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Towards safer helmets: characterisation, modelling and monitoring

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Abstract

Bike and ski helmets are mainly made up of two layers: the external shell and the foam liner. The foam liner, typically made of expanded polystyrene (EPS) or polypropylene (EPP), is asked to provide energy absorption in case of impacts. Standard helmet design requires the foam to maximize this energy absorption, thus achieving large deformations (up to 25% in compression) while maintaining the stress level below a threshold value. To optimize the helmet construction in terms of foam composition, structure and density, reliable numerical models are required, which in turn need to be fed with accurate experimental data.

A characterisation of several foams was performed, including EPS and EPP having varying densities, under tensile and compressive stress states at varying strain rates. Typical mechanical parameters (elastic moduli and plateau stress in compression, Poisson's ratio) were compared with literature data and applicability of existing models to experimental results was discussed. A marked strain rate dependence – very important for impact applications – was accurately described using the Nagy phenomenological model. The foam microstructure was investigated using scanning electron microscopy (SEM) to assess structural changes before and after compression. The aforementioned mechanical features were then adopted in a rate-dependent constitutive law for crushable foams, to model the shock attenuation properties of helmets and validate the approach against available data.

Finally, a microelectromechanical system based in-helmet wireless micro monitoring system was developed and inserted in a helmet prototype. The system is capable of acquiring impact load spectra, providing valuable information to investigate generic impacts with varying angles and energy. In particular, it can monitor the effect of repeated micro-impacts on the residual energy absorption characteristics of the foam.

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Keywords: traumatic brain injury (TBI); polymeric foams; numerical modelling; in-situ monitoring

1. Introduction

In recent years, sport injuries have attracted more and more interest, not only because of the short-term impact on athletes' performance but also because of the costs of possibly long rehabilitation periods and difficulties to fully recover. One striking example in this sense is represented by the Head Health Initiative of National Football League [1].

Focusing on traumatic brain injuries (TBIs) only, the Centre for Disease Control and Prevention (CPSC) estimated that around 450,000 sports-related head injuries were treated in U.S. hospital emergency rooms in 2009 [2]. Among the most impressive data is that children in the range of 10 to 14 years old show the highest rate of emergency visits associated with such sports-related TBIs. The actual incidence of head injuries may be potentially higher, as not-severe cases are typically self-treated. In Italy, a survey conducted by the Istituto Superiore di Sanità also revealed that every year around 30,000 accidents occur in ski areas, of which 25% involve underage children and 10% lead to mild TBIs [3].

In case of impacts, helmets have to prevent or reduce the outcome of mild TBIs thanks to a kind of cushioning effect, mainly linked to the mechanical behavior of their inner liner. The level of the impact-induced acceleration hitting the athlete brain is reduced by mechanisms of energy dissipation occurring while the mentioned liner deforms and possibly locally fails.

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Accordingly, international standards like [4-6] provide requirements for the shock absorbing capacity in terms of acceleration peaks in the range of 250-300 g (g being the gravity acceleration) depending on country and sport, all measured in case of (guided) falls of headforms wearing the protective helmet. Not much care is usually devoted to the impact duration and to rotational accelerations, which were instead highlighted as further important parameters to classify the severity of the impact in, e.g. [7-8].

In this work, the focus is on bike and ski helmets that are basically made of a hard outer shell of polycarbonate, and a soft inner liner of polymeric foam, typically expanded polystyrene. With the goal of either enhancing the protection level, or reducing size and weight of the helmet to improve the athlete's comfort at the same safety level, the study was developed following three main research lines. First of all, tensile and compressive properties of polymeric foams were characterized in relation to their density and strain rate, the foam being the helmet constituent which is mainly responsible for cushioning. These data then allowed finite element numerical modelling of the whole helmet to be performed in order to describe its response to impacts. In parallel, a novel monitoring system based on microelectromechanical systems (MEMS) was designed and realized to perform measurements on existing helmets and new prototypes.

2. Characterisation

2.1. Experimental

Expanded Poly-Propylene (EPP) and Expanded Poly-Styrene (EPS) foams with varying relative densities were considered; materials nominal densities are reported in Table 1. These foams were produced from pre-expanded beads which were subsequently moulded into sheets/blocks.

Table 1. Materials.

Material	Expanded polystyrene				Expanded polypropylene							
Density [kg/m^3]	10	13	19	25	20	35	55	60	75	90	110	120
(Relative density [-])	(0.01)	(0.013)	(0.019)	(0.025)	(0.022)	(0.039)	(0.061)	(0.067)	(0.083)	(0.100)	(0.122)	(0.133)

Uni-axial compression and tensile tests were run on screw-driven dynamometer under crosshead displacement control conditions. All the tests were performed at 23°C temperature and 50% relative humidity. Five samples per density were tested.

EPS compression specimens were cut having nominal dimension of 40x40x40 mm, while EPP samples nominal dimensions were 13x13x13 mm. Strain rate dependence was investigated at three nominal values: 3×10^{-3}, 3×10^{-2} and 3×10^{-1} s^{-1}. A 10MPixel camera was used for the measurement of Poisson's ratio in compression.

Tensile tests were performed on dumbbell specimens having gauge length of 70 mm, width of 13 mm and thickness of about 12 mm; a fixed strain rate of 3×10^{-3} s^{-}1was adopted. Axial strain was measured with a Trio VE5000 video-extensometer.

To investigate foam morphology, samples were broken by bending a notched bar immersed in liquid nitrogen. Fracture surface were then metallized with palladium for scanning electron microscopy (SEM) observation.

2.2. Results

A good repeatability was observed in both tensile and compression tests, with exception of EPP compressive elastic modulus data, which presented a particularly high scatter. Poisson's ratio in compression was measured to be zero within experimental accuracy for EPP and EPS foams up to 0.6 strain.

The foam compression behaviour is consistent with the expected behaviour: a linear elastic region was followed by a collapse plateau and a final densification. Elastic moduli were evaluated in the initial region and plateau stresses were defined at 0.25 strain. In Fig. 1. mechanical properties are plotted against density and compared to the predictions from Ashby's model [9], which are given in Eq.s (1-2):

$$\frac{E^*}{E_S} \approx \Phi^2 \cdot \left(\frac{\rho^*}{\rho_S}\right)^2 + (1-\Phi)\cdot\frac{\rho^*}{\rho_S} + \left(\frac{p_0}{E_S}\right)\cdot\frac{(1-2\cdot\nu^*)}{\left(1-\rho^*/\rho_S\right)} \tag{1}$$

$$\frac{\sigma^*_{pl}}{\sigma_y} \approx 0.3\cdot\left(\Phi\cdot\frac{\rho^*}{\rho_S}\right)^{3/2} + 0.4\cdot(1-\Phi)\cdot\frac{\rho^*}{\rho_S} + \left(\frac{p_0-p_{at}}{\sigma_y}\right) \tag{2}$$

where E^* is the foam modulus; E_S stands for the solid material elastic modulus; Φ is the volume fraction of solid in the edges; ρ^* is the foam nominal density; ρ_s is the base material density; p_0 is the pressure inside the cells; ν^* is the foam Poisson's coefficient; σ^*_{pl} is the plateau stress; σ_y is the solid material yield stress and p_{at} is the atmospheric pressure.