DEVELOPMENT OF ANISOTROPIC FOAMS AND CHARACTERIZATION METHODS FOR BICYCLE HELMETS

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ABSTRACT

Although current standard bicycle helmets provide protection against so-called linear acceleration, they cannot deliver sufficient protection against rotational acceleration during oblique impact events. These events can cause severe head injuries and the rotational accelerations need to be minimized. We pursue this goal by developing anisotropic foams for bicycle helmets and define test methods to characterize foams under oblique loading.

1. INTRODUCTION

In bicycle accidents, impacts are generally oriented at oblique angles and result in foam deformation with both a shear and a compressive component and can be correlated to the rotational acceleration. According to previous research carried out by the departments of Neuroscience and Biomechanics at KU Leuven a very serious type of brain injury, namely acute subdural haematoma, occurs when the brain is subjected to large rotational decelerations. One of the potential solutions developed by the bicycle helmet research group in KU Leuven is to replace standard expanded polystyrene foams (EPS) with an anisotropic foam in which the direction of anisotropy is perpendicular to the head. This foam must have similar energy absorption properties as EPS in compression, but a weaker shear resistance. This will reduce the transfer of the rotational forces to the head via the relative motion and internal slip within the foam [1,2].

Since bicycle helmets are produced in complex shapes, it is necessary to implement a foaming method and a material formulation that could give the possibility of producing strongly anisotropic foam (shape anisotropy ratio R >3) with cell geometries oriented perpendicular to the head surface in the shape of a bicycle helmet. A survey of commercially available foams reveals that no such material or process is currently available. Therefore, anisotropic formulations were developed in cooperation with the University of Valladolid, starting with HDPE.

Simultaneously, it is of great importance to develop a machine and a test method which can apply a combination of shear and compressive displacements to the foam and characterize the behavior of the foam (energy absorbing capacity and maximum stresses) over large deformations when loaded under an angle.

Rotational impact is a testing method related to bicycle helmet standardization where an oblique impact accident is mimicked and rotational acceleration applied to the head is measured.

Rotational acceleration of standard EPS helmets and prototype helmets made of anisotropic PES were measured and compared.

This paper will first summarize the development of a foaming process to create anisotropic foams. The second part of the paper will focus on the development of testing methods to characterize foams for the helmet application.

2. DEVELOPMENT OF ANISOTROPIC FOAM

2.1 Foaming process methodology

The polymer that was used in this study was RIGIDEX® HD5226EA high density polyethylene (HDPE) supplied by INEOS Olefins & Polymers Europe. It has a melt flow index (MFI) of 26 g/10min (190°C, 2.16 kg, ISO 1133) and a density of 0.953 g/cm³. The melting point of this polymer is 131 °C, with a Vicat A softening point of 123°C.

Additives that were used include azodicarbonimide as blowing agent (AZDC), dicumyl peroxide (DCP) as crosslinking agent, lubricating agent (*stearic acid)*, and antioxidant (*Irganox 1010)*.

Table 1. Formulation and material range for this case study

Components	Weight percent	Investigated range
azodicarbonimide	15 wt%	12-18%
dicumyl peroxide	2 wt%	1-3%
stearic acid	1 wt%	1%
Irganox 1010	1 wt%	1%
HDPE	81 wt%	85-77%

The material was compounded into these formulations (Table1) using a small twin-screw extruder. The extrudate was cooled in a water bath and subsequently pelletized.

For the process of foaming the cross-linked HDPE, which is the case study used in this paper, the process is as follows:

1. First, the compounded polymer pellets are placed in a mold and melted and fused to form a solid precursor.
2. Secondly, the temperature is increased to above the decomposition temperature of DCP. Several of the decomposition products of DCP are gasses including CO, CO_2 and CH_4 [4], so at sufficient loading, this causes a first expansion of around 3 times. Characterisation of the structure of this “prefoam” shows that the density is still comparatively high, and the cells, though already anisotropic, are only slightly so, and the degree of anisotropy is in the order of R=1.5.
3. In the third step, the prefoam is stabilized by DCP crosslinking, which is kinetically slower than the decomposition and therefore takes place after the first expansion by DCP, though in the same temperature step.
4. In the fourth step, the temperature is again increased to above the decomposition temperature of the AZDC blowing agent which is around 170°C. During this step, the expansion is restricted to one direction (in this case, the vertical direction) in order to achieve maximum anisotropy.

5. In the final step the foam is quenched to room temperature and demolded.

2.2 Optical analysis of foam architecture

Using the image analysis program from SkyScan (producer of the SkyScan Micro-CT scanner), the cell sizes, distributions and shape anisotropies of the developed cross-linked HDPE foams were investigated (figure 1).

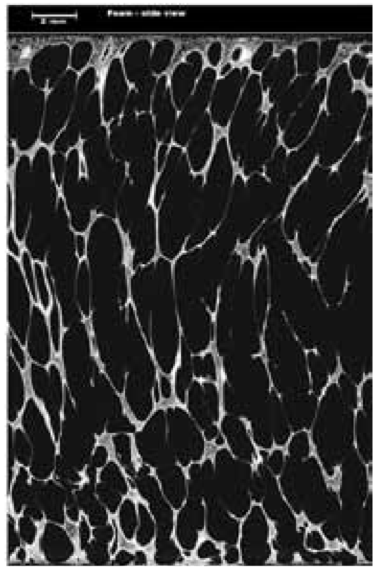

Figure 1. Micro-CT scan slice of final foam

The total density of the HDPE foam is measured around 150 Kg/m^3. The aspect ratio distribution of cells in the foam produced in the method is $R=3.5 \pm 2.3$. As observed in Figure 1, it becomes clear that there is a distribution of aspect ratios from around R~1 to R~6, with the average and the majority of cells around R~3.5. Further research is going on to increase the anisotropy ratio via changing the material formulation and also cross-linking method from chemical cross-linking to electon-beam irradiation.

2.3 Benchmarking the mechanical properties of developed x-HDPE against anisotropic PES

According to Gibson and Ashby [3], the ratio of plateau stress between the growth direction and the orthogonal direction is related to, and scales with, the anisotropy ratio (at least for anisotropy ratios between 1 and 2). In Figure 2, compression testing shows the compression strength of the strongly anisotropic crosslinked HDPE material in the growth direction (length direction of the cells) is significantly higher than in the orthogonal in-plane direction. The ratio of the stress in the growth-direction to the stress in the in-plane direction as a function of strain is shown in Figure 3. It is notable that this ratio, corresponding to the average shape anisotropy ratio, is stable at 3.2 for most of the compressive plateau (that is, after the elastic region and initial force peak of the curve in the growth direction) in the range of strains from 0.1 to 0.4.

It is interesting to compare the mechanical properties of the experimental anisotropic crosslinked HDPE foam to the properties of the commercial PES foam discussed in the introduction. The compressive stress-strain curve of the PES foam with a shape anisotropy ratio of 10 is presented in Figure 4 along with the curves of the anisotropic HDPE foam. It is observed that the in-plane

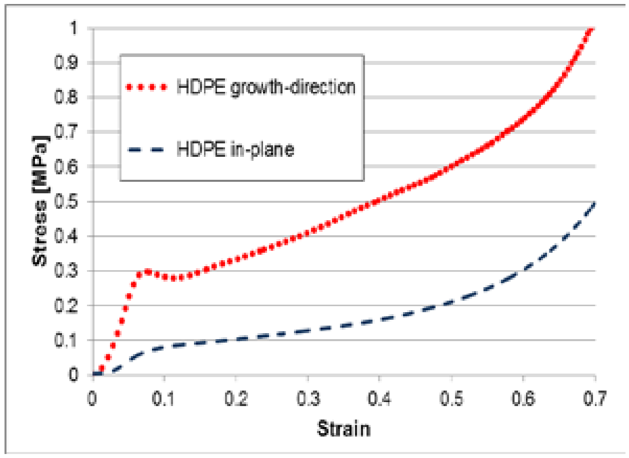

Figure 2. Compressive stress-strain curve of anisotropic cross-linked HDPE (R=3.5) in the growth (out-of-plane) direction, and the orthogonal in-plane direction

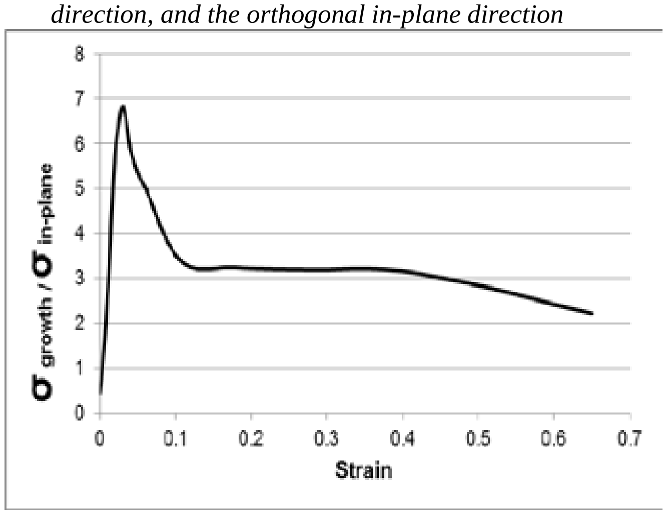

Figure 3. Ratio of stresses in the growth direction to the in-plane direction as a function of strain.

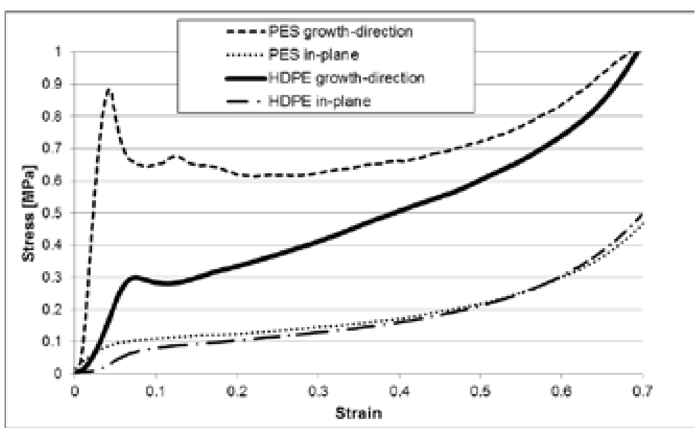

Figure 4. Comparison of compressive properties of commercial anisotropic PES (R=10) and experimental anisotropic crosslinked HDPE (R=3.5).

behavior of both foams is very similar; however the PES foam shows enhanced compressive strength in the through-the-thickness (or growth) direction due to its larger anisotropy ratio which confirms the necessity of increasing the anisotropy ratio of our developed cross-linked HDPE foam.

3. DEVELOPMENT OF TEST METHODS FOR CHARACTERIZATION OF FOAMS UNDER OBLIQUE LOADING AND EVALUATION OF ANISOTROPIC FOAM PROPERTIES

3.1 Shear-Compression test methodology

The test apparatus for this study was developed as an insert into an existing biaxial tensile/compression testing machine. In this design, two blocks of foam are glued to 3 steel sample frames (figure 5). This insert device allows for the testing of foams by the application of compression displacements along one machine axis and the application of shear displacements along the orthogonal axis. The displacement rate of each axis can be varied continuously from 0 (fixed) to 20 mm/min which allows for any resultant angle of deformation from simple shear to pure compression.

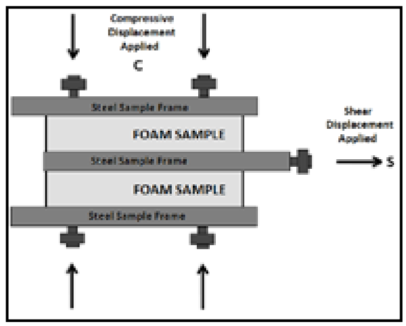

Figure 5. Graphical representation of the sample frame for shear-compression testing.

In this initial study, the behaviour of different foams is studied under shear-compression loading. Isotropic bicycle helmet grade expanded polystyrene (EPS) foam serves as the standard material in this study. This foam material has a density (ρ_f) of 75 kg/m^3. It is compared under shear-compression loading to a highly anisotropic commercial polyethersulphone (PES) foam with shape anisotropy ratio, R, of approximately 10. It is therefore expected to exhibit significantly lower shear resistance than the standard EPS material when tested under shear loading. The PES foam has a density (ρf) of 57 kg/m3. The materials are tested over various loading angles from 0º (simple shear) to 90º (pure compression). Oblique angles tested include 15º, 30º, 45º, and 60º. The output of these tests is two simultaneous curves: a compressive stress-strain curve and a shear stress-strain curve. Because the strain rates in the two directions will be different (except in the case of 45º), the curves are first analyzed over the time domain (stress vs. time) in order to pinpoint the time in which one of the curves reaches a critical point (i.e. the end of the elastic region, a maximum design load, etc). The corresponding point in time on the other stress-time curve is determined, and then both curves are analyzed up until the designated corresponding point in the strain domain. Designed corresponding point in the bicycle helmet application is related to the biomechanical limit for head injury which means the stress in the foam should not exceed 1.12 MPa [1,2].

3.2 Static shear-compression behavior of standard EPS and anisotropic PES foams under different angles

For application in bicycle helmets, the foam property that is of most interest is the energy absorption capacity of the foam up to the point that the stress exceeds a biomechanical limit. Stress is related to transmitted force, which is related to the acceleration or deceleration of the head during an impact. According to safety standards for bicycle helmet manufacture, which limit the maximum impact deceleration to 250 g, this critical stress level is approximated as 1.12 MPa.

Figure 6 shows the total energy that is absorbed (by adding the energies absorbed in compression and shear). We see that the helmet grade EPS generally absorbs more energy until a critical compressive stress (1.12 MPa) than the PES material. However, energy until a critical compressive stress only tells one side of the story.

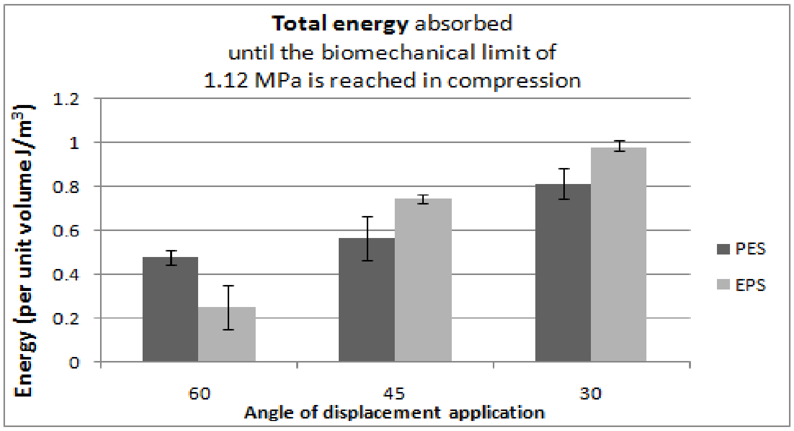

Figure 6. Total energy (from compression and shear) absorbed in the foam for both materials, under 3 different angles of displacement.

Figure 7 shows the shear stress when the compressive stress exceeds a critical value (1.12 MPa). This is interesting because it indicates the relative forces (tangential force at critical normal force) that would be transferred to the head in an oblique impact situation. We can see here that, while EPS absorbs more total energy than PES up until a critical compressive value, it does so at a higher shear stress, which may lead to an increase in brain injuries that are caused by tangential forces or rotational accelerations.

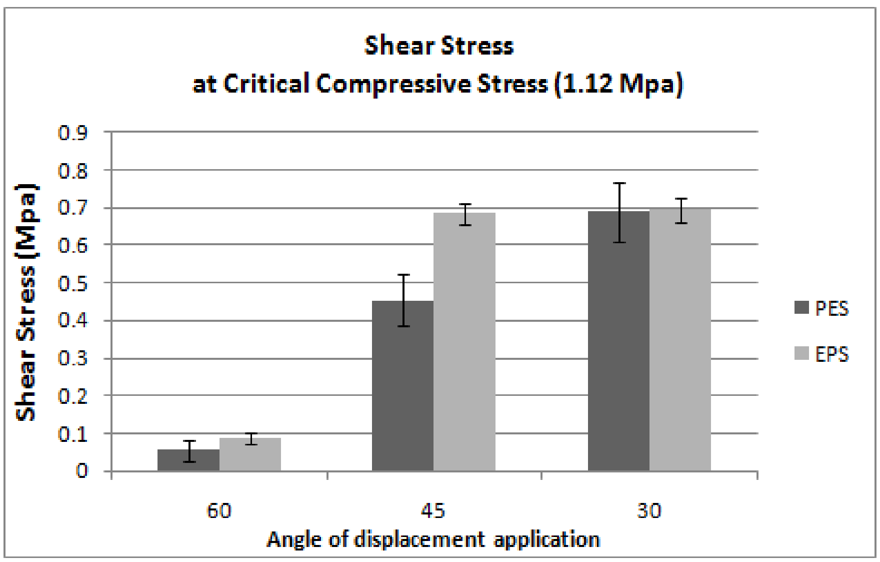

Figure7. Shear stress when the compressive stress reaches the critical value of 1.12 MPa.

3.3 Oblique impacts tests on standard EPS and PES prototype helmets

In this section, prototype helmets made with anisotropic PES cushioning foam were made and comparative experimental tests between a standard PES helmet and a prototype PES helmet have been performed on the *Oblique Impact Test Rig* of the Royal Institute of Technology (KTH) in Stockholm together with their spin-off company, MIPS [4]. Helmets were dropped from a height of 0.7m causing a vertical impact speed and tangential speed of 3.8 and 5.2 m/s respectively onto a target (shooting sled) moving at 6.8 m/s. The angle of impact is 28.5°. Three helmets of each type were impacted.

Figure 8 illustrates the peak translational acceleration for both EPS and PES prototype helmets. As observed, there is a decrease of about 39% in translational peak acceleration which is accompanied with an increase in pulse duration.

As shown in figure 9, peak rotational acceleration of the impact with the prototype PES helmet is reduced by 42% from 13,000 to 7,500 rad/s². However, just as in the translational accelerations, this is accomplished at a cost of the pulse time which increased from 6.6 ms to 9.3 ms.

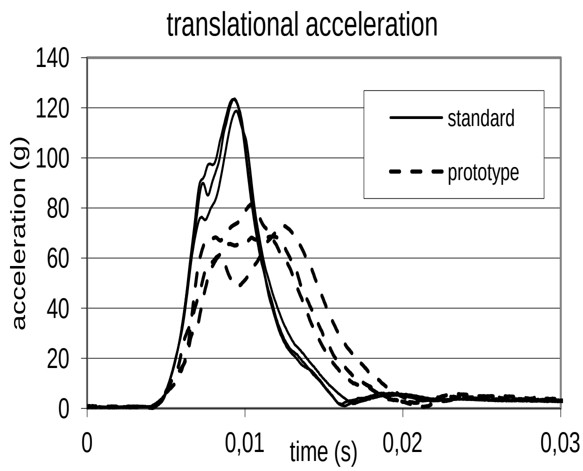

Figure 8: Resultant translational accelerations as measured under oblique impact loading (v_v = 3.8 m/s; v_v = 6.8 m/s; θ=28.5°) for standard commercial helmets (EPS) and prototype helmets (anisotropic PES).

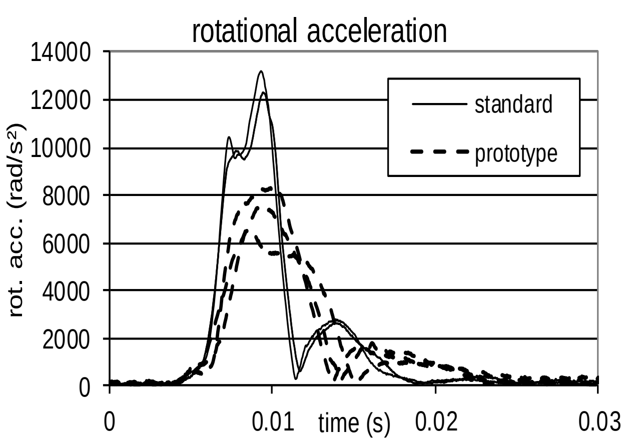

Figure 9 Resultant rotational accelerations as measured under oblique impact loading (v_v = 3.8 m/s; v_v = 6.8 m/s; θ=28.5°) for standard commercial helmets (EPS) and prototype helmets (anisotropic PES).

4. CONCLUSIONS

The current paper describes a novel foaming method that results in a foam with significant anisotropy (R>3) and can be foamed in complex shapes. On the other hand, a newly designed shear-compression apparatus is validated and standard isotropic EPS and strongly anisotropic PES foams were tested under different angles. The idea of a combined shear-compression test is to mimick an oblique impact condition. Shear stresses in the anisotropic PES foams under different angles in the combined shear-compression test are lower than for standard EPS. This is interesting for the bicycle helmet application in which high shear stresses should be avoided because they lead to high rotational acceleration.

The results of rotational impact experiments performed on PES helmet prototypes and standard EPS show, in terms of rotational acceleration reduction, that replacing standard EPS foam by strongly anisotropic PES leads to a decrease of rotational acceleration and additionally, translational acceleration of around 40%.

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