHER-STRIP SEAL

Figure 8 illustrates the FEM and real product deformation process of the weather-strip seal under bending stress, highlighting the areas prone to wrinkling due to the mechanical stresses involved. Figure 9 provides a cross-sectional view that offers a detailed perspective on how and where wrinkles form during bending, particularly noting the accumulation of stress at the top and sidewalls of the weather-strip.

From Figure 10, it is evident that the initiation and propagation of wrinkles are concentrated in specific regions, labelled as A & B. These areas are critical because they show a significant tendency for wrinkle formation. In these zones, the material properties of the seal components—dense rubber and foam—play significant roles in the mechanical behaviour observed.

The dense rubber part of the weather-strip is capable of withstanding the applied loads better, thus helping to minimize wrinkling. However, the foam, given its inherent material properties, is more susceptible to deformation. Wrinkling primarily occurs in two key locations:

1. **Sidewall Junction:** At the junction where the dense rubber and foam meet, the robustness of the dense rubber tends to pull on the more flexible foam material. This interaction leads to gradual wrinkling as the foam cannot sufficiently resist the pulling force exerted by the contracting dense rubber during bending.
2. **Top Section of the Weather-strip:** Composed entirely of foam, this area is particularly vulnerable due to its softness and the hollow nature of its cross-section. Under bending stress, this part starts to lose its structural integrity, resulting in a loss of shape and progressing into a stage of instability, which manifests as wrinkling.

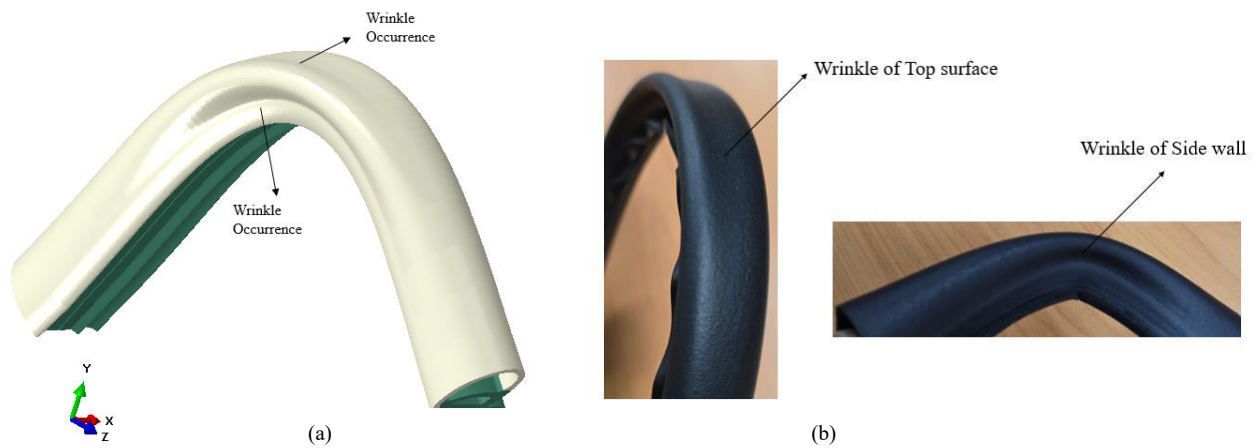


Figure 8. Deformation of the seal in bending - a. FEM, b. manufactured part

Understanding these dynamics is crucial for improving the design of weather-strip seals. By reinforcing these critical areas or modifying the material properties to enhance compatibility between the dense rubber and foam, it is possible to reduce the incidence of wrinkling, thereby enhancing the functional performance and longevity of the seal. This analysis not only helps in pinpointing the flaws in the current design but also aids in developing more resilient sealing solutions for automotive applications.

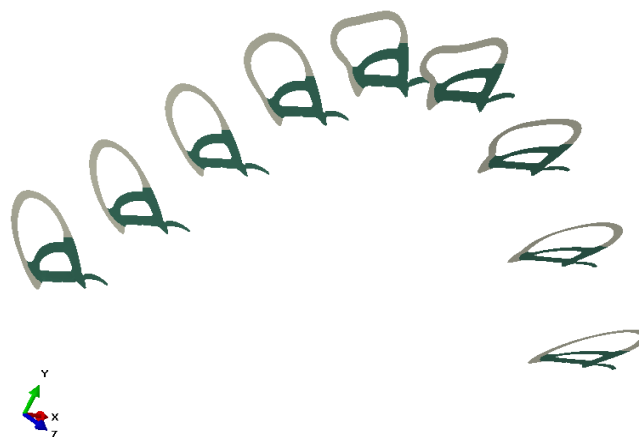


Figure 9. Cross-sections of the seal in the process of bending.

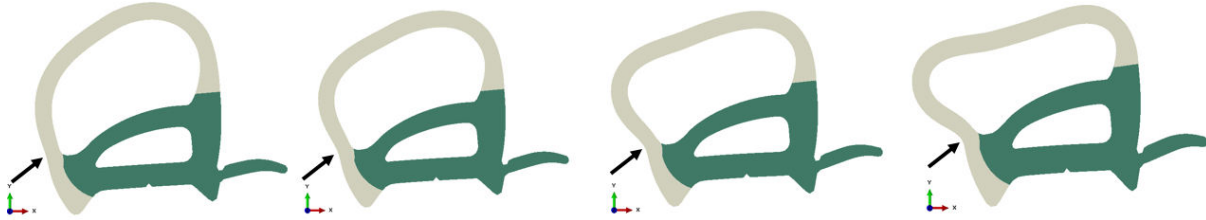


Figure 10. Cross-sections of the seal in the process of bending.

## V. THE CRITICAL CRITERION OF FAILURE AND WRINKLE

The critical criteria for failure and wrinkling in materials, particularly in flexible, elastomeric components like automotive weather-strips, involve understanding the material's behaviour under stress and deformation. This analysis is crucial in sectors such as automotive manufacturing, where seal integrity directly impacts vehicle performance and durability.

**Material Response:** Elastomeric materials, such as those used in weather-strip seals, exhibit complex responses to mechanical stresses. These materials are often modeled using hyper elasticity theories, which predict how materials behave when stretched, compressed, or twisted. Critical failure occurs when the material no longer responds elastically and starts to experience permanent deformations or structural breakdown.

**Wrinkling Phenomenon:** Wrinkling in such materials typically manifests at zones of stress concentration or material inconsistency. For a weather-strip, these zones could be areas where the material's thickness changes, or where different materials meet. Wrinkles are not just aesthetic issues but are indicative of potential failure points where the seal might not perform effectively, leading to leaks or noise infiltration.

### Factors Influencing Failure and Wrinkle Formation:

1. **Material Composition:** The choice of material affects the resilience and flexibility. Dense rubber might withstand more pressure compared to foam, which might wrinkle under less stress due to its lower tensile strength.
2. **Design Geometry:** The shape and the profile of the weather-strip influence how forces are distributed across the material. Sharp bends or complex profiles are more prone to wrinkling.
3. **Load Conditions:** The magnitude, direction, and duration of loads applied to a weather-strip can determine the onset of failure or wrinkling. Repeated or sustained loads might accelerate failure modes.

## VI. CONCLUSION

The identification of critical criteria for failure and wrinkling in weather-strip seals is a complex yet essential task. It requires a multi-disciplinary approach involving material science, mechanical engineering, and design principles. Understanding these aspects helps in enhancing the overall performance and longevity of the seals, ensuring they meet the rigorous demands of their applications. This detailed insight into material behaviour under operational stresses not only aids in improving product quality but also in driving innovations in seal design and material formulation. The research integrated material testing and Finite Element Analysis (FEA) to examine the formation of wrinkles in automotive weather-strip seals when subjected to bending. The hyper elastic behaviour of the rubber was modeled based on parameters obtained from material tests. Deformations were recorded through FEA, noting significant increases in regions typically vulnerable to wrinkling. The essential factors for wrinkle development were deduced by analysing the reaction forces in these key areas. This analytical method has the potential to substantially shorten product development cycles, considerably reduce design and prototyping expenses, and improve the quality of the seals.



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