Design and optimization of layered composite foam liners and shell material for protective helmets

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Abstract

In this study, different configurations of layered composite foam liners for a protective helmet were prepared by arranging layers of EPS foams with different densities in a series configuration. The performance of the layered "composite foams" in terms of peak force/accelerations and time duration in linear impact were compared with single layer homogenous EPS foam. Linear impact tests were performed for two different initial energies of 40 and 66 J. Results demonstrate that in a liner with a density gradient through the thickness, positioning the higher density close to the head can reduce the peak accelerations transferred to the head. In addition, in his paper, the effect of using different materials as a helmet shell on the performance of a helmet in linear impact has been studied. For this purpose high energy absorbing composites such as Curv® and silk/HDPE have been benchmarked against conventional shell materials such as polycarbonate. Results demonstrated the superior performance of silk/HDPE composite compared to the other materials for more localized loads.

1. Introduction

Polymeric foams consist of an interconnected network of a large amount of microscopic cells, and are widely used as packaging cushions, light-weight sandwich structures, thermal-acoustic insulators and sport goods [1]. The high energy absorption capability of foams makes them an excellent choice as cushioning liner in designing protective helmets to reduce the stress levels transferred to wearer's head below the injury threshold[2-3]. The most widely used foam in commercial helmets is expanded polystyrene (EPS) due to its high impact performance in a wide temperature range and its relatively low cost. EPS parts with different thicknesses and density can be found in the various positions of the helmet (top, rear, sides) to ensure sufficient protection to the cyclist.

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Apart from the liner, the outer shell also plays a crucial role in a helmet. The function of the outer shell is to distribute the impact energy over a larger area, avoiding concentrated loads and penetration of sharp objects. Another function of the outer shell is enabling the sliding when hitting the road thus minimizing rotation and neck injury. Also, a significant share (34%) of the impact energy is dissipated by shell deformation. In commercial bicycle helmets, a very thin shell composed of thermoplastic material such as polycarbonate generally made of polycarbonate (PC), acrylonitrile-butadiene-styrene copolymer (ABS) or polymer composites is used. The thickness of the shell can vary from 0.5 mm in case of a micro shell to around 1.5-2.0 mm in case of a stiff hard shell [4-6].

The first objective of this work is to compare the performance of layered configurations compared to a single layer liner in linear impact. The layered foam liner consists of discrete layers of uniform foams, each having different densities. For this, three different configurations have been prepared. These configurations consist of 3 layers Top/Middle/Bottom. Bottom stands for the layer close to the head and Top represents the outer layer adjacent to the helmet shell. Three different configurations were prepared by gluing layers of EPS foam with densities of 120, 80 and 40 kg/m3 to each other using double sided tape, namely 120/80/40, 40/80/120, and 120/40/120. All the configurations are optimized for an overall density of 80 kg/m^3, and a thickness of 25 mm.

The second objective of this paper is to study the effect of the shell thickness and shell material on the peak forces in linear acceleration. For this purpose, two different thickness of Polycarbonate shell has been tested under linear drop weight impact conditions with a flat and a sharp projectile. In addition, high impact performance composites such as silk/HDPE and CURV® has been used as shell materials. The composite shells have been compared with conventional PC shells. Results indicate that the shell thickness influences the peak forces, thus the peak accelerations. Thinner PC shells allow larger deformations of the foam liner resulting in lower peak forces. In addition, results indicated that a tough composite shell such as Silk/HDPE can withstand more localized loads and puncturing by sharp projectiles.

2. Materials
2.1. Composite foam preparation

Blocks of expanded polystyrene (EPS) foam were provided by LAZER Sports. The layered composite foams were made by cutting blocks of EPS foam with different densities of 40, 100 and EPS 120 kg/m^3 using hot wire. The acquired pieces were then attached to each other using double sided tape. The layered composites were prepared in three different configurations. Each configuration consists of 3 layers Bottom/middle/Top, Bottom stands for the layer close to the head and Top represents the layer adjacent to the helmet shell (See figure 1). Three different configurations namely 120/80/40, 40/80/120, and 120/40/120 were prepared by joining layers of EPS foam with densities of 120, 80 and 40 kg/m^3. All different configurations are optimized for an overall density of 80 kg/m^3, and thickness of 25 mm. The layered composite for linear impact test were prepared in 7cm (length) x 7cm (width) x 2.5 cm (thickness).

Figure 1. Three different configurations of composite foams (a), B40/80/120T; (b), B120/80/40T; (c), B120/40/120T.

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2.2 Helmet shell material and production method

The effect of shell thickness and shell material have been studied by impact testing of a PC shell with thickness of 0.5 and 1.5 mm. For this, some sheets of PC shells with thickness of 0.5 mm was sourced from the helmet manufacturing company Lazer Sports (Belgium). PC shell with thickness of around 1.5 mm were produced from compression molding of two separate PC sheets with a thickness around 0.75 mm. Self-reinforced polypropylene (CURV®) shell is a commercial material with an average thickness of a 1.4 mm, obtained from Propex Fabrics (Germany). Another composite shell chosen for this study was a silk/HDPE composite. A silk twill woven fabric with areal weight of 80 g/m^2 was sourced from the company Hermes (France). High density polyethylene modified with maleic anhydride (HDPE-MA, Bynel 40E529) in the form of a film (thickness of around 0.065 mm) was supplied by Du Pont. The thermoplastic silk/HDPE composite shells were produced by compression molding on a Fonteine press. Processing temperature was set at 150° C. The applied pressure was set to 15 bar for 8 mmin. Then samples were cooled to 90°C. After 15 min holding time at 90°C the samples were cooled to room temperature and removed from the hot press. The sample code of the different shells and their actual thickness are listed in table 1.

Table 1. Different shell materials and their thicknesses.

Shell sample code	**Material type**	**Thickness (mm)**
PC o.5	Polycarbonate	**0.48 ±0.005**
PC 1.5	Polycarbonate	**1.49±0.02**
Curv	Self-reinforced polyethylene composite	**1.39±0.01**
Silk/HDPE	Composite of silk twill weave/density polyethylene	**1.50±0.03**

3. Methods

3.1. Linear impact testing of layered composite

The samples were glued to the impactor projectile which is a steel flat tub with a 5 cm diameter and then dropped onto a flat steel plate. This setup is shown in fig.2. All the specimens for impact testing were cut into cuboids of 70mm x70mm x 25mm (thickness). Each test has been performed with at least three iterations. The initial energy was fixed to 66 J. Falling height and weight were set to 1.5 m and 4.5 kg which results in a speed of 5.4 m/s.

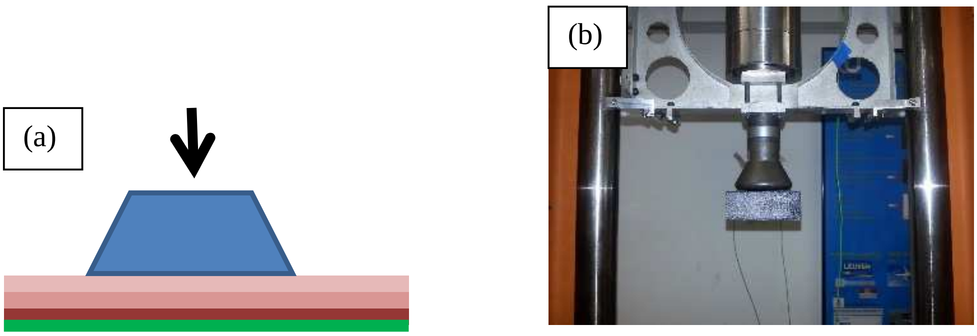

Figure 2. a) an illustration of a layered composite foam connected to impact tub; b) an image of impact set up whilst the foam specimen connected to flat tub.

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3.2. Linear impact testing of different shells.

The outer shell of a bicycle helmet is used to spread out the impact force and to prevent objects from puncturing the helmet. For performing the impact tests, the shells were glued to 100x100x25mm EPS60 foam samples. Instead of gluing the samples to the impact tub, they were placed on a steel bottom plate and constrained and fixed in the position using a ring as shown in fig.3. The bolts on the ring were tightened using the same amount of torque 20 N.m were applied on every bolt to avoid misalignment using a torque meter.

Figure 3. Linear drop weight impact set-up with flat steel tub on a foam+shell sample.

Two different projectiles were used for this impact study. One is a steel flat tub with a diameter of 50 mm and the other is a steel finger (diameter 16 mm) with a hemispherical tip for applying localized loads. The initial impact energy was set 66 J, resulting in a drop height of 1.5 m and impact velocity of around 5.4 m/s.This is the speed suggested by the current EN 1078 bicycle helmet standard.

4. Result and discussion

4.1 Impact properties of layered composite liner

The comparative force-time graphs, obtained from linear impact experiments of the single layer EPS foam with a density of 80 kg/m^3 and three equally thick composite foam liners with equal overall density of 80 kg/m^3, are shown in fig.4.

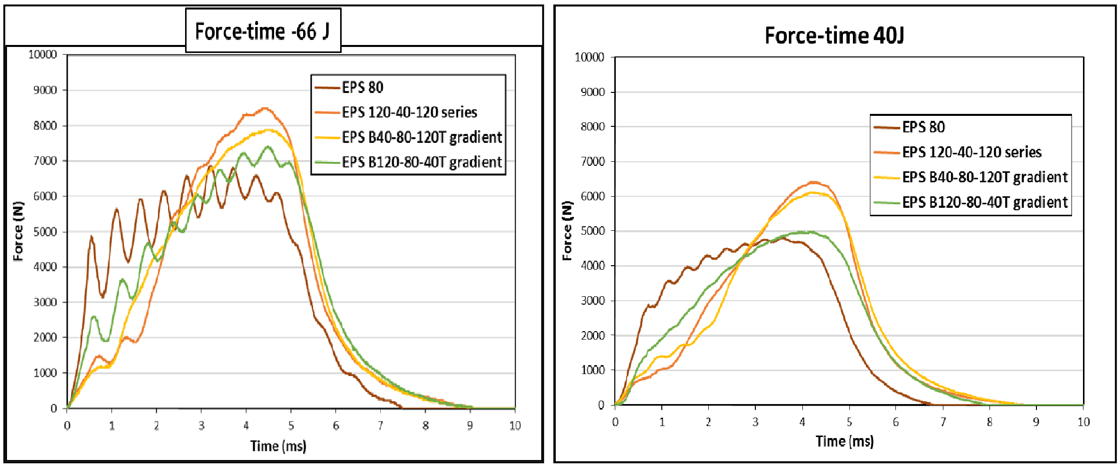

Figure 4. Force-time graph of different composite foams obtained from linear impact with initial energy of 66 J and 40 J.

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As observed in fig.4.a all the layered composite foams exhibit higher peak forces, which can be translated to peak accelerations, compared to single layer foam except for initial part of the graph which all the composite foam exhibit lower levels of force/accelerations. However in both energy levels of 66 and 40 J, it can be observed that the lowest peak force amongst different configurations of layered composite foam is related to EPS B120-80-40T. This configuration means in a gradient distribution of the density, it is more favourable to position the higher density close to the head and the lower density foam adjacent to the outer shell. This can be explained by the area of the contact. At the moment of impact when the head touches the liner, a lower density foam situated closest to the head, results in localized deformation avoiding the spread of plastic deformation / damage. Therefore, the contact area is smaller due to damage localization. Lower contact area leads to higher peak forces and accelerations.

4.2. The effect of the shell material and thickness on linear impact response

Linear impact tests were performed on different shells with 2 projectiles, the steel flat (fig.5a) and a steel finger (fig5b) to see the effect of shells on the impact results. During the impact tests using the steel flat projectile, none of the shells were punctured. All samples except for PC0,5 showed similar peak force and impact time duration. As observed in fig.5a the thickness of PC shells plays a role in peak force/acceleration and time duration which can be related to lower bending stiffness of PC0.5 which allows for larger deformation and contact area between the projectile and the sample.

During the impact tests using the steel finger projectile (fig5.b) all the samples with PC 0.5, PC 1.5 and Curv® 1.5 shells were punctured except for the samples with silk/HDPE shell. This is due to higher penetration impact resistance of silk/HDPE composite. The combination of tough silk fibres (with strain to failure of 20%) and a highly deformable thermoplastic matrix of HDPE-MA leads to higher deformability and a better spread of the damage in the composite, avoiding localization. This indicates the importance of a suitable tough composite material in protecting the head against sharp objects which can be more probable in e.g. mountain biking.

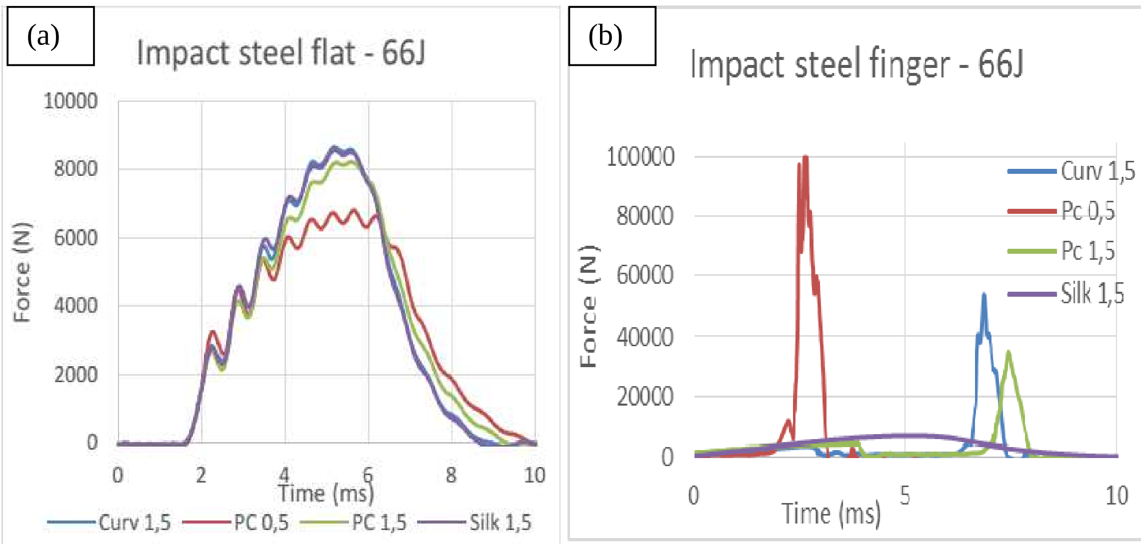

Figure 5. Linear impact force-time graphs with a) flat steel tub and, b) finger steel tub.

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5. Conclusions

Results demonstrate that the layered composite foam with equal thickness and overall density did not outperform the single layer EPS80 foam in linear impact. Of course drawing definitive conclusion needs further investigation. However, this study shows in a gradient structure positioning the higher density foam adjacent to the head can lead to lower levels of accelerations due to higher contact area and prevention of localization. It was observed using thinner PC shell could lead to lower peak accelerations due to lower bending stiffness which allows for higher deformability and area of contact. The study on effect of shell materials on both flat and sharp projectiles, tough composite of silk/HDPE outperforms the conventional shell materials in impact with sharp objects.

Acknowledgments

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References

[1] L.J. Gibson, M.F. Ashby. *Cellular solids: Structure and properties.* Second Edition, Cambridge University Press, 1997.

[2] M.J. Tzeng, M.C. Lee. Mechanical properties of impact absorbing liner of motorcycle helmets, American Society of Mechanical Engineers, New York 98 381–384, 1989.

[3] J. Miltz, O. Ramon. Energy absorption characteristics of polymeric foams used as cushioning materials, *Polymer Engineering and Science* 30: 129–133, 1990.

[4] A. Gale, N.J. Mills. Effect of polystyrene foam liner density on motorcycle helmet shock absorption, *Plastics and Rubber Processing and Applications* 5: 101–108, 1985.

[5] A. Gilchrist, N.J. Mills. Modelling of the impact response of motorcycle helmets, *International Journal of Impact Engineering* 15: 201–218, 1994.

[6] V. R. Hodgson.Skid Tests on a Select Group of Bicycle Helmets to Determine Their Head-Neck Protective Characteristics. Department of Neurosurgery, Wayne State University, Michigan,(*BHSIDOC#310, Bicycle Helmet Safety Institute, Arlington VA)*.

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