MAE 263F Fall 2025 Final Report

Luke Chang 905954847

***Abstract*— Thermoplastic Polyurethane (TPU)'s uniquely large strain capabilities and hyper elastic behavior make the material a prime candidate in a wide range of impact-resistant applications. Specifically within Combat Robotics, fused deposition modeling (FDM) printing of such TPU armor is widely used to protect robots from high energy impacts and attacks during combat. The possibilities are endless with being able to tune TPU prints' infill geometry, layer lines, and wall thicknesses to control stiffness and energy absorption, however predictive modeling of such infill structures provides to be challenging due to the hyper elastic, nonlinear nature of the material. The work presented revolves around a reduced order discrete elastic simulation framework for modeling compressive loading of FDM printed TPU grid infill geometry. The model simulates in plane loading of the infill structure as a spring-network with the incorporation of nonlinear stretching energy, linear bending energy, numerical Rayleigh damping, and position based dynamics for robust output. Realistic deformation modes are developed and the behavior aligns with published experimental studies.**

I. INTRODUCTION

The 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.

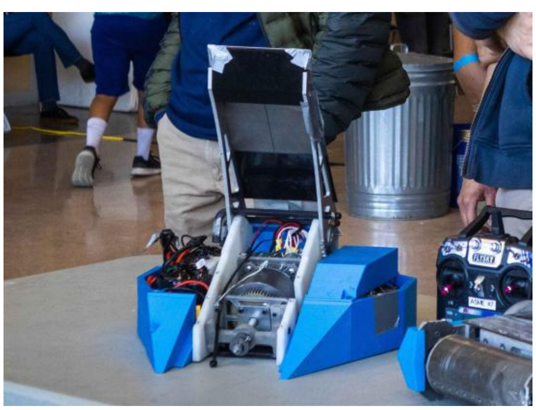


Figure 1. ASME at UCLA FLAGSHIP 2023 15 lb Flywheel Flipper Combot (FDM Printed TPU in blue).

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 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, sizable research has been conducted in terms of determining the mechanical properties behind FDM printed TPU but not much especially in the realm of shock absorbent combat robotics armor. TPU design for combat robotics armor is often largely guided by empirical testing compared to predictive modeling, so the development of non-computationally expensive and reduced order simulation to build design intuition and guide armor development is key.

II. LITERATURE REVIEW

Bruère et al. dove into the mechanical properties of 3D-printed TPU elastomers and revealed their strong dependence on strain magnitude and different printing parameters. Linear elastic models are concluded to be insufficient for capturing TPU behavior at large deformations [3]. Gallup et al. focus on the bending behavior of 3D-printed hyperelastic polymer components made from NinjaFlex TPU and gave way to experimentally validated nonlinear material modeling. Their work supplies the stress-strain data used to construct the nonlinear stretching energy in this simulation [5]. Birosz et al. examined FDM infill pattern effects on mechanical performance, demonstrating that geometry strongly influences stiffness and deformation modes. Although the study does not specifically look into elastomers such as TPU, the findings support the use of lattice-based modeling to study deformation mechanisms independent of material properties [2]. Wilińska et al. also characterized elastic properties of additively manufactured TPU through multijet fusion and not filament deposition modeling layering, emphasizing process-dependent variability in mechanical response. Although different in foundation, the paper provides further insight on limitations and also motivates the use of reduced-order exploratory models rather than attempting absolute quantitative prediction [10].

Khatri and Egan analyzed energy absorption in ABS and TPU grid/honeycomb structures as well as multi-material combinations under compression. Their observations and results of dominating bending collapse and dense crumpling behavior are qualitatively reproduced by the present simulation [7]. Zou et al.'s research revolve around dynamic crushing of honeycomb structures and identified progressive collapse mechanism modes governing the geometric instability. The findings here help inform interpretation of local buckling and energy absorption, albeit hex infill structures were not pursued in the end [11]. Farshbaf et al. analyzed large deformation and collapse of auxetic and hexagonal lattices using nonlinear numerical methods largely similar to the compression in Khatri and Egan's study. The infills explored here do not include the simple grid implemented but still lay the path for simulation formulation [4].

Mueller et al. introduces the concept of position-based dynamics (PBD) as robust way to simulate enforced constraints on the positional level instead of via force integration methods. PBD allows for stable large-deformation simulations, a key notion for robust contact/collision handling in the TPU infill model here [9]. Bender et al. comprehensively summarizes various position based simulation methods and shows the pros and cons for real time applications. Largely used in the graphics community, position based methods are not as accurate as forced based methods but are fast and controllable, a practical alternative to force-based methods when robustness is prioritized over egregious physical accuracy [1]. Macklin et al. present unified particle physics and show combined energy-based constraints and projection methods for stable simulation of deformable materials from gases to clothes. This work furthers the motivation behind the hybrid energy approach implemented in the present model [8].

III. Modeling Framework

To briefly overview the framework, a two dimensional discrete structure with nodes and connecting elastic elements serve as the foundation for the TPU infill model. Global vectors retain nodal positions and the system evolves with discrete energy minimization of inertia, damping and external forces. Overall an implicit backward Euler time integration scheme is used with Newton Raphson iteration to continuously solve the governing system of equations:

Equations of Motion: $\mathbf{M}\ddot{\mathbf{q}} + \mathbf{C}\dot{\mathbf{q}} + \nabla E(\mathbf{q}) = \mathbf{F}_{\text{ext}},$

Backward Euler: $\dot{\mathbf{q}}^{n+1} = \frac{\mathbf{q}^{n+1} - \mathbf{q}^{n}}{\Delta t},$

Residual: $\mathbf{f}(\mathbf{q}^{n+1}) = \mathbf{f}_{\text{inertia}} - \mathbf{f}_{\text{elastic}} - \mathbf{f}_{\text{damp}} - \mathbf{F}_{\text{ext}},$

Jacobian of the residual: $\mathbf{J} = \frac{\mathbf{M}}{\Delta t^2} - \mathbf{J}_{\text{elastic}} - \frac{\mathbf{C}}{\Delta t}.$

Hessian of elastic energy: $\mathbf{J}_{\text{elastic}} = \frac{\partial^2 E}{\partial \mathbf{q}^2} = \mathbf{H}_s + \mathbf{H}_b,$

where M is the lumped mass, C is viscous damping, $\mathbf{F}_{\text{ext}}$ are the applied loads, $\mathbf{H}_s$ is the stretching Hessian (tangent stiffness in nonlinear mode) and $\mathbf{H}_b$ analytically computed bending Hessian.

The energy basis of the model relies on nonlinear stretching and linear bending energy (although linear or nonlinear stretching energy can be toggled). The total elastic energy of stretching Energy and bending Energy is given as:

$$E(\mathbf{q}) = E_s(\mathbf{q}) + E_b(\mathbf{q}),$$

Where internal elastic forces come directly from the gradient of this energy: $\mathbf{f}_{\text{elastic}} = -\nabla E(\mathbf{q}).$

Linearly when not representing TPU strain stiffening, every edge is a Hookean axial spring with rest length l_0 under small strains and constant stiffness.

$$E_s^{\text{lin}} = \sum_e \frac{1}{2} \frac{EA}{l_0} (L - l_0)^2$$

The nonlinear basis to capture TPU elasticity utilized the experimental uniaxial tests from Gallup et al. (2023) in the final model.

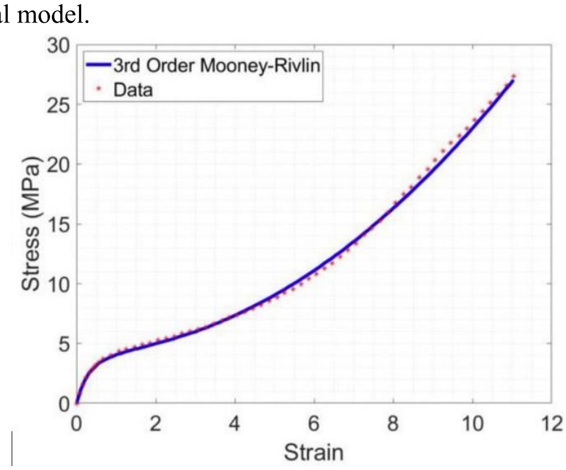


Figure 2. Non linear stress strain curve from *Predicting the Bending of 3D Printed Hyperelastic Polymer Components - Gallup L. et al. (2023)*

When toggled, nonlinear stretching energy is now computed with stress integration in respect to strain:

$$E_s^{\text{nl}} = \sum_e A\, l_0 \int_0^{\varepsilon} \sigma(\varepsilon')\, d\varepsilon'$$

Where axial force is $N = A\sigma$, $\sigma = \sigma(\varepsilon)$ is from experimental data, and the tangent modulus $E_t = \frac{d\sigma}{d\varepsilon}$ state dependent stiffness to approximate in place of a full geometric Hessian.

To enable buckling, bending within the model utilized discrete curvature penalty between edges given by:

$$E_b = \sum_k \frac{1}{2}\frac{EI}{l_k}(\kappa_k - \kappa_k^0)^2$$

Every connection node to node involves the calculation of stretching and the curvature amongst adjacent nodes. This is the basis of stretching and bending. Axial deformations along these connections or "springs", Hookean spring formulation for linear and experimentally fitted TPU stress strain interpolation for the nonlinear model.

As for damping and energy dissipation, the model utilizes velocity proportional Rayleigh damping:

$$\mathbf{f}_{\text{damp}} = -\mathbf{C}\dot{\mathbf{q}}^{n+1}.$$

Which is inherently numerical, stabilizing Newton convergence, suppresses additional energy additions from position based contact, as well as in the TPU case very roughly adds energy losses for TPU's material energy absorption.

IV. Simulation Setup

Initial simulations with Hookean spring network demonstrated the need of bending and collision implementations as non realistic compressions consistently developed as seen below.

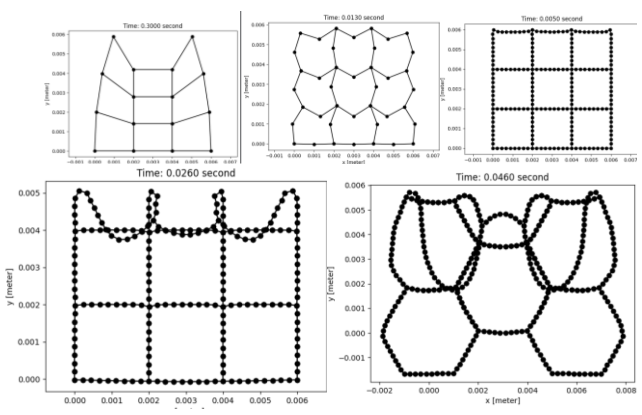


Figure 3. Hookean Spring Network Infill collision and buckling inaccuracies

Figure 4. Kathri and Egan [7] physical testing grid and hex samples.

The final simulation model currently creates a 3x3 grid cell infill with additional 2 nodes along each edge. Additional nodes can easily be changed as well as cell count and sizes. To establish a realistic precedent Khatri and Egan's physical tests where made a baseline to reference such that for the remainder of this paper, simulations shown are of 12.5mm x 12.5mm squares of 12mm deep. Top row of nodes are loaded initially and then released with the bottom row being fixed to simulate a top compressing force.

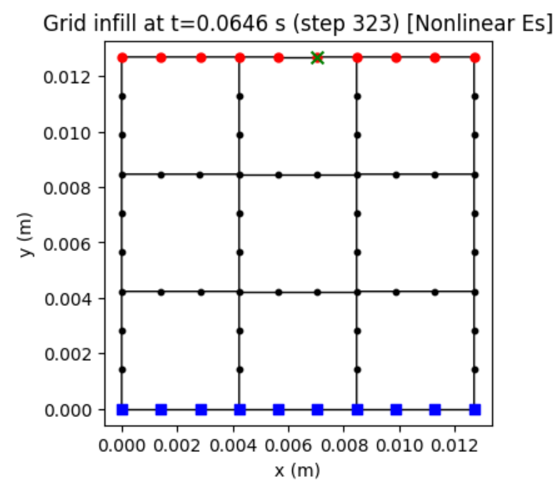
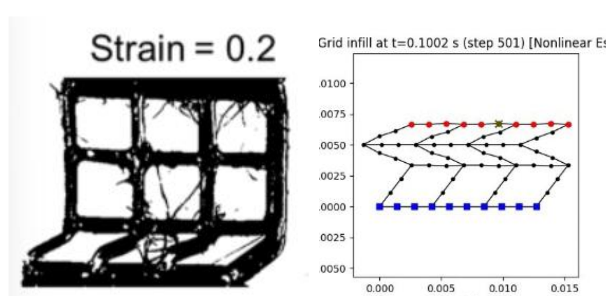


Figure 5. 12.5mm x12.5mm grid infill model

V. Results & Discussions

With Bending Energies incorporated, the discrete grid simulation finally buckles in an intuitive sense. From originally a pure spring network, pivoting to a hybrid combo of nonlinear stretching energy and linear bending energy, the grid like structure could finally hinge and collapse. Below shows how compared to the results of Kathri and Egan [7] the resemblance to approximately correct compression.



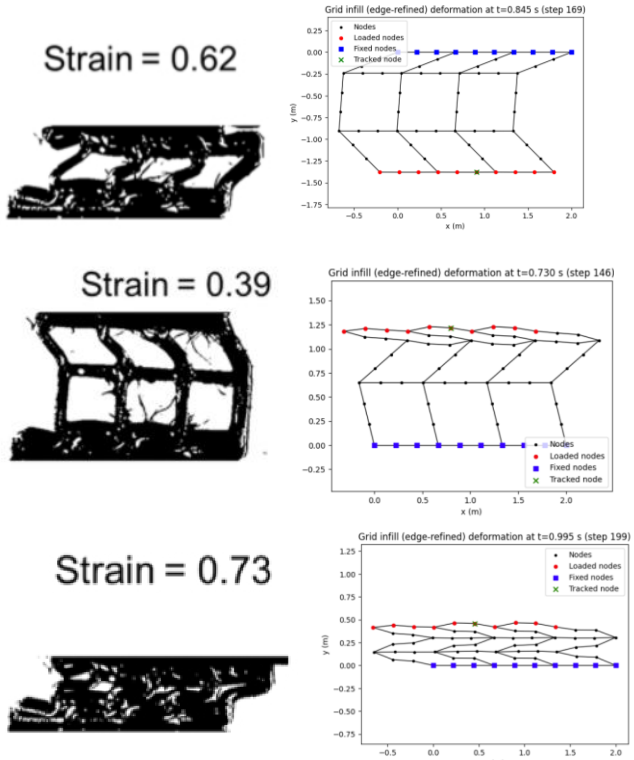
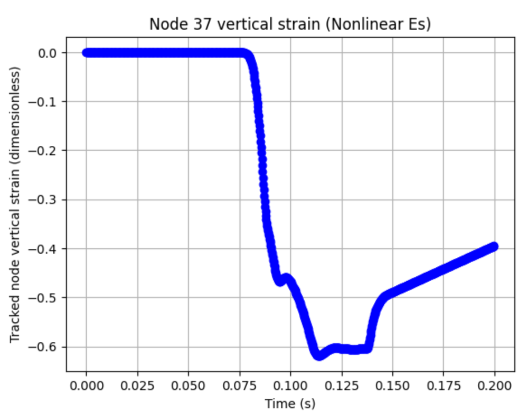


Figure 6. Visual comparison of structure compression (literature left[7], simulation right)

Looking at the vertical strain with time in Figure 7, the top row is initially loaded until a relative stable strain is reached. We see the critical buckling load occur after some time in the middle, however we also must note these are short time wise still <1s of loading. The 2 ridges where strain slightly bumps show the rows collapsing onto the next, where damping isn't perfect and collisions between close nodes. And finally when load is released at around .14s, we do see the structure start to return to its original shape.



.

Figure 7. Top Row Vertical Strain with time (Loading Removed at t = 0.138s)

Within the energy plot in the next figure, we can see how the bending energies dominate most of the total green energy, nearly twice the energy that of stretching which makes sense as the main deformation mode consist of the rows collapsing and hinging.

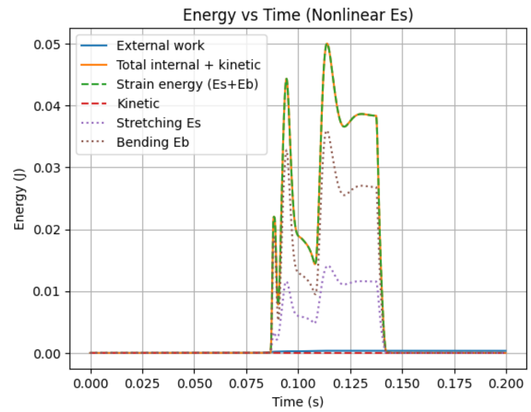


Figure 8. Energy changes with time (Middle Dotted – Eb, Lower Dotted - Es)

What's curious however is what is seen in comparison between nonlinear and linear stretching simulations, where we should see more divergence hypothetically. This could be due to purely the fact that force loading is applied rather than displacement based. Less divergence than anticipated more so could be due to most of the vertical strain coming from bending and the collapse of the structure rather than node to node axial stretching.

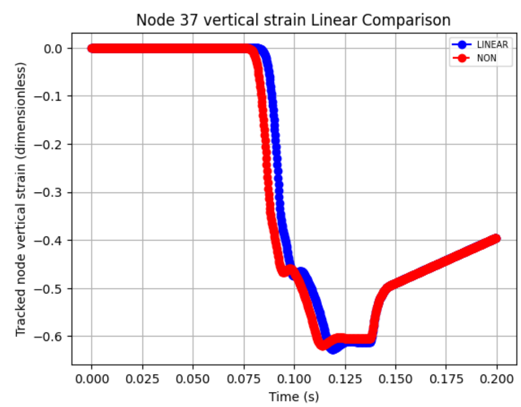


Figure 9. Top Row Vertical Strain with time (Red – Nonlinear, Blue - Linear)

What we do see though through the energy plots is the increase in stretching energies overall between nonlinear and linear simulations. While bending energies stay the same, an increase in stretching energies in the nonlinear model is observed.

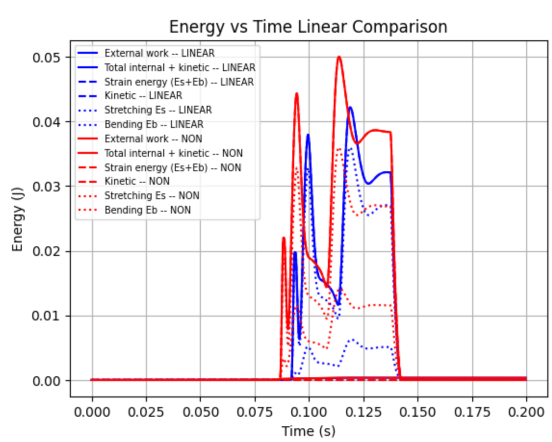


Figure 10. Energy changes with time (Red – Nonlinear, Blue - Linear)

VI. Limitations & Future work

Currently the present model subsists as more of a qualitative design exploration tool than a fleshed out quantitative physical prediction solver, especially with tradeoffs of implementation resources and output efficiency. Simulation wide numerical damping is currently implemented rather than more physically realistic viscoelastic damping such as Kelvin Voigt Models. Position based constraints in contact add to this realm of energy realism where forced based collisions would provide more accuracy. Hexagonal infill as well as out of plane deformations should be explored due to the higher benefits to energy absorption and as previously mentioned, displacement controlled loading could be added to better analyze linear vs nonlinear stretching implementation as well as for measuring reaction forces. All in all however, these suggestions can be directly added to the current model or rebuilt but caution must be taken if desire to maintain the current agile simulation with reduced complexities.

VII. Conclusions

A reduced order discrete elastic simulation of FDM printed TPU grid infill structure for energy absorption is presented in this work. Combining a hybrid energy framework and robust position based collision contact foundation, deformations consistent with experimental observations are reproduced in a computationally efficient matter. The simulator serves as the groundwork as a practical and intuitive tool and foundation for exploring future infill design choices for impact resistant TPU within the combat robotics world and beyond.

References

[1] Bender, J., Müller, M., Otaduy, M. A., Teschner, M., & Macklin, M. (2013). A survey on position-based simulation methods in computer graphics. Computer Graphics Forum, 33(6), 228–251.

[2] Birosz, M. T., Ledenyák, D., & Andó, M. (2022). Effect of FDM infill patterns on mechanical properties. Polymer Testing, 113, 107654.

[3] Bruère, V. M., Lion, A., Holtmannspötter, J., & Johlitz, M. (2023). The influence of printing parameters on the mechanical properties of 3D printed TPU-based elastomers. Progress in Additive Manufacturing, 8, 693–701.

[4] Farshbaf, S., Dialami, N., & Cervera, M. (2025). Large deformation and collapse analysis of re-entrant auxetic and hexagonal honeycomb lattice structures subjected to tension and compression. arXiv preprint arXiv:2503.18736.

[5] Gallup, L., Trabia, M., O'Toole, B., & Fahmy, Y. (2023). Predicting the bending of 3D printed hyperelastic polymer components. Polymers, 15(2), 368.

[6] Jawed, M. K. (2025). Colab notebook, MAE 263F: Mechanics of Flexible Structures and Soft Robots. University of California, Los Angeles.

[7] Khatri, N. R., & Egan, P. F. (2024). Energy absorption of 3D printed ABS and TPU multimaterial honeycomb structures. 3D Printing and Additive Manufacturing, 11(2), e840–e850.

[8] Macklin, M., Müller, M., Chentanez, N., & Kim, T.-Y. (2014). Unified particle physics for real-time applications. ACM Transactions on Graphics, 33(4), 1–12.

[9] Müller, M., Heidelberger, B., Hennix, M., & Ratcliff, J. (2007). Position based dynamics. Journal of Visual Communication and Image Representation, 18(2), 109–118.

[10] Wilińska, K., Kozuń, M., & Pezowicz, C. (2025). Elastic properties of thermoplastic polyurethane fabricated using Multi Jet Fusion additive technology. Polymers, 17(10), 1363.

[11] Zou, Z., Reid, S. R., Tan, P. J., Li, S., & Harrigan, J. J. (2009). Dynamic crushing of honeycombs and features of shock fronts. International Journal of Impact Engineering, 36(1), 165–176.