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Hybrid Honeycomb/EPS Foam Liner for Enhanced Energy Orption in Motorcycle Helmets

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Motorcycle helmets play a critical role in preventing head injuries during road accidents. The energy-orbing liner, typically made of Expanded Polystyrene (EPS) foam, is the key component that dissipates impact kinetic energy through crushing. However, conventional EPS liners exhibit limitations under high-speed and oblique impacts. This study investigates a hybrid energy-orbing structure combining an aluminum honeycomb core with EPS foam, replacing monolithic EPS liners. Quasi-static and dynamic compression tests were conducted on three hybrid configurations with varying honeycomb-to-foam thickness ratios (10/30, 20/20, and 14/26 mm) and EPS densities (40–60 kg/m³). Results were compared with standalone EPS foam and standalone aluminum honeycomb. The aluminum honeycomb alone exhibited the highest energy orption (134 J under impact) but suffers from manufacturing complexity and poor in-plane strength. Hybrid configurations significantly outperformed monolithic EPS foam. Specifically, the hybrid specimen with 20 mm honeycomb and 20 mm EPS (density 60 kg/m³) achieved 89.02 J under impact loading, representing a 40.0% increase over EPS foam alone. Energy orption increased with honeycomb thickness, foam density, and loading rate. Based on these findings, a conceptual helmet design is proposed consisting of an outer composite shell, an intermediate honeycomb layer for primary energy orption, and an inner EPS layer for multidirectional protection. The proposed hybrid liner offers a promising pathway toward next-generation helmets with substantially improved protective performance.

Keywords: Honeycomb, Expanded polystyrene foam, Energy orption, Motorcycle helmet, Hybrid liner.

1 | Introduction

Road traffic accidents remain a leading cause of death and severe disability worldwide, with motorcyclists being particularly vulnerable due to the lack of external protective structures. According to the World Health Organization (WHO), more than 1.3 million people die annually in road crashes, and motorcyclists account

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for a disproportionate share of fatalities, especially in low- and middle-income countries. Head injuries are the primary cause of death and long-term disability among injured motorcyclists, making effective head protection a public health priority [1–3].

The motorcycle helmet is the single most effective device for preventing head injuries. A properly designed helmet reduces the risk of fatal head injury by approximately 40% and the risk of severe brain injury by more than 70% [4], [5]. However, the level of protection offered by commercially available helmets is highly variable, and even certified helmets do not always prevent concussion or diffuse axonal injury, particularly under oblique impact conditions where rotational accelerations are present [6], [7].

A typical modern motorcycle helmet consists of three main components: 1) a rigid outer shell (usually Polycarbonate (PC), Acrylonitrile Butadiene Styrene (ABS), or fiber-reinforced composite) that resists penetration and spreads impact loads over a larger area, 2) an energy-absorbing liner (traditionally made of Expanded Polystyrene (EPS)) that crushes to dissipate kinetic energy, and 3) a comfort padding and retention system [8], [9]. Among these, the EPS foam liner is the primary energy absorber. EPS foam is widely used due to its low density, low cost, ease of molding into complex shapes, and relatively stable crushing behavior under compression [10], [11]. However, EPS foam has several inherent limitations: 1) its energy absorption per unit volume is moderate compared to metallic cellular materials, 2) its response is highly strain-rate sensitive, but its performance degrades under repeated or very high-speed impacts, 3) it offers little resistance to in-plane shear loads, which are present during oblique impacts, and 4) it has a relatively low recovery ratio, meaning it cannot withstand multiple impacts without replacement [12], [13].

To overcome these limitations, researchers have explored alternative materials and structures. Metallic honeycombs, particularly aluminum honeycombs, are well-known for their excellent specific energy absorption (SEA), stable plateau stress over a large crush stroke, and high strength-to-weight ratio [14], [15]. Under out-of-plane compression (i.e., loading parallel to the cell walls), aluminum honeycombs exhibit a long, flat plateau region followed by densification, making them ideal for single-impact energy absorption applications such as helmets, crash boxes, and aerospace landing systems. However, honeycombs alone are not directly applicable to helmet liners for two main reasons: 1) they are extremely difficult to form into double-curvature shapes that conform to the human head, and 2) they have very low stiffness and strength under in-plane (off-axis) loading, which can lead to premature collapse or buckling under oblique impact [16], [17].

A promising alternative is the use of hybrid structures that combine a honeycomb core with a polymeric foam. In such a hybrid configuration, the honeycomb provides high energy absorption under normal impact (the dominant loading direction in most real-world accidents, where the impact force is nearly perpendicular to the helmet surface). In contrast, the foam layer provides multidirectional protection, in-plane stability, and a comfortable interface with the head [17], [18]. Moreover, the foam can fill the cells of the honeycomb or be placed as a separate layer, potentially creating synergistic effects that enhance total energy dissipation through mechanisms such as cell wall-foam interaction, friction, and progressive crushing [19], [20].

Several recent studies have investigated hybrid foam-honeycomb structures for protective applications. Tobola et al. [21] conducted a comprehensive experimental study on the static and dynamic energy absorption of aluminum honeycomb, EPS foam, and their composites, reporting improvements up to 40% for hybrid configurations compared to foam alone. Other studies have explored functionally graded honeycombs [22], 3D-printed polymeric honeycombs [23], and multi-material liners [24] for helmet applications. Despite these advances, there remains a gap in translating these laboratory findings into a practical helmet design that balances manufacturability, comfort, and crashworthiness.

This study aims to address this gap by systematically analyzing the energy-absorption performance of hybrid honeycomb-EPS structures using existing experimental data, comparing them with conventional EPS liners, and proposing a feasible helmet design incorporating the optimal hybrid configuration. The specific objectives are: 1) to quantify the improvement in energy absorption achieved by replacing monolithic EPS with hybrid honeycomb-EPS, 2) to identify the most effective honeycomb-to-foam thickness ratio and foam density, 3)

to discuss the practical challenges of manufacturing double-curvature hybrid liners, and 4) to present a conceptual helmet design that maximizes protection while addressing these challenges.

2 | Helmet Structure and Function

A conventional motorcycle helmet consists of a rigid outer shell, a polymeric inner liner (crushable foam), comfort padding (typically soft foam and fabric), and a retention system (a chin strap). The protective function is primarily provided by the outer shell and the inner liner, while the remaining components ensure comfort and stability on the rider's head.

The inner liner is responsible for energy orption through plastic crushing of the polymeric foam cells. Among commercially available energy-orbing materials, EPS foam is most commonly used for helmet liners due to its multidirectional strength, low weight, and relatively low cost [1–4].

The outer shell serves two main functions: 1) resisting penetration by sharp objects, and 2) spreading the applied impact load over a larger area, thereby reducing stress and increasing the energy orbred by the inner liner. Typical shell materials include thermoplastics such as PC or , as well as fiber-reinforced composites (e.g., epoxy matrix reinforced with Kevlar, glass, or carbon fibers) [4], [5]. The outer shell can dissipate approximately 10–30% of the incident impact energy [3].

In recent decades, helmet design research has focused on optimizing material properties for greater head protection. Several studies have investigated the influence of shell stiffness and foam liner density on impact energy orption [5-8]. Other studies have developed innovative test methods to evaluate helmet performance under impact and head protection during rotational acceleration [10], [11].

3 | Honeycomb Structure

A honeycomb core is composed of open cells formed from very thin sheets bonded together. Although hexagonal cells are most common, other cell geometries also exist. The honeycomb structure closely resembles natural bee hives, from which it derives its name. Honeycombs can be manufactured from any thin material, and more than 500 different types have been developed to date. The most common type is made from aluminum foil. Honeycombs crush uniformly under a specified load, exhibit a long crush stroke, and possess the highest crushing strength-to-weight ratio among all energy-orbing materials [12]. *Fig. 3* shows a typical aluminum honeycomb.

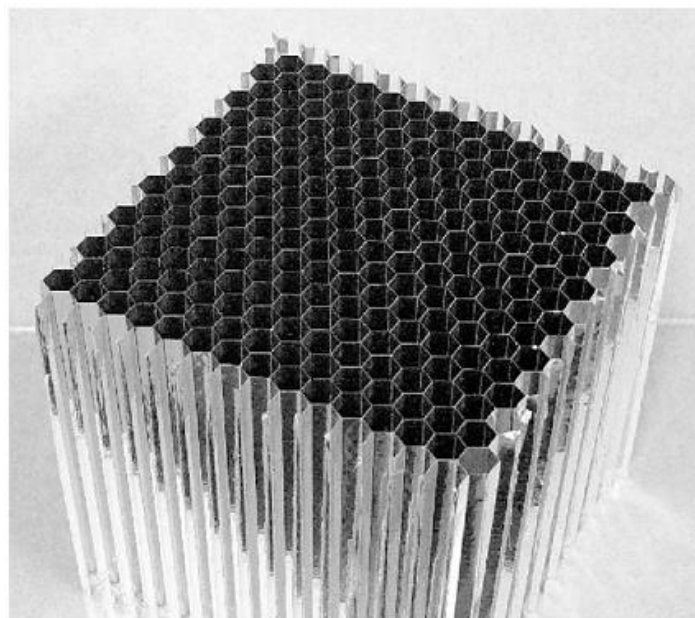


Fig. 3. Aluminum honeycomb.

4 | Experimental Tests

4.1 | Test Methodology

Caserta et al. [9] conducted an experimental investigation on the energy orption of EPS foams, aluminum honeycombs, and hybrid (combined) specimens. Three types of double-layer structures composed of honeycomb and polymeric foam were tested under both quasi-static and dynamic (impact) compression loading. Identical tests were performed on standalone EPS foam and standalone honeycomb specimens of the same dimensions. The objective was to compare the energy orption properties of these materials and to determine the interaction effects between the honeycomb and foam layers, as well as the contribution of each layer to total energy orption. *Fig. 4* shows the hybrid specimens, the test setup, and the resulting force–displacement curves.

4.2 | Energy Orption Calculation

The orbred energy for each specimen was calculated by integrating the force–displacement curve up to the densification point:

$$E = \int F(x), \quad (1)$$

where:

- I. E= orbred energy (J)
- II. F(x)= instantaneous force as a function of displacement (N)

4.3 | Experimental Results

The orbred energy values calculated from the force–displacement curves using *Eq. (1)* are presented in *Table 3*. Aluminum honeycomb exhibited the highest energy orption under both static and dynamic loading. Compared to monolithic EPS foams, all hybrid configurations showed improved energy orption (percentage improvements are shown in parentheses in *Table 3*). Specifically, the use of hybrid specimens increased orbred energy by 18.5% to 39.1% under static loading and by 22.65% to 40.02% under impact loading. Furthermore, a higher honeycomb thickness fraction resulted in greater orbred energy (see *Tables 1* and *3*). The greater percentage improvement of hybrid specimens under impact loading (relative to EPS alone) may be attributed to synergistic interaction between the honeycomb texture and the foam.

Table 1. Tested hybrid configurations.

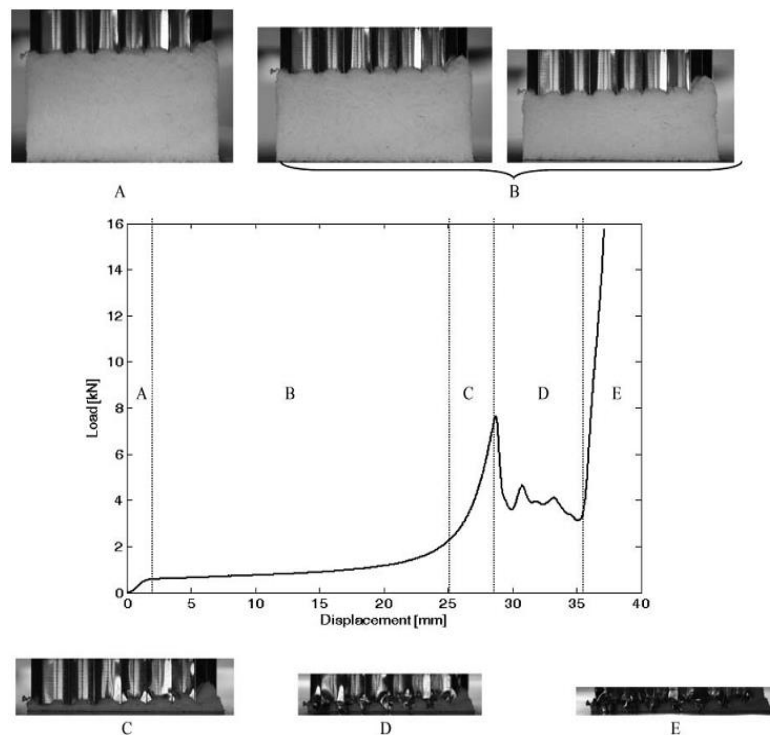
Hybrid No.	EPS Height (mm)	Honeycomb Height (mm)	EPS Density (kg/m ³)	Hybrid Density (kg/m ³)
1	30	10	40	50
2	20	20	40	60
3	26	14	50	60

Table 2. Mechanical properties of materials.

Property	Aluminum Honeycomb (3003 H18)	EPS 40	EPS 50	EPS 60
Density (kg/m ³)	80	40	50	60
Young's modulus (MPa)	2730	16	16	24
Poisson's ratio	0.33	0.01	0.01	0.01
Yield stress (MPa)	186	–	–	–
Plastic hardening (MPa)	5.5	–	–	–

Table 3. Absorbed energy under quasi-static and impact loading.

Material	Density (kg/m ³)	Absorbed Energy – Quasi-Static (J)	Absorbed Energy – Impact (J)
EPS 50	50	46.11	52.00
EPS 60	60	55.36	63.49
Aluminum honeycomb	80	115.75	134.00
Hybrid 1	50	54.66 (+18.5%)	63.78 (+22.65%)
Hybrid 2	60	77.01 (+39.1%)	89.02 (+40.02%)
Hybrid 3	60	68.97 (+24.6%)	80.77 (+27.2%)

**Fig. 4. Force–displacement curve for a representative hybrid honeycomb/EPS specimen.**

In *Fig. 4*, a typical force-displacement curve for an experiment performed on a composite honeycomb/EPS sample during dynamic impact loading is provided. In this graph, displacement (in mm) is plotted on the x-axis, while compressive force (in N) is plotted on the y-axis. Three different zones in such material can be recognized:

- I. a-Linear elastic zone: As loading starts, both honeycomb and EPS foam undergo elastic deformation, and there is almost a linear increase in force with respect to displacement.
- II. b-Plateau zone: After an initial stage of yield, the buckling of cell walls in honeycomb and plastic crushing of cells in EPS foam start. In this stage, there is little change in the force over a wide range of displacements, suggesting efficient energy orption.
- III. c-Densification zone: As cells become fully compressed, there is a sudden increase in force, indicating densification.

When compared with an all-EPS foam specimen (which is not illustrated here), the hybrid specimen demonstrates a more extended plateau range and a greater mean value of the plateau force. This enhancement can be explained by a synergy between the honeycomb structure and the foam, whereby the foam prevents premature buckling of the honeycomb walls, while the honeycomb contributes additional energy orption through plastic bending and frictional forces. Therefore, the area under the force-displacement graph (energy orption) is much larger for the hybrid structure than for the sum of its components.

5 | Conclusion

This research was carried out to establish the potential of substituting conventional monoliner EPS foams with hybrid energy orbers comprising an aluminum honeycomb and an EPS foam layer for use as a motorcycle helmet liner. The following results were obtained from this study;

- I. The monolithic aluminum honeycomb exhibited the highest energy orption (134 J under impact). However, due to the material's inability to be formed into complex double-curved geometry and its lower in-plane strength, it is not suitable for use solely as helmet liners.
- II. All the proposed hybrid configurations were observed to perform better than the mono-liner EPS foam. The best-performing configuration was Hybrid 2 (20 mm honeycomb + 20 mm EPS, density 60 kg/m³), which orbed 89.02 J, representing a 40.0% improvement over the monolith EPS foam.
- III. The amount of energy orbed by the hybrid materials increased with increasing honeycomb thickness, higher foam density, and faster loading rates. This indicates that the energy orption of the hybrid materials was significantly affected by both layers.
- IV. Based on the experimental data, a conceptual three-layered helmet design is proposed: an outer composite shell for protection against penetration and load distribution, a middle honeycomb layer for energy orption during regular impacts, and an EPS inner layer for protection against multi-directional loading (in particular, oblique impacts).

Thus, the proposed hybrid liner represents a very attractive direction for the development of future-generation motorcycle helmets with enhanced protective properties. The following steps should be taken to improve helmet performance further: develop a technology for manufacturing double-curved hybrid liners, conduct finite-element analyses of helmet-level impacts, and validate the results experimentally.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

Data Availability

All data generated or analyzed during this study are included in this published article. No additional data are available.

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