Design of a Nature-Inspired Honeycomb Bicycle Helmet for Prevention of Traumatic Brain Injury

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Background

Following a head impact, current foam bicycle helmets effectively mitigate translational kinematics (linked to skull fracture) but not rotational kinematics (associated with traumatic brain injury, TBI). Nature-inspired honeycomb structures can potentially be an advantageous alternative to foam due to their superior energy absorption potential and anisotropic properties. Specifically, honeycomb allows deformation in the shear loading direction to absorb impact energy that causes rotational head kinematics. In beeswax and graphene lattice structures, pentagon-heptagon pairs (known as 5-7 defects) are observed within the array of hexagons in areas of curvature. In this study, a new helmet design was proposed that uses hexagonal honeycomb with 5-7 defects to accommodate the curvature of the human head, and preliminary mechanical tests were performed. The ultimate objective is to determine the optimal honeycomb design for head protection, which involves (1) maximizing energy absorption capacity, (2) reducing the peak force on the head to below the injury threshold, and (3) minimizing weight.

Methodology

Hexagonal honeycomb specimens were designed in nTopology and 3D-printed using a fused deposition modelling printer with Thermoplastic polyurethane. The relative density of these models was determined according to an analytical model based on injury thresholds for skull fracture and concussion. Quasi-static in-plane and out-of-plane compression tests were performed using an Instron materials testing machine to obtain stress-strain data. Compressive properties were evaluated using the volumetric energy absorption efficiency U_v/σ_{peak} for three design variations: regular honeycomb, honeycomb with staggered 5-7 defects, and honeycomb with stacked 5-7 defects. Shear testing is ongoing to determine an optimal honeycomb design for multi-directional protection.

Results and Discussion

The inclusion of 5-7 defects improved the mechanical properties of the honeycomb under in-plane compression. The design variation with stacked 5-7 defects had the highest U_v/σ_{peak} ratio of 0.51 ± 0.03, a 38% increase compared to regular honeycomb. Out-of-plane compression tests suggested the inclusion of 5-7 defects had no appreciable effect on the peak stress or energy absorption capacity of the honeycomb. According to an analytical model developed using the injury threshold of skull fracture, out-of-plane compressive peak stress must remain below 5.32 MPa, corresponding to a relative density of 37%. The effect of relative density on the out-of-plane compressive and shear properties will be determined to achieve the optimal honeycomb design for head protection that maximizes energy absorption while minimizing weight.

Conclusions

Honeycomb shows potential for head protection largely due to its anisotropy that allows sufficient strength under compressive loading to protect against fracture and allows sufficient deformation under shear loading to prevent concussion. The proposed helmet design, made of 3D-printed honeycomb with 5-7 defects, can accommodate the curvature of the head while also potentially improving the mechanical properties. Results suggest that honeycomb geometry and arrangement of 5-7 defects can be modified to develop a design optimized for head protection. The bicycle helmet design demonstrates potential improvement over current foam helmets to effectively protect against both skull fracture and TBI by mitigating the translational and rotational head kinematics following impact.