MAE 263F Fall 2025 Midterm Report

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Abstract— **The goal of this project is to develop a Python-based discrete simulation to simulate FDM-printed TPU components for impact-resistant combat-robot armor and bridge theory of discrete elastic structures from MAE 263F with real-world combat robotics soft armor applications.**

I. Problem Statement & motivation

The main focus of this project is to model energy absorption and deformation behaviors of FDM (Fused Deposition Modeling) printed Thermoplastic Polyurethane (TPU) components within the context of combat robotics armor. The simulation model will build upon the theoretical foundations of discrete elastic structures in the MAE 263F – Discrete Simulation of Flexible Structures - course and extend it to soft robotics armor in real life. By analyzing the discrete modeling of TPU parts and how it deforms with various infill topologies, the end goal is to create a simple but insightful computational model that will aid in the design optimization process of weight and energy efficient combat robot armor as every ounce of weight counts in combat.

Fig. 1. ASME at UCLA FLAGSHIP 2023 15 lb Flywheel Flipper Combot (The blue material shown is made out of TPU).

II. Background & literature Review

Combat Robotics is a sport where individuals/teams of all skill levels build and compete robots to fight other robots in 3-5 minute matches. These remote controlled robots are fought in different weight classes from as small as plastic 150gram robots to 250lb Heavyweight chunks of metal. Most robots can be broken down into a main weapon and chassis system where weapons can range from flying discs to rotating hammers and different chassis designs protect the robot as a whole / provide the robot with wheeled or nonwheeled mobility. With strict weight restrictions at each weight class, it is imperative to strike a good balance in weight distribution for weapon energy output versus durability in self-robot protection. With impacts of thousands of Joules of energy in large impulse, short time frames within most matches, armor and energy absorption is critical when it comes to shock protection for electronic internals and other part failures.

TPU (Thermoplastic Polyurethane) comes into play, especially in lower weight classes <30lb robots as a great armor option in absorbing enemy impact hits while weighing much less than commonly rigid used metals such as aluminum and steel. As an elastomer with uniquely extreme flexibility, high elongation, superior abrasion resistance properties AND specific tunability (through infill, density, and wall thickness) in FDM printing, TPU is great for performance optimization under strict weight constraints, where every ounce of weight impacts the robot's survivability or could be alternatively put to weapon energy output. In the following literature, a good amount of research has been done already in terms of figuring out the mechanical properties behind FDM printed TPU but not much especially in the realm of shock absorbent combat robotics armor.

1. *The influence of printing parameters on the mechanical properties of 3D printed TPU-based elastomers - Bruère et al. (2023)*

In this paper, tensile and relaxation tests were conducted on variations of infill deposition angle and contour lines. IT was found alternating infill orientations had similar benefit to part integrity and the absence of outlines without out contour lines hindered tensile strength. The ultimate percent strain were all very high around the 1,000 range for majority of the samples and infill orientation was ambiguous in terms of relaxation time but deformation was for the most part large. 50% strain young modulus and maximum stresses were evaluated and all together provide good insight as a basis to printed TPU mechanical properties at 70A shore hardness.

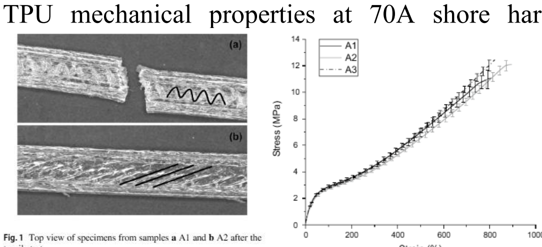
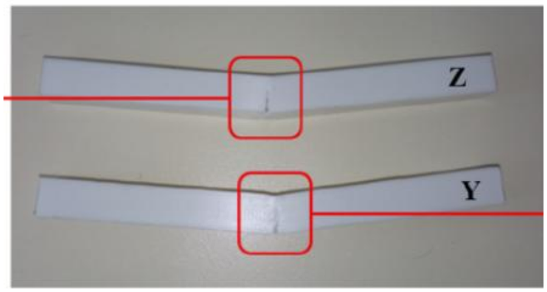


Fig. 1 Top view of specimens from samples **a** A1 and **b** A2 after the tensile test

2. *Effect of FDM infill patterns on mechanical properties - Birosz et al. (2022)*

In this paper 3 point bending tests were conducted on FDM printed samples with grid, Honeycomb, and gyroid infill. Print times and infill percentages were analyzed and found masses to be relative similar between different infill types and also that patterns did not have remarkable mechanical anisotropy despite the 2D infill structure. Crack propagation however was interesting in terms of layer orientation and how infill intersected with side or top walls. Although not 100% applicable specifically to more nonlinear and stretchier material like TPU, this paper gives good insight on the basis of 3D printing infill and bending stresses.



3. *Experimental Determination of Elastic and Rupture Properties of Printed Ninjaflex - Reppel T. et al. (2018)*

Uniaxial tension tests for young's modulus, maximum stretch, tensile strength, and fracture toughness are performed and resultant experimental results are applied to form Ogden's hyper elastic material model as well as a Neo-Kookena and Money Rivlin model. Fundamental relations from strain energy density are derived for said models and theoretical values are overlayed to that of the experiment results. Tests are conducted with one line to 4 line shells. This paper is phenomenal in setting up the foundations for TPU elastic model and surrounds specifically Ninjaflex TPU.

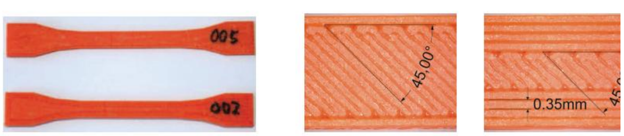
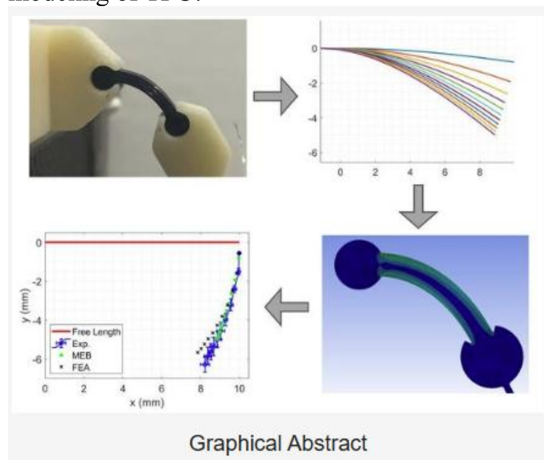


Figure 3: Specimens printed according to DIN EN ISO 527-2 with 58 mm distance between should (left). Closeup of specimen type 005 (middle) with one and type 002 (right) with four shell lines

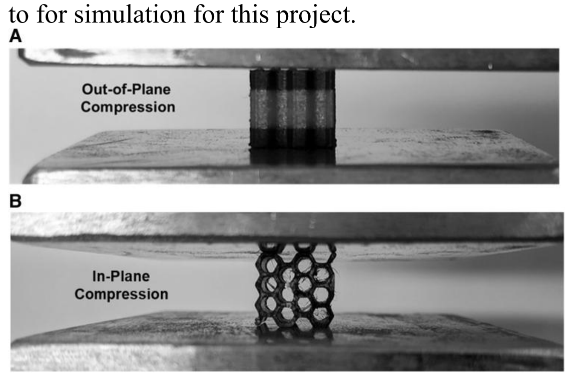
4. *Predicting the Bending of 3D Printed Hyperelastic Polymer Components - Gallup L. et al. (2023)*

This paper focuses also on NinjaFlex but in bending using various rectangular prints in loaded cantilever. The deflections are measured and the results are compared to a modified version of the Euler Bernoulli beam theory and in FEA which both pose to be relatively accurate. Due to the linear basis of the model derivation, deflection underestimation was seen but the paper gives a strong start to small to larger deformation modeling of TPU.



5. *Energy Absorption of 3D Printed ABS and TPU Multimaterial Honeycomb Structures - Khatri N. R. et al. (2024)*

Honeycomb, infill like structures were tested for in plane and out of plane compression for multiple energy absorption materials such as ABS and TPU and in combination. The tunability of wall thicknesses are emphasized here as TPU band thickness increases, energy absorption decreases. This paper directly relates energy absorption to material loading in both in plane and out of plane compression for both grid and hexagonal structures, which can be pivotal to compare to for simulation for this project.



III. Proposed Approach & Anticipated Contributions

The approach to this project can be broken down into 2 main stages for realistic implementation and insight output.

1. First a simple thin walled print with no infill will be simulated by modeling the wall as a beam fixed at its both ends and a point load of high impulse over a short time exerted on the wall. Here the nonlinear elastic properties from the articles above will be implemented and checked before moving onto the next step.
2. In this second part, simple internal infill patterns will be explored, beginning with grid and hex structures like those tested in the literature above. This would be done similar to a spring network where the cross

sectional in plane infill structure would be modeled to be the network.

Through this project, the deformation and energy dissipation of varying infills and TPU weights/ thicknesses can be simulated and visualized, in turn to both further theoretical principles of the model as well as provide more intuitive understanding of material behavior under impact conditions.

With the energy based foundational framework, weight and energy absorption tradeoffs can be identified and guidelines for design optimization specifically for geometric combat robotics armor printing can be an interesting output to this study.

IV. PRELIMINARY RESULTS & FINDINGS

The general approach to the project has been slightly altered in order to accurately simulate the non linear hyper elastic foundation of the TPU material and for the fact that the thin wall fixed beam ends was not intuitively able to be verified. Thus pivoting to simulate grid and hex structures first became the priority in order to match such simulations with specific similar real life tests.

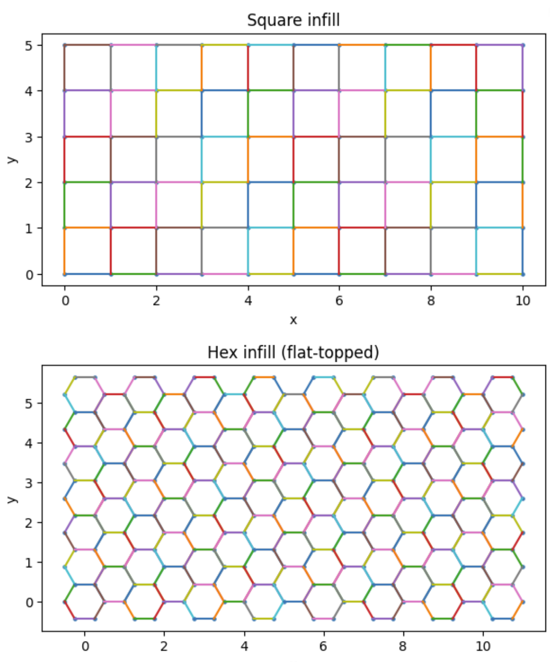


Fig. 2. Initial Grid and hex infill node and spring setup

Above shows the first step of the project setup process as material properties and layer thickness on the scale of 0.2mm and 2mm cells were used to replicate that in *Energy Absorption of 3D Printed ABS and TPU Multimaterial Honeycomb Structures - Khatri N. R. et al. (2024)* with the goal of replicating the deformation seen in their compression tests to verify non Hookean spring setup

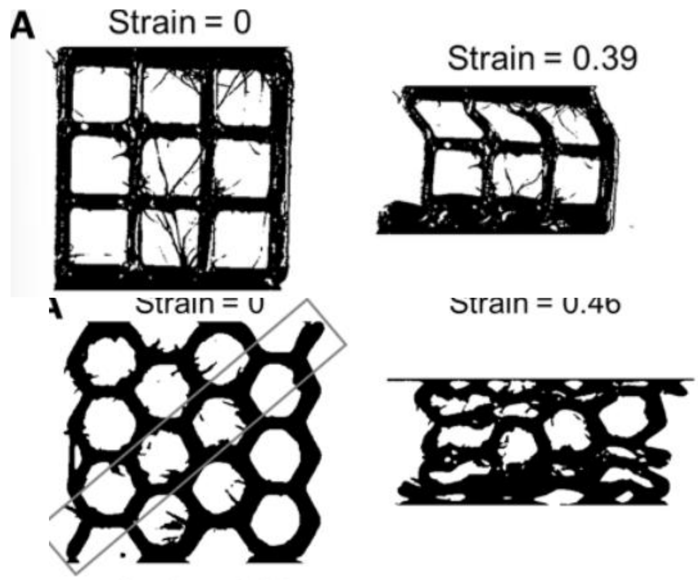


Fig. 3. In plane compression simulation hopes to replicate.

Above shows the article strains with increased node simulation setup below.

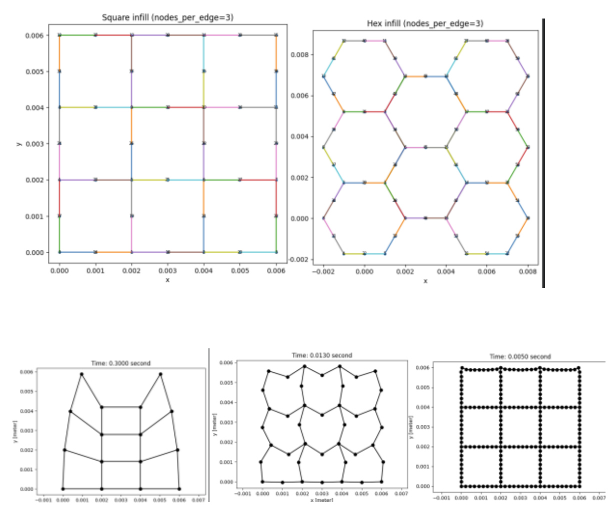


Fig. 4. Increased nodal setups for grid infill structure

Initial simulations with still Hookean springs showed the need for increased nodes. Furthermore, bending, curvature, and collision implementation was shown to be needed in order to crumple as the compression tests.

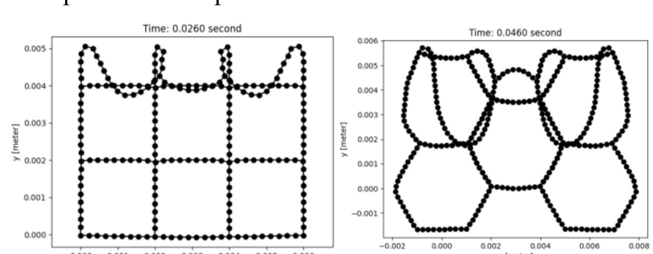


Fig. 5. Increased nodal setups with initial non Hookean springs and simple repulsion force collision…

V. NEXT STEPS & ANTICIPATED OUTCOMES

In finishing out this project, the nonlinear springs and collision fully flushed out are the final next steps. Very simple force repulsion is implemented currently but the repulsion forces must be tuned or other methods can be explored. Compression crumple has yet to fully resemble that of the example literature and the 3rd order mooney Rivlin stress strain bending curves must be accurately added. Furthermore it seems for the grid like structure to crumple as it does, imperfect initial conditions such as the imperfect layer lines causing buckling to a certain side must be added.

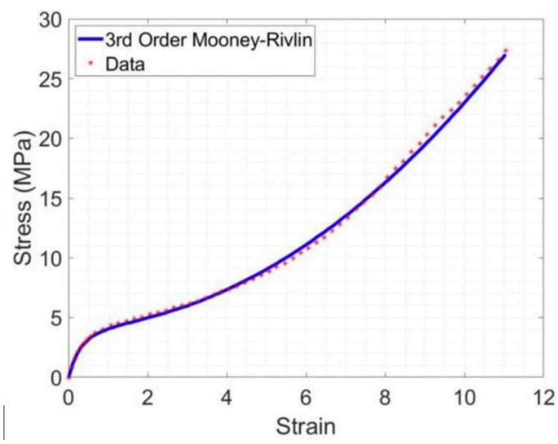


Fig. 6. Non linear stress strain curve from *Predicting the Bending of 3D Printed Hyperelastic Polymer Components - Gallup L. et al. (2023)*

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