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A Nonlinear Finite Element Analysis of a Tapered Soft Actuator for Improved Bending Performance in Soft Robotics

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Abstract: Compared to hard robots, soft robots, often referred to as nature-inspired robots, offer a safer approach to interact with delicate goods like agricultural and food products. This study suggests a novel soft actuator design that takes inspiration from a soft pneumatic actuator with a rectangular shape including a row of channels. The actuator is tapered to optimise its bending angle and decrease energy losses caused by its form. Due to their nonlinearities varying geometries, soft actuators are challenging to model, and the Finite Element Method should be used to deal with these problems. This research paper proposes a finite element analysis–based deformation model. In order to forecast the impact of boundary conditions and support the behaviour of large deformable materials utilised in soft robotic gripper applications. This paper presents a finite element analysis-based deformation model to predict the effect of boundary conditions and supports the behavior of large deformable materials used in soft robotic gripper applications. Future research in this field can be developed on the findings of this area.

Keywords: Soft Actuator, Soft Robot, Nonlinear, Finite Element Analysis, Bending Performance, Bending Angle, Adaptability.

1. Introduction

Soft actuators are considered as the essential building blocks for soft robots, Soft pneumatic actuators (SPA) are considered the most prominent and commonly used kind of soft actuator in the field of soft robotics [1]-[3]. These actuators operate through pneumatics to produce motion and are extensively used in research studies and practical applications. Soft pneumatic actuators are economical, possess an effective human-robot interface and a high power-to-weight ratio. The concept of human-robot collaboration in production environments has gained significant attention due to its ability to perform various flexible handling and assembly tasks. To achieve variant flexibility, robots are designed with standard hardware that is freely programmed for various procedures and products,[4]-[5]. Although mechanical grippers are frequently not very flexible, as they require specific contours to establish a precise and stable grip. To address this issue, the use of soft materials in grippers has emerged as a solution, allowing them to adapt to various surface shapes and sizes to a certain extent,[6]. This has improved the situation significantly. One of the primary concerns is the safety of the human operator in human-robot collaboration using grippers. Although various robot manufacturers have addressed these issues, mechanical grippers used in industrial applications are often rigid, making them a significant risk element for injury. Biological systems as inspiration, soft robotics research has developed soft grippers manufactured of soft materials just like Shape Memory Material (SMM),[7], Silicon Rubber and elastomers. Unlike traditional robotic grippers, In order to assure safe operation, they do not mainly rely on numerical control.

In recent years, there have been significant advancements in the design of soft actuators that are specifically tailored to grasp soft or delicate objects. The bending ability of soft actuators is recognized as a critical performance parameter. For instance, Polygerinos et al. utilized a soft actuator with incorporated channels functioning as pen-nets to generate bending movements that resemble the movement of a finger. [8]. Similarly, Mosadegh et al. established to increasing the chambers per unit length and reducing internal wall's thickness of the actuator can enable greater bending at lower input pressures. These findings highlight the importance of the bending ability of soft actuators and provide valuable insights for the development of advanced actuation mechanisms. This research paper aims to build upon these prior studies and further explore the impact of bending on the overall effectiveness of soft actuators [9]. Like, Hao et al. [10] presented an analytical approach for determining deflection of chamber walls in the plate mode. The analysis was based on two angles generated by inflating characterizing deflection of lateral walls and bending angle of bottom layer in a soft actuator under varied input pressure. Wang et al [11] presents the segment pneumatically actuated serial flexible robot, employing the hyper-elasticity theory of Yeoh and the serial robot Lagrange equations. This model focuses on the bending actuator of segmented pneumatic robots driven by an inflation chamber. and in another Wang et al,[12] analyze A novel approach for examining the bending angle of the Pneu Net soft actuator has been introduced, utilizing a method that analyzes the correlation between the pressure applied during inflation and the resulting bulging angle of the actuator's chamber. This methodology is rooted in the foundational principles of bottom-up modeling in the context of soft actuators. A common trait in these methods is its bending properties were obtained by considering the local deformation of one unit. Matheus et al,[13] This research paper introduces a novel method utilizing the concept of independent constraints. The method presents a methodical method for choosing pneumatic components, focused at getting soft actuators to respond to pressure changes in closed loop in the proper manner.

SPAs (Soft Pneumatic Actuators) use the air pressure to induce bending action and movement, and some variations employ shape-memory alloy [14], [15] or hydraulics [16] to drive the peripheral components. SPAs can be applied in a pneumatic network to generate movement and bending inspired by animals, such as a soft gripper that mimics human fingers and can play a digital keyboard [17]. The design of a soft actuator is inspired from a rectangular shape actuator. This unique tapered design is made of the substance silicone rubber M4601. The Silicone rubber M4601,[18] used in this study possesses a high degree of flexibility, allowing it to be stretched under the influence of applied air pressure. Silicone rubber M601 typically demonstrates isotropic behavior, which implies that their properties remain similar in all directions. Furthermore, it can undergo significant deformations that are beyond their initial dimensions. Therefore, the use of hyper elastic material models in FEM analysis is used for optimizing the performance of soft robotic devices,[19]. FEM is a highly effective analytical tool that is widely used for evaluating the stresses and bending behavior of soft actuators,[20]. Hyper elastic material models such as Yeoh and Neo-Hookean are utilized to simulate rubber-like materials,[13]. These materials are commonly found in soft pneumatic actuators (SPAs), which possess distinct advantages such as safe interaction with humans and machinery, as well as the ability to perform various tasks. This research focuses on unique design of actuators which is inspired from rectangular shape actuators. The Finite Element Method (FEM) is used to simulate soft pneumatic actuators, which involve the use of soft material Silicon rubber M4601. The research analyzes the bending behavior of hyper elastic material with the aim of developing a tapered multi-chambered soft pneumatic actuator. which results in a reduced input pressure requirement. The simulation was conducted by using Yeoh hyper elastic model under pressure 700Pa. With one end fixed and the other free to move in reaction to applied pressure, the soft actuator functions similarly to a cantilever beam.

2. Methodology

The CAD model is designed prior to a model is studied. When the CAD model has been created, Typically, parameterization is used to it, which entails determining and quantifying the different factors that influence its behavior. After the parameters have been determined and defined, the model proceeds through finite element modelling (FEM), which involves dividing the model into smaller components and using mathematical formulas to simulate these components' behavior under different conditions,[21]. The steps for developing and analyzing the model are set out in a workflow chart that is created to make the process easier. Typically, the process diagram shows phases like CAD model development, parameterization, material selection, and FEM.

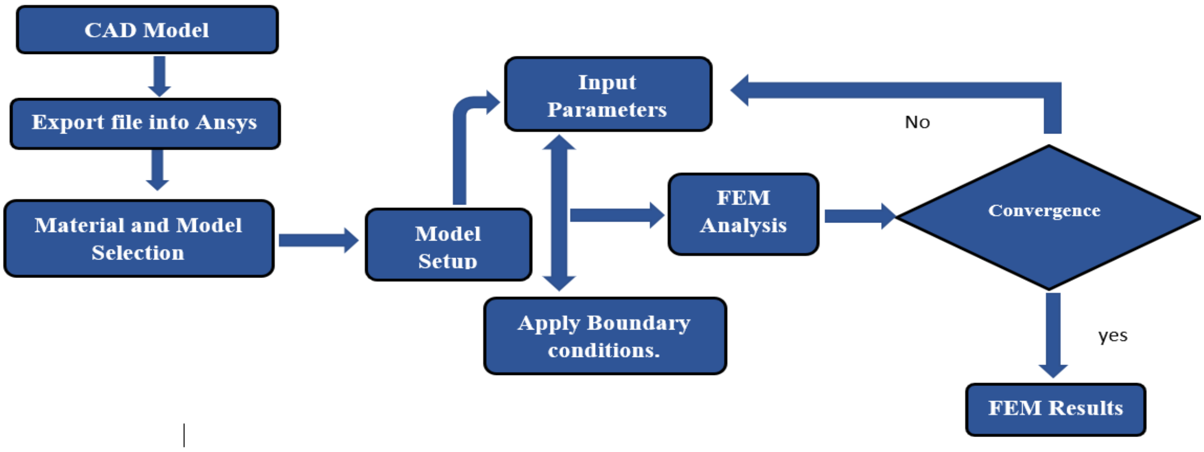


Figure 1. Methodology of Design of Tapered Shape Soft Actuator

3. Design of Tapered Shape Soft Actuator

Computer-Aided develop (CAD) software SolidWorks was used to develop and model the soft corrugated structure. By using the length of a human finger as a reference, the soft actuator's length was determined to be 85 mm. [22]. width, and height of the soft actuator are 26 mm, and 20 mm, respectively. In order optimize energy resources, The soft actuator features a rectangular shape that is tapered. The 11 chambers of the actuator are arranged in a tapered shape to increase the effectiveness of its motions. The CAD model provides a thorough visual representation of the design for more study and development. It precisely depicts the soft actuator's physical dimensions and properties. The soft corrugated structure has the potential to revolutionize the field of soft robotics and enable the creation of novel applications due to its advanced characteristics and distinctive visual appearance. In Figure:2 presents various views of the soft actuator, as follows:

Isometric View Shaded with Edges: This image shows the soft actuator in three dimensions, with the actuator's surface faded and its edges clearly visible. This perspective makes it possible to clearly grasp the actuator's fundamental design and structure.

Isometric View with Edges and Hidden Lines Shown: This view also reveals hidden lines that indicate the actuator's internal structure, like the first image. Understanding how the actuator's chambers are related to one another and how they are arranged is possible with the aid of this perspective.

Left View to Show Air Nozzles: The air nozzles that are used to inflate and deflate the actuator's chambers are observed in detail in this picture. The size of the holes as well as the position and form of the nozzles are visible in this image.

Front View of Tapered Shape Actuator: In this perspective, the actuator's front face is represented in two dimensions, emphasizing its tapering design. This illustration demonstrates how the actuator's base is wider and its top is narrower, which enables it to optimize energy resources.

Each of these perspectives provides important details regarding the layout and construction of the soft actuator and used to influence future research and development. These precise and accurate views, which support the comprehension and improvement of the soft actuator design, were made possible using advanced modelling tools, such as SolidWorks.

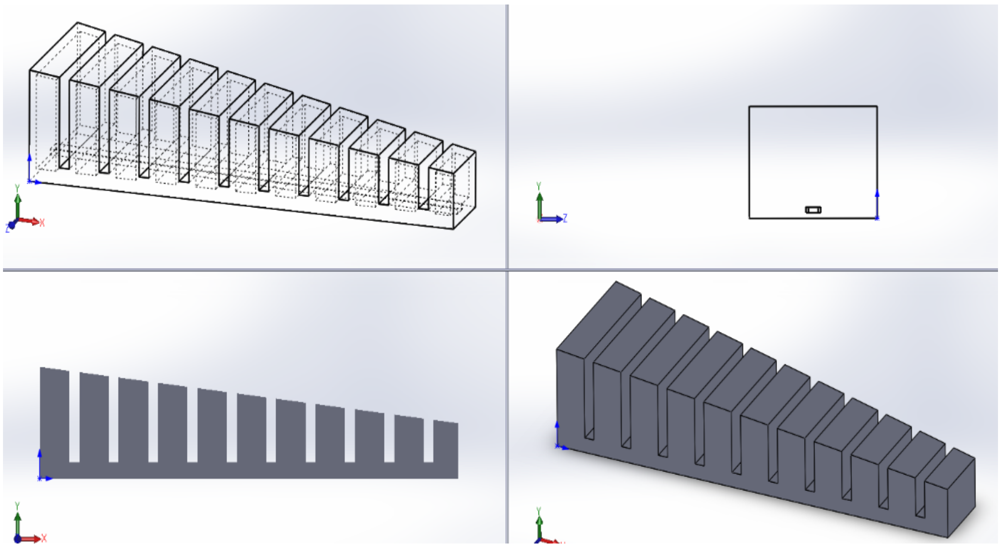


Figure 2. Different Views of Tapered- Shape Actuator

Table 1. The performance of the soft actuator is influenced significantly by the parameters mentioned below.

Parameters	**Explanation**	**Dimensions(mm)**
Length of soft actuator (L)	The distance between the soft actuator's two ends. This determines the extent to which the actuator can extend and contract.	85mm
Height of soft actuator (H1)	The maximum height of the non-tapered side of the actuator.	20mm
Height of soft actuator (H2)	The height of the tapered side of the actuator.	10mm
Width of soft actuator (W)	The width of the soft actuator, which determines the amount of force it can exert.	26 mm
Length of air pipe	The length of the pipe that supplies air to the actuator.	82mm
Width of air pipe	The diameter of the pipe that supplies air to the actuator.	3mm

4. Selection of Material

The choice of silicone rubber as the actuator material was based on several factors, including its low cost, ease of molding into numerous shapes, and desirable characteristics for the actuator. It is crucial to select a material with reasonable stiffness that provides sufficient bending angle and blocking force to carry out gripping tasks for soft robotic gripper applications. Furthermore, when choosing materials, the possibility of pneumatic passages bursting should be considered.

Various methods can be employed to evaluate soft materials' mechanical measurement. In a previous study, the elastomers Sylgard 184, Smooth-Sil 950, and Ecoflex 00-50 were measured [23]. The silicone rubber M4601 was employed as the test material in this investigation. However, the actual modulus of elasticity of the actuator differs from the specific modulus of elasticity of the material due to the composite development of the actuators with pneumatic networks inside. The actual modulus of elasticity, which was proposed and determined in [24] The actuator simulations included the use of numerical and experimental findings. The material rubber M4601 has a 386.66 kPa effective modulus of elasticity, and Table 2 lists some of its physical characteristics. it should be noted that the modulus of elasticity for hyper elastic materials is variable, and the actuator's movement is not linear.

Table 2. Properties of Elastosil M4601.

Shore Hardness	28A
Young's Modulus	35 psi
Tear Strength	18kN/m
Elongation	450%

5. Selection of Hyper elastic Material Model

Models of hyper elastic materials are used to describe the behavior of elastomers that can withstand large strains without permanent deformation or fracture. Only small stresses are modelled using linear elastic theory. The relationship of stress-strain of silicone rubbers is typically described as nonlinear elastic model, and incompressible [25]. The Neo-Hookean, Mooney-Rivlin, Ogden, and Yeoh models are the most popular for incompressible and elastic materials, respectively. One or more material properties that used to define these models are obtained from experimental stress-strain curves through curve fitting. Of With strain rates ranging from 400% to 100%, the Yeoh model is one of the most used hyper elastic models for large strain issues. [25,26]. It has been found to successfully determine stress-stretch behavior in numerous deformation modes based on data obtained from basic uniaxial testing. This makes it a useful tool for simulating how elastomers and other hyper elastic materials behave in intricate applications. In this study ElastosilM4601[27] materials while using the Yeoh model.

Yeoh Model

The mathematical representation of the Yeoh model is expressed by the strain energy density function, which is given below:

$$W = C_1(I_1 - 3) + C_2(I_2 - 3)^2 + C_3(I_3 - 3)^3$$

The Yeoh model incorporates materials, parameters, C1, C2, and C3, along with the invariants of the right Cauchy-Green deformation tensor, I1, I2, and I3. When developing actuators, the Yeoh model is an excellent choice for simulating the behaviour of silicone rubbers.

Table 3. Properties of Elastosil M4601.

Soft Material	Hyper elastic Model	Material Constants
Elastoli M4601[27]	Yeoh Model	C1=0.1MPa C2= 0.02Mpa

6. FEM Analysis

In this study, the behavior of a CAD model was predicted using the finite element technique software Ansys. The analysis was performed using the Static Structural analysis type, to analyze the behavior of Elastoli M4601, the material was subjected to various loads and boundary conditions. To model the material behavior, a hyper elastic material Yeoh model of 2nd order was employed, and the material constants are listed below in Table:1 [25]. The findings of this research have significant implications for the design and optimization of components made from Elastoli M4601. By accurately predicting the material behavior under different loading conditions, it is possible to design more efficient and reliable components, reducing the risk of failure and improving overall performance.

A quadratic order type element with a size of 0.3m was utilized to perform a nonlinear mechanical analysis. To improve the accuracy of the simulation results, proximity capture was enabled for faces and edge elements. The resulting mesh is depicted in Figure showing the details of the element distribution and the overall quality of the mesh. For this study, specific load and boundary conditions were applied to the pneumatic arm model. To ensure a stable system, a At one end of the arm, a fixed support was employed. Additionally, pressure of 700Pa was introduced into the channels on the inner walls of the arm to simulate the pneumatic pressure. To further simulate real-world conditions, standard earth gravity of 9.806

m/s2 was applied in the negative Y direction. These load and boundary conditions are crucial in accurately representing the system's behavior under various operating conditions.

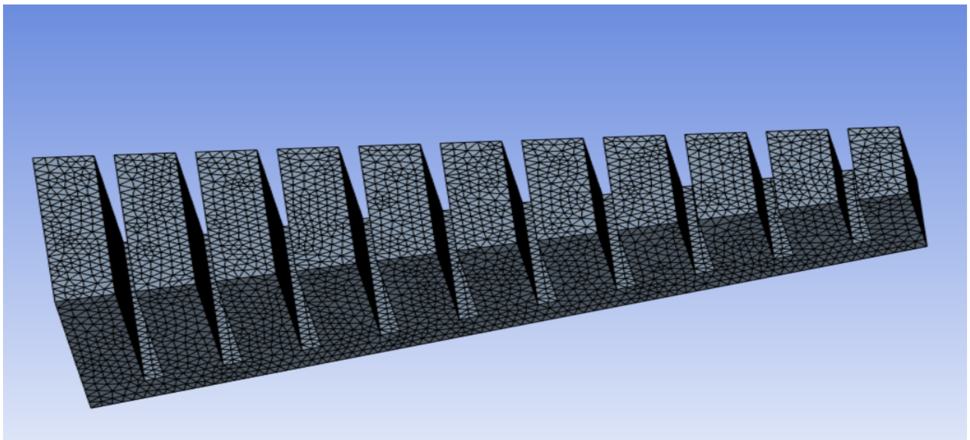
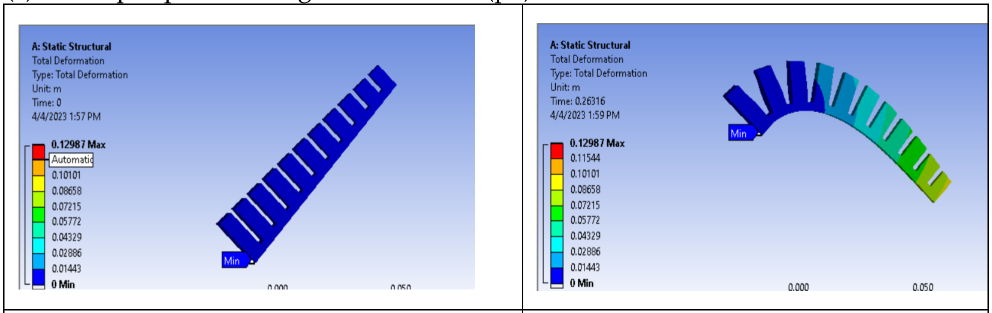


Figure 3. Meshing of Tapered Shape Actuator.

7. Results and Discussion

The aim of this study is to analyze the bending deformation and Stress generation of a tapered soft actuator when subjected to varying levels of input pressure. To evaluate the working principle and design of the developed actuator, simulation was carried out using FEM (Finite Element Method) based Software and to achieve a large bending angle in comparison to other rectangular shape soft actuators, while minimizing stresses on the actuator material. For any Simulation process model design is important we have design unique model of actuator by using solid works in Figure 2. For simulating non-linear behavior of actuator, ANSYS software is selected. To evaluate the bending characteristics of the soft actuators, tapered shape actuators were subjected to an actuating pressure of 700 Pa. The deformation of the soft actuator is highly dependent on the bending angle, which is directly influenced by the applied air pressure. A series of simulation images of the actuator were captured to visually represent its behavior, as depicted in Figure 4. Each image attached in Figure 4 shows total deformation in meters (m), where time is represented in seconds (s) and input pressure is given in Pascals(pa).



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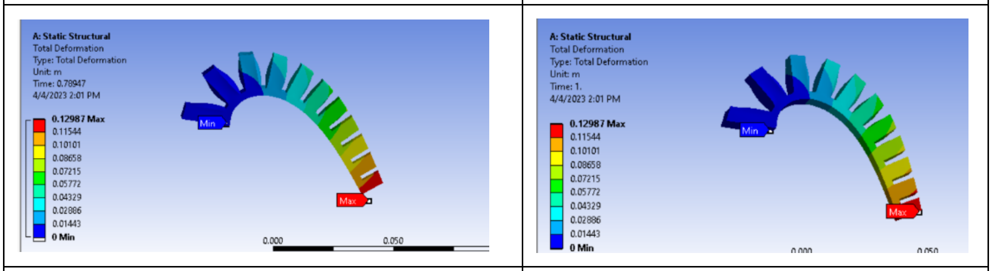

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Figure 4. Results of Tapered-Soft Actuator

These simulations provide valuable insights into the actuator's response to different input pressures. The soft actuator behaves similarly to a cantilever beam having one end fixed and the other end free to move in responses to pressure. This behavior is illustrated in the Figure4. The graph depicts the relationship between the applied pressure and the total deformation exhibited by the actuator in Fig 5, providing valuable insights into its behavior.

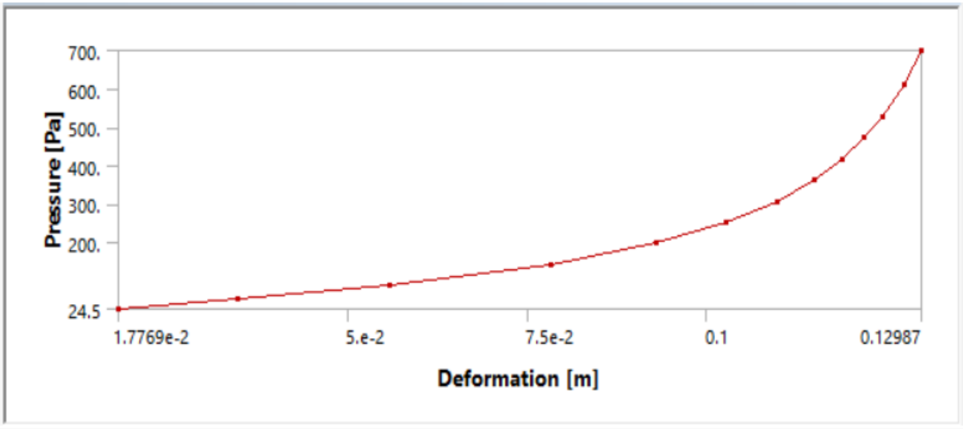

Figure 5. Relationship between Deformation and Pressure

In the Figure 6 graph observations indicate that angle of bending for the soft actuator displays a nearly linear relationship with applied pressure below 200Pa. However, when the pressure exceeds 200Pa, the adjacent channels come in contact and exert forces on one another, leading to a more complex interaction and a deviation from the linear relationship [10]. These findings shed light on the behavior of soft actuators under varying pressures.

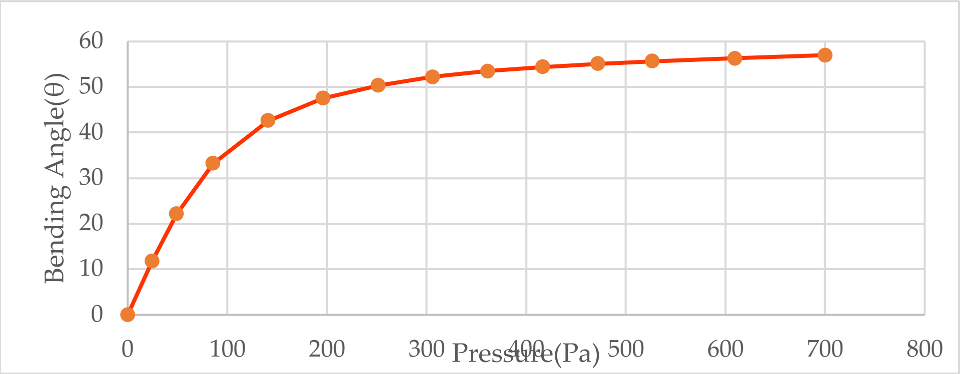

Figure 6. Relationship between Bending Angle and Pressure.

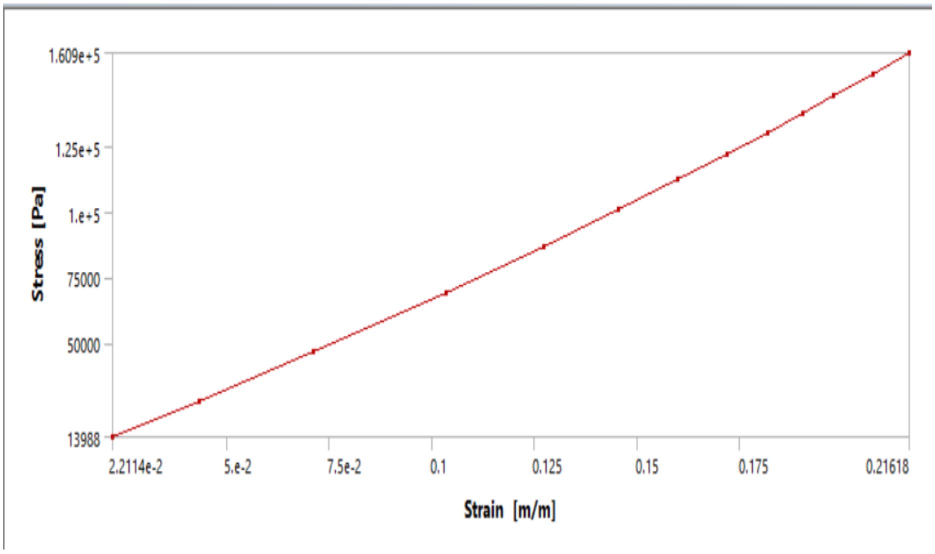

Figure 7: Relationship between Stress and Strain

Additionally, corresponding stress-strain relationships were analyzed and displayed in Figure 7. After analyzing the tapered shape actuator, the bending angles stresses generated by soft actuator Experimental results have shown that the tapered shape actuator requires a lower input pressure of 700 Pa, while achieving a high bending angle of approximately 56 degrees. These findings highlight the potential benefits of tapered shape actuators in a variety of applications, including soft grippers, soft gloves for rehibitions and crawling robots etc. Furthermore, this simulation and design is guideline for users to fabricate soft gripers which consume less energy and generates high bending angle.

Conflicts of Interest: Declare conflicts of interest or state "The authors declare no conflict of interest."

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