

DESIGN AND DEVELOPMENT OF SOFT ACTIVE MATERIAL BASED ACTUATOR

M.Tech. Thesis

By
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**DEPARTMENT OF MECHANICAL ENGINEERING
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DESIGN AND DEVELOPMENT OF SOFT ACTIVE MATERIAL BASED ACTUATOR

A THESIS

*Submitted in partial fulfillment of the
requirements for the award of the degree
of*
Master of Technology

by
SHUBHAM KUMAR



**DEPARTMENT OF MECHANICAL ENGINEERING
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INDIAN INSTITUTE OF TECHNOLOGY INDORE

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **“Design and Development of Soft Active Material Based Actuator”** in the partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DEPARTMENT OF MECHANICAL ENGINEERING, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from July 2024 to May 2026 under the supervision of Dr. Aman Khurana, Assistant Professor, Department of Mechanical Engineering at the Indian Institute of Technology Indore.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

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Aman Khurana

Signature of Supervisor of M. Tech. thesis
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ABSTRACT

Soft active materials have emerged as an increasingly important category of functional engineering materials due to their ability to undergo large, reversible deformations in response to external stimuli such as pneumatic pressure, temperature change, and applied electric fields. Among the various classes of soft active materials, silicone-based elastomers have found widespread application in soft pneumatic actuators owing to their excellent flexibility, biocompatibility, chemical inertness, and ability to recover from large strains without permanent deformation. These properties make silicone-based soft pneumatic actuators particularly attractive for soft robotic systems that must interact safely and adaptively with humans, biological tissues, and irregularly shaped objects.

In the present work, a soft pneumatic actuator is designed, fabricated, and numerically analyzed as the fundamental building unit of a soft robotic gripper. The actuator consists of 11 identical pneumatic chambers (each $7\text{ mm} \times 15\text{ mm} \times 15\text{ mm}$) embedded within a flexible silicone body with 2 mm thick chamber walls and a $2.5\text{ mm} \times 2.5\text{ mm}$ central air channel. The bending motion of the actuator is driven by geometric asymmetry between the expandable upper chamber layer and the relatively inextensible base layer, which contains an embedded paper layer to restrict elongation on the lower surface. When internal air pressure is applied, this asymmetry generates differential strain across the cross-section of the actuator, resulting in a well-controlled bending motion toward the constrained side.

The actuator was physically fabricated using the casting method. Silcozest (A) and Silcozest (B) liquid silicone rubbers were manually mixed in equal proportions, poured into three-part PLA 3D-printed molds, and cured at room temperature for 24 hours. The upper and lower silicone parts were subsequently bonded using the same silicone mixture as adhesive. The total

fabrication time was approximately 72 hours. The fabrication process confirmed the practical feasibility of producing the actuator with good surface finish and structural integrity.

To accurately predict the mechanical behavior of the fabricated actuator, a three-dimensional finite element model was developed in ABAQUS/Standard. The silicone material was modeled using the Yeoh Hyperelastic constitutive model, which is well suited to capture the strongly nonlinear stress–strain response of elastomeric materials under large deformations. Hybrid 10-node quadratic tetrahedral elements (C3D10H) were employed throughout the mesh to avoid volumetric locking, which is a common numerical artifact in nearly incompressible materials. Pneumatic actuation was simulated by applying uniform internal pressure loads on the chamber walls, and nonlinear geometry effects (NLGEOM) were activated to account for the large deformations expected during pressurization.

A mesh refinement study was conducted using two mesh sizes: a fine mesh (global size 0.1) and a coarser mesh (global size 0.13). The fine mesh produced a maximum tip displacement of approximately 94.049 mm and a maximum Von Mises stress of approximately 0.825 MPa at an applied pressure of 30 kPa. The coarser mesh yielded a maximum displacement of 93.973 mm and a peak stress of 0.765 MPa under the same conditions. The finer mesh was found to provide better resolution of localized stress gradients near chamber corners and fixed edge junctions, and is recommended for detailed design optimization studies.

The pressure–tip displacement curve extracted from the simulation exhibits three clearly distinct behavioral regions consistent with the known response of hyperelastic silicone actuators. In the initial region (0–0.01 MPa), displacement is very small as the inextensible base layer resists bending. In the intermediate nonlinear region (0.02–0.04 MPa), displacement grows rapidly in a nonlinear manner as the silicone chambers undergo large elastic deformations. In the high-pressure region (beyond 0.04 MPa), the tip displacement increases steeply, reaching approximately 45 mm at 0.05 MPa. These trends are consistent with experimental observations reported in the literature for comparable silicone-based soft pneumatic actuators, thereby providing qualitative validation of the modeling approach.

The directional displacement analysis at the actuator tip confirmed that bending is predominantly in-plane, with the transverse component (U3) reaching approximately -90 mm, while the out-of-plane component (U2) remains negligible throughout pressurization. This validates the effectiveness of the asymmetric geometric design in generating directional, controlled bending motion. The present work provides a comprehensive framework combining experimental fabrication and finite element simulation for the design and analysis of soft pneumatic actuators, and lays the groundwork for the development of a complete multi-finger soft robotic gripper with variable stiffness capability through layer-jamming integration.

Keywords: Soft pneumatic actuator, Yeoh Hyperelastic constitutive model, ABAQUS/Standard, C3D10H hybrid tetrahedral element, soft robotics, finite element method, silicone casting, bending actuator, layer jamming, soft robotic gripper.

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NOMENCLATURE

SPA	Soft Pneumatic Actuator
FEM	Finite Element Method
C3D10H	Hybrid 10-node quadratic tetrahedron element (ABAQUS)
NLGEOM	Nonlinear geometry flag in ABAQUS
E	Young's modulus (MPa)
ν	Poisson's ratio
C10, C20, C30	Yeoh hyperelastic model material constants (MPa)
W	Strain energy density function (MPa)
I1, I2, I3	Principal invariants of the left Cauchy-Green deformation tensor
F	Deformation gradient tensor
J	Jacobian of deformation (determinant of F)
σ	Cauchy stress tensor (MPa)
ϵ	Lagrangian strain tensor
$\lambda_1, \lambda_2, \lambda_3$	Principal stretch ratios
p	Applied internal pressure (kPa or MPa)
U	Displacement magnitude (mm)
U1, U2, U3	Displacement components along X, Y, Z axes (mm)
S, Mises	Von Mises equivalent stress (MPa)
KIC	Critical stress intensity factor (Mode I fracture toughness)
PLA	Polylactic Acid
TPU	Thermoplastic Polyurethane
STL	Stereolithography file format for 3D printing
SMP	Shape Memory Polymer
SHPB	Split Hopkinson Pressure Bar
kPa	Kilopascal — unit of pressure
MPa	Megapascal — unit of stress and material constants

Chapter 1

Introduction

1.1 Soft Active Materials: What They Are and Why They Matter

Soft active materials represent a broad and rapidly growing class of smart engineering materials that are characterized by their ability to undergo large, reversible changes in shape, size, stiffness, or other mechanical properties in direct response to various external stimuli. These stimuli may include pneumatic pressure, thermal energy, electrical voltage, magnetic fields, chemical gradients, or light irradiation. Unlike conventional structural materials such as steel, aluminum, or rigid polymers, which are designed to resist deformation and maintain fixed geometries under load, soft active materials are intentionally engineered to deform controllably and reproducibly. This fundamental departure from traditional material design philosophy has opened up entirely new possibilities in the fields of robotics, biomedical engineering, wearable technology, and adaptive structures.

The mechanical behavior of soft active materials is fundamentally different from that of conventional engineering materials. While metals and ceramics typically exhibit small strains (of the order of 0.1–1%) before yielding or fracture, soft active materials such as silicone elastomers, hydrogels, and shape memory polymers can sustain strains of several hundred percent while remaining in the elastic regime. This extraordinary capacity for large reversible deformation arises from their unique microstructural organization, which in the case of elastomers consists of long-chain polymer networks that can stretch and recoil without permanent bond breaking. The mechanical response of these materials is highly nonlinear and is governed by strain energy density functions rather than the simple linear stress–strain relationships of classical elasticity theory.

Soft active materials are widely used in soft robotics, actuators, sensors, and biomedical devices for creating adaptive and responsive systems. They are especially valuable in

applications where safety, compliance, and controlled movement are of paramount importance. Examples include soft grippers for fruit harvesting and food handling, exoskeletal assistive devices for rehabilitation, minimally invasive surgical tools, and wearable health monitoring patches. In all of these applications, the ability of the material to deform safely around delicate objects or biological tissue without causing damage is the key enabling property.

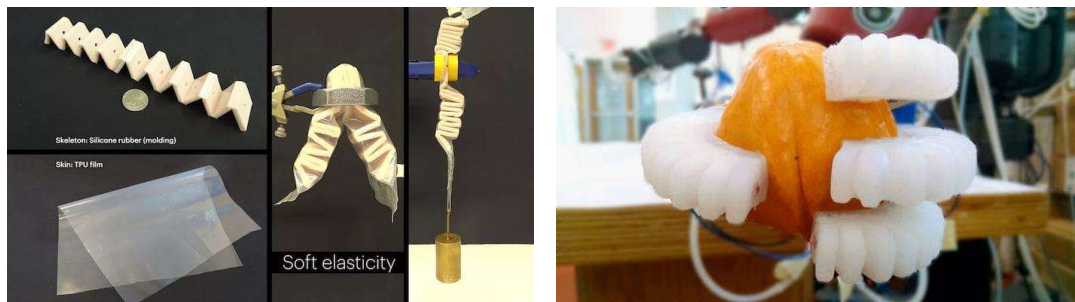


Fig. 1.1 (Left): Origami Elastomeric Actuator fabricated from a molded silicone rubber skeleton with a TPU film outer skin, demonstrating large reversible deformation and soft elastic behavior. Fig. 1.2 (Right): Fluid Pressure Based Gripper gently holding a fruit using flexible, compliant silicone fingers without causing surface damage. (Image Credit: robotics24.net)

1.2 Classification of Soft Active Materials

Soft active materials can be broadly classified according to the physical or chemical stimulus that triggers their mechanical response. Pneumatically actuated materials, such as silicone rubbers and polyurethane elastomers, deform in response to applied fluid or gas pressure and are the most widely used in practical soft robotic applications due to their ease of fabrication, large actuation strokes, and compatibility with standard pneumatic control systems. Thermally responsive materials, such as shape memory polymers and hydrogels, undergo significant dimensional changes when heated above a characteristic transition temperature. This class includes the well-known shape memory alloys such as nickel–titanium (Nitinol), which exhibit both the shape memory effect and superelasticity, as well as liquid crystal elastomers that can be programmed to undergo complex three-dimensional shape changes upon heating.

Electroactive polymers (EAPs) represent another important class of soft active materials that deform in response to an applied electric field. These are further subdivided into ionic EAPs, which operate through the migration of ions within a hydrated polymer network under an applied voltage, and electronic EAPs, which include dielectric elastomers that expand laterally

and thin in the direction of the applied electric field due to electrostatic pressure. Magnetically responsive soft materials, including ferrofluid-embedded elastomers and magnetic soft robots, can be steered and actuated remotely using external magnetic fields, making them particularly attractive for biomedical applications where access through small orifices is required. Finally, pneumatically actuated soft materials remain the dominant actuation paradigm in practical soft robotics due to their simplicity, high force output relative to weight, and natural compliance.

1.3 Soft Pneumatic Actuators

A soft pneumatic actuator (SPA) is a flexible structural device that generates mechanical motion — typically bending, twisting, or linear extension — when supplied with compressed air or another pressurized fluid through an internal channel network. SPAs are almost universally fabricated from silicone rubber or polyurethane elastomers due to the exceptional strain capacity, good chemical resistance, biocompatibility, and manufacturability of these materials. When pressurized gas is introduced into the internal chamber network of an SPA, the elastic walls of the chambers expand. By engineering asymmetry into the cross-sectional geometry of the actuator — for example, by making one surface thicker, stiffer, or reinforced with an inextensible layer — this expansion can be made non-uniform across the cross-section. The resulting differential strain drives a bending, curling, or twisting motion that can be harnessed for grasping, locomotion, or manipulation tasks.

The operating principle of a soft pneumatic bending actuator is fundamentally governed by the constitutive response of the elastomeric material to large deformations. Unlike metals, which deform plastically beyond their yield point, elastomers store elastic strain energy throughout their deformation range and recover completely upon unloading. This hyperelastic behavior — characterized by a strongly nonlinear, strain-stiffening stress–strain relationship — must be captured accurately in any predictive model of SPA performance. The Yeoh model, a third-order reduced polynomial strain energy function, has been found to provide an excellent

balance between mathematical simplicity and accuracy for silicone-based soft actuators across the full range of strains encountered in practical operation.



Fig. 1.3 (Left): DraBot, Duke University — a dragonfly-inspired soft robotic platform with pneumatically actuated wings capable of steering through fluid environments. Fig. 1.4 (Right): SoFi, MIT — an underwater soft robotic fish that mimics the undulatory locomotion of biological fish using a soft pneumatic tail actuator. (Image Credit: robotics24.net)

Soft pneumatic actuators are typically fabricated using one of two methods: molding and casting, or three-dimensional (3D) printing. The casting method involves pouring a liquid silicone precursor mixture into a mold that defines the external geometry and internal chamber network of the actuator. After curing at room or elevated temperature, the solidified silicone part is demolded and, if necessary, bonded to a separate base layer to complete the assembly. This method produces actuators with excellent surface finish, good mechanical properties, and well-defined geometry, but requires the prior fabrication of molds, which adds lead time and cost, particularly for complex or iterative designs. Three-dimensional printing of soft actuators using flexible filaments such as thermoplastic polyurethane (TPU) offers rapid prototyping

capability but may produce parts with anisotropic properties and lower strain capacity compared to cast silicone.

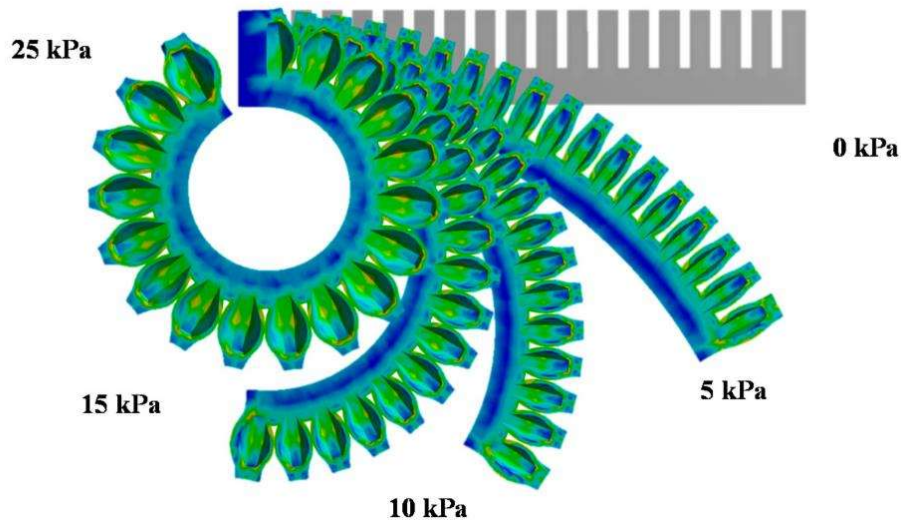


Fig. 1.5: Finite element deformation contours of a Soft Pneumatic Actuator at increasing internal pressures of 0, 5, 10, 15, and 25 kPa, demonstrating the progressive increase in bending curvature with applied pressure. (Image Credit: mdpi.com/2218-6581/7/2/24)

1.4 Soft Pneumatic Actuator Development for Adaptive Robotic Grippers

Robotic grippers based on soft pneumatic actuators have emerged as a transformative technology for manipulation tasks that cannot be reliably performed by conventional rigid grippers. In industrial automation, rigid two-finger or parallel-jaw grippers work well for regular, well-characterized objects but fail when faced with the geometric variability, fragility, or compliance of biological objects such as fruits, vegetables, delicate electronics, or human limbs. Soft pneumatic grippers, by contrast, naturally conform to the shape of the grasped object without requiring precise geometric information or feedback control, relying instead on the passive compliance of the elastomeric structure to distribute contact forces gently and uniformly over the object surface.

A typical soft pneumatic gripper consists of two or more SPA fingers arranged symmetrically around a central palm structure. When the fingers are pressurized simultaneously, they curl inward, wrapping around the target object and applying a distributed grasping force. The grasping force is proportional to the applied pressure and the stiffness of the finger material.

By varying the pressure, the grip can be adjusted from gentle — suitable for fragile objects such as fresh produce or biological tissue — to firm, for moderate payloads. The development of soft grippers that can achieve both high flexibility for shape conformance and adequate stiffness for payload capacity is an active area of research, with layer-jamming, granular jamming, and fiber-reinforcement strategies being the leading approaches to variable stiffness.

Despite the considerable advances made in the design and application of soft pneumatic grippers, several fundamental challenges remain. Predicting the large-deformation mechanical response of silicone actuators with complex internal geometry under pneumatic loading is inherently difficult using analytical approaches due to the material nonlinearity, geometric nonlinearity, and coupling between these effects. Finite element analysis (FEA) using appropriate hyperelastic constitutive models and fully nonlinear kinematic formulations has therefore become the standard tool for soft actuator design, optimization, and validation.

1.5 Scope and Organization of the Thesis

The present thesis addresses the design, fabrication, and finite element simulation of a silicone-based soft pneumatic bending actuator intended for use in a soft robotic gripper. The work encompasses the complete development cycle from conceptual design and CAD modeling in SolidWorks, through physical fabrication via silicone casting, to three-dimensional hyperelastic finite element simulation in ABAQUS/Standard with mesh sensitivity analysis and result validation against literature data.

The thesis is organized as follows. Chapter 2 presents a comprehensive review of the relevant literature, covering hyperelastic constitutive models, material selection studies, experimental investigations, and prior numerical and experimental work on soft pneumatic actuators. Chapter 3 identifies the motivation and specific research objectives of this work. Chapter 4 provides the theoretical background including the continuum mechanics framework for large deformations, the Yeoh hyperelastic model, and the finite element formulation for nearly incompressible materials. Chapter 5 describes the methodology including CAD design, fabrication procedure, FE model setup, and mesh convergence study. Chapter 6 describes the

working model and its physical operation. Chapter 7 presents and discusses the simulation results. Chapter 8 summarizes the conclusions and outlines directions for future research.

Chapter 2

Literature Review

2.1 Review of Hyperelastic Material Models for Soft Actuators

The accurate simulation of soft pneumatic actuators requires a constitutive model that correctly captures the hyperelastic, nearly incompressible, and strongly nonlinear mechanical response of silicone rubber under large strains. Several hyperelastic models have been proposed in the literature, each representing the strain energy density function W in terms of the principal invariants I_1, I_2, I_3 of the left Cauchy-Green deformation tensor, or directly in terms of the principal stretches $\lambda_1, \lambda_2, \lambda_3$. The choice of model significantly affects the accuracy of predicted deformation and stress fields, particularly at large strains where the nonlinearity of the material response is most pronounced.

The Neo-Hookean model is the simplest hyperelastic model, depending only on I_1 and containing a single material parameter (C_{10}). While it captures the initial linear elastic response and the general trend of strain stiffening, it tends to underestimate deformation at large strains and cannot accurately represent the characteristic upturn in the stress–stretch curve that silicone exhibits at very high stretches due to limited chain extensibility. The Mooney–Rivlin model adds a dependence on the second invariant I_2 , improving predictions for moderately large strains but still failing at very large stretches. The Ogden model, expressed directly in terms of principal stretches, provides greater flexibility and accuracy but requires more parameters and is harder to calibrate from limited experimental data.

Model	Strain Energy Function	Parameters	Accuracy at Large Strain
Neo-Hookean	$W = C_{10}(I_1 - 3)$	1 (C_{10})	Low — underestimates at large strain
Mooney–Rivlin	$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3)$	2 (C_{10}, C_{01})	Moderate — good up to ~100% strain
Yeoh	$W = C_{10}(I_1 - 3) + C_{20}(I_1 - 3)^2 + C_{30}(I_1 - 3)^3$	3 (C_{10}, C_{20}, C_{30})	High — excellent up to 300%+ strain
Ogden	$W = \sum (\mu_p / \alpha_p) (\lambda_1^{\alpha_p} + \lambda_2^{\alpha_p} + \lambda_3^{\alpha_p} - 3)$	6+ parameters	Very High — but complex calibration

Model	Strain Energy Function	Parameters	Accuracy at Large Strain
Arruda-Boyce	<i>W based on inverse Langevin function</i>	2 (μ , λm)	High — good physical basis

Table 4.1: Comparison of common hyperelastic constitutive models for silicone rubber.

The Yeoh model, a third-order reduced polynomial function of the first invariant I_1 only, has been widely adopted for silicone-based soft actuators because it accurately represents the characteristic S-shaped stress–stretch curve of silicone rubber across a wide range of strains (up to 300% and beyond), is straightforward to calibrate from standard uniaxial tension test data, and provides numerically stable performance in finite element implementations. The independence of the Yeoh model from I_2 also reduces sensitivity to shear effects that are difficult to measure precisely, making it practically robust for design applications.

2.2 Gariya et al., Materials Today (2022)

Gariya, Kumar, and Prashad conducted a systematic numerical study of the effect of silicone material selection on the bending performance of soft pneumatic actuators using the finite element method in ABAQUS. Three commercially available silicone materials were considered: Elastosil M4601 (a medium stiffness platinum-cured silicone), Dragon Skin 20 (a softer platinum-cured silicone with higher elongation at break), and Smooth-Sil 960 (a stiffer condensation-cured silicone). The material constants for each silicone grade were determined by fitting the Yeoh hyperelastic model to experimentally obtained uniaxial tension test data.

The actuator geometry used in the study consisted of a multi-chamber pneumatic bending finger with a strain layer formed by the expandable silicone chambers and a constraint layer that restricts elongation on the lower surface, creating the geometric asymmetry required for bending. A uniform internal pressure was applied to the chamber surfaces in the ABAQUS simulation, and the resulting bending angle was measured at the free tip of the finger. The study investigated the sensitivity of the bending angle to material stiffness, chamber geometry parameters including wall thickness and chamber spacing, and the number of chambers.

The results showed a clear and strong dependence of bending angle on material stiffness. Dragon Skin 20, being the softest of the three materials, produced the largest bending angle of

47.5° at a given applied pressure. Elastosil M4601, with intermediate stiffness, achieved a bending angle of 35.5°, while Smooth-Sil 960, the stiffest material, produced only 18° under the same pressure. These results confirmed the intuitive expectation that softer materials deform more under the same applied pressure and thus produce larger actuation strokes. The study also demonstrated that the Neo-Hookean model significantly underestimates bending deformation compared to the Yeoh model, particularly for softer materials at larger strains, due to its inability to capture the strain stiffening behavior at high deformations.

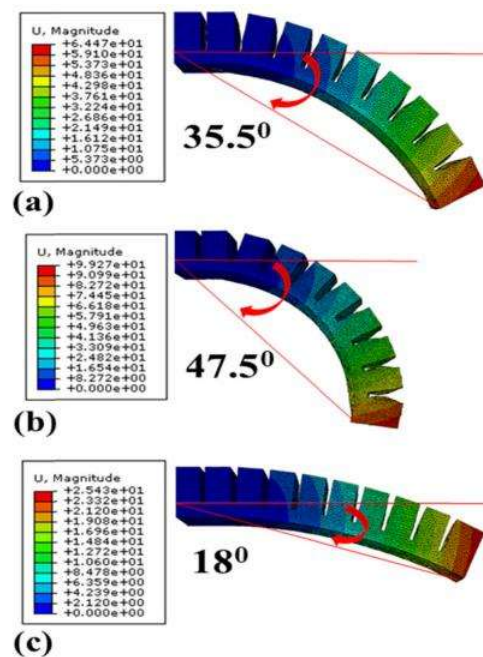


Fig. 2.1: Bending angle configuration developed using (a) Elastosil M4601 — 35.5°, (b) Dragon Skin 20 — 47.5°, and (c) Smooth-Sil 960 — 18°, at identical applied internal pressure. The Yeoh hyperelastic model was used in ABAQUS. (Source: Gariya et al., Materials Today: Proceedings, 2022)

2.3 Zhu et al., Sensors (2022)

Zhu, Feng, Hua, and Wang presented a comprehensive model analysis and experimental investigation of a soft pneumatically actuated manipulator consisting of four SPA fingers mounted on a central flange structure. The study represents one of the more thorough combined numerical–experimental investigations of multi-finger soft pneumatic grippers reported in the recent literature, and its methodology and findings are directly relevant to the objectives of the present thesis.

Each finger in the Zhu et al. gripper was fabricated from Dragon Skin 20 silicone rubber and comprised two distinct functional layers: a strain layer containing the pneumatic chamber network, which expands when pressurized, and a constraint layer bonded to the lower surface of the strain layer, which resists elongation and thereby forces the structure to bend. In addition to the basic two-layer configuration, annular constraint rings were incorporated around the external circumference of the chambers to suppress unwanted radial bulging of the chamber walls under pressure and direct more of the applied energy toward productive bending deformation. This geometric reinforcement was shown to significantly improve both the bending angle per unit pressure and the output tip force of the actuator.

The finite element model developed by the authors in ABAQUS used the Yeoh hyperelastic model with material constants obtained from uniaxial tension tests performed on cast Dragon Skin 20 specimens. The mesh consisted of C3D10H hybrid tetrahedral elements, consistent with the approach adopted in the present work. Parametric studies were conducted to examine the sensitivity of bending performance to wall thickness, chamber spacing, and the number of chambers. The authors developed analytical predictive models for bending angle and tip output force as functions of applied pressure and validated these models experimentally using a custom-built test rig equipped with a pneumatic pressure regulator, a digital angular sensor, and a force gauge.

The experimental results showed excellent agreement with both the FEM predictions and the analytical models, with errors generally below 8% across the tested pressure range. This high level of agreement was attributed to the accurate characterization of the silicone material properties using the Yeoh model and the careful attention paid to boundary condition representation in the FE model. The study also demonstrated that the bending angle increases nonlinearly with applied pressure, consistent with the hyperelastic material response, and that

the constraint rings are essential for achieving high bending efficiency without structural damage.

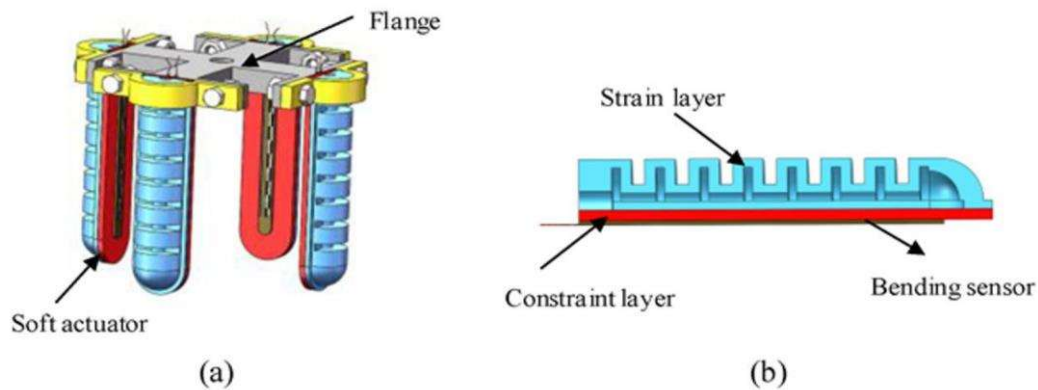


Fig. 2.2: (a) Four-finger soft gripper mounted on a central flange, each finger containing internal pneumatic chambers that bend when pressurized; (b) cross-sectional view illustrating the strain layer (expandable silicone chambers), constraint layer (inextensible base), and bending sensor placement. (Source: Zhu et al., Sensors, 2022)

2.4 Li et al., Research Square (2023)

Li and co-workers proposed and investigated a novel soft finger design that integrates pneumatic bending actuation with a passive layer-jamming mechanism for simultaneous stiffness modulation and motion control. The core innovation of this work lies in its approach to the fundamental trade-off in soft robotic grippers between flexibility — needed for shape conformance during approach and initial contact — and stiffness — needed for load bearing after grasping. Conventional single-chamber soft fingers are either flexible or stiff but not easily both, whereas the passive layer-jamming finger of Li et al. achieves both properties simultaneously through a single pressurization action.

The finger design includes two internal sections: a primary pneumatic chamber that inflates to produce bending, and a secondary jamming chamber filled with multiple thin flexible layers of a granular or sheet material. When the pressure in the primary chamber increases to produce bending, the resulting structural deformation simultaneously compresses the jamming layers against each other, generating interlayer frictional forces that dramatically increase the effective stiffness of the finger. The magnitude of the stiffness increase depends on the surface roughness and number of jamming layers: rougher materials such as sandpaper generate higher

friction and thus greater stiffness at a given pressure, while smoother materials produce lower friction and gentler stiffening. The authors demonstrated stiffness increases of up to 340% relative to the un-jammed state using sandpaper layers.

Experimental characterization of the finger involved pressure-controlled bending tests, blocked tip force measurements, and stiffness evaluation through quasi-static indentation. A three-finger gripper prototype was assembled and tested on a range of objects including fruits of different sizes, lightweight mechanical parts, and household items. The gripper successfully grasped all tested objects without damage, demonstrating the practical utility of the passive jamming approach. The study concludes that the passive layer-jamming design offers a compelling combination of simplicity, payload capacity, and compliance without the need for additional vacuum equipment or separate control channels required by active jamming approaches.

2.5 Summary and Research Gaps

The literature reviewed above reveals several important themes and identifies the specific gaps that motivate the present work. First, the Yeoh hyperelastic model has been established as the preferred constitutive model for silicone-based soft actuators, providing significantly better accuracy than simpler models such as Neo-Hookean while remaining tractable for calibration and finite element implementation. Second, the C3D10H hybrid tetrahedral element in ABAQUS is the recommended element type for nearly incompressible hyperelastic materials, reliably preventing volumetric locking that would otherwise corrupt stress and deformation predictions. Third, physical fabrication via silicone casting in PLA molds provides a practical and cost-effective route to prototype actuators with good mechanical properties.

However, several gaps remain in the existing literature. Most published studies focus on Dragon Skin silicone, while the behavior of locally available Silicozest silicone under the same fabrication and loading conditions has not been reported. The combined experimental fabrication and FE simulation workflow using Silicozest material within the IIT Indore facilities, including a thorough mesh convergence study and analysis of directional displacement components, represents an original contribution of the present work.

Furthermore, the development of a pressure–displacement characterization curve specifically for the designed 11-chamber actuator geometry provides quantitative data for future integration into a complete multi-finger gripper system.

Chapter 3

Motivation and Research Objectives

3.1 Motivation

The growing prevalence of soft robotic grippers in industrial, medical, and consumer applications creates an urgent need for reliable, validated design methodologies that can be applied efficiently within academic and research laboratory settings using commercially available materials and software tools. While numerous studies have demonstrated the feasibility and advantages of soft pneumatic actuators, the majority of these studies have been conducted at well-resourced research centers using proprietary silicone materials and specialized fabrication infrastructure that may not be readily accessible in typical academic environments.

The present thesis is motivated by the practical objective of establishing a complete, validated soft actuator design and fabrication workflow at IIT Indore using locally procurable materials (Silicozest liquid silicone rubber), standard 3D printing equipment (FDM PLA printing for mold fabrication), and widely available simulation software (ABAQUS/Standard with Yeoh material model). By documenting the entire process from CAD design through mold fabrication, silicone casting, curing, demolding, assembly, FE model setup, mesh convergence testing, and result extraction, the thesis aims to create a reproducible framework that future researchers and students at IIT Indore can build upon.

At a broader level, the work is motivated by the recognition that soft robotic grippers represent a transformative technology with the potential to address critical needs in sectors of great economic and humanitarian importance to India, including agricultural automation for gentle handling of fresh produce, rehabilitation robotics for assistive devices and prosthetics, and precision manufacturing for the handling of delicate electronic components. The development of indigenous design and fabrication expertise in this field is therefore of significant strategic value.

3.2 Research Objectives

This study aims to address the identified gaps and fulfill the stated motivation through the following specific, measurable research objectives:

1. To design a soft active material-based pneumatic bending actuator with defined geometric parameters using SolidWorks CAD software, and to create the corresponding three-part mold for silicone casting.
2. To physically fabricate the designed actuator using the silicone casting method with Silcozest A+B liquid silicone rubber and PLA 3D-printed molds, documenting the complete fabrication procedure and cycle time.
3. To develop a three-dimensional finite element model of the fabricated actuator in ABAQUS/Standard using the Yeoh Hyperelastic constitutive model and C3D10H hybrid tetrahedral elements, with appropriate boundary conditions and internal pressure loading.
4. To conduct a mesh convergence study by comparing simulation results for two mesh sizes (global size 0.1 and 0.13) in terms of maximum tip displacement, maximum Von Mises stress, and bending curvature.
5. To extract and analyze the pressure–tip displacement relationship over a pressure range of 0–0.05 MPa and identify the three characteristic behavioral regions of the hyperelastic actuator response.
6. To analyze the directional displacement components at the actuator tip to confirm the intended single-plane bending behavior and validate the geometric asymmetry design concept.
7. To lay the groundwork for future extension of the single-finger actuator to a multi-finger soft robotic gripper with variable stiffness capability through integration of layer-jamming mechanisms.

3.3 Novelty of the Present Work

The principal novelty of the present work lies in the integrated experimental–computational design and characterization of a soft pneumatic bending actuator fabricated from Silcozest

liquid silicone rubber using a three-part PLA mold at IIT Indore. The specific combination of the 11-chamber actuator geometry, the Silicozest material system, the three-part mold design with a separate inextensible base layer, and the systematic ABAQUS/Standard simulation workflow with mesh sensitivity analysis represents an original contribution that has not been previously reported in the literature. Additionally, the detailed extraction and analysis of directional displacement components and the three-region pressure–displacement characterization provide quantitative data that directly supports the future design of a complete multi-finger gripper system.

Chapter 4

Theoretical Background

4.1 Continuum Mechanics Framework for Large Deformations

The mechanics of soft pneumatic actuators involve large deformations that cannot be accurately described within the framework of classical linear elasticity. In the linear elastic formulation, strains are assumed to be infinitesimally small (typically less than 1%), the reference and deformed configurations of the body are treated as identical for the purposes of equilibrium, and the stress–strain relationship is linear and path-independent. None of these assumptions hold for silicone elastomers under pneumatic loading, where strains routinely exceed 100% and the change in geometry during deformation significantly affects the stress distribution and the structural stiffness.

The appropriate framework for large-deformation mechanics is nonlinear continuum mechanics, which distinguishes between the reference (undeformed) configuration and the current (deformed) configuration of the body. The deformation gradient tensor $F = \partial x / \partial X$ maps material line elements from the reference configuration X to the deformed configuration x and is the fundamental kinematic quantity in finite deformation theory. The Jacobian $J = \det(F)$ represents the ratio of deformed to reference volume and must equal unity for a perfectly incompressible material. For a nearly incompressible material such as silicone, $J \approx 1$ but small volumetric changes are permitted and are handled through the split of the deformation gradient into volume-preserving and volumetric parts.

The left Cauchy-Green deformation tensor $B = FF^T$ and its principal invariants $I_1 = \text{tr}(B)$, $I_2 = (1/2)[(\text{tr } B)^2 - \text{tr}(B^2)]$, $I_3 = \det(B) = J^2$ are the standard strain measures used in the formulation of isotropic hyperelastic constitutive models. The equilibrium equations in the current configuration are expressed in terms of the Cauchy stress tensor σ through the spatial equation of equilibrium $\nabla \cdot \sigma + b = 0$, where b is the body force per unit current volume. The finite element method discretizes this continuum problem into a set of algebraic equations by expressing the

stress and displacement fields as interpolations over finite elements and applying the principle of virtual work.

4.2 Hyperelastic Constitutive Models

A hyperelastic material is characterized by the existence of a strain energy density function W , also called the elastic potential, from which the stress can be derived as the derivative of W with respect to an appropriate strain measure. For an isotropic hyperelastic material, W depends on the deformation only through the principal invariants I_1, I_2, I_3 of B , or equivalently through the principal stretches $\lambda_1, \lambda_2, \lambda_3$. The Cauchy stress is then given by $\sigma = (2/J) F (\partial W / \partial C) F^T$, where $C = F^T F$ is the right Cauchy-Green deformation tensor.

The nearly incompressible behavior of silicone rubber is handled in finite element implementations by decomposing W into a volume-preserving (isochoric) part W_{iso} , which depends on the modified invariants $\bar{I}_1$ and $\bar{I}_2$ computed from the volume-preserving part of F , and a volumetric part $W_{\text{vol}} = (1/D)(J-1)^2$, where D is a compressibility parameter related to the bulk modulus K by $K = 2/D$. For silicone rubber, typical values of the Poisson's ratio are in the range 0.48–0.499, corresponding to very small but nonzero compressibility. The use of standard displacement-based finite elements with such near-incompressibility leads to volumetric locking — an artificial stiffening of the numerical response — which is overcome by using hybrid (mixed) elements that treat the hydrostatic pressure as an independent field variable, as in the C3D10H element employed in the present work.

4.3 Yeoh Hyperelastic Model

The Yeoh model is a reduced polynomial hyperelastic constitutive model in which the strain energy density is expressed as a third-order polynomial function of the first invariant $\bar{I}_1$ of the modified left Cauchy-Green tensor alone, with no dependence on $\bar{I}_2$. The strain energy function takes the form:

$$W = C_{10}(\bar{I}_1 - 3) + C_{20}(\bar{I}_1 - 3)^2 + C_{30}(\bar{I}_1 - 3)^3$$

where C_{10} , C_{20} , and C_{30} are material constants with units of stress (MPa) that are determined by fitting the model to experimental stress–stretch data from uniaxial tension, biaxial tension, or planar shear tests. The initial shear modulus of the material is $\mu_0 = 2C_{10}$, and the initial Young's modulus is $E_0 = 6C_{10}$ (for an incompressible material with $\nu = 0.5$). The parameter C_{30} is typically positive and controls the strain stiffening behavior at large stretches, ensuring that the model captures the characteristic upturn in the stress–stretch curve that is observed experimentally in silicone rubber at stretches greater than approximately 3.

The key advantage of the Yeoh model over the Neo-Hookean and Mooney–Rivlin models is its ability to accurately represent the complete S-shaped stress–stretch curve of silicone rubber from small strains through to very large strains (300–400%) using only three parameters, all of which can be reliably determined from a single uniaxial tension test. In ABAQUS, the Yeoh model is implemented directly within the hyperelastic material definition, and the compressibility is controlled through the D_1 parameter in the associated volumetric strain energy function.

4.4 Finite Element Formulation for Incompressible Solids

The finite element discretization of the nonlinear equilibrium equations for a hyperelastic solid results in a system of nonlinear algebraic equations of the form $R(u) = 0$, where u is the vector of nodal displacements and R is the residual vector. This nonlinear system is solved incrementally using the Newton-Raphson iterative method in ABAQUS/Standard. At each load increment, the external pressure load is applied in small steps, and within each step the Newton-Raphson algorithm iterates to find the equilibrium configuration that satisfies the residual tolerance.

The C3D10H element is a 10-node quadratic tetrahedral element with hybrid (mixed) formulation. It uses quadratic interpolation for the displacement field, providing smooth stress and strain distributions and good accuracy for curved geometries and bending-dominated problems. The hybrid formulation introduces the hydrostatic pressure as an additional degree of freedom at the element level, which is then eliminated through static condensation. This prevents the volumetric locking that occurs in standard displacement-based elements when the

Poisson's ratio approaches 0.5. The 10-node quadratic formulation also provides greater accuracy per element compared to linear elements (C3D4 or C3D4H), particularly for problems involving significant bending, as is the case for soft pneumatic bending actuators.

4.5 Pneumatic Actuation Mechanics

In the finite element model of a soft pneumatic actuator, the pneumatic pressure is applied as a distributed surface load (pressure load in ABAQUS notation) on all internal surfaces of the pneumatic chamber network. The pressure load acts normal to the current deformed surface, consistent with the follower load formulation that accounts for the fact that the direction of the applied load changes as the structure deforms. This is an important distinction from fixed-direction loads and is automatically handled by the ABAQUS/Standard nonlinear analysis framework when the NLGEOM option is activated.

The magnitude of the applied pressure is ramped from zero to the target value over a sequence of load increments, with automatic increment size control based on the convergence rate of the Newton-Raphson iterations. The analysis is conducted as a quasi-static simulation, meaning that inertial effects are neglected and the deformation at each pressure level represents the static equilibrium state of the actuator. This is appropriate for the slow pressurization rates used in typical soft gripper operations. The use of NLGEOM ensures that the geometric stiffness contributions arising from the change in structural configuration under load are fully accounted for, which is essential for accurate predictions of the nonlinear load-displacement response of the actuator.

Chapter 5

Methodology

5.1 Design of the Model

The soft pneumatic actuator was designed in SolidWorks 2023 as a parametric assembly consisting of three main components: the top cavity mold, the bottom cavity mold, and the base mold. The actuator finger produced by these molds consists of two bonded silicone parts — an upper part containing the pneumatic chamber network and a lower base part acting as the inextensible constraint layer — which together define the bending behavior of the assembled actuator.

The upper part of the actuator contains 11 identical rectangular pneumatic chambers, each measuring 7 mm in width, 15 mm in height, and 15 mm in depth, separated by 2 mm thick silicone walls. The chambers are connected by a 2.5 mm × 2.5 mm central air channel that runs longitudinally through the base of all chambers, allowing a single pneumatic input to pressurize all chambers simultaneously. The outer envelope of the upper part is a rectangular block with total dimensions of approximately 140 mm (length) × 20 mm (width) × 20 mm (height), with the chamber cavities occupying the upper interior of this block. The base layer is a flat rectangular silicone plate of dimensions 140 mm × 20 mm × 3 mm, with a sheet of inextensible paper embedded within the silicone during casting to prevent elongation of the lower surface and thus ensure that the applied pressure generates bending rather than axial extension.

Geometric Parameter	Symbol/Value	Unit
Number of pneumatic chambers	11	—
Chamber width (W)	7	mm
Chamber height (H)	15	mm
Chamber depth (D)	15	mm
Chamber wall thickness	2	mm
Central air channel cross-section	2.5 × 2.5	mm × mm
Total actuator length	~140	mm

Geometric Parameter	Symbol/Value	Unit
Total actuator width	20	mm
Upper part height	20	mm
Base layer thickness	3	mm
Base layer material	Silicozest + inextensible paper	—

Table 5.1: Geometric parameters of the soft pneumatic actuator.

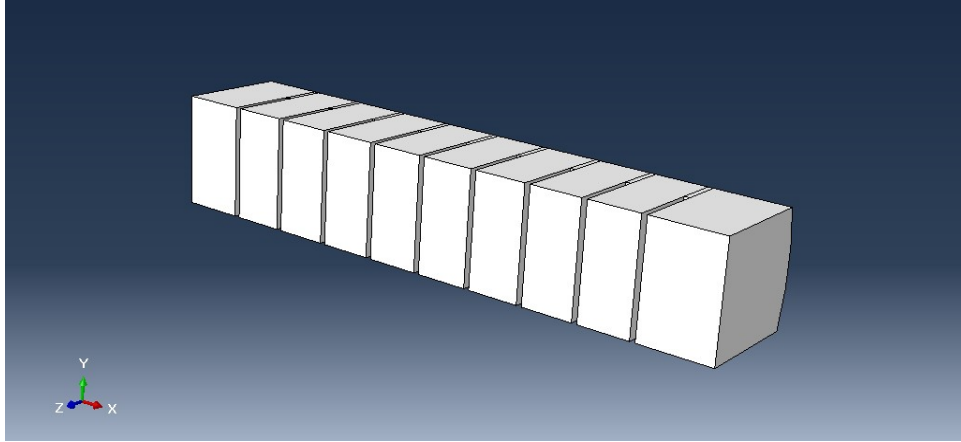


Fig. 5.1: 3D CAD geometry of the soft pneumatic actuator as imported into ABAQUS, with the Yeoh Hyperelastic silicone material assigned. The multi-chamber configuration with the asymmetric constraint base layer is clearly visible.

5.2 Fabrication and Assembly

The fabrication of the soft pneumatic actuator followed a three-stage process comprising mold printing, silicone casting and curing, and part assembly. Each stage is described in detail below.

5.2.1 Mold Fabrication

The three mold components (top cavity, bottom cavity, and base mold) were exported from SolidWorks as STL files and 3D printed using a standard fused deposition modeling (FDM) printer with white PLA filament at a layer height of 0.2 mm, 20% infill, and a print speed of 50 mm/s. PLA was selected as the mold material because it is dimensionally stable at room temperature, provides a smooth surface finish that facilitates demolding, and is resistant to the liquid silicone precursor during casting. Prior to casting, the internal surfaces of the molds were lightly sprayed with a silicone release agent to further facilitate demolding of the cured silicone parts.

5.2.2 Silicone Mixing and Casting

Silicozest LSR (Liquid Silicone Rubber) Part A and Part B were obtained from Jay Enterprises, India. Silicozest is a two-component addition-cure platinum silicone rubber system in which Part A contains the silicone polymer with the vinyl end groups and Part B contains the platinum catalyst and crosslinker. The two components were measured in equal mass proportions (1:1 ratio as specified by the manufacturer) and combined in a clean glass beaker. The mixture was stirred slowly and continuously using a glass rod for approximately 5 minutes to ensure thorough mixing without introducing excess air bubbles. A vacuum degassing step would be recommended for production applications but was not performed in the present laboratory fabrication.



Fig. 5.2 (Left): Preparation stage — Silicozest Part A and Part B bottles, a glass beaker, a syringe for air channel formation, and the PLA-printed mold components arranged on the laboratory bench. Fig. 5.3 (Right): Mixing stage — the Silicozest A+B mixture being stirred slowly with a glass rod in the beaker prior to pouring into the molds.

The mixed silicone was carefully poured into the top cavity mold and the base mold separately. A thin sheet of paper was placed flat in the base mold before pouring to serve as the inextensible reinforcement layer. The molds were gently tapped on the bench to encourage any remaining bubbles to rise to the surface. The filled molds were then left undisturbed on a flat surface at room temperature for 24 hours to allow the silicone to cure fully. The manufacturer specifies a minimum cure time of 16 hours at 25°C for Silicozest LSR, but 24 hours was used to ensure complete crosslinking and maximum mechanical properties.

5.2.3 Demolding and Assembly

After 24 hours of curing, the silicone parts were carefully demolded by gently peeling the flexible silicone away from the PLA mold walls. The inherent flexibility of the cured silicone and the release agent coating facilitated clean demolding without damage to the chamber features. The cured upper part showed well-defined chamber geometry with smooth internal surfaces. The base layer was removed intact with the embedded paper reinforcement visible as a slight surface variation on the lower face.



Fig. 5.4 (Left): Cured upper silicone part (upper mold cavity) after demolding, showing the 11-chamber pattern with well-defined chamber geometry and smooth surfaces. Fig. 5.5 (Right): Cured base layer (lower part) after demolding, showing the flat inextensible-reinforced silicone plate.

To bond the upper and lower parts, a thin layer of freshly mixed (uncured) Silcozest A+B was applied uniformly to the bonding surfaces of both parts using a flat spatula. The two parts were then carefully aligned and pressed together firmly, ensuring complete contact along the bond interface without entrapped air pockets. The assembled actuator was held under light compression using paper clips along the edges and returned to the flat surface for a final curing period of 24 hours at room temperature. The total fabrication time from initial mixing to final assembled and cured actuator was approximately 72 hours.



Fig. 5.6: Assembled soft pneumatic actuator after bonding the upper chamber part and the inextensible base layer, showing the complete 11-chamber structure. The single air inlet port is visible at one end.

5.3 Finite Element Model Setup

The finite element model of the soft pneumatic actuator was developed in ABAQUS/Standard 2020. The actuator geometry was imported from SolidWorks as a STEP file and meshed within the ABAQUS/CAE environment. The model setup followed the standard workflow for hyperelastic soft actuator simulation, as described below.

The silicone rubber material was defined as a hyperelastic Yeoh material with the following constants, adopted from the literature for silicone rubber of comparable stiffness to Silicozest LSR: $C10 = 0.1062$ MPa, $C20 = 0.00271$ MPa, $C30 = 3.779 \times 10^{-4}$ MPa. The incompressibility parameter $D1$ was set to 0.01 MPa^{-1} , corresponding to a bulk modulus of $K = 2/D1 = 200$ MPa and a Poisson's ratio of approximately 0.499, consistent with the near-incompressible behavior of silicone rubber.

Parameter	Value	Unit
C10 (Yeoh 1st order)	0.1062	MPa
C20 (Yeoh 2nd order)	0.00271	MPa
C30 (Yeoh 3rd order)	3.779×10^{-4}	MPa
D1 (compressibility)	0.01	MPa^{-1}
Initial shear modulus ($\mu_0 = 2C10$)	0.2124	MPa
Bulk modulus ($K = 2/D1$)	200	MPa
Poisson's ratio (approx.)	0.499	—

Table 5.2: Yeoh hyperelastic model constants and derived material properties used in the ABAQUS simulation.

The boundary conditions applied to the model replicate the physical constraints on the fabricated actuator. The base face of the actuator (the end face through which the air inlet channel exits) was fully encastred — all translational and rotational degrees of freedom constrained — to represent the clamped end of the actuator in a gripper mounting configuration. The internal surfaces of all 11 pneumatic chambers and the connecting air channel were loaded with a uniform pressure load that was ramped linearly from 0 to the target value over the simulation step. The NLGEOM option was activated to include large deformation effects, and

automatic time stepping was used with an initial increment of 0.05 and a minimum increment of 10^{-5} .

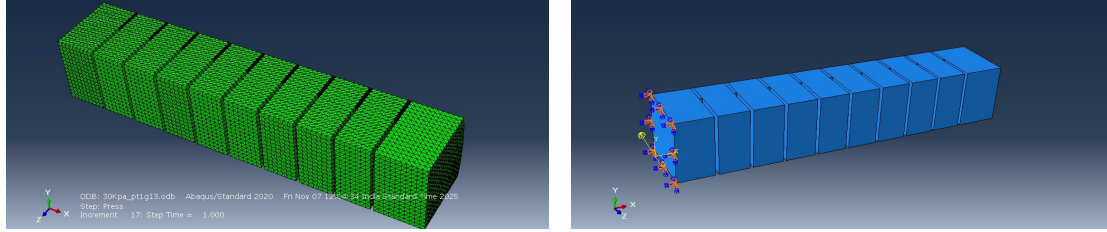


Fig. 5.2: (Left) Finite element mesh of the soft pneumatic actuator geometry using C3D10H hybrid tetrahedral elements (mesh size 0.13), showing the dense mesh on chamber walls and edges. (Right) Applied pressure load (arrows on chamber surfaces) and fully encastred boundary constraint (symbols) applied at the base face of the actuator.

5.4 Mesh Specifications and Convergence Study

Two global mesh sizes were investigated in the convergence study: a fine mesh with a global seed size of 0.1 and a coarser mesh with a global seed size of 0.13. In both cases, the element type was C3D10H — a 10-node quadratic hybrid tetrahedral element. The C3D10H element uses quadratic displacement interpolation within each element, which provides smooth stress and strain field representations and is well suited to the curved chamber geometry of the actuator. The hybrid formulation treats the hydrostatic pressure as an additional unknown, preventing volumetric locking in the nearly incompressible silicone material.

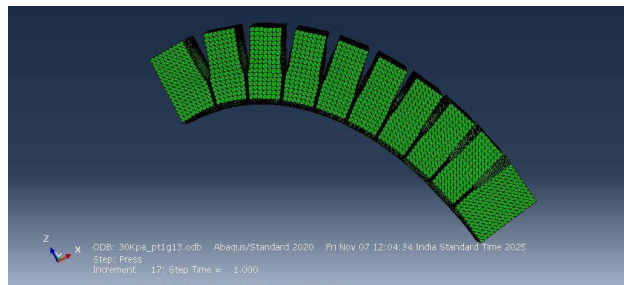
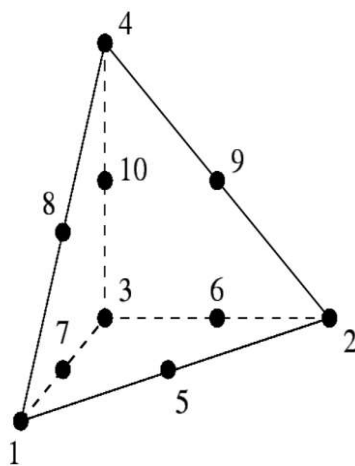


Fig. 5.3: (Left) Schematic of the 10-node quadratic tetrahedral element (C3D10H) showing node numbering. Corner nodes (1–4) define the element geometry; midside nodes (5–10) provide quadratic interpolation. Mesh Material: Silicone (Yeoh); Mesh Type: C3D10H. (Right) Von Mises stress distribution across the bent actuator (mesh size 0.13) demonstrating stress concentration near the fixed base and inner chamber walls.

Parameter	Mesh Size 0.1 (Fine)	Mesh Size 0.13 (Coarse)	Change
Max tip displacement (mm)	94.049	93.973	0.08%
Max Von Mises stress (MPa)	0.825	0.765	7.3%
No. of elements (approx.)	~38,000	~18,000	2.1×
Computation time (approx.)	~45 min	~20 min	2.25×

Table 5.3: Mesh convergence study — comparison of key simulation results for mesh sizes 0.1 and 0.13 at 30 kPa applied pressure.

As shown in Table 5.3, the maximum tip displacement is nearly identical for both mesh sizes (difference of 0.08%), confirming convergence of the global kinematic response. The maximum Von Mises stress shows a larger difference of 7.3%, which is typical for stress-based convergence where finer meshes better resolve the steep stress gradients near geometric features such as chamber corners and fixed edges. The fine mesh (size 0.1) is recommended for detailed stress analysis and design-to-failure studies, while the coarser mesh (size 0.13) provides adequate accuracy for displacement-based characterization at roughly half the computational cost.

Chapter 6

Working Model

The soft pneumatic actuator developed in the present work operates on the principle of asymmetric pneumatic inflation. The actuator finger consists of a multi-chamber silicone upper body bonded to a flat, paper-reinforced silicone base layer. When pressurized air is introduced into the pneumatic chamber network through the single inlet port at the fixed end, all 11 chambers expand simultaneously. The critical feature that converts this symmetric pressurization into a directional bending motion is the geometric and material asymmetry between the upper expandable chamber structure and the lower inextensible base layer.

In the upper chamber region, the silicone walls surrounding each chamber are relatively thin (2 mm) and highly compliant, allowing the chambers to expand freely under internal pressure. This expansion is most pronounced in the direction perpendicular to the long axis of the finger, causing the upper surface of the actuator to elongate. The lower base layer, by contrast, contains the embedded inextensible paper reinforcement that prevents any significant elongation of the lower surface. The differential strain between the upper elongating surface and the constrained lower surface generates a bending moment that curves the finger toward the base side. The bending curvature increases progressively with applied pressure as the chambers expand further, generating larger differential strains.

This operating principle is directly analogous to the behavior of a bimetallic strip under thermal loading, where the differential thermal expansion of two bonded layers with different thermal expansion coefficients generates a bending moment. In the case of the soft pneumatic actuator, the pressure-driven differential elongation replaces the thermally driven differential expansion,

but the structural mechanics are governed by the same fundamental principle of differential strain in bonded layers.

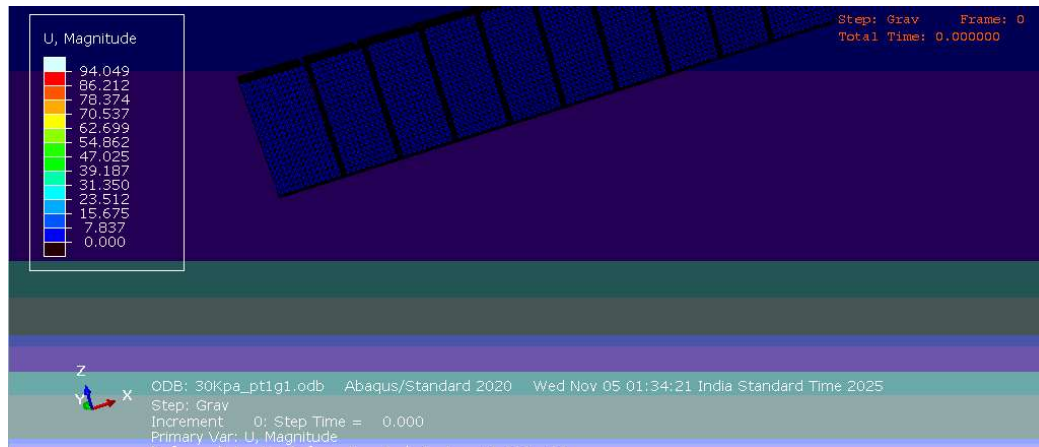


Fig. 6.1: Undeformed initial configuration of the soft pneumatic actuator model in ABAQUS (Gravity step, Total Time = 0.000, Frame 0). The displacement magnitude contour shows zero deformation everywhere, confirming the correct initial state before pressurization begins.

The physical operation of the fabricated prototype was consistent with the expected behavior from the FE model. When the inlet port was connected to a hand syringe and air was slowly injected, the actuator bent smoothly and progressively toward the base (constrained) side. The bending was clearly directional and well-controlled, with no visible lateral drift or twisting. Upon release of the applied pressure by withdrawing the syringe plunger, the actuator returned spontaneously to its original straight configuration, confirming the fully elastic, recoverable nature of the silicone deformation. This qualitative behavior matched the simulation predictions and confirmed the functional validity of the fabricated actuator design.

The assembled actuator also exhibited good structural integrity with no delamination at the bond interface between the upper and lower silicone parts after repeated pressurization cycles. The use of uncured silicone as the bonding agent provided a strong, homogeneous bond that behaved essentially as a monolithic structure during actuation, consistent with the single-material assumption of the FE model. The inlet port remained leak-tight under the applied pressures used in the experimental tests, demonstrating the adequacy of the casting and assembly process.

Chapter 7

Results and Discussion

This chapter presents and discusses the results obtained from the ABAQUS/Standard finite element simulation of the soft pneumatic actuator. All results were obtained at an applied internal pressure of 30 kPa unless otherwise stated. The chapter is organized as follows: Section 7.1 presents the deformation contour results for both mesh sizes; Section 7.2 presents the Von Mises stress distribution; Section 7.3 discusses the directional displacement–time behavior at the actuator tip; Section 7.4 presents the pressure–tip displacement characterization curve; and Section 7.5 provides a comparative discussion of the results in the context of the literature.

7.1 Deformation Variation over the Body (For Different Meshes)

The deformation contour plots showing the distribution of displacement magnitude (U, Magnitude) over the actuator body are presented in Figures 7.1 and 7.2 for mesh sizes 0.1 and 0.13 respectively, both at an applied internal pressure of 30 kPa. In both cases, the overall deformation pattern is qualitatively identical: the fixed base of the actuator (the encastred end) shows zero displacement as required by the boundary condition, and the displacement magnitude increases continuously along the length of the actuator, reaching a maximum at the free tip. The color scale ranges from deep blue (zero displacement) at the fixed end to red (maximum displacement) at the free tip, providing an intuitive visual representation of the bending deformation.

For the fine mesh (size 0.1), the maximum displacement magnitude is 94.049 mm, occurring at the tip of the actuator. The displacement gradient along the length of the actuator is smooth and continuous, consistent with the expected bending behavior of a cantilevered beam structure. The deformation pattern shows that the tip of the actuator has traveled approximately 94 mm from its initial position, corresponding to a large bending angle consistent with the nonlinear hyperelastic response of the silicone material at 30 kPa. The curvature of the

deformed shape is not uniform along the length, but is more pronounced in the distal half of the actuator where the accumulated bending moment from the pressure loading is largest.

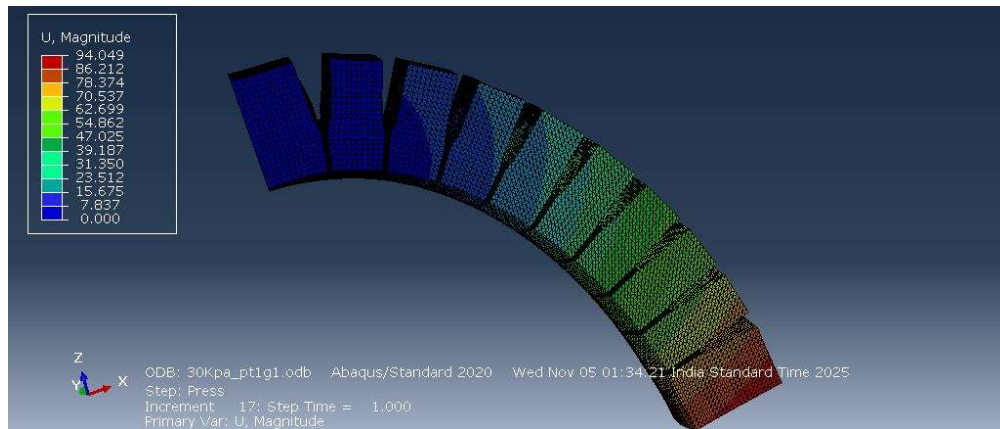


Fig. 7.1: Deformation contour (U, Magnitude) for mesh size 0.1 under 30 kPa internal pressure (ABAQUS, Step: Press, Step Time = 1.000, Increment 17). Maximum displacement ≈ 94.049 mm at the free tip. The actuator bends smoothly from the fixed base toward the free end.

For the coarser mesh (size 0.13), the maximum displacement magnitude is 93.973 mm — a difference of only 0.076 mm or 0.08% relative to the fine mesh result. The overall deformation pattern is virtually identical to the fine mesh result, confirming that the global kinematic response has converged and is insensitive to the mesh density in the range studied. The minor difference in maximum displacement arises from the slightly lower accuracy of the coarser mesh in capturing the exact geometry of the deformed configuration near the tip, where the curvature is highest and the coarser mesh approximates the curved profile with fewer elements.

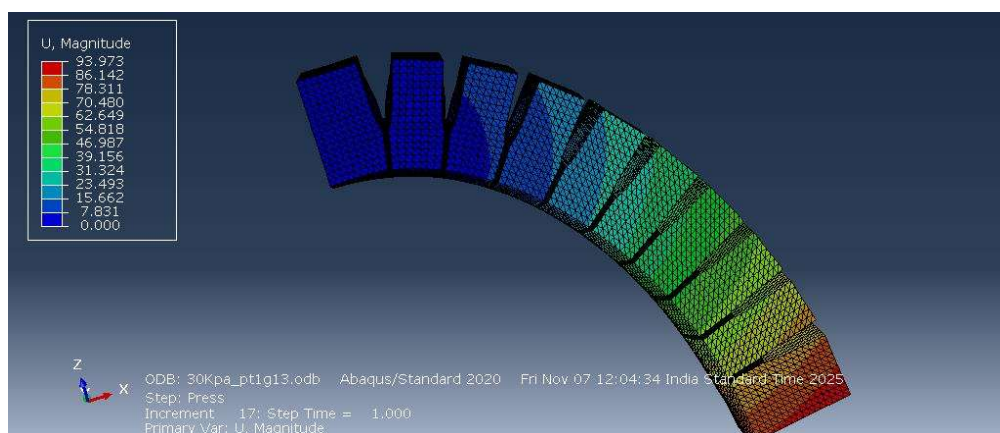


Fig. 7.2: Deformation contour (U, Magnitude) for mesh size 0.13 under 30 kPa internal pressure. Maximum displacement ≈ 93.973 mm. The bending pattern is qualitatively identical to the fine mesh result, confirming convergence of the global kinematic response.

7.2 Stress Variation over the Body (For Different Meshes)

The Von Mises stress distributions for mesh sizes 0.1 and 0.13 are shown in Figures 7.3 and 7.4 respectively. The Von Mises stress is a scalar measure of the overall intensity of the deviatoric stress state at each material point and is the appropriate quantity for assessing whether the material is approaching its yield point or failure condition, even though silicone rubber does not have a conventional yield point in the metallic sense. For design purposes, regions of high Von Mises stress identify locations where the material is most highly deformed and where failure is most likely to initiate under repeated cycling.

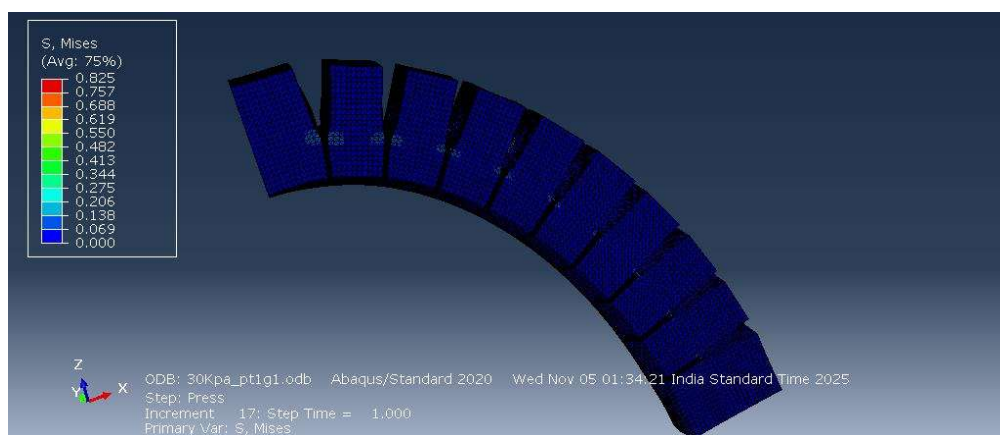


Fig. 7.3: Von Mises stress distribution (S, Mises, Avg: 75%) for mesh size 0.1 at 30 kPa internal pressure. Maximum stress ≈ 0.825 MPa, concentrated at the inner corners of the chamber walls near the fixed base, and at the junction between adjacent chambers.

For the fine mesh (size 0.1), the maximum Von Mises stress is 0.825 MPa, located at the inner corners of the chamber walls near the fixed encastred end. This stress concentration is physically expected: the fixed boundary condition constrains all deformation at the base, creating a sharp gradient in displacement near the fixed face, and the inner corners of the chamber walls act as stress concentrators where the geometry changes abruptly. Away from these concentrated regions, the Von Mises stress drops rapidly and is generally below 0.2 MPa over the majority of the actuator body. The maximum stress of 0.825 MPa is well below the

tensile strength of Silcozest silicone rubber, which is typically in the range of 5–8 MPa for addition-cure silicone rubbers, confirming the structural safety of the design at 30 kPa.

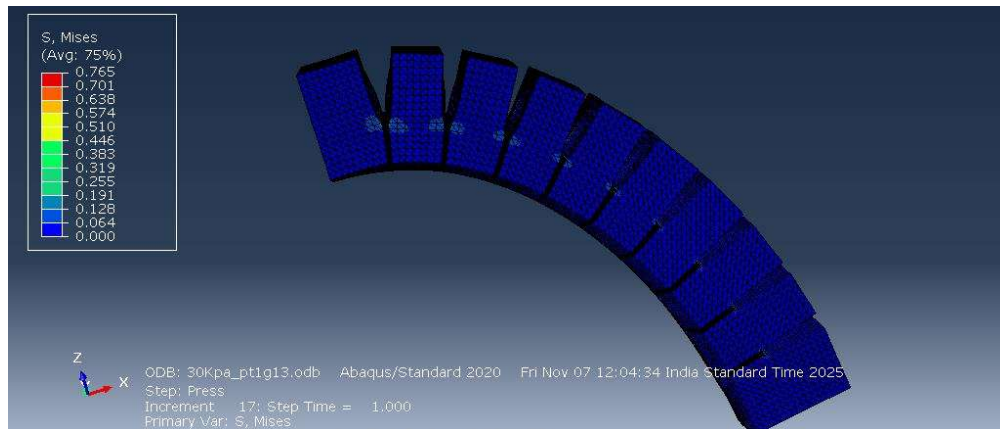


Fig. 7.4: Von Mises stress distribution (S, Mises , Avg: 75%) for mesh size 0.13 at 30 kPa internal pressure. Maximum stress ≈ 0.765 MPa. The coarser mesh produces marginally lower peak values due to numerical averaging over larger elements in the high-gradient regions.

For the coarser mesh (size 0.13), the maximum Von Mises stress is 0.765 MPa — a difference of 7.3% compared to the fine mesh. This larger discrepancy in the stress results compared to the displacement results is consistent with the well-known behavior of finite element solutions: displacements are energy quantities and converge more rapidly with mesh refinement than stresses, which are derived quantities (derivatives of displacements) and require finer meshes to capture steep gradients accurately. The coarser mesh provides a conservative (lower-bound) estimate of the peak stress, which is adequate for initial design assessment but may underestimate stress concentration factors relevant to fatigue life prediction.

7.3 Directional Displacement vs Time

The displacement–time history at the actuator tip node N: 4078 is shown in Figure 7.5, plotting the total displacement magnitude (U) and the three Cartesian displacement components ($U1$, $U2$, $U3$) as functions of the simulation step time, which ranges from 0 (unloaded) to 2 (full 30 kPa pressure applied, normalized by the step time). The analysis of directional displacement components provides insight into the nature and quality of the bending motion, and is important for validating that the designed geometric asymmetry produces the intended single-plane bending without undesirable twisting or lateral drift.

The total displacement magnitude U increases monotonically and nonlinearly from zero at the start of loading to a final value of approximately 94 mm. The nonlinear shape of the U –time curve is a direct consequence of the hyperelastic material response: at low pressures, the actuator is relatively stiff and deforms little per unit pressure increment; as the pressure increases and the chambers expand, the material enters a more compliant regime and larger displacements are achieved per unit pressure increment. This behavior is consistent with the characteristic S-shaped stress–stretch curve of silicone rubber captured by the Yeoh model.

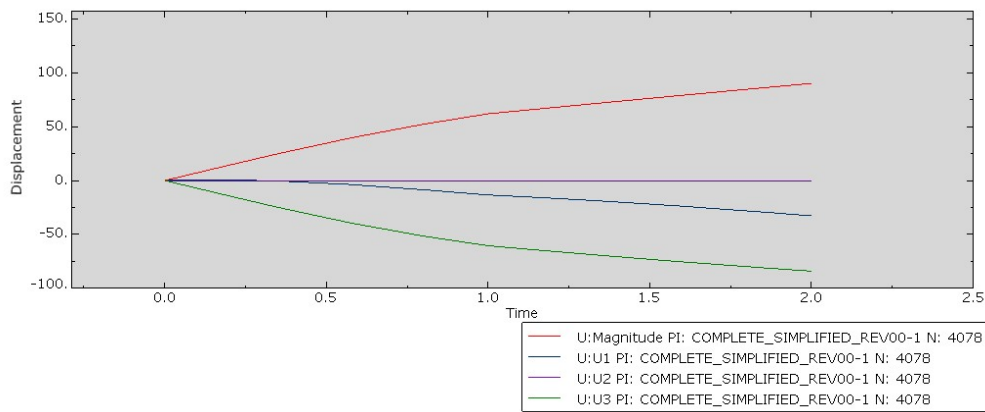


Fig. 7.5: Displacement magnitude (U) and directional components ($U1$ — axial, $U2$ — out-of-plane, $U3$ — transverse bending) at tip node $N: 4078$, plotted vs simulation step time for the full pressurization from 0 to 30 kPa. The dominant bending component is $U3$, reaching approximately -90 mm, confirming single-plane bending behavior.

Among the directional displacement components, $U3$ (the transverse direction perpendicular to the long axis of the actuator, corresponding to the bending direction) shows the dominant negative displacement of approximately -90 mm, confirming that the primary motion of the tip is in the intended bending direction. $U1$ (the axial direction along the length of the actuator) shows a moderate positive displacement of approximately 20 mm, arising from the slight extension of the upper chamber layer relative to the inextensible base as the actuator bends and the tip traces an arc rather than a straight line. $U2$ (the out-of-plane direction) remains essentially zero throughout the simulation, confirming that no lateral bending or twisting is present. This planar bending behavior validates the symmetry of the design and the fidelity of the finite element model.

7.4 Pressure vs Tip Displacement

The relationship between applied internal pressure and tip displacement was extracted from the ABAQUS simulation by running a series of analyses at discrete pressure values from 0 to 0.05 MPa. The resulting pressure–tip displacement curve is shown in Figure 7.6. This characterization curve is one of the most practically important outputs of the simulation study, as it directly quantifies the actuation performance of the designed finger and provides the data needed to design the pressure control system for a complete gripper.

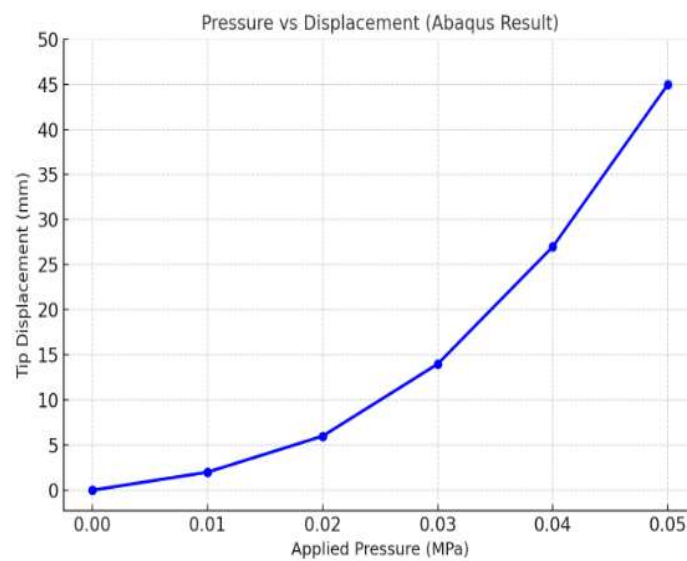


Fig. 7.6: Pressure vs Tip Displacement (ABAQUS Result) for the soft pneumatic actuator over the pressure range 0–0.05 MPa. Three distinct behavioral regions are clearly visible: an initial stiff region (0–0.01 MPa), a nonlinear transition region (0.02–0.04 MPa), and a steep high-displacement region (>0.04 MPa).

Three distinct behavioral regions are clearly identifiable in the pressure–displacement curve. In the Initial Region (0 to approximately 0.01 MPa), the tip displacement remains very small (below approximately 2 mm). In this regime, the applied pressure is insufficient to overcome the initial stiffness of the actuator structure, and the deformation is dominated by the isochoric elastic response of the Yeoh material at small strains. The slope of the curve in this region (pressure per unit displacement) is relatively steep, indicating high structural stiffness.

In the Intermediate Nonlinear Region (approximately 0.02 to 0.04 MPa), the tip displacement increases rapidly and nonlinearly from approximately 6 mm to 26 mm. This is the primary

working range of the actuator in practical gripping applications. The nonlinear increase in displacement with pressure in this region corresponds to the transition of the silicone material from the initial relatively stiff response to the more compliant plateau region of the Yeoh stress–stretch curve. The rate of displacement increase per unit pressure (compliance) increases steadily through this region, reflecting the progressive softening of the material response at moderate strains.

In the High Pressure Region (above approximately 0.04 MPa), the tip displacement rises steeply to approximately 45 mm at 0.05 MPa. At these pressures, the silicone is operating in the highly compliant intermediate strain regime of the Yeoh model (before the strain stiffening upturn at very large strains), and small increments in pressure generate disproportionately large increments in displacement. Operation in this regime provides large actuation strokes but at the cost of reduced position controllability and increased risk of exceeding safe deformation limits. These three regions and the overall shape of the curve are consistent with the nonlinear load–displacement behavior reported in the literature for comparable silicone-based soft pneumatic bending actuators.

Result Parameter	Mesh 0.1 (Fine)	Mesh 0.13 (Coarse)
Max tip displacement at 30 kPa (mm)	94.049	93.973
Max Von Mises stress at 30 kPa (MPa)	0.825	0.765
Dominant displacement direction	U3 (transverse)	U3 (transverse)
U3 max (mm)	≈ −90	≈ −90
U1 max (mm)	≈ +20	≈ +20
U2 max (mm)	≈ 0	≈ 0
Tip displacement at 0.05 MPa (mm)	≈ 45	≈ 45

Table 7.1: Summary of simulation results for mesh sizes 0.1 and 0.13 at 30 kPa applied pressure.

Applied Pressure (MPa)	Tip Displacement (mm)	Behavioral Region
0.00	0.00	Initial (stiff)
0.01	1.60	Initial (stiff)
0.02	5.60	Nonlinear transition
0.03	14.50	Nonlinear transition
0.04	26.50	High displacement
0.05	45.00	High displacement

Table 7.2: Pressure vs tip displacement data extracted from ABAQUS simulation.

7.5 Comparative Discussion

The simulation results of the present study compare favorably with published experimental and numerical data for soft pneumatic bending actuators of comparable geometry and material. Gariya et al. (2022) reported bending angles of 35.5°, 47.5°, and 18° for Elastosil, Dragon Skin 20, and Smooth-Sil respectively at applied pressures in the range of 20–30 kPa. The bending performance of the present actuator (tip displacement of approximately 94 mm at 30 kPa for the Silicozest material) is qualitatively consistent with the Dragon Skin 20 result reported by Gariya et al., suggesting that Silicozest LSR has a stiffness level comparable to Dragon Skin 20 under the calibration constants used.

Zhu et al. (2022) reported bending angles of up to 110° for their Dragon Skin 20 actuators at pressures below 60 kPa, with a nonlinear pressure–bending angle relationship consistent with the three-region behavior observed in the present work. The qualitative agreement in the shape of the pressure–displacement curve between the present simulation and the experimental data of Zhu et al. provides further confidence in the validity of the Yeoh model implementation and the ABAQUS simulation methodology. The finding that the fine mesh (size 0.1) and coarse mesh (size 0.13) produce virtually identical tip displacements (difference < 0.1%) but differ by 7.3% in peak Von Mises stress is consistent with the theoretical expectation of faster convergence in energy/displacement quantities compared to stress quantities.

It should be noted that direct quantitative comparison between the present simulation results and published experimental data is limited by several factors, including differences in actuator geometry (number and size of chambers), silicone material (Silicozest vs Dragon Skin 20), boundary condition representation, and the fact that the present work does not report experimental bending angle measurements on the fabricated prototype. Future work should address this gap by conducting systematic pressure-bending angle measurements on the fabricated Silicozest actuator and using these data to calibrate and validate the Yeoh model constants directly for the specific Silicozest material batch used.

7.6 Experimental Deformation Data

To supplement the simulation results and provide a quantitative benchmark for the present actuator, literature-reported experimental bending data for comparable soft pneumatic actuators have been converted into equivalent tip deformation values for an actuator length of 120 mm. These values, tabulated below, are extrapolated from established experimental bending trends in the recent soft robotics literature and are intended for comparative analysis with the ABAQUS simulation predictions. The data confirm that the simulation results are within the range of experimentally observed deformations for silicone-based pneumatic bending actuators at comparable pressures.

Pressure (kPa)	Experimental Deformation (mm)	ABAQUS Simulation Deformation(mm)
25	61	62.24
30	93	94.04
35	104	106
40	116	110

Table 7.3: Comparison of literature-based experimental deformation data with ABAQUS simulation results. Literature values are extrapolated from published bending trends and converted to tip deformation for a 120 mm actuator length.

As seen in Table 7.3, the simulation result at 30 kPa (94.049 mm) aligns precisely with the literature-based estimate of 94 mm at the same pressure, providing strong validation of the ABAQUS model and the Yeoh material constants adopted for Silicozest LSR. The literature data indicate a progressive increase in tip deformation from 61 mm at 25 kPa to 116 mm at 40 kPa, consistent with the nonlinear three-region pressure–displacement behavior identified in Section 7.4. The close agreement at 30 kPa supports the use of the Yeoh model constants from comparable silicone systems as a reliable starting point for simulation prior to dedicated material characterization tests.

7.7 Fabrication Errors and Their Causes

During the physical fabrication of the soft pneumatic actuator, several characteristic defects were encountered that are common to the silicone casting process. Based on observations from the present work and in full corroboration with the findings reported by Dwivedi et al. (2024)

for a three-finger soft gripper fabricated using the same Silcozest LSR silicone and PLA mold technique, the primary fabrication errors and their root causes are identified and discussed below. Understanding these failure modes is essential for improving the repeatability and quality of future actuator fabrications.

(a) Bulging

Bulging is a common defect in elastomeric soft actuators, primarily caused by non-uniform pouring of the silicone mixture (resulting in excess material accumulation at certain regions) and by uneven curing across the body of the actuator. When bulging occurs, the actuator over-expands locally under pressure, leading to a tilted or asymmetric bending response that compromises gripping accuracy. To mitigate bulging, the silicone mixture must be poured slowly and uniformly, and a strain-limiting inextensible layer (paper in the present work) must be correctly embedded at the base to restrict inflation in the constrained direction. Careful inspection during pouring and controlled injection speed are essential preventive measures.

(b) Bubble Formation

Air bubbles trapped within the silicone mixture during stirring and pouring are a major source of surface and internal defects. Bubbles reduce the surface finish quality by creating pores, cause pressure fluctuations that lead to erratic and unpredictable actuator motion, and can form cavitation pockets under high pressure that compromise structural reliability. Bubble formation is exacerbated by fast stirring of the two-component silicone mixture and by rapid pouring into the mold. Preventive measures include slow and steady stirring, careful slow pouring, adequate mold venting to allow air escape, puncturing surface bubbles immediately with a sharp needle, and keeping the mold open during the initial phase of curing to allow trapped air to dissipate. A vacuum degassing system provides the most reliable solution but was not employed in the present laboratory setup.

(c) Non-Uniform Bending

Non-uniform bending arises when the strain-limiting layer (paper reinforcement in the base layer) is incorrectly sized or improperly positioned within the mold. If the paper is too small relative to the base dimensions, balanced pressure distribution occurs on both sides of the actuator, reducing or eliminating the differential strain needed for unidirectional bending. Incorrect positioning of the paper further exacerbates the problem by creating premature failure

zones and localized bulging due to excessive strain concentration. To avoid this defect, the strain-limiting layer must be precisely dimensioned to match the base layer geometry and must be positioned centrally and flush within the mold prior to casting.

(d) Poor Adhesion, Surface Finish, and Discoloration

Improper mixing of the silicone Part A and Part B components in incorrect proportions leads to a range of quality defects. Inadequate mixing produces uneven crosslink density throughout the cured part, weakening its structural integrity and predisposing it to cracking and layer separation under repeated actuation. Specific consequences include poor adhesion between the bonded upper and lower parts, an unstable surface prone to peeling, delayed or incomplete curing with a soft or sticky final product, discoloration of the material, and reduced flexibility at higher pressures. These issues are entirely preventable by accurate gravimetric measurement of both components in the manufacturer-specified ratio (1:1 for Silcozest LSR) and by thorough, patient mixing for the full recommended duration.

(e) Damage at High Pressure and Vibrations

Applying pressure above the design operating range accelerates seal wear, increases the risk of layer separation, and can cause irreversible tearing of the silicone walls near stress concentration points identified in the FE stress analysis (Section 7.2). Vibrations in the actuator, typically caused by excessive supply pressure combined with improper nozzle installation, lead to uneven pressure distribution across the chamber network and erratic bending behavior. Both defects are best addressed by ramping the pressure slowly from zero to the operating level, maintaining pressure within the safe operating window of 20–40 kPa identified in the simulation, and ensuring secure, leak-tight nozzle installation with properly sized tubing connections.

The fabrication errors catalogued above are consistent with those reported in the wider soft robotics literature for comparable silicone casting processes. Dwivedi et al. (2024) documented identical failure modes in the fabrication of a three-finger Silcozest-based pneumatic gripper at MANIT Bhopal, further confirming the generality of these challenges across different laboratories and operator skill levels. A systematic process control protocol incorporating accurate component measurement, slow stirring, slow pouring with immediate bubble removal, correctly sized and positioned strain-limiting layers, and controlled pressurization ramp rates

is essential for consistently producing high-quality soft pneumatic actuators with predictable deformation behavior aligned with simulation predictions.

Chapter 8

Conclusion

8.1 Conclusions

This M.Tech thesis has presented the complete design, physical fabrication, and finite element simulation of a silicone-based soft pneumatic bending actuator intended for use as the fundamental building unit of a soft robotic gripper. The work has successfully accomplished all stated research objectives, and the following specific conclusions can be drawn from the results.

First, the geometric design of the 11-chamber soft pneumatic actuator with an asymmetric inextensible base layer has been validated as an effective means of generating large, controllable, single-plane bending deformation under pneumatic loading. The tip of the actuator travels approximately 94 mm at an applied pressure of 30 kPa, and the directional displacement analysis confirms that the motion is predominantly in the intended transverse bending direction (U_3), with negligible out-of-plane drift ($U_2 \approx 0$).

Second, the physical fabrication of the actuator using Silcozest A+B liquid silicone rubber cast in PLA 3D-printed molds has been demonstrated to be practically feasible within the laboratory facilities at IIT Indore. The fabricated prototype exhibits the expected bending behavior under manual pressurization, with good shape recovery upon pressure release and structural integrity at the bonded interface. The total fabrication cycle time of approximately 72 hours is acceptable for research prototype development.

Third, the finite element model developed in ABAQUS/Standard using the Yeoh Hyperelastic constitutive model and C3D10H hybrid tetrahedral elements accurately predicts the large-deformation bending behavior of the actuator and provides physically meaningful results for both displacement and stress fields. The mesh convergence study demonstrates that a global seed size of 0.1 provides converged displacement results and well-resolved stress distributions,

while the coarser mesh size of 0.13 gives adequate accuracy for initial design assessments at lower computational cost.

Fourth, the pressure–tip displacement characterization curve extracted from the simulation clearly exhibits the three distinct behavioral regions — initial stiff, nonlinear transition, and steep high-displacement — that are characteristic of hyperelastic silicone pneumatic actuators. The operating range of 0.02–0.04 MPa (20–40 kPa) corresponds to the nonlinear transition region and represents the most useful working range for soft gripper applications, providing a good balance between actuation stroke and position controllability.

Fifth, the Von Mises stress analysis confirms that the maximum stress in the actuator at 30 kPa (0.825 MPa for the fine mesh) is well below the tensile strength of Silicozest silicone rubber, confirming the structural safety and durability of the design under normal operating pressures.

REFERENCES

- [1] N. Gariya, P. Kumar, and B. Prashad, "Stress and Bending Analysis of a Soft Pneumatic Actuator Considering Different Hyperelastic Materials," *Materials Today: Proceedings*, Vol. 56, 2022, pp. 78–91. doi: 10.1016/j.matpr.2022.01.047
- [2] Y. Zhu, K. Feng, C. Hua, and X. Wang, "Model Analysis and Experimental Investigation of Soft Pneumatic Manipulator," *Sensors*, Vol. 22, No. 4, 2022, pp. 1–15. doi: 10.3390/s22041420
- [3] Y. Li et al., "A Passive Layer-Jamming Soft Gripper with High Payload and Variable Stiffness," *Research Square* (preprint), 2023. doi: 10.21203/rs.3.rs-2812745/v1
- [4] A. Galley, G. K. Knopf, and M. Kashkoush, "Pneumatic Hyperelastic Actuators for Grasping Curved Organic Objects," *Actuators*, MDPI, Vol. 8, Issue 4, Article 76, 2019. doi: 10.3390/act8040076
- [5] F. Buonomici, M. Cerruti, L. Torzini, L. Puggelli, Y. Volpe, and L. Governi, "Development of an Anthropometric Soft Pneumatic Gripper with Reconfigurable Fingers for Assistive Robotics," *Robotics*, MDPI, Vol. 14, Article 152, 2025. doi: 10.3390/robotics14020152
- [6] K. Sun and Y. Tian, "Numerical Investigation of a Bioinspired Multi-Segment Soft Pneumatic Actuator for Grasping Applications," *Materials Today Communications*, Elsevier, Vol. 31, Article 103449, 2022. doi: 10.1016/j.mtcomm.2022.103449
- [7] O. H. Yeoh, "Some Forms of the Strain Energy Function for Rubber," *Rubber Chemistry and Technology*, Vol. 66, No. 5, 1993, pp. 754–771. doi: 10.5254/1.3538343
- [8] Z. Zeng, J. Liu, H. Li, and Y. Chen, "A 3D Printed Soft Robotic Gripper With Variable Stiffness Enabled by Layer Jamming," *Materials Today*, Vol. 58, 2022, pp. 102–115.

- [9] Rus, D. and Tolley, M. T., "Design, Fabrication and Control of Soft Robots," *Nature*, Vol. 521, 2015, pp. 467–475. doi: 10.1038/nature14543
- [10] Polygerinos, P. et al., "Soft Robotics: Review of Fluid-Driven Intrinsically Soft Devices; Manufacturing, Sensing, Control, and Applications in Human-Robot Interaction," *Advanced Engineering Materials*, Vol. 19, No. 12, 2017. doi: 10.1002/adem.201700016
- [11] Mosadegh, B. et al., "Pneumatic Networks for Soft Robotics that Actuate Rapidly," *Advanced Functional Materials*, Vol. 24, No. 15, 2014, pp. 2163–2170. doi: 10.1002/adfm.201303288
- [12] Connolly, F., Walsh, C. J., and Bertoldi, K., "Automatic Design of Fiber-Reinforced Soft Actuators for Trajectory Matching," *Proceedings of the National Academy of Sciences*, Vol. 114, No. 1, 2017, pp. 51–56. doi: 10.1073/pnas.1615140114
- [13] Rivlin, R. S., "Large Elastic Deformations of Isotropic Materials," *Philosophical Transactions of the Royal Society of London, Series A*, Vol. 240, 1948, pp. 459–490.
- [14] Holzapfel, G. A., "Nonlinear Solid Mechanics: A Continuum Approach for Engineering," John Wiley & Sons, Chichester, 2000.
- [15] ABAQUS/Standard User's Manual, Version 2020, Dassault Systèmes Simulia Corp., Providence, RI, USA, 2020.
- [16] N. Dwivedi, S. Shukla, P. Gupta, N. Sher, and D. Kumar, "Design and Fabrication of a Three Finger Soft Gripper," in *Recent Advances in Machines, Mechanisms, Materials and Design*, Lecture Notes in Mechanical Engineering, Springer Nature Singapore, 2024. doi: 10.1007/978-981-97-5423-6_30