Evaluation of FDM-Printed Soft Pneumatic Actuators in TPU

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This work investigates the mechanical performance of soft pneumatic actuators fabricated using TPU 95A material via Fused Deposition Modeling (FDM) for industrial applications. The study focuses on the influence of wall thickness and infill density on the pressure resistance of the actuators. Nine pneumatic chambers with varying wall thicknesses (1 mm, 2 mm, and 3 mm) and infill densities (30%, 50%, and 100%) were tested under high-pressure conditions. The experimental results indicate that increasing the wall thickness generally enhances pressure resistance; however, lower infill densities (30%) surprisingly demonstrated the highest resistance. Computational simulations using the Finite Element Method (FEM) corroborated these findings, revealing that increased wall thickness significantly improves structural integrity. At the same time, the influence of higher infill density diminishes near the 100% threshold. These results provide valuable insights into optimizing FDM-printed pneumatic components for industrial use, contributing to the advancement of soft robotics.

Keywords: 3D Printing. Pneumatics. Actuators. FDM. TPU.

Soft robotics is a growing field focused on developing actuators, sensors, and technologies that deviate from traditional rigid structures. Its key advantages include high adaptability to complex environments, reduced manufacturing time and cost, and enhanced mechanical resilience [1][2]. Realizing soft robotics requires ongoing materials science research to identify flexible yet durable materials capable of executing mechanical functions effectively—especially actuators, which are crucial to the performance of soft robotic systems.

Soft robotic actuation is generally achieved through two main approaches: (i) the use of innovative materials such as electroactive polymers, shape memory alloys, magnetorheological elastomers, and electrorheological fluids; and (ii) fluidic actuation using hydraulic or pneumatic systems [3].

Pneumatic actuators, in particular, are widely adopted in robotics and automation due to their ability to deliver substantial power, cost-effectiveness, and versatile motion [4].

Nevertheless, achieving flexibility and extension with pneumatic systems can pose significant design and material challenges [5].

Soft pneumatic actuators are essential to mobile robotics and can operate in one, two, or three dimensions. One-dimensional actuators extend and expand, two-dimensional systems enable bending, and three-dimensional actuators can rotate or perform more complex motions [6].

Among various manufacturing methods, 3D printing—especially Fused Deposition Modeling (FDM)—has become a key technique in fabricating soft pneumatic actuators. FDM enables rapid prototyping and design customization, making it highly accessible for research and industrial applications [7]. This technique extrudes thermoplastic material layer by layer, allowing for precise control over parameters such as wall thickness, print speed, and infill density, significantly affecting the actuator's mechanical performance [8]. Additionally, FDM offers significant advantages in cost and design iteration, eliminating the need for specialized molds or tooling [9,10].

This study evaluates the mechanical performance of soft pneumatic actuators fabricated

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using FDM with TPU 95A material. The analysis focuses on the impact of wall thickness and infill density on the actuator's pressure resistance. By combining experimental testing and finite element simulations, this work aims to better understand the structural behavior of 3D-printed pneumatic components under pressure, offering design insights for future industrial applications [11].

Materials and Methods

Nine pneumatic chambers with the same external volume were designed and manufactured using TPU 95A material through FDM 3D printing. The primary printer configuration parameters are presented in Table 1. The chambers were categorized based on their wall thickness (1 mm, 2 mm, and 3 mm) and infill density (30%, 50%, and 100%). The chamber design, with dimensions in millimeters, is shown in Figure 1.

Each chamber was subjected to a gradually increasing internal pressure via a pneumatic valve until failure occurred, defined as the point at which air leakage was observed. The pressure at the moment of failure was recorded for analysis. A comparative assessment was conducted to evaluate the pressure resistance of each chamber configuration. Additionally, this study examined the relationship between wall thickness and infill density, aiming to identify optimal design parameters for maximizing structural integrity in soft pneumatic actuators.

The chamber was simulated considering an infill density of 100%. The models were developed using Finite Element Method (FEM) with a linear isotropic analysis approach imputing symmetry boundary conditions to save processing time. We can see only ¼ of the model in the analysis figures. The fixed boundary condition was applied at the top face of the nodal, while the pressure loading was applied at all the internal faces of the model. The analysis was done using Ansys Mechanical software. The TPU chosen has the following properties shown in Table 2. The internal pressure was gradually increased from 0 to 2MPa (20 bar), happening in 10s, and the failure time was observed, which was when the Von Mises tension got close to the Tensile Ultimate Strength.

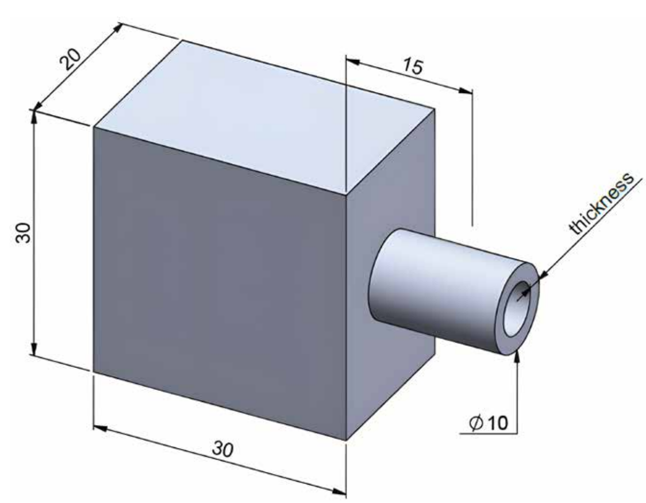
Table 1. Parameters used for print pneumatics chambers.

Parameters print	Values
Layer height	0.2 mm
Infill pattern	cross 3D
Retraction amount	4 mm
Retraction speed	40.0 mm/s
Print speed	30.0 mm/s
Wall thickness	1.2 mm

Table 2. TPU properties.

Properties	Values
Tensile Yield Strength	38.88MPa
Tensile Ultimate Strength	43.84MPa
Young's Module	1.6 GPa
Poisson's Ratio	0.4
Density	1.17 x 10-6 kg/mm³

Figure 1. Main dimensions.



Results and Discussion

Table 3 illustrates the pressure values that caused rupture in pneumatic chambers with varying thicknesses and filling percentages. Three different chamber thicknesses were tested: 1 mm, 2 mm, and 3 mm, under three filling percentages: 30%, 50%, and 100%. For the 1 mm thick chambers, rupture occurred consistently at 1.0 Bar for 30% and 100% filling, increasing to 1.1 at 50%. In contrast, the 2 mm thick chambers exhibited a higher rupture pressure, with values of 7.62 Bar, 6.97 Bar, and 7.25 Bar for 30%, 50%, and 100% filling, respectively. The 3 mm thick chambers showed the highest resistance to pressure, rupturing at 7.9 Bar for 30% filling, 7.81 Bar for 50% filling, and 7.2 Bar for 100% filling

The data suggest that increasing the wall thickness of pneumatic chambers enhances their ability to withstand higher pressures before rupturing, with variations in performance depending on the infill percentage. While this finding may appear intuitive, a surprising observation emerged: increasing the infill density does not necessarily correlate with higher pressure resistance. Chambers with lower infill levels (30%) demonstrated the highest resistance—particularly among those with 3 mm wall thickness—where the low infill significantly influenced rupture pressure. The mechanical behavior associated with infill density was further analyzed using computational simulations. As illustrated in Figure 2, simulations modeled chambers with a 100% infill density and corroborated the experimental observations. The results revealed that the maximum von Mises stress occurred near stress concentration regions, specifically at the corners and the interface between the infill and the chamber's outer wall. These stress distributions aligned well with the rupture points observed during physical testing.

Moreover, the simulations indicated that although a higher infill density generally improves pressure resistance, the benefit diminishes significantly at densities approaching 100%. This plateau effect suggests that additional material beyond a certain point offers marginal structural reinforcement, potentially due to limitations in interlayer adhesion or the inherent mechanical characteristics of TPU.

Figure 3 presents the von Mises equivalent stress as a function of applied pressure for chambers with wall thicknesses of 1 mm, 2 mm, and 3 mm. The red dashed line represents the Ultimate Tensile Strength (Sut) of TPU, fixed at 43.84 MPa, which marks the material's failure threshold.

For chambers with 1 mm wall thickness, the von Mises stress increases rapidly with pressure, reaching the ultimate tensile strength at approximately 0.2 MPa. Beyond this point, material failure is expected. This indicates that 1 mm chambers have the lowest pressure tolerance, consistent with their limited structural integrity. For 2 mm thick chambers, the von Mises stress increases gradually, reaching the ultimate tensile strength at approximately 0.65 MPa. This demonstrates improved pressure resistance, which is attributed to the enhanced support provided by thicker walls.

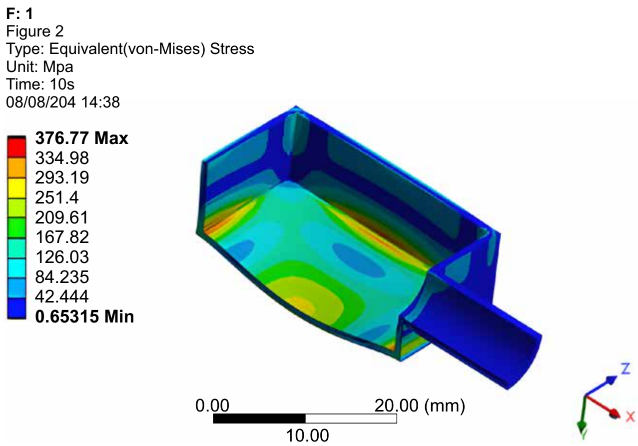
Chambers with 3 mm wall thickness displayed the highest resistance to internal pressure. Even at

Table 3. Pressure values that ruptured the pneumatic chambers.

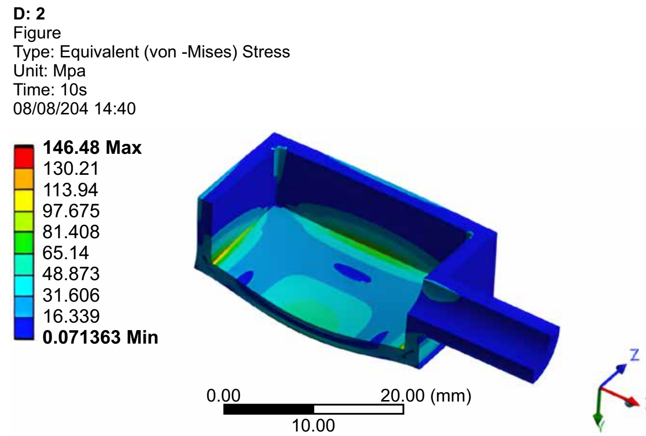
Filling (%)	Thickness 1 1 mm	Thickness 2 2 mm	Thickness 3 3 mm
30%	1.0 Bar	7.62 Bar	7.9 Bar
50%	1.1 Bar	6.97 Bar	7.81 Bar
100%	1.0 Bar	7.25 Bar	7.2 Bar

Figure 2. Distribution of Von-Misis stress at different thickness bodies.

a) *1 mm wall thickness body*



b) *2 mm wall thickness body*



c) *3 mm wall thickness body*

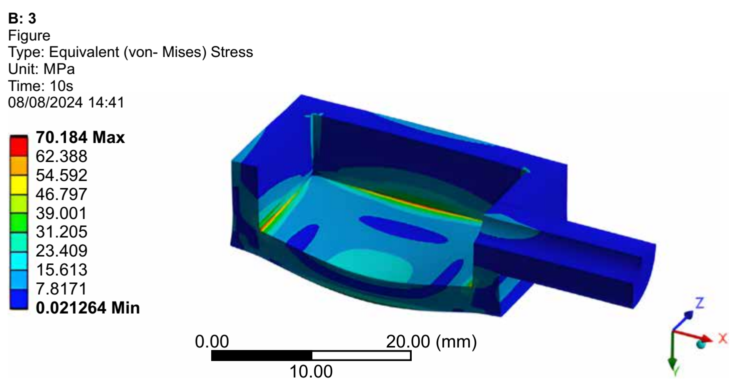
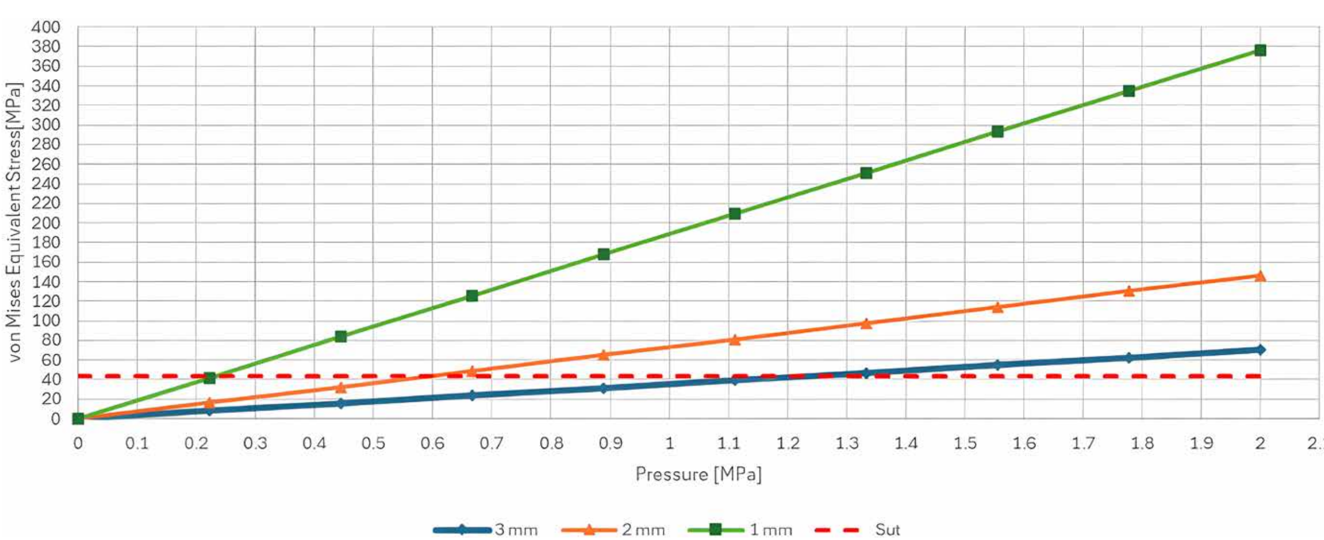


Figure 3. Simulated results of the pneumatic chambers rupture pressures.



1.3 MPa, the simulated von Mises stress remained below the ultimate tensile strength, indicating that no material failure would occur within the tested pressure range. These results underscore the superior structural integrity of thicker chambers. Comparing simulation and experimental data reveals reasonable consistency. For the 1 mm chambers, the experimental rupture pressure was approximately 1.0 bar (0.1 MPa), which aligns with the simulation prediction of failure at around 0.2 MPa. Minor discrepancies are likely due to material inconsistencies or real-world factors not fully represented in the model.

For 2 mm chambers, experimental rupture pressures ranged from 6.97 bar (0.697 MPa) to 7.62 bar (0.762 MPa), whereas the simulation predicted failure at 0.65 MPa. This suggests that the computational model may be conservative, slightly underestimating real-world performance.

For 3 mm chambers, experimental failure occurred between 7.2 bar (0.72 MPa) and 7.9 bar (0.79 MPa). However, simulations showed no failure even at 1.3 MPa, implying that these chambers could likely endure even greater pressures than those tested. The discrepancy highlights the simulation's conservative nature or possible model simplifications. The simulation results provided a reliable predictive framework, particularly for the 1 mm and 2 mm configurations. The 3 mm chambers exhibited higher real-world pressure resistance than predicted, emphasizing their potential for demanding industrial applications.

Conclusion

This study assessed the mechanical performance of soft pneumatic actuators manufactured via FDM using TPU 95A, with varying wall thicknesses and infill densities. Experimental results, supported by computational simulations, confirmed that wall thickness is a primary factor influencing the chambers' pressure resistance.

Thicker walls significantly enhance structural integrity, allowing for higher operating pressures. Among the samples, 1 mm thick chambers failed at the lowest pressures, while 2 mm and 3 mm chambers showed progressively greater resilience. Notably, 3 mm chambers withstood the highest pressures, showing no failure within the tested limits. Surprisingly, lower infill densities, especially 30%, resulted in greater pressure resistance. This counterintuitive finding underscores the importance of not assuming linear improvement with increased infill density.

The results suggest that increasing wall thickness is a practical design strategy for high-pressure applications, while optimizing infill density is equally crucial to balance material efficiency and structural performance. These insights are particularly relevant to designing and developing soft robotic actuators for industrial environments where durability and efficiency are essential.

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