COMBINED SHEAR-COMPRESSION TEST TO CHARACTERIZE FOAMS UNDER OBLIQUE LOADING FOR BICYCLE HELMETS

Yasmine Mosleh[1]*, Kelly Vanden Bosche[1], Jos Vander Sloten[2], Ignaas Verpoest[1], Jan Ivens[1,3]
[1] Department MTM, Scalint Section, KULeuven, Kasteelpark Arenberg 44, 3001 Leuven, Belgium
[2] Department of Mechanical Engineering, Biomechanics Section, KULeuven, Celestijnenlaan 300, 3001 Leuven, Belgium
3 Department MTM, Materials Technology Cluster, KU Leuven, campus De Nayer, J.P. De Nayerlaan 5, 2860 Sint-Katelijne Waver, Belgium
*Yasi.mosleh@mtm.kuleuven.be

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Abstract
Cyclists during bicycle traffic accidents, are prone to oblique impact which leads to rotational accelerations. Rotational acceleration is known to cause significant brain injuries, and should be minimized. Foam materials inside bicycle helmets undergo a combination of shear and compression loads during oblique impact. Therefore, developing an apparatus and a test method which can apply a combination of shear and compression loads to the foam at the same time is of great importance. This testing method has a broad application which is not only limited to the foams for bicycle helmet applications but has general relevance to sandwich core materials in structural composites. In this paper, the shear-compression behavior of different types of foams under different angles, particularly 15°, 45° and 60° is investigated and compared to the standard EPS foam used in bicycle helmets. Shear stresses in anisotropic PES foams under different angles in the combined shear-compression test were lower than for standard EPS, which is favourable because they lead to high rotational acceleration. The peak rotational and translational accelerations of the PES prototype helmets were measured by a rotational impact test set-up and showed a dramatic decrease of around 40% compared to the reference EPS helmet, however at increased pulse duration.

1. Introduction

In bicycle traffic accidents, impacts are generally oriented at oblique angles resulting in rotational accelerations and in liner deformation inside the helmet with both a shear and compressive component. Primary studies show that rotational accelerations play an important role in traumatic brain injuries, like diffuse axonal injury (DAI), and acute subdural hematoma (ASDH) [1, 2]. Rotational acceleration is a result of the tangential component of the force in an oblique impact. The transfer of this force to the human head depends on the shear properties of the cushioning liner and needs to be minimized. One of the potential solutions for decreasing the rotational acceleration, proposed by the multidisciplinary helmet

research group of KU Leuven is using an anisotropic foam (a foam with elongated cells) with a cell orientation perpendicular to the surface of the head, instead of current standard isotropic EPS liner. This way the tangential forces transmitted to the skull-brain system can be limited due to the lower shear resistance of anisotropic foam compared to isotropic structures, thereby reducing rotational acceleration [3]. There is a need for test standards that take into account rotational accelerations during head impact. Yet at the same time, simpler test methods are needed to study the behavior of liner and helmet materials under combined shear-compression loading, allowing not only a fundamental understanding of the deformation and crush behavior of the material, but also to allow material selection and optimization without the need to first produce full helmets. For this purpose, a test method was developed in which the foam is loaded under combined shear and compression, with separate measurement of the shear and compressive force components. This test method is not only limited to bicycle helmet application but can be used for evaluation of any foam type under biaxial loading, for instance for sandwich panels. The multiaxial behavior of foams has not been studied extensively in the literature. However, there are failure criteria for foams under combined loading. But these are only strength based (Modified Tsai-Wu).
To verify the concept of using anisotropic foam for decreasing rotational acceleration, helmet prototypes made of anisotropic polyether sulfone (PES) foam as helmet liner were prepared. The rotational impact tests in this study were carried out on the “Oblique Impact Test Rig” equipment of the Royal Institute of Technology (KTH) in Stockholm, Sweden, [4]. Moreover, the results achieved by this test are analysed according to the head impact power (HIP) criterion, which is one of the very few general head impact criteria where the effects of both translational and rotational accelerations are both taken into consideration.

2. Experimental methodology

2.1. Biaxial shear-compression set-up and test method

The test apparatus for this study was developed as an insert into an existing biaxial picture frame set-up for textiles. 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 design of the apparatus is such that two blocks of foam are glued to 3 steel sample frames (figure 1). Each axis has an independent displacement actuator and an independent load cell. The displacement rate of each axis can be varied from 0 to 20 mm/min meaning that mimicking any resultant angle of deformation, from pure compression (angle 0°) to simple shear (angle 90°), is possible.

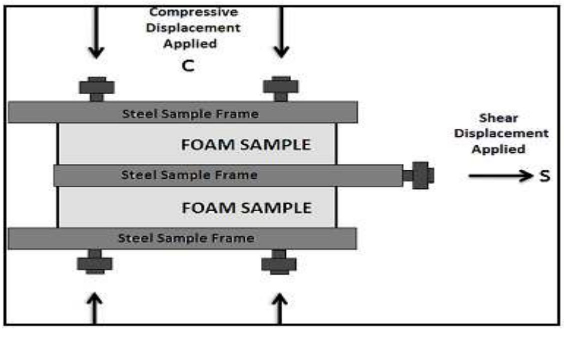


Figure 1. Representative illustration of biaxial shear-compression test set-up.

In this study, the behavior of 3 different foams under combined shear-compression loading has been studied. The three foams consist of commercial bicycle helmet grade expanded polystyrene (EPS) foam with a density (ρ_f) of 75 kg/m^3, EPS foam with density of 40 kg/m^3, and anisotropic polyether sulfone (PES) foam with anisotropy ratio (R = longitudinal cell size /cross-sectional cell diameter) around 10 and a density of 56 kg/m^3 . The PES foam has a similar relative density ρ_f/ρ_s (foam density / solid polymer density) as EPS 40 kg/m^3, which is around 0.04.Foam samples were cut into 5 cm x 5cm x 2.5 cm. Samples were glued to the test plates with two component fast epoxy glue (Araldite) with 5 min curing time.

Tests were performed at room temperature. Different compression/shear ratios were obtained by setting the corresponding ratio of compression displacement rate/ shear displacement rate (C/S), equal to the tangent of the loading angle. For example C/S=1 corresponds to 45°.The different materials were tested over various loading angles of 15º, 45º and 60º. Crosshead displacements were used to calculate strains. The accuracy of the crosshead displacement was verified by performing compression tests on reference foam materials on a standard calibrated tensile testing machine. Loads were measured using a load cell of 5 kN.

The output of these tests consists of two simultaneous curves: a compressive stress-strain curve and a shear stress-strain curve. Because the strain rates in 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 at which the stress in the compressive curve reaches a critical point.

The critical point is selected by extrapolating the linear acceleration limit of 250g (according to EN 1078) to a maximum compressive stress of 1.12 MPa [7]. The corresponding point on the shear stress-time curve is determined, and the total amount of energy absorption (both in shear and compression) up until the critical point and the maximum shear stress at the critical point are calculated.

2.2. Rotational acceleration test method

The rotational impact tests in this study were carried out on the “Oblique Impact Test Rig” equipment of the Royal Institute of Technology (KTH) in Stockholm [4]. The dummy head used in this set-up is a ”Hybrid III”, equipped with nine accelerometers, allowing the measurement of the three linear accelerations and the three rotational accelerations.

The data from the three accelerometers at the centre of gravity of the head, namely a_{0x}, a_{0y}, and a_{0z}, are taken as the translational acceleration components. The resultant acceleration experienced by the head would be according to equation 1.

$$a_r = \sqrt{a_{0x}^2 + a_{0y}^2 + a_{0z}^2} \qquad (1)$$

Software, which was written in-house by KTH, converts the translational accelerations to rotational accelerations (α_x, α_y, α_z) according to equations 2, 3, and 4:

$$\alpha_x = \frac{1}{2}\left(\frac{a_{y_{z1}} - a_{0_z}}{r_{y_{z1}}} - \frac{a_{z_{y1}} - a_{0_y}}{r_{z_{y1}}} \right) \qquad (2)$$

$$\alpha_y = \frac{1}{2}\left(\frac{a_{z_{x1}} - a_{0_x}}{r_{z_{x1}}} - \frac{a_{x_{z1}} - a_{0_z}}{r_{x_{z1}}}\right) \qquad (3)$$

$$\alpha_z = \frac{1}{2}\left(\frac{a_{x_{y1}} - a_{0_y}}{r_{x_{y1}}} - \frac{a_{y_{x1}} - ax}{r_{y_{x1}}}\right) \qquad (4)$$

A popular commercial children's helmet, the Sport Atlas Hardtop Mini (medium size), was chosen as the reference standard helmet. Prototype helmets were produced using the shells of the reference helmet, with the cushioning foam replaced by anisotropic PES; this in order to control the variables of geometry, contact friction, and retention system. To do this, first the EPS foam was removed from the commercial helmet. Then, the PES material (23 mm thickness) was cut and shaped via cold forming to fit inside the helmet.
Helmets were dropped from a height of 0.7m onto a target (shooting sled) moving at 6.8 m/s, causing a vertical impact speed and tangential speed of 3.7 and 5.2 m/s (reduced from 6.8 to 5.2 during collision) respectively. The angle of impact was 28.5°. Three helmets of each type were impacted.

3. Results

3.1. Shear-compression test

One of the determining parameters in a bicycle helmet application is the amount of absorbed energy of the foam per volume up to the point that the compressive stress exceeds a biomechanical limit of 1.12 MPa. Another parameter which will be compared for the 3 tested types of foams, will be the level of the shear stress component at the point where the compressive stress component reaches 1.12 MPa. The ideal foam in this application is the one which absorbs the highest amount of energy whilst experiencing the lowest peak shear stress up to the point where the compressive component of the stress reaches the biomechanical limit (to minimize the rotational peak acceleration). However, the current test method is in quasi-static mode which means it does not take into account the strain rate effects on foam materials which are present during an impact event. Therefore, in future, dynamic shear-compression tests will be performed.
For calculating the total amount of absorbed energy until the biomechanical limit is reached, the procedure below has been followed. First, the time at which the compression curve exceeds the critical level was determined (figure 2-a). The corresponding point in time in the shear curve was then found in figure 2-a. In the next step, the compressive and shear stress-strain curves were plotted, and the areas under the curve up until the biomechanical limit were calculated (Figure 2-b). The mentioned procedure was performed for each material, and for all three different angles.
Figure 3 (a-b) shows the compression and shear stress-strain curves of all 3 foams under an angle of 60°. The biomechanical compressive stress has been marked in the compression graphs and the corresponding shear stress and shear strain values when the compressive stress reaches the value of 1.12 MPa are also highlighted in the shear stress strain graphs. As it is

observed, the biomechanical limit in case of PES an EPS 40 is far into the densification region of the foam. The total absorbed energy of all 3 foams under different angles is plotted in figure 4a. Figure 4b shows the shear stress at the biomechanical compressive stress limit for all 3 foams under different angles.

As shown in figure 4, the total absorbed energy and shear stress at critical compressive stress are both a function of the angle of loading and increase when increasing the angle from 15° to 60°. As the shear stress component increases, all 3 foams absorb more energy. On the other hand, by increasing the angle of loading from 15° to 60°, there is an increase of the shear stress when the critical compressive stress is reached, indicating that the rotational acceleration will increase as well. The maximum shear stress level is an indication for the tangential force at the critical normal force transferred to the head. We see that under these static loading conditions, the helmet grade EPS 75 absorbs more energy until the critical compressive stress than the other materials.

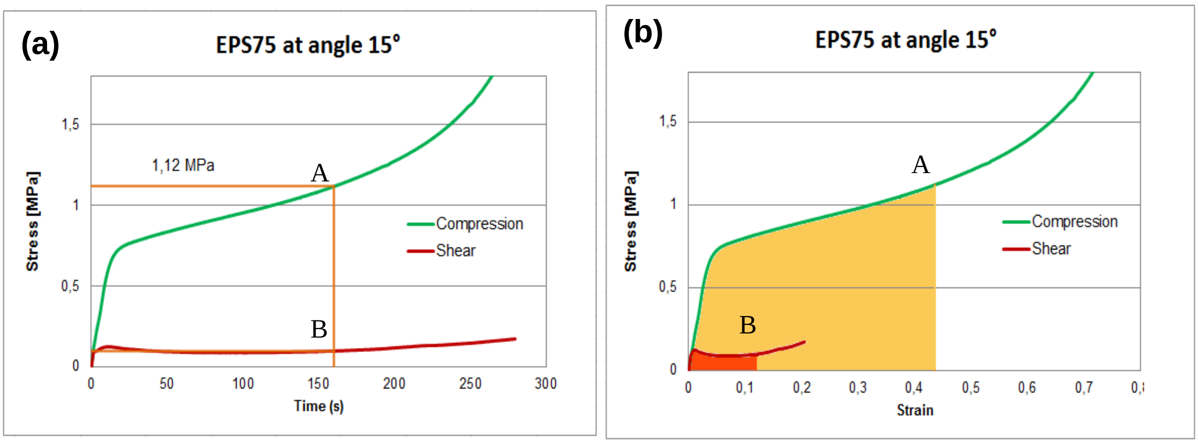


Figure 2. (a) Shear and compression stress-time curves of helmet grade EPS 75; the biomechanical limit is highlighted in both graphs as point A and B. (b) Energy under the stress-strain curves for both shear and compressive components up until the biomechanical limit.

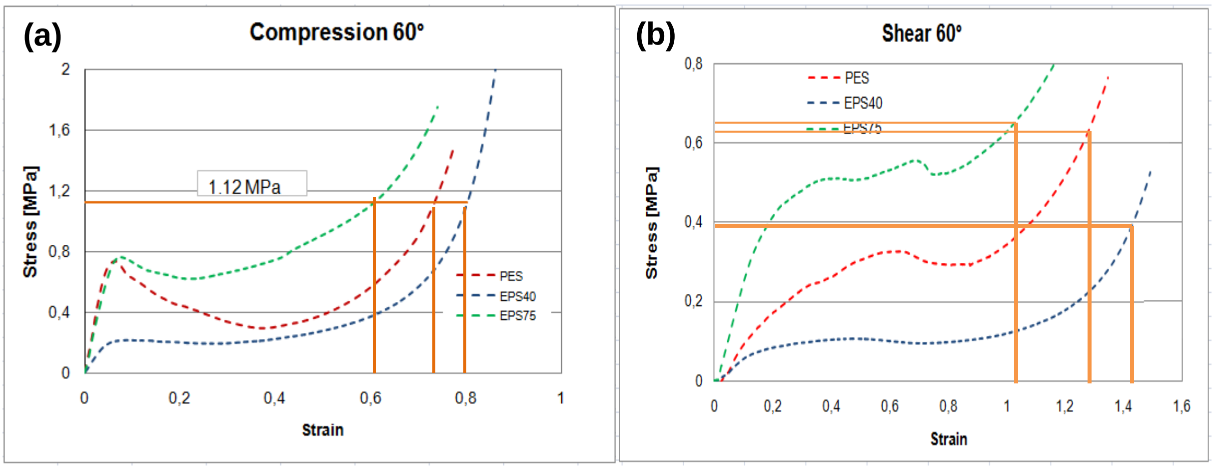
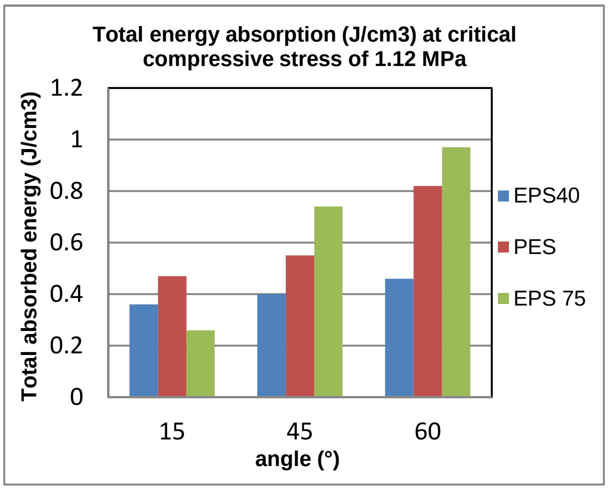


Figure 3. Comparative stress-strain curves of different foams; compressive component (a), and shear component (b); stress and strain values corresponding to biomechanical limit are highlighted.

However, in our application, we are interested in a combination of high energy absorption and low shear stress transferred to the head. Consequently, in this benchmarking, one cannot conclude that EPS 75 outperforms the anisotropic PES foam. The anisotropic PES foam shows lower shear stress forces, which is beneficial. For the interpretation of these results, one must also bear in mind that the tests are performed at much lower strain rates than what is observed during impact testing.

To evaluate if anisotropic foams are better in impact, a helmet prototype made of PES foam was made and subsequently tested by a rotational acceleration test set-up. The results were compared to these from a standard bicycle helmet with EPS liner of density around 75 kg/m^3. Results of the experiments will be discussed in the following section.



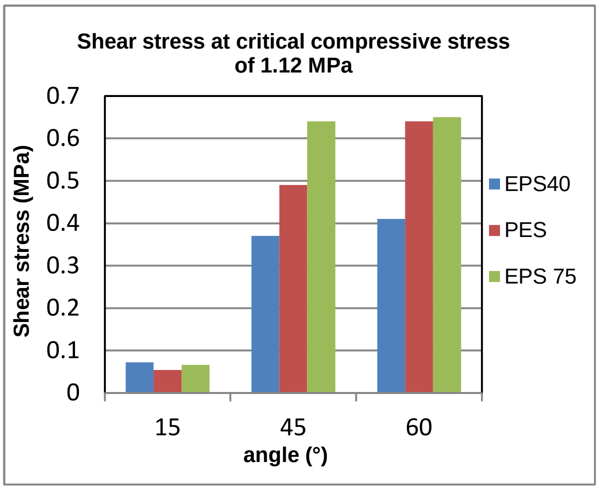


Figure 4. Total energy absorption of different foams versus loading angle up to the biomechanical limit (a); Corresponding shear stress component at biomechanical compressive limit for different foams versus loading angle (b).

3.2. Rotational acceleration

Figure 5 shows the linear (a) and rotational accelerations (b), as measured during the impact test. The results show that both the average peak rotational and translational acceleration of the prototype PES helmets are reduced by a factor of 39% and 42% respectively. However, this is accomplished at a cost of an increase in the pulse duration. While the EN 1078 only imposes a limit on the peak linear acceleration, it is well known that head traumas are caused by peak accelerations and by pulse duration. The Head Impact Criterion (HIC) takes into account both aspects, yet it does not incorporate the effect of rotational accelerations.

Head traumatic injuries are related to translational acceleration or rotational acceleration or a combination of both accelerations. The major injuries that are related to high translational accelerations are skull fracture, contusions, and subarachnoid hemorrhages. The lesions attributed mainly to rotational accelerations (and velocities) are acute subdural hematomas and diffuse axonal injury. Concussions are strongly connected to a combination of translational and rotational accelerations.

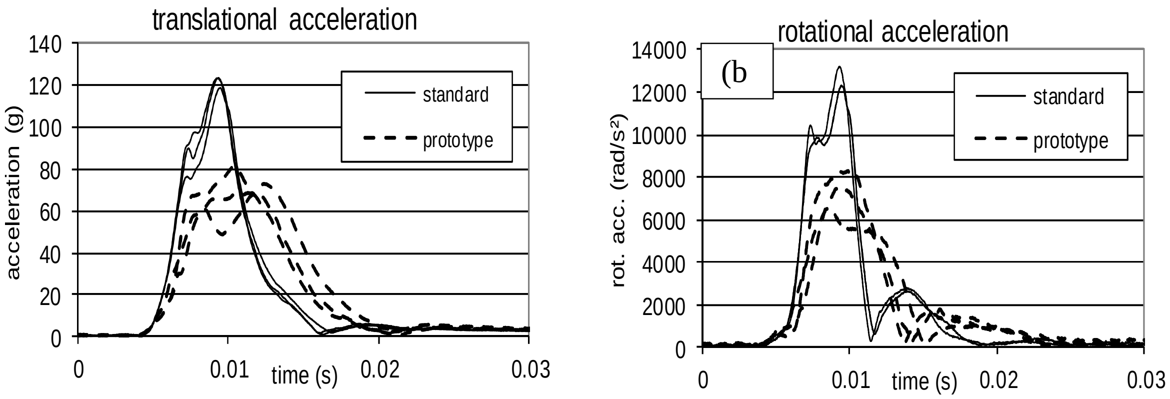


Figure 5. Resultant translational (a), and rotational (b) accelerations versus time under oblique impact loading (ν_v = 3.8 m/s²; ν_v = 6.8 m/s²; θ=28.5°) for standard helmets (EPS 75) and prototype helmets (anisotropic PES).

There are several proposed translational and rotational acceleration injury criteria which have been proposed by several researchers [5,6]. However, there are many arguments against the precision of them mainly because they consider the translational and rotational behaviours separately. Therefore criteria that combine linear and rotational accelerations are preferred.
In 2000, Newman *et al.* [7] proposed the head impact power criterion, which postulates that the maximum rate of change of kinetic energy (power) of the head can predict head injury.
The power of a moving, rotating body is given by equation 5:

$$P = \sum (ma * v) + \sum (I\alpha * \omega) \quad (5)$$

Therefore, the head impact power (HIP) is given by equation (6):

$$\begin{aligned} HIP = & \, ma_x \int a_x(t)dt + ma_y \int a_y(t)dt + ma_z \int a_z(t)dt \\ & + I_{xx}\alpha_x \int \alpha_x(t)dt + I_{yy}\alpha_y \int \alpha_y(t)dt + I_{zz}\alpha_z \int \alpha_z(t)dt \end{aligned} \quad (6)$$

Where m represents the mass of the head plus the helmet (kg), a stands for translational acceleration (m/s²), I is the moment of inertia (m^4), and α is the rotational acceleration (rad/s²). In their initial proposal of using the HIP to predict injury [7], Newman et al. determined that a HIP_{max} of 12.8 kW predicts a 50% chance of concussion, considered a mild traumatic brain injury. It can clearly be seen in Table 1 that the prototype PES helmets were significantly below this level, whereas the reference EPS helmets were above.

28.5° *(0.7m drop height)*					
Sample	*#*	*HIPmax (kW)*	*HIPmax (ave) (kW)*		
	1	15.68			
standard (EPS)	*2*	13.41	**14.77**	+/-	1.198
	3	15.21			
	1	6.92			
prototype (PES)	*2*	6.78	**7.31**	+/-	0.806
	3	8.24			

Table 1. HIP_{max} values of oblique experiments carried out on standard EPS helmets and prototype PES helmets.

4.Conclusions

A new test method for combined shear-compression has been proposed. Three different foams were tested at low strain rates to validate the shear-compression apparatus. Standard isotropic EPS and strongly anisotropic PES foams were tested under different angles of 15°, 45°, and 60°. The idea of a combined shear-compression test is to mimick an oblique loading and to probe if it can be a proper way of evaluation of small foam coupons. Shear stresses in anisotropic PES foams under different angles in the combined shear-compression test were 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 peak rotational and translational accelerations of the PES prototype helmets showed a decrease of around 40% compared to the reference EPS helmet. However, they did so at the cost of increased pulse duration.
The large difference between the PES and EPS75 foams that was observed in helmet impact testing, was not found in the static tests. The most important difference is the large difference in strain rates. Therefore, a modified test set-up is under development that can be used over a wide range of strain rates, from static to impact test conditions.

Acknowledgement

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