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Modeling of non-elastic properties of polymeric foams used in sports helmets

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Abstract

Personal protection equipment for the head used in various sporting disciplines must meet at least three fundamental criteria: safety, comfort and aesthetics. Safety is understood as protecting as much head area as possible and, in case of a crash, spreading the resultant forces over the maximum area and absorbing as much impact energy as possible. After the occurrence of non-elastic deformations, this energy is absorbed by the helmet shell and protective liner, most commonly made of polymeric foams. Non-elastic properties of the foams are evaluated with the use of descriptors of energy absorption capability.

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Keywords: helmets; protective foams; non-elastic properties;

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1. Introduction

Sporting helmets are composed of a shell, a protective liner, and a retention system. The retention system has a function of maintaining the helmet in a stable position. The main task of the shell is to distribute the impact-induced stress over the maximum area possible. The protective liner, typically made of polymer foams, e.g., expanded polyethylene (PE) or polystyrene (EPS), absorbs the impact energy so as to minimize the accelerations and forces acting on the head [1]. This paper aims at analysing the impact energy absorption capability of polymeric foams.

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2. Analysis of mechanical properties of foam materials used in helmets

Polymer foams have open- or closed-cell structures. Their mechanical properties are dependent on their structure and on the type of polymer of which the cells are made [2]. The mechanisms of cell edge and wall deformations are major factors in the mechanical properties of foams. Another factor is a ratio of the volume and amount of open cells to those of the closed cells. The cells can have a shape similar to a cube [3] or polyhedron with eight hexagonal and six square faces, as in the so-called Kelvin model. One of the best known analytical models of foam mechanical properties was described in [3], where geometric shapes of real cells were replaced with cubes, which allowed relating the mechanical characteristics to the relative density of the foams. Elastic properties of a closed-cell structure result from elastic deformations of the edges (beams) and walls (thin-walled plates) as well as from the pressure of gas present in the cell. Stresses in the elastic range cause 3% to 5% strains. Young's modulus of the foam can be expressed as [3]

$$\frac{E_f}{E_s} \approx \Phi^2 \left(\frac{\rho_f}{\rho_s}\right)^2 + (1-\Phi)\frac{\rho_f}{\rho_s} + \frac{P_0(1-2\nu_f)}{E_S\left(1-\frac{\rho_f}{\rho_s}\right)} \tag{1}$$

where: Φ - is the ratio of the material mass contained in the cell edges to the mass of the cell, E_S- is Young's modulus of the polymer, E_f- is Young's modulus of the foam, v_f- is Poisson's constant, ρ_f- is the foam apparent density, ρ_S- is the density of the polymer, P_0- is the initial pressure of the gas contained in the foam cell, and $R=\rho_f/\rho_S$ – is the relative density of the foam. In the elastic strain region, the amount of absorbed impact energy is small. After exceeding the elastic limit, deformations of cell edges and walls occur in the plastic region and the gas pressure increases. These deformations make the cell walls collapse progressively. The walls of some of the cells meet and touch. A further, even slight, increase in stress produces considerable strains up to 70%. This is the main mechanism of impact energy absorption by polymer foams. The stress-strain behaviour can thus be written as [3]

$$\sigma = \sigma_{Yf} + \frac{P_0\,\varepsilon}{1-\varepsilon-R} \qquad for\ \ \varepsilon_{yf} < \varepsilon < \varepsilon_D\left(1-\frac{1}{D}\right) \tag{2}$$

where: σ_{Yf}– is the flow stress of the foam at compression, ε_{yf}– is the flow strain at compression, ε_D - is the strain at complete densification of the foam. Further loading causes the majority of cells to crush at a small increase in strain but with exponential rise in stress and loss of cohesion.

$$\sigma = \sigma_Y \frac{1}{D}\left(\frac{\varepsilon_D}{\varepsilon_D-\varepsilon}\right)^m + \frac{P_0\varepsilon}{1-\varepsilon-R} \quad \text{for}\ \ \varepsilon > \varepsilon_D\left(1-\frac{1}{D}\right) \tag{3}$$

where: D, m – coefficients (e.g., for EPS D=2.3 and m=1).

Investigations carried out after impact tests showed that the layer of the material closer to the impact surface are subject to higher strains. This makes the thickness of the impact absorbing material an important structural parameter [4]. The compressive stress applied dynamically has a minor effect on Young's modulus and quite a noticeable effect on the number of crushed cells. When the foam density increases, the values of Young's modulus and flow stress also increase at decreasing strain value that starts the exponential stress rise. Foams with low density absorb impact energy in a large volume of the material adjacent to the impact site. Foams with high densities absorb this energy through brittle crushing of the cells that are near the impact site. These foams absorb larger amounts of energy than low-density foams (at the same strains) but transfer to the head higher maximum forces and accelerations that act near the impact site. To be able to absorb the same amount of energy, low-density foam has to be thicker. Elements made of foams of insufficient density may be destroyed under a high-energy impact and fail to protect the head. In the case of foams whose density is too high, a low-energy impact will fracture a certain number of cells but the effect sufficient to reduce the forces acting on the head will not occur. In this situation the foam acts as an obstacle and may itself pose a serious risk of head injury.