

Investigating Polygon Patterned Cylindrical Crush Tubes for Crashworthiness

ME REU

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Executive Summary

Cylindrical crush tubes with hexagonal cutouts were explored for application in aircraft crash mitigation. Adding twist coupling in the structure proved to increase the crush tube's performance relative to a control hex tube in simulations through a 10% increase in crushing force efficiency and a more predictable crush. However, it is noted that increasing angular distortion decreases energy absorption, due to earlier onset of densification. The effect of alternating twist design was also explored. The alternating angle design proved to be more effective than the non-alternating design in the case that the impactor was not given the freedom to rotate. This highlights the practicality and convenience of the alternating angle design, as the impactor may just be a solid block rather than a rotating structure.

Background

Electric vertical takeoff and landing vehicles (eVTOL) transportation has become an attractive possibility for the future of commercial. However, safety features are mandatory for these eVTOL vehicles to become commercially available. Past research by NASA on eVTOL crashworthiness has suggested that seat-level crashworthiness mechanisms, such as the use of energy absorbing tubes, are among the most effective ways to increase crash survivability [1]. Crushable columns are the simplest and most reliable energy absorbers, being the choice in VTOL vehicles such as the Bell 222 [2].



Fig. 1: Future eVTOL vehicle concepts

The effectiveness of a crushable column in crash mitigation can be described as its **crashworthiness**, which combines two fundamental metrics of success. Specific energy absorption (SEA) describes how much energy the tube can absorb per unit mass. Crushing force efficiency (CFE) is the ratio between the average load and the peak load. Optimal crash mitigating structures have both high SEA and CFE [3].

Hexagonal patterned materials made using additive manufacturing has shown to have high levels of crashworthiness, displaying high SEA as well as high CFE. We aim to explore implementing this pattern into a condensed cylindrical crush tube, as well as implement a unique twist coupling design to further enhance crashworthiness.

Experimental Setup

Constraints on the crush tube were imposed to minimize the design space, allowing for easier analysis and later implementation of machine learning. An initial sensitivity study was conducted to identify the design parameters that had the greatest effect on the energy absorption characteristics of the crush tube.

Parametric modelling of the crush tube was performed in SolidWorks, with the model reaching 13 degrees of freedom. Following a sensitivity study conducted through simulations, the distortion of hexagonal cutouts via linear transformation was selected for further investigation, as illustrated in Fig. 2. Fig. 3 shows the specific samples and configurations used to be tested.

Table 1: Parameter Constraints

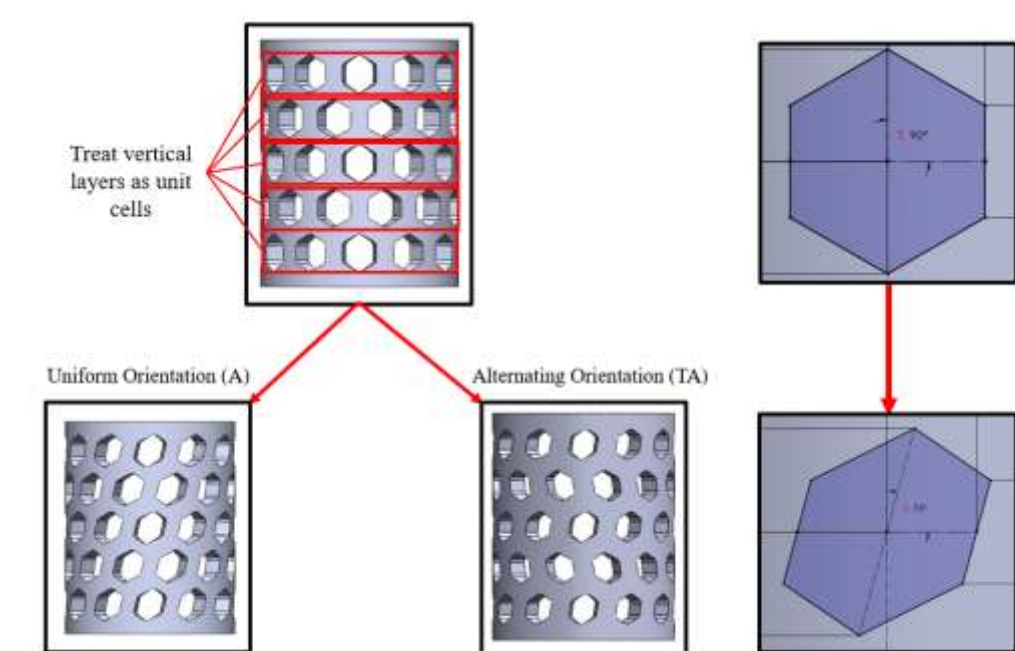


Fig. 3: Twist-Design Formulation

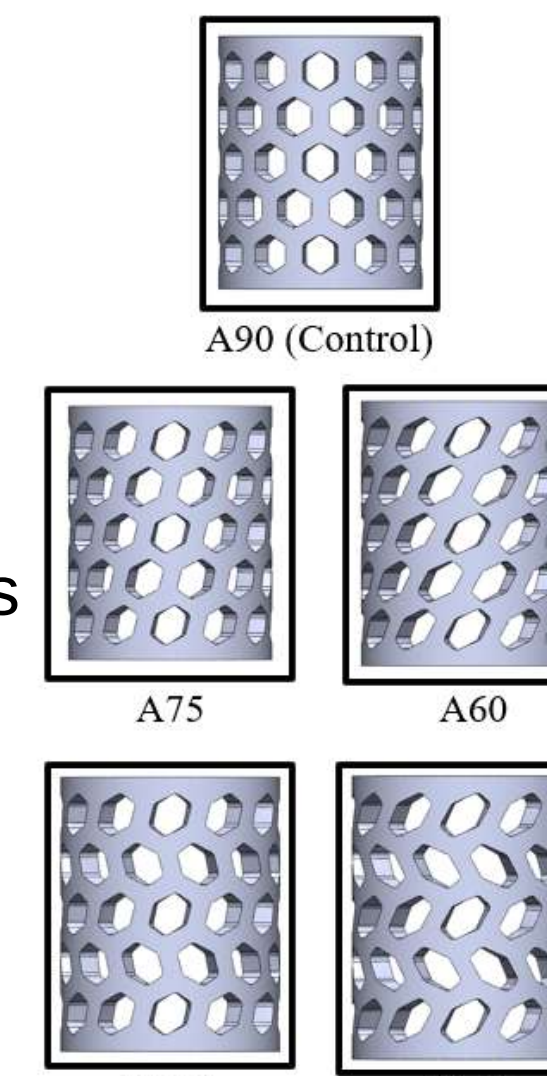


Fig. 2: Samples

Most twist couple structures rely on the impactor's ability to rotate. Though feasible in a laboratory setting, this may be difficult to implement in a seat. For this reason, situations where the impactor was free to rotate vs fixed were both simulated.

Experimental Test Plan

Hexagonal pattern qualities with promising uniaxial energy absorption behavior were identified through literature review. Composite materials were incorporated to expand design flexibility, and promising candidates were modeled in SolidWorks and simulated in ABAQUS.

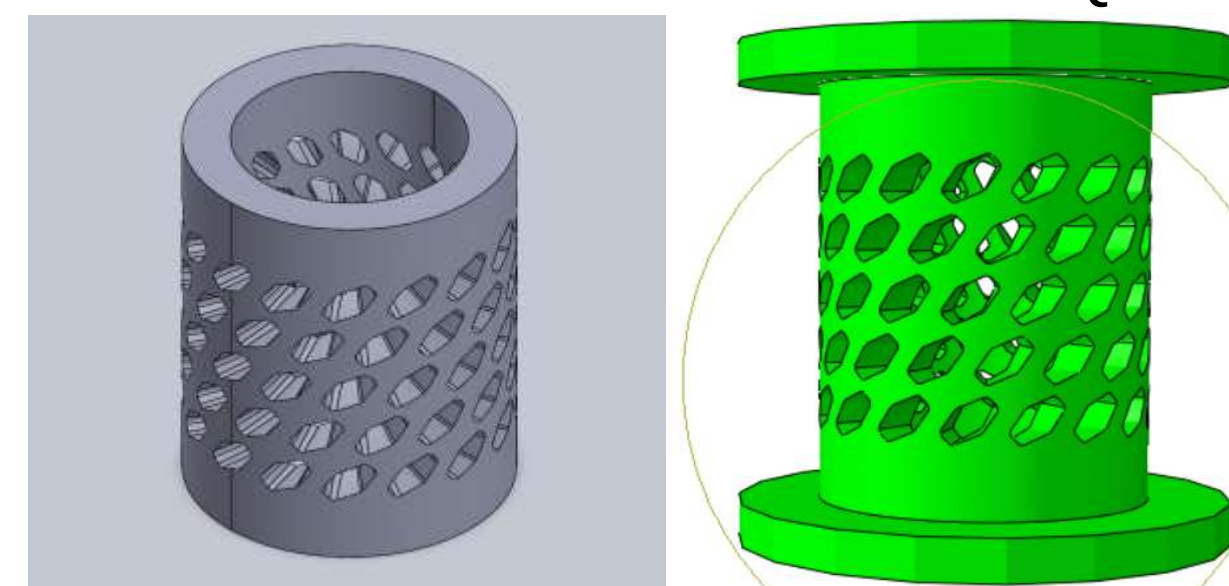


Fig. 4-5: SolidWorks & ABAQUS Workflow.



Fig. 6: 8-ft Drop Tower.

The hexagonal crush were parametrically modeled in SolidWorks to enable design variation. For ABAQUS dynamic simulations, tubes were compressed between rigid plates with and without top-plate rotation to quantify twist coupling. Initial simulations used elastic-plastic properties of ABS. Force-displacement and twist rate data from promising cases were extracted via history outputs.

Promising designs were 3D printed using a J35 multi material printer or Mark Forged printer. Material characterization was done to determine the ductile properties of materials for physical testing and simulations. Testing was conducted using a 8-ft drop tower. Impact energy was characterized by the gravitational potential of the drop mass. A piezoelectric sensor measured impact force, and high-speed cameras with lighting captured footage for postprocessing and force-displacement analysis.

Experimental Results

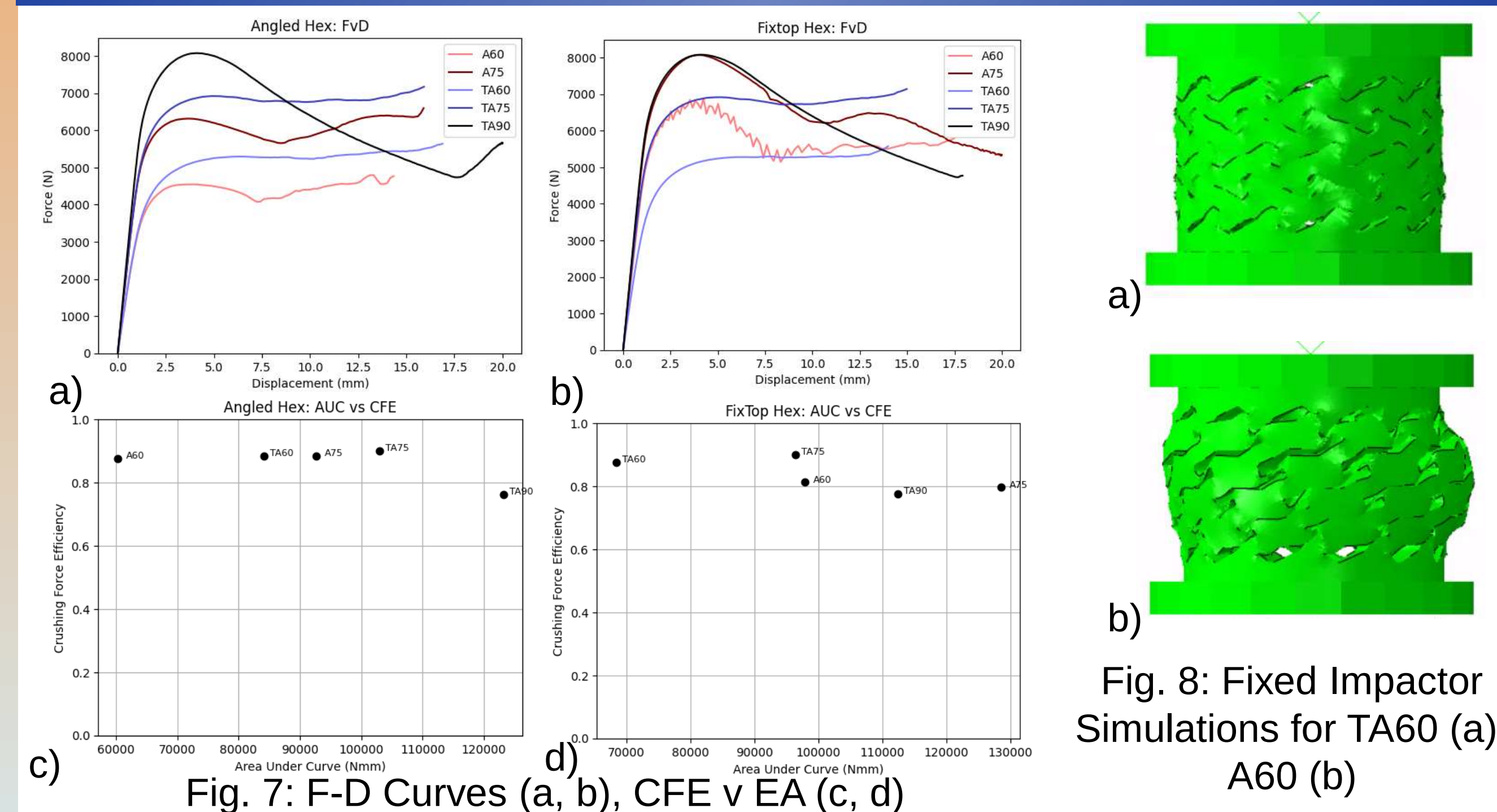


Fig. 7: F-D Curves (a, b), CFE v EA (c, d)

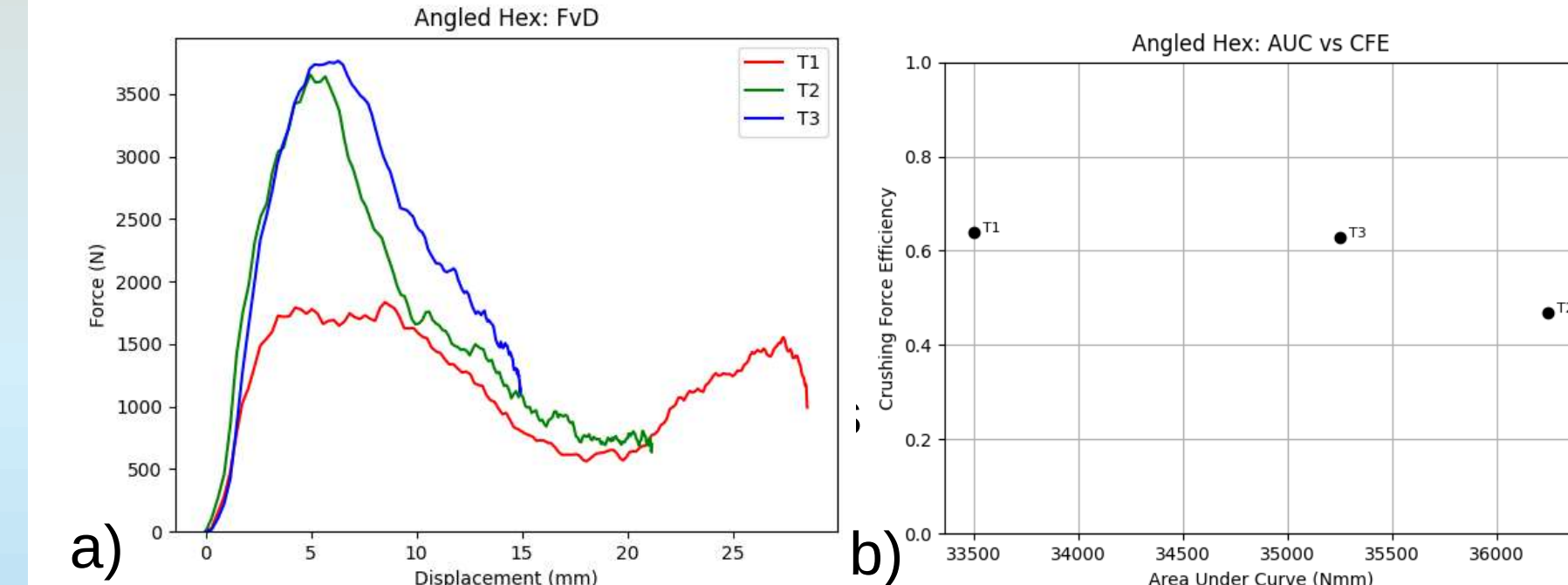


Fig. 9: Experimental F-D Curves (a), CFE v EA (b)

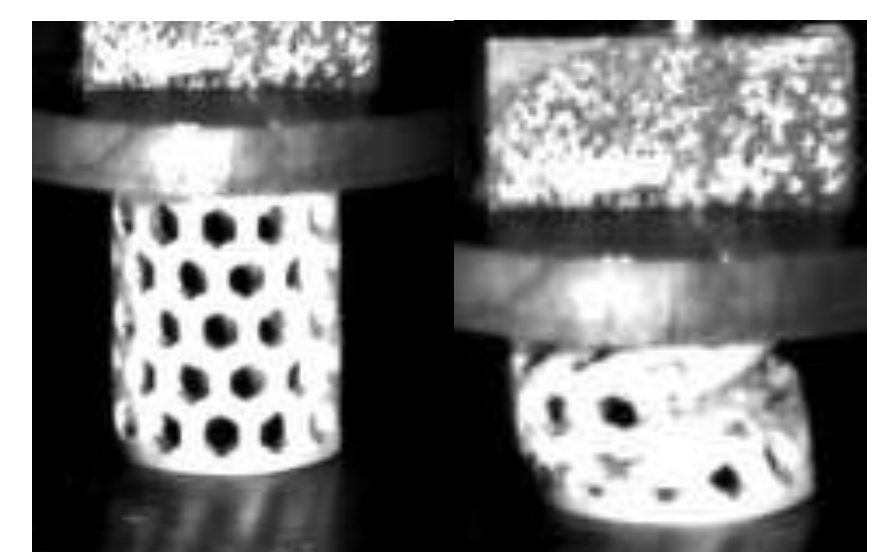


Fig. 10: Drop Tower Test

Conclusions

As shown in Fig. 7 c–d, fixing the top plate increased energy absorption for all non-alternating angle designs at the cost of lower CFE's and less predictable crush patterns. This highlights an alternating twist pattern advantage over non-alternating, as alternating pattern does not require the impactor's freedom to rotate. Introducing greater twisting distortion does increase CFE, but this comes at the cost of EA, due to an earlier onset of densification.

To optimize the hexagonal tube design, a parameter sensitivity study is underway. Machine learning automates .stp file generation, while an ABAQUS simulation pipeline is being developed that automatically simulates each file and extracts force-displacement and twist rate data.

After completing the parameter sensitivity study, optimized designs will be 3D printed and impact tested. Eventually, said designs will be implemented into a custom-made set base for final testing along with vibration mitigating materials.

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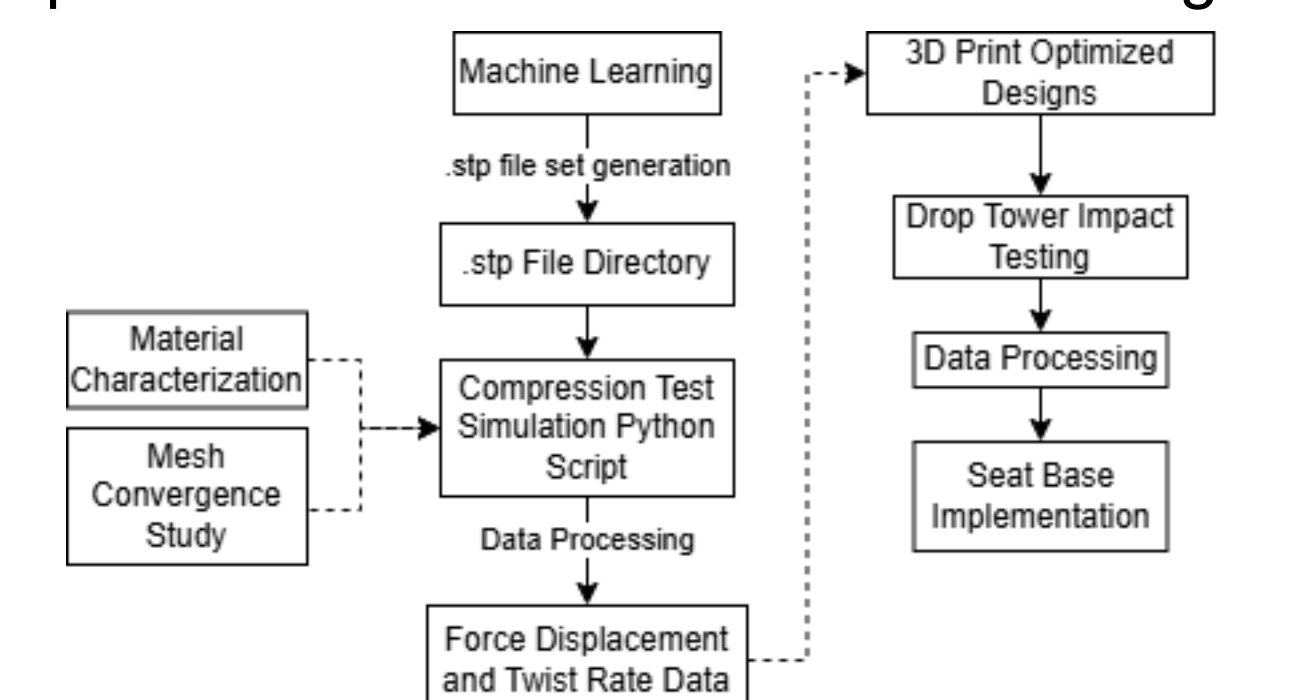


Fig. 11: Simulation and Physical Workflow.

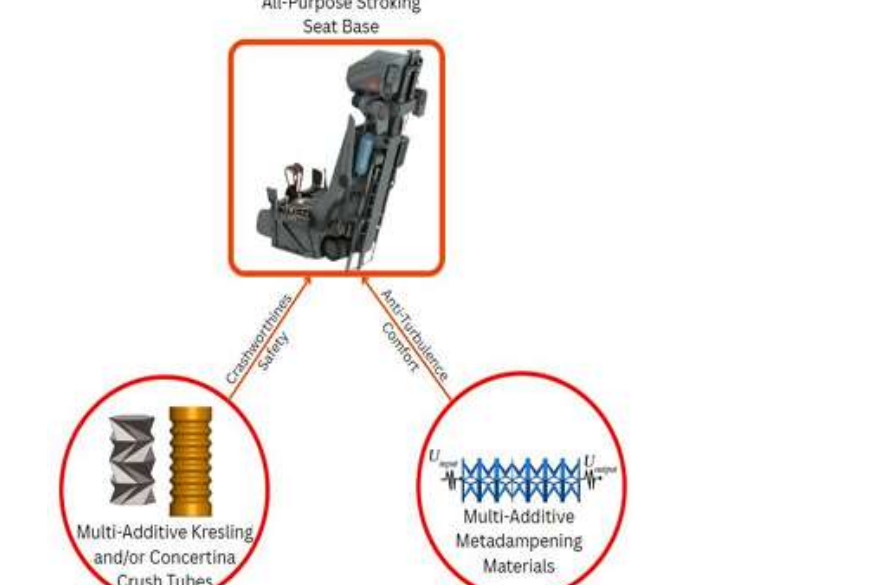


Fig. 12: All Purpose Seat Base.

References

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