Experimental and Numerical Characterisation of 3D-Printed Onyx: From Material Behaviour to Structural Performance

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INTRODUCTION

Additive manufacturing (AM) enables lightweight, architected structures with tailored mechanical performance for impact-relevant applications. Among AM materials, Onyx—a polyamide 6 matrix reinforced with chopped carbon fibres—offers improved stiffness and toughness compared to neat polymers, but its behaviour is strongly influenced by printing parameters and loading conditions. This work investigates the strain-rate-dependent response of Onyx at both material and structural scales under quasi-static and intermediate rates and explores how anisotropy and lattice architecture govern energy absorption. Numerical simulations complement experiments to establish predictive design guidelines.

MATERIALS AND METHODS

Onyx specimens were fabricated via fused filament fabrication (FFF) using a Markforged Mark Two printer. At the material scale, tensile coupons were printed in three orientations (XY, XZ, ZX) to capture anisotropy, while compression tests employed four geometries (ASTM prism, two dogbone variants, and CUBE) to identify a robust configuration for rate-dependent characterisation. Strain rates ranged from 10^{-3} to 1 s^{-1} for both tension and compression. Digital image correlation (DIC) was used for full-field strain measurement.
At the structural scale, four lattice cores were examined:

- Hexagonal honeycomb (HC)
- Trabecular architecture (TC) inspired by beetle elytron plates
- Functionally graded weak-to-strong (FG-WS)
- Functionally graded strong-to-weak (FG-SW)

All lattices shared equal envelope dimensions and relative density for comparability. Compression tests quantified stiffness, collapse mechanisms, and specific energy absorption (SEA).

RESULTS AND DISCUSSION

Material behaviour: Tensile tests revealed pronounced anisotropy. XZ specimens achieved the highest stiffness and strength ($E \approx 2.84$ GPa, $\sigma \approx 49.7$ MPa), XY offered similar strength with greater ductility ($\varepsilon \approx 0.22$), while ZX underperformed due to weak interlayer bonding ($\sigma \approx 28.5$ MPa). Compression screening identified the CUBE geometry as the most reliable for intrinsic response, avoiding buckling and stress concentrations observed in ASTM and dogbone specimens. Both CUBE and compact dogbone showed clear rate sensitivity, with increased tangent stiffness and peak stress at $1\ s^{-1}$.
Structural performance: Under quasi-static loading, HC exhibited early yielding and a long bending-dominated plateau, whereas TC reached higher peak stress with gradual densification. Graded lattices collapsed progressively through sequential layer activation, delaying global failure and enhancing energy absorption. At intermediate rates, all cores stiffened and SEA increased; FG-SW benefitted from early engagement of its stiffer upper layers, achieving the highest performance. These results demonstrate that both material anisotropy and architectural grading amplify rate effects.
Numerical modelling: Finite element simulations incorporating rate sensitivity reproduced observed collapse mechanisms and stress–strain trends. The combined experimental–numerical approach provides a framework for designing lightweight, impact-resistant cores without mass penalties.

CONCLUSIONS

Onyx exhibits strong anisotropy and moderate rate sensitivity, which must be considered when transitioning from material coupons to lattice-scale designs. Functionally graded architectures outperform uniform lattices in stiffness and energy absorption, particularly under increasing strain rates. Simulation tools validated against experiments enable predictive optimisation of AM cores for crashworthiness.