Material property determination of the lining layers of a versatile helmet

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Abstract. This paper deals with material property identification of a helmet lining consisting of an outer layer of an expanded polystyrene (EPS) and inner layer of an open-closed cell foam (OCCF). A combined numerical simulation and experimental testing was used for the material property identification. Compression and drop tests were performed. The ABAQUS finite element commercial code was used for numerical simulations in which the OOCF was modelled as a rate dependent viscoelastic material, while the EPS as a crushable foam. The reaction force time histories coming from the numerical simulation and the experiment have been used as a criterion for material parameter determination. After the identification of the material properties, numerical drop-tests were used to study the behaviour of a plate and a conical composite OOCF and EPS liners to decide which of them suits more for the helmet.

Keywords: helmet liner, foam, expanded polystyrene, drop test, identification

1 Introduction

Common property of composites and foams is their low specific weight. A utilization of these two materials in suitable combination allows the creation of lightweight impact energy absorbers where composite layers advantageously distribute impact forces into foam layers. Expanded polystyrene (EPS) is a crushable foam which, in case of compression, absorbs energy during the plastic deformation stage when the stress reaches a roughly constant plateau value (plateau region in force compression diagram) over a large percentage of total strain (typically 60-70%)[1]. Open-closed cell foam (OCCF) is modern energy absorbing material having different viscoelastic mechanical response according to strain rate (produced e.g. by D3O®).

The aim of this work is the identification of parameters of material models which would sufficiently characterize the foams for the thickness determination of a versatile sport helmet lining using the finite element method (FEM) model. The versatile sport helmet having a removable chin guard and a peak is shown in Fig. 1. The helmet should be suitable for cycling, inline skating, skateboarding, horse riding, paragliding and other similar sports.

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It has outer carbon fibre reinforced plastic (CFRP) shell with thickness of 2 mm (more detail description of the composite shell and its modelling can be found in [1]). The helmet lining consists of an outer layer of the EPS and inner layer of the OCCF.
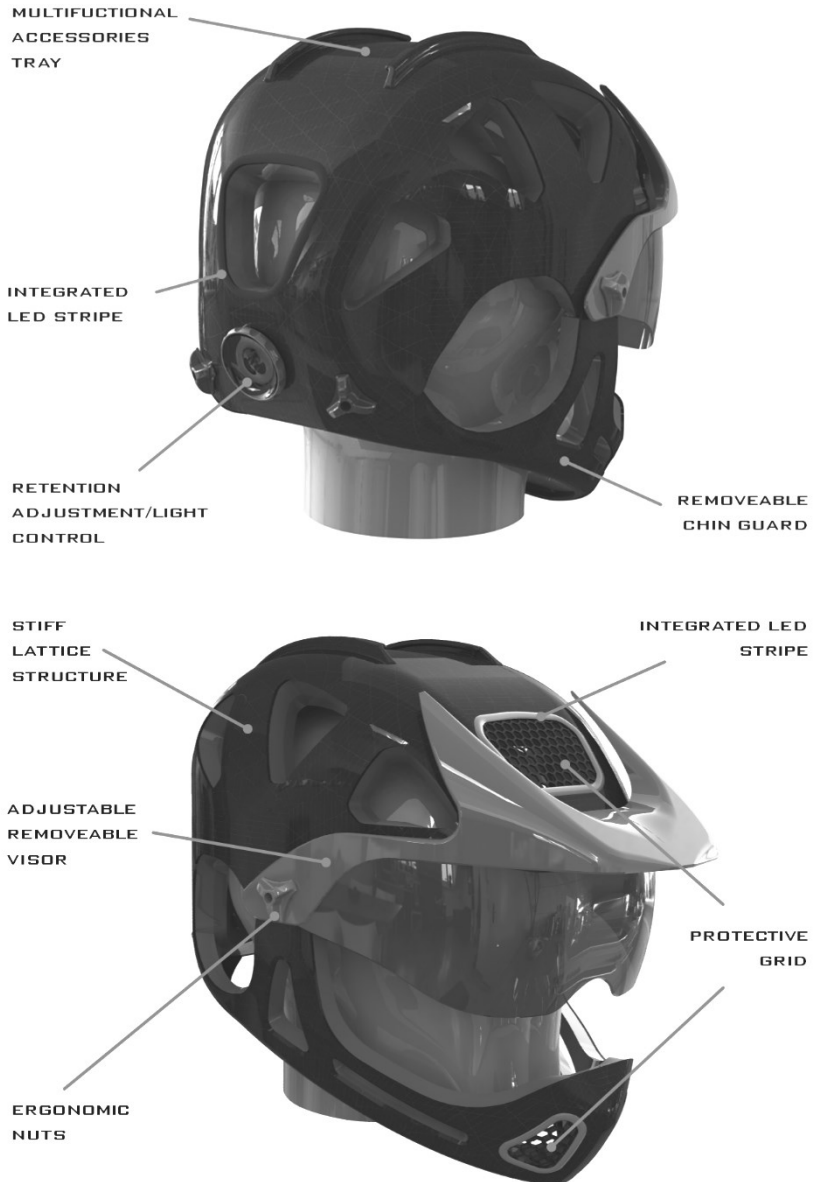

Fig. 1. Versatile sport helmet

2 Experiments

Compression and drop tests were performed using a Zwick/Roell Z050 universal testing machine and a drop tower designed by the authors [3], respectively. The temperature was 23 ± 1 °C, the atmospheric moisture was 50 ± 6 %. Rectangular samples of the foams measured 20×20 mm and had a height (thickness) of 10 or 20 mm. Densities of the EPS and OCCF were 100 kg/m^3 and 500 kg/m^3, respectively.

Two identical loading cycles were applied on the samples in the compression test using flat clamping grips. The samples were loaded and unloaded with velocity of 10 mm/s. Value of nominal strain 0.35 was prescribed as the upper limit. After reaching the upper limit of nominal strain, the testing machine maintained the strain for one minute. Zero strain was maintained also for one minute between the loading cycles.

The total weight of impactor were 246 g or 350 g in dependence of the used impactor head (spherical or flat head). The impactor was equipped by KISTLER 9712B load cell that enabled to record the time-force response (contact force) between the impactor head and a tested sample. The radius of the spherical head of the impactor was 15 mm (detailed description of the impactor geometry can be found in [3]), the flat head of the impactor had a square contact surface with side length of 30 mm. Reached impact velocity v varied from 1 m/s to 5.5 m/s. The time-displacement response (impactor displacement during the impact) was investigated using the Micro-Epsilon optoNCDT laser. Data were supplemented with images from the high-speed camera OLYMPUS i-SPEED 2 (frame rate 2000 fps).

3 Numerical simulations

The tests were simulated in the FEM system ABAQUS. The crushable foam material model was used for the EPS tests simulations. In this model, the contribution of the mean stress on the yield function is realised through a material parameter known as a shape factor [4, 5]. It defines the aspect ratio of the elliptical stress. The yield function Y is given by

$$Y = \sqrt{q^2 + \alpha^2 p^2} - B = 0, \qquad (1)$$

where q is the von Mises equivalent stress and p is the mean stress. B defines the size of the yield ellipse and is given by

$$B = \alpha p_c = \sigma_c \sqrt{1 + (\alpha/3)^2}, \qquad (2)$$

where p_c is the yield strength in hydrostatic compression. σ_c is the absolute value of the yield strength in uniaxial compression.

$$\alpha = \frac{3k}{\sqrt{9-k^2}}, \qquad (3)$$

is the shape factor of the yield surface and k is the ratio of initial yield stress in uniaxial compression and initial yield stress in hydrostatic compression.

The Prony series were used to describe viscoelastic behaviour of the OCCF. The relaxation function was assumed in the normalized series expansion [6]

$$g_R(t) = \frac{G_R(t)}{G_0} = 1 - \sum_{i=1}^{N} g_i\left(1 - e^{-t/\tau_i}\right), \qquad (4)$$

where G_R is the stress relaxation shear modulus and G_0 is the instantaneous shear modulus. N, g_i, and τ_i, $i = 1, 2,…, N$, are material parameters. Since long-term Young's

modulus E_{OCCF} was identified, the instantaneous Young's and shear moduli can be determined from

$$G_\infty = G_0(1 - \textstyle\sum_{i=1}^{N} g_i) \tag{5}$$

and

$$E_{\text{OCCF}} = 2G_\infty(1 + \nu_{\text{OCCF}}), \tag{6}$$

where ν_{OCCF} is the Poisson's ratio of the OCCF.

The finite-strain forms of the models were considered. Parameters of the material models were identified based on comparison of data from the tests and the numerical simulations using an optimization algorithm in optiSLang software. Since the thickness of the helmet lining can be determined using numerical simulations of helmet drop tests according to standards ČSN EN 1078 (Fig. 2) and ČSN EN 1385, the emphasis was placed on the fitting of the drop tests. Moreover, the OCCF parameters were identified separately for four different impact velocities of the flat impactor.
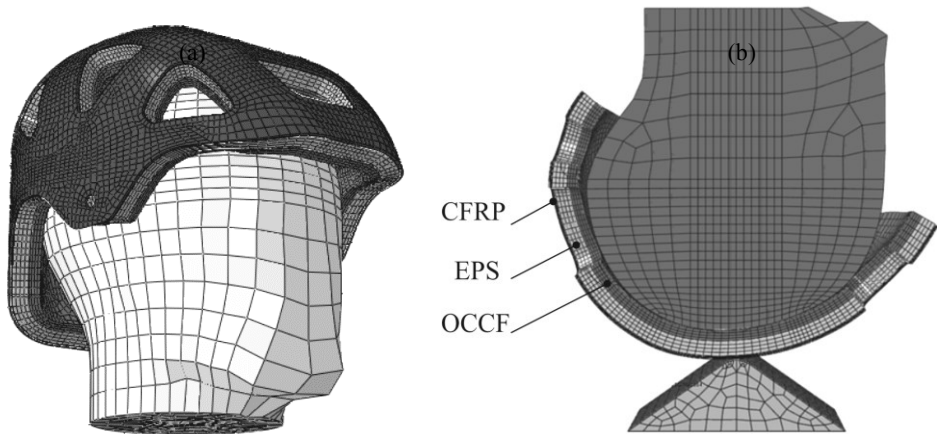

Fig. 2. FEM model of helmet (a), numerical simulation of one of helmet drop test according to ČSN EN 1078 (b)

Performed simulations were supplemented by the numerical drop test of a sample representing one cell of helmet foam liners. Two types of samples having different shapes of the interaction surface (see **Fig. 3**) were tested using a virtual flat impactor.
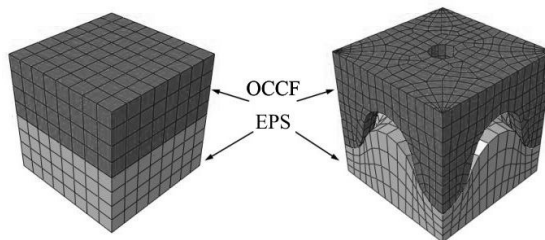

Fig. 3. "Plate" (left) and "conical" (right) design of liners

4 Results and discussion

Different mechanical behaviour of the EPS and the OCCF is obvious from the compression test (Fig. 4(a)). The EPS absorbed a great amount of energy in first loading only. Size of the hysteresis loop in case of the second EPS loading was nearly negligible, which is in agreement with [7]. Size of the first loading hysteresis loop in case of the OCCF compression test was lesser, nevertheless, OCCF behaviour was almost identical in both loading cycles.

Average maximum forces measured in the drop test using the flat impactor are shown in Fig. 4(b). It is obvious that the value of the maximum force increased with the impact velocity more significantly in case of the OCCF.
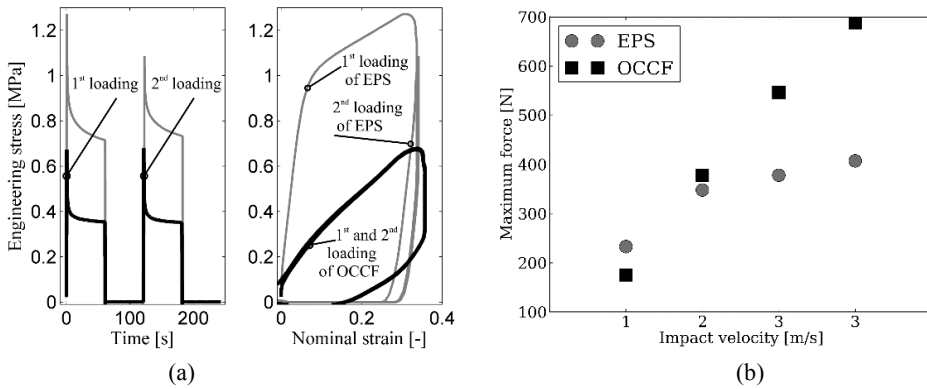

Fig. 4. Typical dependences of engineering stress on time and nominal strain in compression test (a), maximum forces measured in drop test using flat impactor (b)

Identified parameters of the material models are listed in Tables 1-2. The EPS parameters are: Poisson's ratio ν_{EPS}, Young's modulus E_{EPS}, compression yield stress ratio k, initial yield stress S_0, yield stress S_1 corresponding to uniaxial plastic strain ε_{p1}, and yield stress S_2 corresponding to uniaxial plastic strain ε_{p2}. The OCCF parameters are: Poisson's ratio ν_{OCCF}, Young's modulus E_{OCCF}, normalized model parameters g_1, g_2 and g_3, and relaxation times τ_1, τ_2 and τ_3. It is obvious that the OCCF parameters differ based on the impact velocity (energy). Therefore, the experimental values were approximated as energy dependent functions in the numerical simulations. The comparison of the force response in case of the OCCF drop test using the spherical impactor for the impact velocity $v = 4.5$ m/s is shown in Fig. 5.

Table 1. Identified parameters of EPS

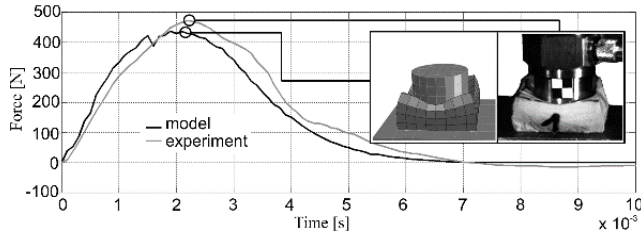| Param.	ν_{EPS}	E_{EPS}	k	S_0	S_1	ε_{p1}	S_2	ε_{p2}
Units	-	MPa	-	MPa	MPa	-	MPa	-
Value	0.07	37.7	1.14	0.53	0.85	0.11	1.2	0.32

Fig. 5. OCCF drop test using spherical impactor for velocity of 4.5 m/s

Table 2. Identified parameters of OCCF

Param.	Units	*v* [m/s]			
		1	**2**	**3**	**4**
v_{OCCF}	-	0.38			
E_{OCCF}	MPa	1.99	0.69	0.62	0.55
g_1	-	0.67	0.54	0.56	0.65
τ_1	μs	103	48	43	11
g_2	-	0.23	0.43	0.41	0.30
τ_2	μs	242	113	101	25
g_3	-	0.046	0.023	0.023	0.043
τ_3	μs	1693	791	708	204

The numerical drop test shown that a significant weight save can be achieved using the "conical" design of the liner. Fig. 6 shows the comparison of the force impact response in case of the "plate" and the "conical" design of the liner. It is obvious that differences between maximum forces are not significant, however, the difference of weight is 20 %. Moreover, the "conical" design has lower stiffness in tangential direction, which is important for the brain protection [8].
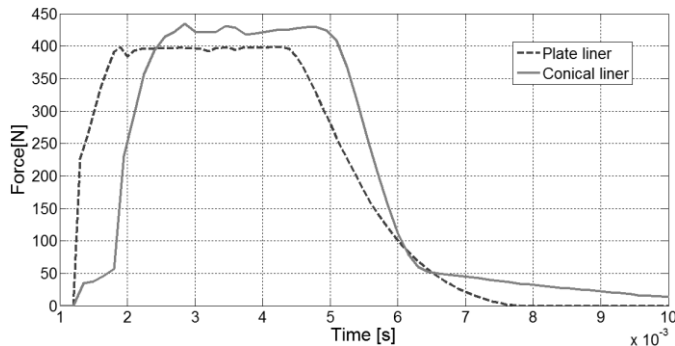

Fig. 6. Comparison of the plate and conical liners design in numerical drop test for velocity of 4 m/s

Numerical simulations of helmet drop tests according to standards ČSN EN 1078 and ČSN EN 1385 showed that the thickness of the EPS layer must be at least 10 mm and the thickness of the OCCF layer must be at least 7 mm (for analysed type of helmet).

Conclusions

The crushable foam material model and the Prony series were used to describe mechanical behaviour of the EPS and the OCCF, respectively. The parameters of the material models were identified, with the emphasis on the fitting of the drop tests. The "conical" design of the helmet liner allows weight savings of up to 20 % and it is also more suitable because of its lower tangential stiffness. Based on the results of the numerical simulations, the thickness of the versatile helmet lining must be at least 17 mm.

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