Compressive Behavior of Cuttlebone-Inspired Design: A Computational study for Structural Scaling

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Introduction

The demand for advanced materials that combine low weight with high mechanical strength drives innovation in aerospace, automotive, and protective technologies. Traditional materials often require trade-offs between weight reduction and structural integrity, limiting their effectiveness in high compressive load environments. Nature, however, offers elegant solutions to these challenges- one of the most notable being the cuttlebone, a marine structure renowned for its unique combination of lightness, strength, and damage tolerance. Cuttlebone achieves this performance through a sophisticated microarchitecture of chambered, wavy walls that efficiently distribute loads and absorb energy. Inspired by these natural design principles, this study explores the development and optimization of polymer structures mimicking cuttlefish architecture. Using advanced computational modelling with ANSYS finite element analysis, we systematically scaled cuttlebone-inspired microstructures to assess how dimensional changes affect mechanical performance. By bridging biomimetic design with simulation, this research establishes scalable frameworks for next-generation materials that can outperform conventional load-bearing structures.

Methodology

Design: The cuttlebone microstructure of 100 μm scale was geometrically scaled into 5mm, 15mm, and 25mm, and the sample size was maintained as a 5mm cube for consistency.

Simulation: Compression tests conducted in ANSYS

Materials: Polymers – Polyurethane and Polyethylene

Results

The finite element simulations revealed pronounced scale-dependent mechanical behavior in the cuttlebone-inspired polymer structures.

Scale-Dependent Performance: Smaller scale 5mm with a high number of chambers showed superior load distribution, low stress concentrations and specific strength. This scaled structure perfectly balances compressive strength(>100MPa) and shows controlled deformation.

Failure modes: Multi-chambered walls enabled predictable and progressive collapse. The energy absorption is 25-30% compared to other scaled structures.

Larger scale: Exhibited localized stress concentrations and reduced energy absorption due to reduced geometric fidelity.

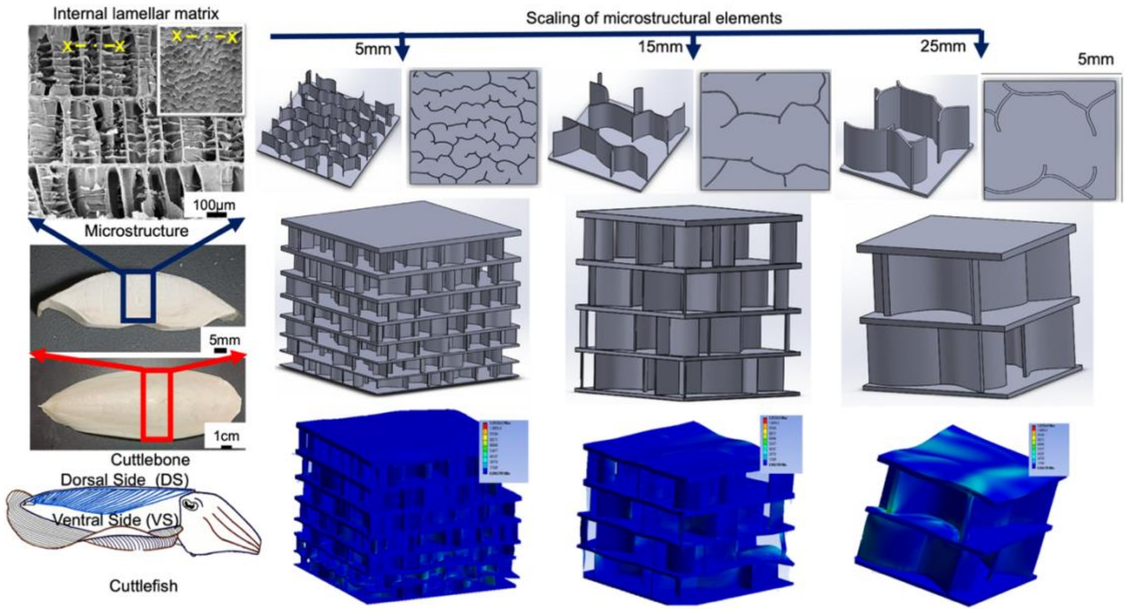

Figure 1. Overview of the proposed methodology

Discussion

This study demonstrates the strong potential of cuttlebone-inspired architectures for engineering lightweight, high-strength polymer structures under compressive loads. The observed scale-dependent behavior emphasizes the importance of hierarchical design and geometric fidelity in optimizing performance, with the 5mm scaled structure offering the best balance of strength, energy absorption, and controlled deformation key for safety and reliability. The computational ANSYS finite element analysis approach enables rapid prototyping and optimization, reducing physical testing needs and providing a robust framework for designing advanced materials.

Conclusion

This work establishes a computational framework for designing nature-inspired, damage-tolerant materials. The 5 mm-scaled cuttlebone structure emerged as optimal, offering a blueprint for a high-strength, lightweight alternative to conventional systems. Future work will focus on 3d-printed prototypes and dynamic load testing.

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