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Investigation of the Effect of Hyper Elastic Material Model and Design Parameters on Gasket Behaviour Using the Finite Element Method

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ABSTRACT

Elastomer gaskets are widely used in sealing applications, and their performance is strongly influenced by material behaviour, gasket geometry, and bolt preload. In this study, the effects of hyper elastic material modelling and design parameters on gasket behaviour were investigated using the Finite Element Method (FEM). Ethylene Propylene Diene Monomer (EPDM) and Polyurethane (PU) gaskets were comparatively analyzed in flange connections within the ANSYS environment using the Mooney-Rivlin hyper elastic material model. Finite element analyses were performed for gasket thicknesses between 2-5 mm under different preload conditions. Material, geometric, and contact nonlinearities were considered throughout the simulations. The results showed that thicker gaskets exhibited more homogeneous deformation, while thinner gaskets experienced localized compression and instability. In addition, the relationship between preload and com- pression ratio was found to be nonlinear. EPDM showed higher deformation capability, whereas PU generated higher contact pressures due to its stiffer behaviour. The study demonstrates that reliable sealing performance requires the combined optimization of gasket thickness and bolt preload, and confirms the effectiveness of hyper elastic FEM modelling for gasket design applications.

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Introduction

Elastomer-based gaskets are critical components widely used in mechanical systems for fluid control and sealing. They play an indispensable role in maintaining system safety and efficiency, particularly in the automotive, energy, aerospace, and chemical industries. Thanks to the flexible structure of elastomers, their ability to tolerate surface roughness, and their adaptability under varying temperature and pressure conditions, these gaskets have a broad range of applications. However, gasket performance is not limited solely to the elastic properties of the material; it is governed by the interaction of numerous factors, including geometric parameters, assembly conditions, and applied bolt preload. While properties such as material hardness, viscoelastic behaviour, chemical resistance, and temperature dependency directly affect the long-term performance of the elastomer, cross-sectional geometry, dimensional tolerances, and contact surfaces also shape sealing success. Furthermore, the preloading force applied during assembly is of critical importance in creating the necessary contact pressure on the gasket surface. Insufficient preloading leads to leakage, whereas excessive preloading increases the risk of material deformation and premature failure. Today, sealing elements play a critical role in many engineering applications, ranging from internal combustion engines to pressure vessels and autoclave systems. When parameters such as operating pressure, temperature, material properties, and surface roughness are not properly selected, severe performance losses and workplace accidents can occur. In the literature, the historical development of pressure vessels began with the early theoretical studies of Leonardo da Vinci, expanded with the Industrial Revolution, and continues today with the use of autoclaves in areas such as composite manufacturing, laminated glass, rubber, and industrial hose production. It is emphasized that specially designed gaskets are required for autoclaves to operate safely under high pressure and temperature, and standard elements such as O-rings or U-rings are insufficient. For this reason, gasket geometry, material selection, and assembly conditions are determined in accordance with international standards (PED, CE, ASME, etc.) and verified through hydrostatic tests and finite element analyses [1].

In traditional design approaches, the effects of these parameters were mostly investigated through experimental methods. Although experimental studies are valuable for observing real system behaviour, they remain limited due to high cost and time requirements. Furthermore, the complex non-linear behaviour of elastomers is difficult to fully capture through experimental methods alone. In this context, finite element analysis (FEA) has gained increasing importance in recent years. FEA allows for the numerical investigation of elastomer-based gaskets using material models (hyper elastic models such as Mooney-Rivlin and Ogden). Thus, gasket deformation, contact pressure distribution, and life expectancy predictions under different loading scenarios can be analyzed in detail in addition to, FEA enables the systematic evaluation of parameters that are difficult to obtain through experimental methods, providing more reliable and cost-effective solutions in the design process [2].

The primary objective of this study is to comparatively investigate the behaviour of elastomer-based gaskets in a flange-type coupling under various material, thickness, and bolt preload approaches. In this context, numerical analyses were conducted for polyurethane (PU) and ethylene-propylene-diene monomer (EPDM) based gaskets using the Mooney-Rivlin hyper elastic material model. In the analyses, different material thicknesses and preloads were applied to both materials, and their effects on compression and gasket deformations were examined. The original aspect of this study lies in comparing the compression behaviour obtained under different materials, preloads, and thicknesses, as well as evaluating the degree of homogeneity of this behaviour. The analysis results revealed that despite varying preload values, the same compression ratio could be achieved in both PU and EPDM gaskets, and that this compression was homogeneously distributed. This finding demonstrates that hyper elastic material models, when utilized with accurate parameters, can provide reliable predictions in gasket design. Hence, this thesis aims to reveal the interaction between material selection, preload and torque determination according to the selected material, and assembly conditions for elastomer-based gaskets; furthermore, it seeks to comparatively evaluate accuracy and reliability across different gasket thicknesses. The obtained results are expected to contribute to the optimization of gasket designs utilized particularly in the automotive and machinery manufacturing sectors.

Hence, understanding and optimizing the performance of elastomer-based gaskets is of great importance for both industrial applications and academic research. In this study, the decisive factors of gasket behaviour and the contributions of finite element analysis in this field will be addressed in detail; in light of the findings obtained, recommendations for design and manufacturing processes will be developed.

Literature Search

In the realm of gasketed joint mechanics and sealing performance, recent numerical and experimental investigations have substantially advanced the understanding of non-linear material behaviour, contact stress distributions, and structural integrity across diverse engineering applications. A significant body of research focuses on hyper elastic and non-linear gasket mechanics: micromechanics-based axisymmetric finite element modelling of Teflon-filled spiral wound gaskets in bolted flange connections reveals that merely half of the gasket width actively contributes to sealing under low bolt preloads, proving that conventional average stress models yield excessively conservative outcomes [3]. Complementing this, three-dimensional finite element analyses incorporating experimental loading-unloading cycles underscore that non-linear material properties and permanent deformations critically govern tightness, with contact stress distribution exerting a far more dominant influence on sealing efficacy than standard ASME flange rotation limits [4]. To validate such hyper elastic material formulations, experimental approaches utilizing Fuji pressure-sensitive film in commercial vehicle air brake systems have demonstrated robust agreement between measured static contact pressure and numerical predictions [5]. Beyond static mechanics, dynamic vibrational environments such as those encountered in transportation fuel cell modules induce clamping force losses in bolted joints, a degradation particularly severe in heavier modules that is notably attenuated by the damping effect of intercalated gaskets [6]. Furthermore, tribological characterizations demonstrate that the friction coefficient and wear behaviour of flanged gaskets depend directly on steel surface roughness and applied loads, wherein joint tightness becomes compromised once critical shear stress induces surface damage [7]. In piping and specialized joint configurations, numerical evaluations employing a third-order Ogden hyper elastic model for T-type rubber gaskets in ductile iron pipelines established that an optimal assembly force of 6.8 kilonewtons (for a 300 milli meters nominal diameter pipe) with an insertion depth tolerance up to 20 milli meters enables high sealing integrity while adapting to seismic ground movements [8]. Finally, empirical investigations into polyurethane foam gaskets applied via foam-in-place methodology delineate that augmenting the polyurethane constituent ratio significantly enhances sealing performance, whereas elevating the adhesive component ratio or mass flow rate during preparation drastically compromises joint tightness, with operational surface temperature exhibiting a negligible impact on both failure pressure and overall sealing efficacy [9].

Material-Method

The Mooney-Rivlin 2-Parameter model is preferred primarily because it yields robust numerical stability and reliable curve fitting under low-to-moderate strain regimes using limited experimental data such as uniaxial tension tests, thereby optimizing solver convergence while mitigating computational cost.

The structural mechanics and sealing behaviour of stiffened, large-diameter flange joints featuring silicone rubber gaskets in food processing evaporators by integrating strain measurements with advanced numerical simulations. The analysis demonstrates that localized sectional modelling offers high computational efficiency for resolving complex contact dynamics and non-linear gasket response without compromising accuracy. Crucially, while flange stiffeners marginally affect gasket contact pressures, they transmit significant stresses that induce localized bending in the adjoining cylinder wall. Furthermore, standard analytical formulations prove inadequate due to severe non-linearities, necessitating sophisticated hyper elastic constitutive models specifically the Mooney-Rivlin model accounting for Mullins effects to accurately capture friction-dependent unloading characteristics and reliably predict overall flange integrity [10].

Mooney-Rivlin Hyper Elastic Material Model

It is based on three fundamental assumptions:

The material is incompressible, it exhibits an isotropic structure prior to deformation, it is homogeneous. Based on these assumptions, the strain energy density function can be defined using 2, 3, 5, or 9 parameters. The strain energy density function equation (W), which in the Mooney-Rivlin Hyper elastic material model is a function of the strain invariants, is defined in Equation 2.1 above:

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + \frac{1}{D_1}(J - 1)^2 \quad (1.1)$$

In this equation, the coefficients C_{10} and C_{01} are material constants determined empirically [1].

Material Types

Two different elastomeric materials were taken into account in the analyses:

EPDM: Selected due to its higher deformation capability.

Polyurethane (PU): Selected due to its more rigid structure and potential to generate higher contact pressure.

Ethylene Propylene Diene Monomer (EPDM) can be utilized within an operating temperature range of -55 °C to 150 °C [1]. It exhibits good performance when used against alcohols, dilute

acids and alkalis, silicone oils and greases, water, ozone, phosphate ester-based hydraulic fluids, and steam systems below 200 °C. Conversely, it shows poor performance against petroleum-based oils and greases, halogenated solvents, diester-based lubricants, and aromatic hydrocarbons. EPDM sealing element material delivers excellent sealing performance in systems containing water vapor at temperatures below 200 °C.

Polyurethane (PU) can be utilized within an operating temperature range of -55 °C to 100 °C [1]. Polyurethane is an elastomeric material that possesses superior wear resistance, high tensile strength, and high elasticity compared to other elastomers. It exhibits good sealing performance against mineral oils and greases, silicone oils and greases, ozone, and water/steam up to 50 °C. However, it exhibits poor sealing performance against ketones, alcohols, esters and ethers, acids, glycol, and water/steam above 50 °C.

Both elastomeric materials were defined in the ANSYS Engineering Data module under the Hyper elastic material class using the Mooney-Rivlin 2-Parameter mathematical model. During the material definition process, experimental uniaxial stress-strain data for each material were imported into the system, and the characteristic material coefficients were derived via curve fitting. Upon examining the material parameters, the Polyurethane material yielded a C_{10} coefficient of 2.6 MPa and a C_{01} coefficient of 0.7 MPa, whereas the Ethylene Propylene Diene Monomer material exhibited a C_{10} coefficient of 0.9 MPa and a C_{01} coefficient of 0.1MPa. The material constants were selected and implemented to model in a company [11]. Consequently, the initial shear modulus calculated as $G_0 = 2(C_{10} + C_{01})$ reached 6.6 MPa for Polyurethane compared to 2.0 MPa for Ethylene Propylene Diene Monomer; this distinct variation demonstrates that Polyurethane exhibits significantly higher rigidity, load-bearing capacity, and stress response under equivalent strain levels. The incompressibility parameter, D_1, representing volumetric deformation resistance, was specified as 0.001 MPa^{-1} for both materials, thereby ensuring near-full nearly-incompressible elastic behaviour with minimal volume change. Furthermore, to accurately account for geometric nonlinearities and severe deformations during solver execution, the Large Deflection option was activated.

Properties of Outline Row 9: özkaConta_PU (Mooney-Rivlin)

	A	B	C	D	E
1	Property	Value	Unit		
2	Uniaxial Test Data	Tabular			
3	Scale	1			
4	Offset	0	Pa		
5	Mooney-Rivlin 2 Parameter				
6	Material Constant C10	2.6	MPa		
7	Material Constant C01	0.7	MPa		
8	Incompressibility Parameter D1	0.001	MPa^-1		

Figure 1a: PU Material Parameters

Properties of Outline Row 9: özkaConta_EPDM (Mooney-Rivlin)

	A	B	C	D	E
1	Property	Value	Unit		
2	Uniaxial Test Data	Tabular			
3	Scale	1			
4	Offset	0	Pa		
5	Mooney-Rivlin 2 Parameter				
6	Material Constant C10	0.9	MPa		
7	Material Constant C01	0.1	MPa		
8	Incompressibility Parameter D1	0.001	MPa^-1		

Figure 1b: EPDM Material Parameters

In this study, the mechanical behaviour of elastomer-based gaskets was investigated using Finite Element Analysis (FEA) within the ANSYS environment. The Mooney-Rivlin hyper elastic material model was employed for both EPDM and polyurethane (PU) components. Design parameters included preloads ranging from 17 to 21 kN for PU (assuming 8.8 grade bolts) and 4 to 7 kN for EPDM, across gasket thicknesses of 2, 3, 4 and 5 mm. To accurately capture large deformations and stress gradients, quarter-symmetry models and refined meshing were utilized, while simultaneously accounting for material, geometric, and contact nonlinearities.

Finite Element Model

Analyses were conducted in the ANSYS software environment using the finite element method. To align with the physical system, the gasket geometry was modelled in thicknesses of 2, 3, 4, and 5 mm. Taking into account the geometric symmetry of the model, analyses were executed on a quarter-symmetry model to reduce computational cost and optimize solution time. Symmetry boundary conditions were applied to the corresponding faces to represent the full model behaviour. Due to the elastomeric nature of the gasket material, large deformations are anticipated. Accordingly, non-linear behaviours were comprehensively incorporated into the model formulation. Specifically, material non-linearity (hyper elastic behaviour), geometric non-linearity (large strain/displacement), and contact non-linearities were defined simultaneously. Based on the stress and deformation distributions obtained during the analysis phase, iterative refinements were made to the model, yielding the optimized final design presented below.

The finite element mesh was refined near contact zones and areas with high expected stress gradients to enhance solution accuracy. Mesh quality was evaluated against standard criteria, including element skewness and aspect ratio.

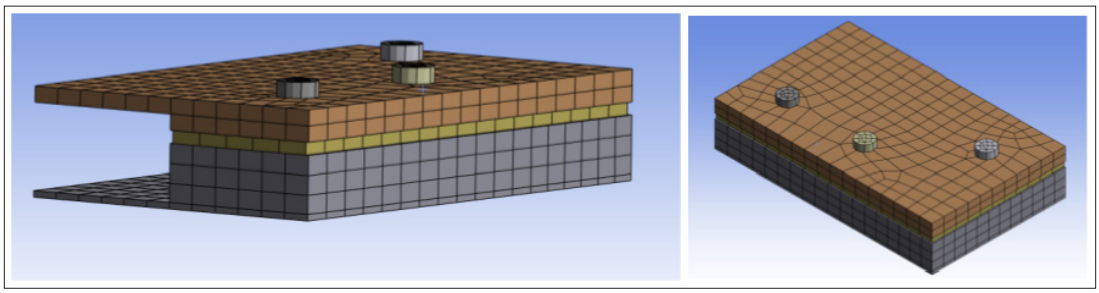


Figure 2ab: Meshed Model

All material, geometric and contact-induced non-linearities were simultaneously accounted for within the model. An appropriate hyper elastic material model was specified for the gasket material, with material constants derived from experimental or literature data. Varying bolt preloads were applied to generate the necessary sealing pressure across the gasket, imposing a compressive effect on the relevant contact surfaces.

To accurately represent interface interactions, suitable contact algorithms (such as the Augmented Lagrange or Penalty method) were implemented at the contact zones. Frictional effects were included in the contact definitions where necessary. Convergence behaviour was closely monitored throughout the solution process; load stepping and sub steps were controlled to minimize convergence issues arising from non-linear contact and large deformations. Additionally, automatic time stepping and solution control parameters were optimized to enhance numerical stability where needed.

Boundary Condition

The mechanical behaviour of gaskets is investigated using FEA within ANSYS. A Mooney Rivlin hyper elastic material model and a quarter symmetry geometric model are employed.

Bottom of the housing is fixed support.

Design parameters included preloads ranging from 17 to 21 kN for PU and 4 to 7 kN for EPDM, across gasket thicknesses of 25 mm.

Contact friction is defined between mating parts Thread engagement is modelled between the bolt and housing

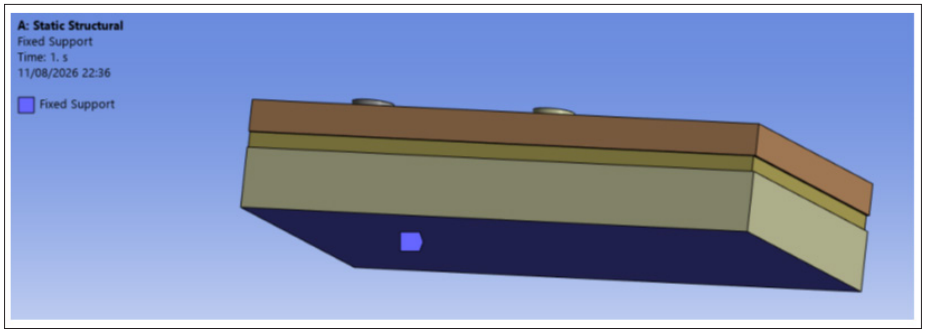


Figure 3a: Fixed Support

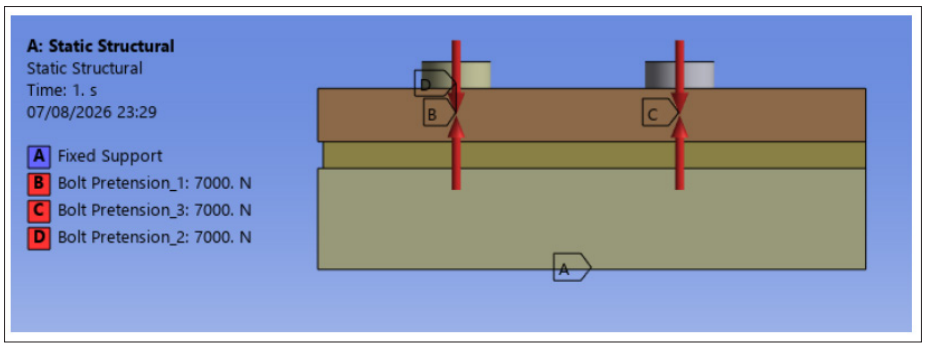


Figure 3b: Pre-Loads

Results

The results demonstrated a nonlinear relationship between preload and compression ratio. While 5 mm thick gaskets exhibited homogeneous and stable deformation, thinner gaskets (2, 3, and 4 mm) displayed localized compression and instability. Thickness was identified as the most critical parameter influencing deformation behaviour, with the impact of bolt preload becoming more pronounced as thickness decreased. For instance, in a 5 mm EPDM gasket analyzed with a 2-parameter Mooney-Rivlin model under

a 7000 N preload, maximum deformation was concentrated at the edges, suggesting that deformation initiates at these boundaries. In this specific model, compression ratios were 12% at the corners, 18% in the middle around the bolt vicinity, and 14% at the edges, indicating a relatively homogeneous distribution. Ultimately, the study emphasizes that achieving a reliable sealing design requires the simultaneous optimization of gasket thickness and bolt preload.

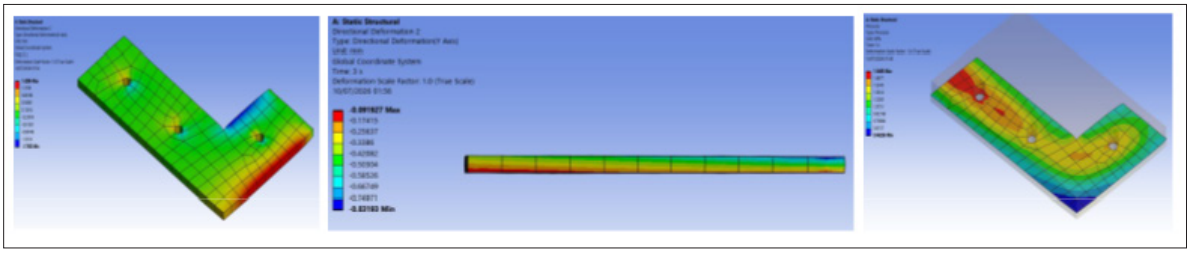


Figure 4a: Squeeze Along Y Axis, **Figure 4b:** Elongation Along X Axis, **Figure 4c:** Maximum Contact Pressure 1.8 MPa

Discussion

When a gasket is compressed from its free height to its assembled height, its thickness is reduced while its width increases due to material expansion. In the literature, the maximum contact pressure between the O-ring and the mating component was reported to be approximately 4.9 MPa, gradually decreasing to 0 MPa toward the edges [5]. In the present study, a similar structural behaviour complying with the literature was observed; the maximum contact pressure was predicted to be around 1.8 MPa, concentrated primarily at the bolt locations.

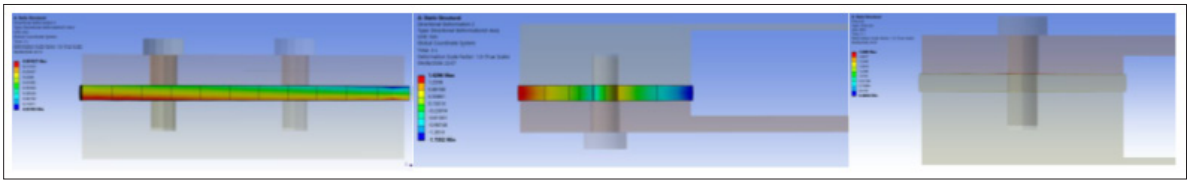


Figure 5a: Squeeze Along Y-Axis, **Figure 5b:** Elongation Along X-Axis, **Figure 5c:** Maximum Contact Pressure 1.8 MPa

The view of in the study conducted by Bülend Demiralp, the factors affecting the performance of sealing elements used in hydraulic systems were examined in detail. Observations particularly made on U-cup (nutring) type elements used in hydraulic cylinder piston and rod applications revealed that replacing sealing elements with new ones during maintenance does not always provide a definitive solution. As a result of experimental investigations, it was determined that the increase in material hardness of sealing elements over time, the occurrence of wear on dynamic surfaces, and the degradation of the elastomer material due to chemical or thermal effects directly influence performance. Furthermore, capillary cuts and mechanical damage such as tearing and fracturing were observed to be the primary causes triggering leakage problems [12].

There exists an extreme value for contact pressure uniformity during the process of increasing bolt load. Higher bolt loads lead to deformation, thereby impeding the improvement of contact pressure uniformity through alterations in bolt load distribution. However, when the average bolt load is below the extreme value, enhancing the bolt load can enhance the uniformity of contact pressure distribution [13].

In addition to, a study demonstrates that achieving annular joint tightness hinges on precise clamping pressure, which is governed by the structural properties of the gasket, clamping rings, and bolt configuration. By integrating the elastic characteristics of these components, the developed physical model accurately predicts the required assembly torque—yielding conservative estimates relative to empirical tests, thereby ensuring enhanced joint reliability and safety. Furthermore, increasing ring thickness optimizes structural stiffness and load distribution, confirming that the joint operates safely within its elastic deformation limits and validating the model's efficacy for optimizing tailored joint architectures across diverse operational conditions [14].

Conclusion

This research provides a comprehensive numerical evaluation of EPDM and Polyurethane gasket behaviour in flanged connections, highlighting the complex interplay between hyper elastic material response, gasket thickness, and applied bolt preload. The key insights derived from the finite element analyses are outlined below:

- Gasket thickness is a critical design parameter that strongly influences compression ratio and deformation behaviour.
- The relationship between bolt preload and compression ratio is nonlinear its effect is limited for thicker gaskets but becomes more pronounced in thinner sections.
- EPDM material provides higher deformation capability, while polyurethane (exhibits a stiffer structure and generated higher contact pressures.
- For reliable sealing design, thickness and preload must be optimized together [15-19].

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