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Modeling and Analysis of Biodegradable Helmet Liner: A Comparative Study

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Abstract: *The improvement in impact energy absorption properties of helmet gear could significantly enhance the rider's safety. The current work focuses on using a biodegradable polymer: E-PLA, as a potential alternative for commonly used solid helmet liner materials. First, a static finite element analysis based on AIS standards is carried out to identify a suitable size of honeycomb cell. Further, dynamic impact analysis of honeycomb liner is carried out to evaluate impact parameters such as Peak Linear Acceleration (PLA), Volumetric Energy Absorption (VEA) and Head Impact Criterion (HIC). The results showed that the chosen honeycomb liner provided better values of impact parameters compared to solid liner.*
Keywords: *Biodegradable polymer, helmet liner, finite element analysis, honeycomb structure, impact parameters*

1. INTRODUCTION

The Head safety is one of the most important concern for two-wheeler riders. Though protective helmets are being used, statistics reveal vast majority fatalities are associated with not wearing a helmet [1]. Commonly used helmets are considered to be made of four parts: shell parts, adjusting devices, hard lining parts and soft lining parts. These hard lining and soft lining parts are collectively referred as liners. A variety of materials have been reported in literature which are used as helmet liners including synthetic cellular materials such as expanded polystyrene (EPS) and expanded polypropylene (EPP) [2]. Mohammed Nasim [3] et al., adopted finite element analysis to study new helmet designs with lattice liners made of polyamide 12 (PA 12). Unit cell topologies like Simple cubic (SC), Dode-medium (DM) and Rhombic Dodecahedron (RD) were considered. The results showed that lattice liners could reduce the Head injury Criteria (HIC), Peak Linear Acceleration (PLA), Brain Injury Criterion (BrIC), and Peak Rotational Acceleration (PRA) by up to 51.28%, 7.63%, 2%, and 58% in comparison to EPS foam liner. Jasdeep Bhinder [4] used different weight percentages of carbon nanotube in Polyurethane foam for helmet inner liner application. The effect of nanotubes on mechanical properties were evaluated with compression tests. It was noticed that with 1.6 wt % of carbon nanotube at -5^0 C processing temperature PU foam sample shows 40 % higher specific elastic modulus and 11 % higher recovery than EPS. Further, an improvement in thermal conductivity was also noticed. Gaetano D. Caserta [5] et al., introduced aluminum hexagonal honeycomb liners in front, top and rear surfaces of a standard helmet to study the energy absorption properties of honeycomb liners. Impact parameters such as PLA and HIC were evaluated. This prototype helmet offered a significant reduction of PLA and HIC during impacts on front and rear surfaces. Muhammad Salman Khan [6] et al., evaluated honeycomb sandwich panels under out-of -plane compressive, tensile and shear loading to understand their deformation mechanics and failure process. The influence of the relative density and cell aspect ratio of the hexagonal honeycomb core on the compression deformation response, out – of- plane properties and characteristic dissipation energy density of the structure was measured from load – displacement responses. Results of the study showed that compressive strength increases exponentially with the variation of relative density and the failure of honeycomb core is governed by elastic buckling of the cells.

Recently, biocompatible materials are being explored as an alternative for medical and industrial applications, including those requiring contact with human body. Mateusz Skwarski [7] and coworkers used blends of biodegradable polymers of PLA with bioplastics such as poly (butylene succinate), poly (butylenadipate – co- terephthalate) – PBAT and thermoplastic starch -TPS and performed bending, static compression, dynamic tension tests. Bending test showed that adding plastics to PLA results in excessive springing action. Static compression test showed the strain rate sensitivity to temperature. Positive strain rates sensitivity for the chosen range was observed for PLA/BAT and PLA/TPS blends. Compression test showed higher energy absorption capabilities of PLA blends compared to expanded styro-foam used in commercial helmets. All these results were observed to be conforming with finite element analysis results of honeycomb structures of the materials. Pawel Kaczynski et al. [8] used PLA matrix added with softening biodegradable plastics such as PBAT [poly (butylene adipate terephthalate)] and TPS (a starch-based biopolymer) in different percentages to produce injection molded energy absorbing honeycomb structures. Crashworthiness of these structures were performed followed with finite element simulation for the material with two different material models. The force-deflection graphs of different blends showed that the amount of plasticizing agent influences strain rate sensitivity. Also, increasing the amount of softening agent from 50 % to 85% resulted in increased elongation at break. The adopted material models in finite element simulation showed a good agreement with experimental results. Fabio A.O. Fernandes [9] studied agglomerated cork performance as padding material in safety helmets with EPS-based motorcycle helmet as reference. Double impact simulation was performed varying the thickness of liners in Abaqus explicit solver. The maximum deformations obtained emphasized the applicability of cork material for multi-impact applications. Kate Parker [10] et al., evaluated thermal and mechanical properties of E-PLA, produced by impregnating PLA beads with CO_2 under a predefined condition, and compared with those of commercial EPS. It was observed that both the materials had similar thermal conductivity. Mechanical tests carried out displayed same trend for both E-PLA and EPS.

2. MATERIALS AND METHODS

2.1 Materials

According to AIS-058 standards suggests that the protective padding shall be expanded polystyrene or any other material having similar properties. Table 1 provides a comparison of different material properties of EPS [12] and E-PLA [10].

Table 1: Material properties of EPS and E-PLA

	Density (kg/m^3)	Young's modulus (MPa)	Poisson ratio
EPS	64.51	27.50	0.275
E-PLA	98.00	356	0.28

2. 2 Honeycomb model

A honeycomb is a bio-inspired structure, also considered a structural composite, provides mechanical properties with better energy-absorbing properties. Lattice structures allow for better ventilation than foam. This is because the struts in a lattice structure create channels for air to flow through the helmet. Lattice structures can be customized to fit the individual head shape. The mechanical properties of honeycomb core (HC) vary with changes in their unit cell size, cell wall thickness and the height of the honeycomb structure. The density and anisotropy of the cell wall material dictates the properties and behavior of the HC core. However, some significant properties of the HC core are strongly influenced by the honeycomb cell geometry, particularly the shape and size of the cell, and the wall thickness. The relative density of a honeycomb is defined as the ratio between geometrical densities to material density. A honeycomb cell, shown in figure 1, is defined by the cell size (c) which is the diameter of the circle inscribed in the honeycomb cell touching the parallel walls of the cell. It is also dependent on the wall thickness (t) of the cell and on the height of the cell (H). The aspect ratio (H/c) plays a critical role in determining the geometry of the required honeycomb structure.

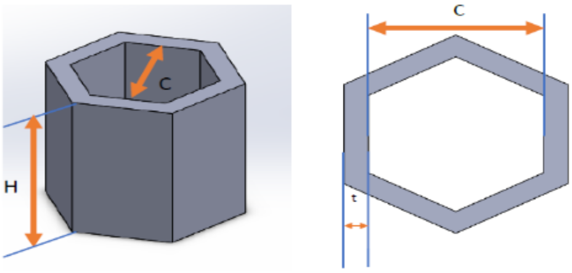
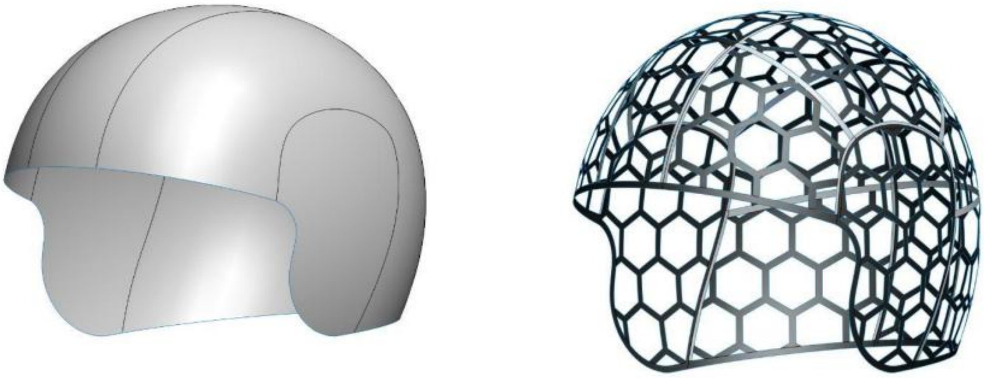


Figure 1: Parameters of honeycomb cell

In this study, four different wall thickness and cell size, table 2, were considered keeping height of the sandwich core (H) at 25 mm. These are modeled using Solid Works v 2022 and are shown in figure 3 (a) - (d). These patterns are individually analyzed under a static load of 630 N as recommended in AIS-058 standards [11] for deformations.

2. 3 Geometric model of helmet liners

The inner surface of the helmet protective liner was modelled in SolidWorks v 2022 using surface modelling technique. The geometric configuration of solid and honeycomb helmet liners is shown in figure 2(a)- (b).



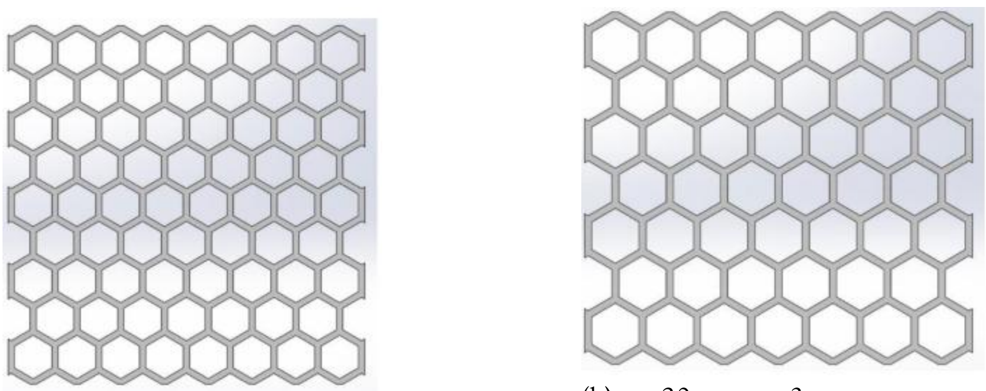
(a) solid helmet liner

(b) honeycomb helmet liner

Figure 2 (a)-(b): Geometric models of Helmet Liner

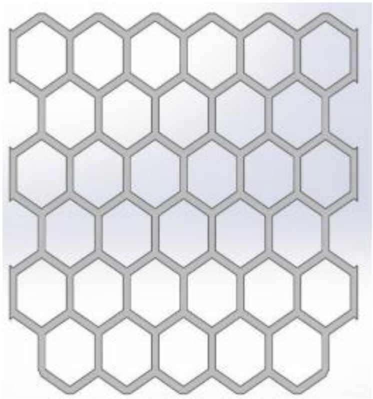
Table 2: values of c and t considered

Trial No.	Cell size(c), mm	Wall thickness (t), mm	Aspect ratio (H/c)
1.	15	2.5	1.66
2.	20	3.0	1.25
3.	25	3.5	1.00
4.	30	4.0	0.83

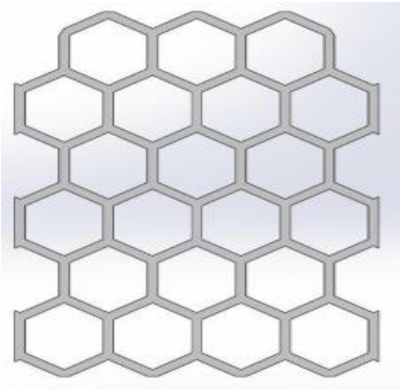


(a) c = 15 mm, t = 2.5 mm

(b) c = 20 mm, t =3 mm



(C) c = 25 mm, t =3.5 mm



(d) c = 30 mm, t = 4 mm

Figure 3: Different sizes of honeycomb pattern

2.4 Drop test analysis and impact parameters

A preliminary study was conducted in order to identify the suitable size of honeycomb structure among the four different sizes considered. Each design was individually analyzed under a static load of 630 N as recommended in AIS-058 standards [11]. Ansys 2024 R1 was used to carry out the finite element analysis. In the finite element model, the bottom surface was constrained to mimic fixed boundary conditions and the simulation results are given in section 3. Drop tests simulations of helmets were carried out in Ansys using explicit dynamics for two cases of helmet liner namely solid and honeycomb patterns as shown in figure 4. The impact parameters considered were Peak Linear Acceleration (PLA), Head Impact Criterion (HIC) and Volume Energy Absorption (VEA).

Peak Linear Acceleration (PLA): It is the maximum amount of acceleration that a helmet can withstand before it fails to protect the head form injury and is measured in g's. It represents the force transferred to the head. The lower the peak linear acceleration, the better the helmet is at protecting the head from injury. The Snell foundation's standard requires that motorcycle helmets should not have more than 275g of peak linear acceleration in a laboratory testing.

Head Impact Criteria (HIC): It is a measure of the severity of a head impact. It is calculated by taking the product of head's acceleration and the duration of the impact. The higher the HIC, the more severe the impact. Helmets that have a lower HIC are more likely to protect the rider from head injury in a crash. Equation 1 is used for calculating HIC

$$HIC = \left[\frac{1}{t_2 - t_1}\int_{t1}^{t2} a(t)dt\right]^{2.5} (t_2 - t_1) \quad (1)$$

Volumetric Energy Absorption (VEA): It is a measure of how much energy a material can absorb per unit volume. In the context of motorcycle helmets, VEA help to predict how well a helmet will protect a rider's head in the event of a crash. A helmet with a high VEA will be able to absorb more energy before it fails, reducing the force of impact in rider's head. It is calculated using equation 2.

$$VEA = \frac{\text{total energy absorbed}}{\text{volume of the test specimen}} \quad (2)$$

The analysis was carried out by simulating the impact of solid liner and the honeycomb liner made of E-PLA over two types of anvils namely flat and curbstone, shown in figure 4. The impact velocity was taken as of 7.5 m/s according to AIS 058 standard [11] along with the gravity effect taken into consideration. The anvils were considered to be made of stainless steel and were modeled as fixed rigid bodies.

Ansys explicit dynamics provide the ability to extract acceleration data from acceleration probes. However, it was observed that the data contained noise and interference. An alternative way was used to obtain acceleration data. First, the velocity data was extracted using a dummy human head, which was then differentiated over time using a suitable MATLAB code. The total energy absorbed by the helmets were captured by calculating the area under the Stress-Strain diagram using a suitable MATLAB code.

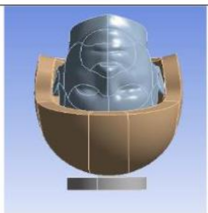
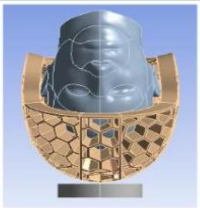
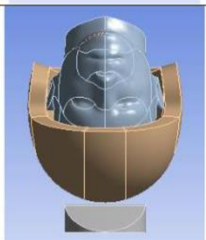
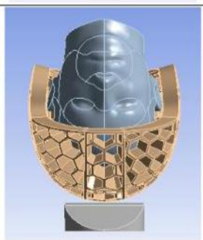
Anvils	Case 1	Case 2
Flat anvil		
Curbstone anvil		

Figure 4: Solid and Honeycomb configurations of helmet liners with flat and curbstone anvils

3. RESULTS AND DISCUSSIONS

The static finite element analysis carried out on four different cell sizes of honeycomb revealed that the cell with an aspect ratio (H/c) equal to 1, predicted a maximum deformation of 1.64 X 10^{-5} mm as shown by the deformation contour in figure 5. Hence, the cell size (c) of 25 mm and wall thickness (t) of 3.5 mm was chosen for dynamic analysis.

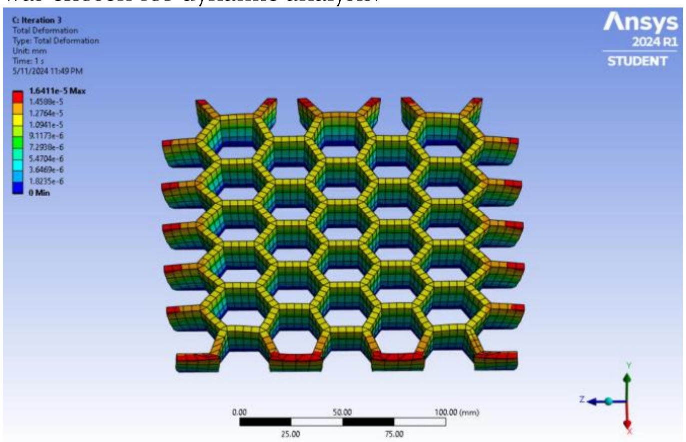
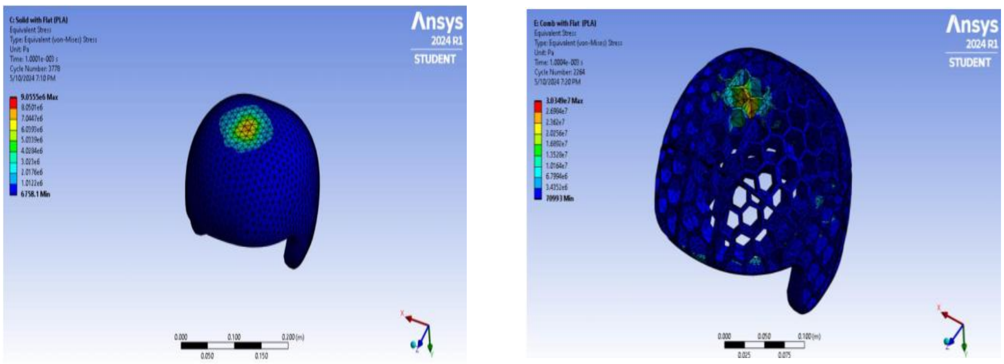


Figure 5: Deformation contour for c = 25mm and t =3.5 mm

Further, explicit dynamic impact analysis was carried out on the chosen cell size for a time period of 1ms. The variation in stress distribution during impact analysis of the helmet liners on flat and curbstone anvils are shown in figure 6 (a)- (d). From these figures, it can be seen that maximum stress carried by honeycomb liner is more than solid liner. Table 3 tabulate the values of von-Mises stress generated from dynamic analysis for the two types of liners.



(a) (b)

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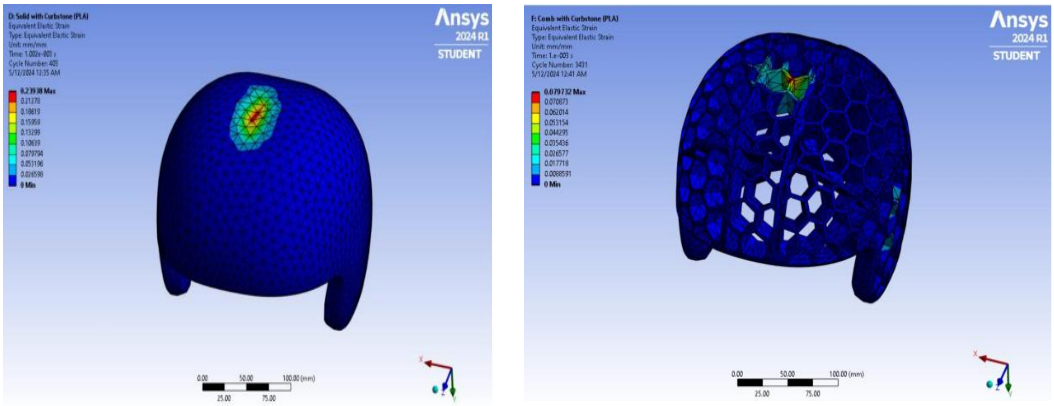


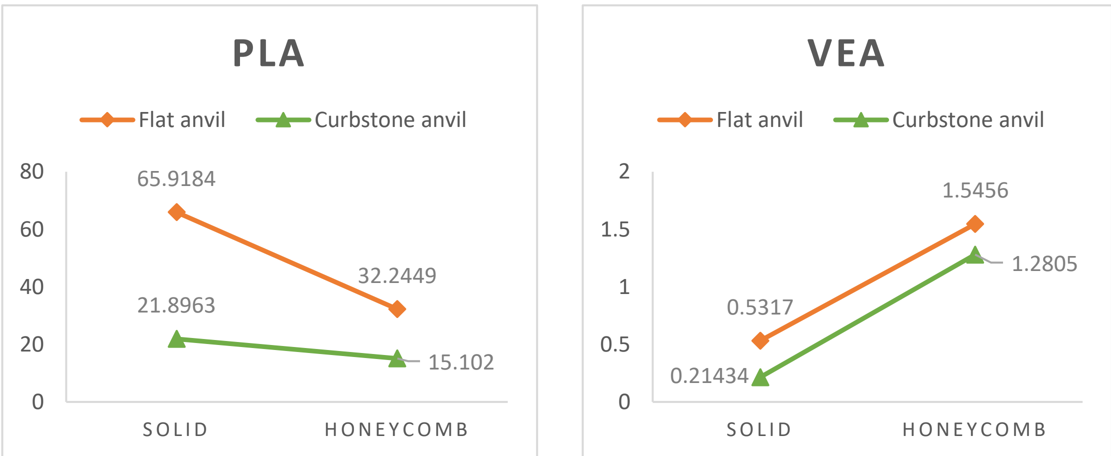
(c) (d)

Figure 6: Stress distribution during impact (a) solid liner on flat anvil; (b) honeycom liner on flat anvil; (c) solid helmet on curbstone anvil; (d) honeycomb helmet on curbstone anvil

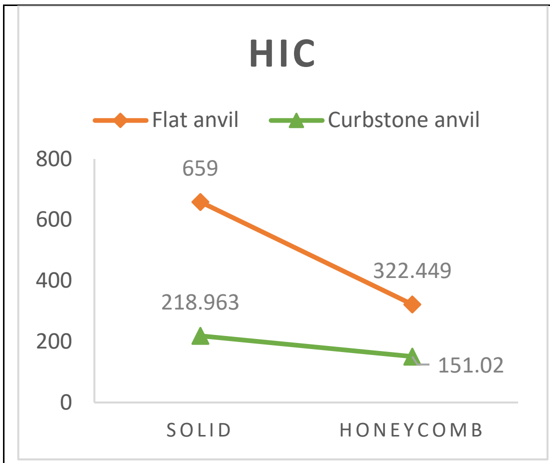
Table 3: von-Mises stress on helmets

	Flat anvil	Curbstone anvil
Solid liner	9.05 MPa	5.4086 MPa
Honeycomb liner	30.3 MPa	26.862 MPa

The effect of the helmet liner types on the impact parameters considered are depicted in figure 7 (a)-(c). From figure 7(a), it is observed that the peak linear acceleration (PLA) for honeycomb helmet liner is 32.2449g and 15.102g for flat and curbstone anvils respectively as against 65.9184g and 21.8963g for solid helmet liner. Figure 7(b) shows that the volumetric energy absorption (VEA) for honeycomb helmet liner is 1.5456 J/m^3 and 1.2805 J/m^3 for flat and curbstone anvils respectively as against 0.5371 J/m^3 and 0.21434 J/m^3 for solid helmet liner. From figure 7(c), the head impact criterion (HIC) for honeycomb helmet is 322.449 and 151.02 respectively for flat and curbstone anvil respectively as against 659.184 and 218.963 for solid helmet liner, a similar observation is reported in [5].



(a) (b)



(c)

Figure 7(a)-(c): Effect of helmet liner types on impact parameters

4. CONCLUSIONS

The use of biodegradable E-PLA as helmet liner material is studied considering two configurations of helmet liners viz. solid and honeycomb liners. From, stress analysis it is observed that the maximum von-Mises stress developed is more in honeycomb liner compared to solid liner. Further, the values of impact parameters suggests that honeycomb liner performs better than the solid liner, making honeycomb liner a better alternative for solid liners in helmets. Also, the use of honeycomb helmet liner helps in volumetric reduction (67.63 %), improved ventilation and in turn comfort making it a preferable choice for two-wheeler riders.

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