Design of a Honeycomb Energy Absorbing Structure for Bicycle Helmets

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I. INTRODUCTION

Bicycle accidents are the leading cause of sports-related head injuries [1] and of these, concussions account for 42% [2]. Following a head impact, current foam helmets effectively mitigate linear kinematics of the head following impact (linked to skull fracture and some traumatic brain injuries (TBIs)) but not rotational kinematics (associated with many diffuse TBIs). 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 [3]. In the present study, a new helmet design was proposed that uses hexagonal honeycomb with 5-7 defects to accommodate the curvature of the human head. The first design requirement was that the helmet must absorb the kinetic energy of the head at impact, through the potential energy of deformation (strain energy). The second requirement was that the force experienced by the head (σ_{peak}) should not exceed a specified limit corresponding to the injury threshold for skull fracture ($\sigma_{critical}$). Based on the above considerations, the optimal helmet design maximises energy absorption per unit volume (U_v) while σ_{peak} remains just below the safety threshold. Furthermore, for practical use of the helmet, it is beneficial to minimise the volume of material, and therefore weight.

II. METHODS

Various honeycomb designs were generated in nTopology, including regular hexagonal honeycomb, and honeycomb with 5-7 defects. The size of the specimens represented the average contact area in a helmeted bicycle accident [4]. The specimens were 3D-printed (2 to 3 per design variation) with thermoplastic polyurethane, an elastoplastic material. Quasi-static (strain rate ($\dot{\varepsilon}$) = 10^{-3} s^{-1}) out-of-plane compression tests (Fig. 1b) were performed using an Instron materials testing machine to obtain stress-strain data. The effects of 5-7 defect arrangement and relative density ($\bar{\rho}$) on U_v and σ_{peak} were determined (t-tests were used to compare means). The strain rate dependence of the specimens was then determined by performing out-of-plane compression tests at $\dot{\varepsilon}$ of 3 x 10^{-2} and 6 x 10^{-2} s^{-1}. U_v was determined by computing the approximate integral of stress with respect to strain, prior to densification (ε_d). ε_d was defined by the global maximum of energy absorption efficiency, according to [5].

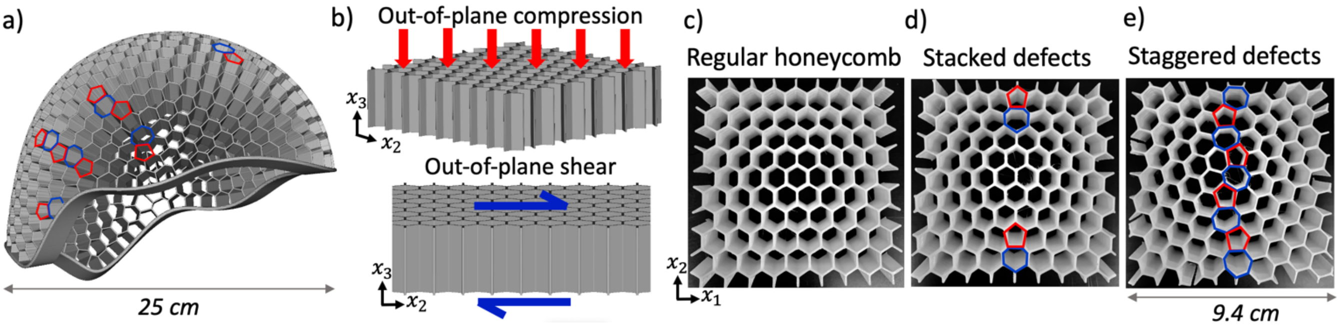

Fig. 1. a) Full-scale helmet model made of honeycomb with 5-7 defects, b) in-plane and out-of-plane loading directions, c) 3D-printed regular honeycomb model, d) 3D-printed honeycomb with stacked 5-7 defects, and e) 3D-printed honeycomb with staggered 5-7 defects (pentagons are outlined in red, and heptagons in blue).

III. INITIAL FINDINGS

Honeycomb specimens with stacked and staggered 5-7 defects (Fig. 1d-e) were successfully 3D-printed with a $\bar{\rho}$ of 17 $\pm$ 1%. There were no statistical differences in mechanical properties between samples with and without 5-7 defects. The mean σ_{peak} for stacked 5-7 defects was 3% greater than that for regular honeycomb (*p = 0.8*),

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and the mean σ_{peak} for staggered 5-7 defects was 13% less than that for regular honeycomb (*p = 0.2*). Regular honeycomb specimens were successfully 3D-printed (Fig. 1c) with six variations in $\bar{\rho}$, ranging from 14% to 28%. Average out-of-plane compressive stress-strain responses of designs with variation in $\bar{\rho}$ are plotted in Fig. 2a. The effects of $\bar{\rho}$ on σ_{peak} and U_v are illustrated in Fig. 2b. Increasing $\bar{\rho}$ from 14 to 28% resulted in a 6-fold linear increase in σ_{peak} (from 0.28 to 1.85 MPa) and a 4-fold linear increase in U_v (from 0.13 to 0.65 kJ/mm^3). Using an injury threshold for skull fracture ($\sigma_{critical}$) of 2.25 MPa [6], the maximum allowable honeycomb $\bar{\rho}$ was 36%. Finally, there were no notable differences in mechanical properties of the honeycomb under various strain rates.

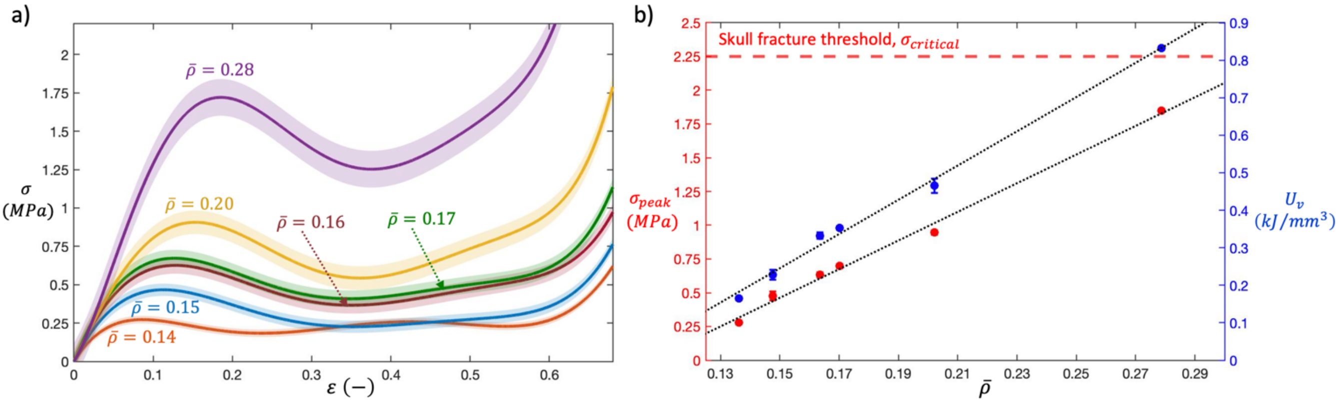

Fig. 2. a) Stress-strain responses for regular honeycomb with variation in $\bar{\rho}$ (shaded region shows confidence interval), and b) effect of $\bar{\rho}$ on σ_{peak} and U_v.

IV. DISCUSSION

A novel bicycle helmet design was proposed using hexagonal honeycomb with pentagon-heptagon (5-7) defects. Results of out-of-plane compression testing suggested that the inclusion of 5-7 defects had no effect on the mechanical properties. Given that 5-7 defects must be included to accommodate the curvature of the head, this result is beneficial. However, a larger sample size is required to be confident in this null result.

σ_{peak} increased linearly in relation to $\bar{\rho}$, indicating the honeycomb cell walls inhibited plastic collapse [7]. In high severity impacts (that can cause skull fracture), energy absorption due to plastic deformation is beneficial; however, because helmets are rarely discarded after moderate impacts (that may cause TBI), it is desirable to achieve elastic deformation under shear loading. The recoverability of honeycomb under shear loading will be explored in future work. There was also a linear increase in U_v in relation to $\bar{\rho}$, in the tested range. It is expected that with a wider range of $\bar{\rho}$, U_v would reach a maximum and then decrease to approach the U_v of the solid material. Future work will test this hypothesis. The relationship between σ_{peak} and $\bar{\rho}$ was extrapolated to determine a maximum allowable $\bar{\rho}$ of 36%, according to the threshold for skull fracture. In extrapolating the observed U_v relationship, honeycomb with 36% $\bar{\rho}$ would be optimal. However, the value of $\bar{\rho}$ at which U_v begins to decrease must be determined to be confident in this result.

A limitation of the current study is that testing was primarily performed at a quasi-static strain rate. Although the results thus far indicate no strain rate dependence, a more realistic impact velocity must be used in future work. In the next phase of this work, small-scale dynamic tests will be performed and the effect of honeycomb geometry on the out-of-plane shear properties (associated with TBI protection) will be determined. Honeycomb is known to be anisotropic, therefore it is expected that sufficient deformation is achievable in the shear loading direction to offer mitigation of rotational kinematics. The collective results will be used to achieve the optimal honeycomb design, and this will be applied to a full-scale helmet (Fig. 1a). The proposed honeycomb helmet design demonstrates potential improvement over current foam helmets to effectively protect against both skull fracture and TBI, by mitigating the translational and rotational kinematics of the head following impact.

V. REFERENCES

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