DEVELOPMENT AND VALIDATION OF A STRAIN-RATE AND TEMPERATURE DEPENDENT CRUSHING MODEL FOR EXPANDED POLYSTYRENE FOAM APPLIED IN BICYCLE HELMETS

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Abstract
This research is aimed at developing a strain-rate and temperature dependent crushing model for expanded polystyrene foam (EPS). EPS is a closed cell foam that is mainly used in applications where energy absorption is critical such as in bicycle helmets. It has good mechanical properties and offers at the same time a reduction on material costs and weight. The main purpose of this work is to study the dynamic properties of EPS foams by deriving stress-strain curves at different strain rates and temperatures. Further objective is to study the compressive loading of EPS foam in bicycle helmets by finite element (FE) simulation and to create a model to simulate the behavior of the EPS foam. Finally, it is also aimed to establish a comparison of the FE analysis in LS-DYNA with the dynamic compression test results. The stress-strain curves for different strain rate and for different temperatures are the output of this experimental test program. During compression, no internal damage was observed in CT-scans. This result allowed the creation of a uniform foam model. The methodology in this research allows developing more accurate FE models for bicycle helmets that can be used during a design process.

1. Introduction

Closed cell foams are often used in sports helmets to allow energy absorption during a crash [1,2]. Expanded polystyrene foam (EPS) is the mostly used material for bike helmets as it allows to design lightweight and cost effective helmets with an open structure. Several remarkable properties have been noted for EPS foam such as: light weight, good thermal insulation, moisture resistance, durability, acoustic absorption and low thermal conductivity, reduction on material costs, excellent energy dissipation properties [3].

The foam in the helmet performs two impact-mitigating functions. First, it redistributes a localised external force over a larger area, reducing the local stress on the skull. Second, it sets an upper limit to the magnitude of this distributed force, as determined by the plateau-stress of the foam. The key step in selecting a suitable helmet liner material is to define the acceptable maximum value for this distributed force. Dynamic processes in this type of materials show interesting physical phenomena. An optimal energy-absorbing material needs to dissipate the kinetic energy of the impact while keeping the force on it below some limit, thus, resulting in a non-dangerous deceleration on the

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occupants [1]. In addition, the geometry of the protective structure will affect the load distribution during impact and the capacity to absorb elastic energy, which controls rebound.

EPS foams are well suited for the above mentioned application. They can undergo large compressive deformation and absorb energy. Energy is dissipated through the cell bending, buckling or fracture, but the stress is generally limited by the long and flat plateau of the stress-strain curve [4]. This behavior explains the high-energy efficiency that can be obtained with foamed materials. Moreover, for the same amount of dissipated energy, the foam specimen always gives a maximum force lower than the corresponding solid specimen of equal volume made of the material from which the foam is derived. EPS foam is also relatively insensitive to temperature changes as compared to most other closed cell foams as it keeps its energy absorbing capacities in both cold (-20°C) as hot conditions (+50°C), as defined by the European bicycle helmet standard EN1078 [5].

Insight of the dynamic behavior of EPS will help creating a Finite Element (FE) model of this material, while it may also aid to seek for alternatives.

2. Experimental work

The performance of these foams has to be studied as a function of several parameters such as density, microstructure and also the strain rate imposed during dynamic loading. Dynamic compression tests were conducted on a cubic specimens of EPS foam with side length of 25mm (Fig. 1). They were cut from a foam plate. The size of the specimens were chosen to obtain a reasonable compromise of relative compression of the entire group of specimens. Four densities of EPS foam were tested in this research: 60 g/L, 80 g/L, 100 g/L and 120 g/L.

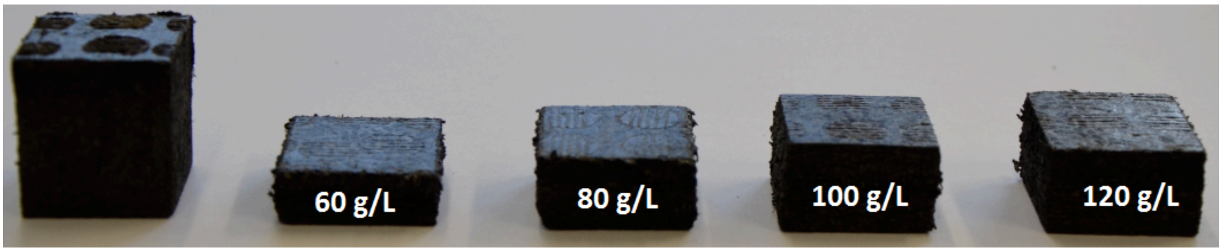

Figure 1. Results of dynamic compression test of EPS foam at high temperature ≈ 50°C.

Specimens were accurately measured and weighed before testing, and the average apparent density was calculated for each foam. The density, volume and mass of the foam material are listed in Table 1.

Table 1. Average parameters for the foam's specimen.

Density from manufacturing, g/L	*60*	*80*	*100*	*120*
mass· 10^{-3}, kg	1.15	1.43	1.94	2.12
Volume · 10^{3}, mm^3	16.13	16.25	16.90	16.25
Density· 10^{-8},kg/mm^3	7.16	8.82	11.50	13.10

An experimental campaign was carried out by means of a Drop Tower Test Machine with flat impactor with the aim to characterize the foam's material. Several drop heights and temperatures were tested to obtain different combinations of stress, strain and strain rate. The obtained data were properly organized for reaching material formulations, which could be generally utilized for a wide range of

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compression-dominated analyses. Displacement, velocity and acceleration were measured during the experiment with an Oscilloscope (Gen5i) and a 2D line grating method [6]. A flat anvil was utilized for the dynamic compression properties of the EPS foam. Each configuration was repeated 3 times. Throughout this experimental work three temperature were used: room temperature 18°C, low temperature -20°C, high temperature +50°C. During one day, part of the specimens were stored in a freezer with temperature -20°C and another part of specimens were stored in a heating chamber with temperature 50°C. After the specimens were used in experiments with the Drop Tower Test Machine. Upon examining the specimen in the course of the compression test, no side elongation was observed as seen in Figure 1. The drop tower energy was 38.37 J when the temperature reached 50°C. This proves that the EPS foam's Poisson coefficient was close to zero. The volume of the material is not conserved during compression. Instead, the density increases while the material is compressed. Poisson's ratio plays an important role in stress strain diagrams. The initial and final cross section areas of the EPS crushable foams in compression remain constant. Thus, the engineering and true stress strain diagrams are identical.

Based on experiments, it is deserved that a typical stress-strain curve obtained by foam compression can be divided in three different parts: 1) *initial region*, in which the material shows some stiffness due to the strength of the matrix, 2) *plateau region*, where the cell walls gradually collapsed and 3) *densification region*, which begins when the cells have totally ruptured or collapsed and, therefore, the curve suddenly rises up. A large amount of energy is dissipated through the plateau region and the densification region [7,8]. However, the transition point between the stress plateau and densification regions were not clear. This is believed to be due to the different size of foam cells and the permanent damage. The cell edges collapse by elastic or plastic buckling, while the faces of these closed cells bend and the bead walls mainly collapse by buckling. During dynamic compression tests, the degree of strength increase depends on the strain rate [9] but also on the complex microstructure of the foam and the entrapped gas in the closed cells [10,11]. The results of the dynamic compression test, with the drop tower energy 38.37 J at room temperature (≈ 18°C), are plotted in Figure 2.

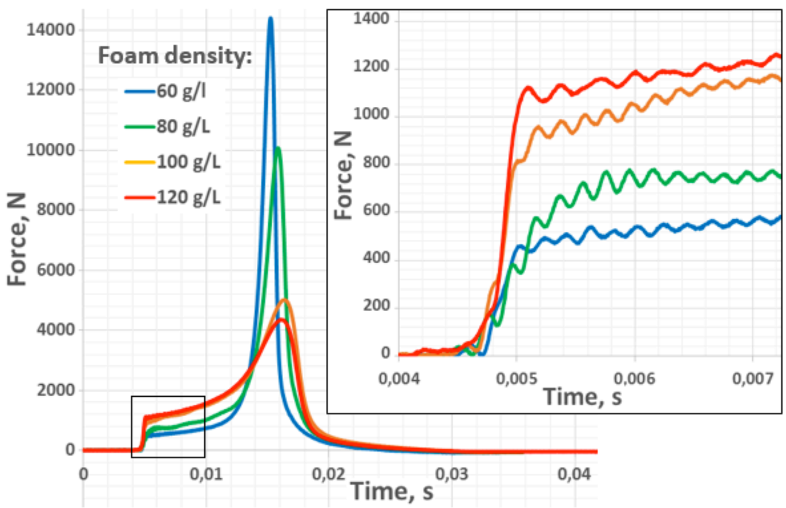

Figure 2. Dynamic compression test results (room temperature (≈ 18°C)).

The thickness reduction in foams with low density (60 g/L) was higher. The thickness reduction increased when decreasing the foams density and increasing the drop height of the test machine. The lighter foam (with lower density 60 g/L) is able to absorb the prescribed amount of energy with large deformations because there is a low-value plateau and the foam starts to become more dense. On the contrary, the heavier foam (with higher density 120 g/L) does absorb the same amount of energy with low deformation and high force, which means the density has a major influence in dynamic

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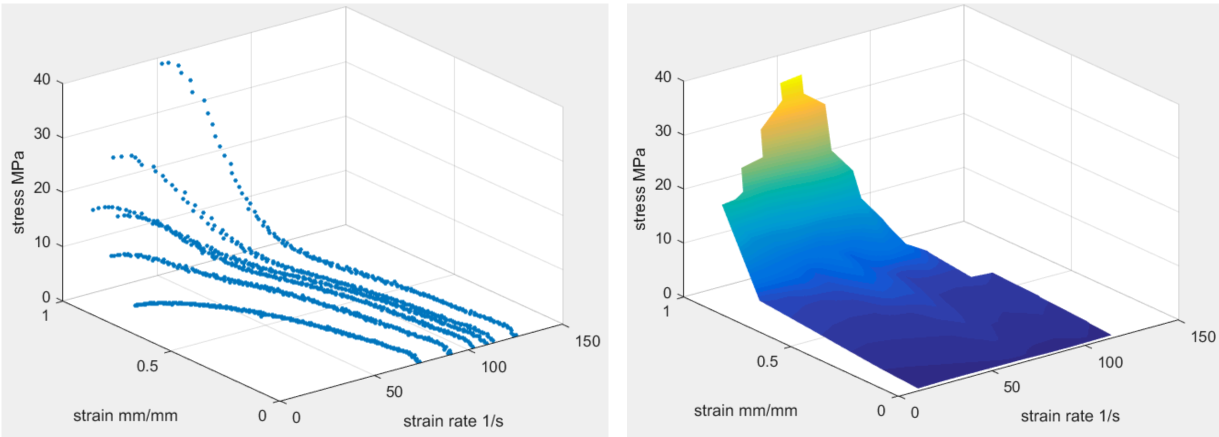
compression of cellular materials. The samples with density 100 g/L and 120 g/L showed a smaller change in the residual thickness for both low temperature (≈ -20°C) and high temperature (≈ 50°C), compared to the other densities of 60 g/L and 80 g/L. The ideal foam is that with intermediate density 80 g/L and 100 g/L. By plotting (Fig. 2) the maximum forces that are reached by the four foams to absorb the same prescribed amount of energy it is possible to determine the optimal density for the application. Also, it was observed that the temperature has an influence on the results. The mechanical properties decrease with the increase of temperature, compression force decreased.

Polymeric foam exhibits a certain degree of strain rate sensitivity through increased elastic modulus, plateau stress and decreased densification strain. The results of the measurement are showed in Figure 3a. The strain rate has small influence on the foam properties [12]. Conventional force–displacement data was obtained from the impact tests and converted to stress–strain data using the sample dimensions.



a) Strain rate, stress and strain history corresponding to different impact heights

b) Surface Stress-Strain-Strain rate

Figure 3. Experimental results (Foam density = 80 g/L, room temperature (≈ 18°C)).

However, dynamic stress strain curves need to be defined for reliably modeling the EPS performance under dynamic loadings and the format must be adapted for using in the finite element program. In this case, interpolation was performed between the true experimental results on the generated XY grid. Linear interpolation has been used in both X- and Y-direction. The results of interpolation are listed in Fig. 3b. Then this surface was cut in the strain rate direction and the stress strain curves were obtained for the modeling.

3. Numerical simulation

3.1. Uniform foam model

There are many studies in literature that present a constitutive models and methods for calculating the materials from the foam. In this experimental work CT-scan images of all type of EPS foam were created and analysed before and after dynamic compression. When a foam is compressed, the beads walls start to bend and cause a linear elastic deformation. Beyond a critical strain the beads collapse by elastic buckling. Whenever the opposing beads walls contact each other, beads collapse. As the beads close up the structure densifies and its stiffness increases rapidly. The in-plane stiffness and strength are the lowest because the beads walls respond to external loads, by bending, and subsequent buckling, yielding, or fracturing. The out-of-plane stiffness and strength are much larger since they require axial deformation of the beads walls. During this dynamic compression experimental work no

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internal damage was observed in specimens. This result allowed the creation of a uniform foam model. The results of EPS foam 60 g/L before and after dynamic compression test at low temperature (≈ -20°C), when the drop tower energy was 47.97 J, are plotted in Figure 4.

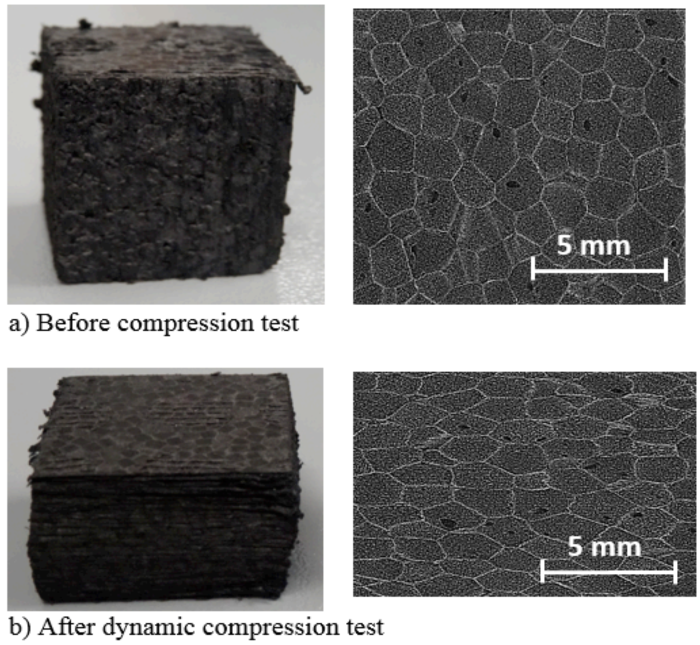

Figure 4. CT-scan images of EPS foam before and after dynamic compression test (Foam density = 60 g/L, low temperature (≈ -20°C)).

3.2. Dynamic compression test simulation

The simulation of the dynamic compression test was successfully performed using LS-Dyna. LS-Dyna provides many material models for different types of foam [13,14]. However, based on previous work by Qasim H. Shah and A. Topa [15], the best candidate for modelling EPS foam is MAT_MODIFIED_CRUSHABLE_FOAM. This is a material model which is dedicated to modeling crushable foam with optional damping, tension cutoff, and strain rate effects. Unloading is fully elastic. Tension is treated as elastic-perfectly-plastic at the tension cut-off value. Rate effects are defined by a family of curves giving yield stress versus volumetric strain. The main parameters were found experimentally, however, tensile cutoff and viscous damping coefficient were obtained from the literature [15].

The lower nodes of the model were contacted with the plate while the upper nodes were contacted with the impactor. AUTOMATIC_SURFACE_TO_SURFACE contact was used in both contact area. To avoid mesh tangling in high compression areas, interior contact was utilized with the activation thickness factor of 0.1. Contact interior type 2 was activated to control a combined mode of compression and shear in LS-DYNA. The impactor was gaven an initial velocity and gravity load. The impactor was modelled as a RIGID_BODY. Its mass and dimension were according to the Drop Tower Test Machine.

The results of the simulation are shown in Figure 5. A comparison between the simulation and the experimental results show a good agreement and thus validates the material model developed for dynamic compression.

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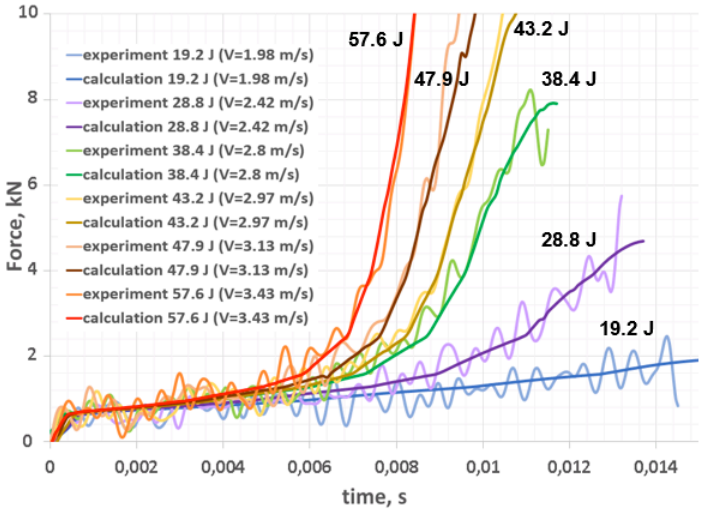


Figure 5. Comparison between the experimental and simulation results of the dynamic compression test (Foam density = 80 g/L, low temperature (≈ -20°C)).

The constructed models can be used for different ranges of material strain rates. Their reliability for predicting the energy absorption was judged by comparing several experimental and numerical results for different impact configurations presented in chapters 3.2 and 3.3.

3.2. Validation

Model validation is possibly the most important step in the model building sequence. Validation was done with tests using the “kerbstone” support, because it can be applied to the foam material to estimate the impact of bicycle helmets. The drop test of the bicycle helmet on a “kerbstone” is part of the European test standards EN1078 [5]. The deformation of EPS foam at high temperature (≈ 50°C) is shown in Figure 6. EPS foam density was 60 g/L. The simulations show 2% difference with the experimental data, the fact that the results were computed by using the same material model for different experimental height of kerbstone and temperature.

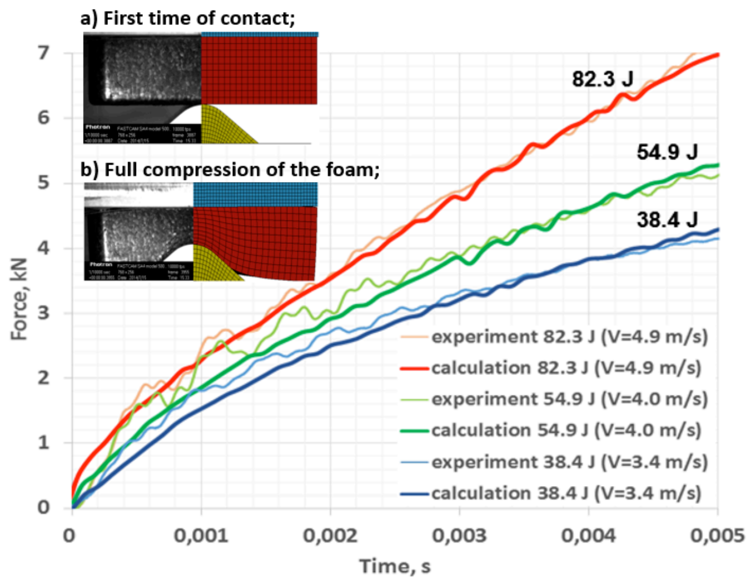
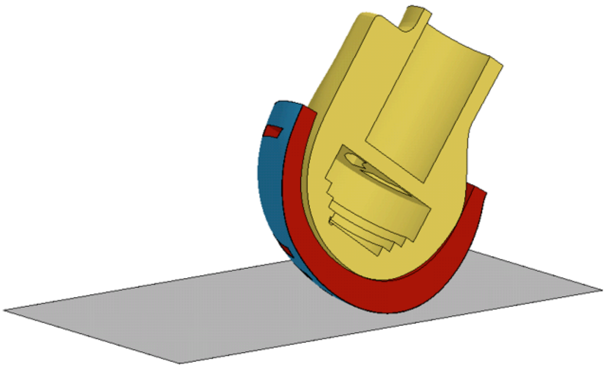


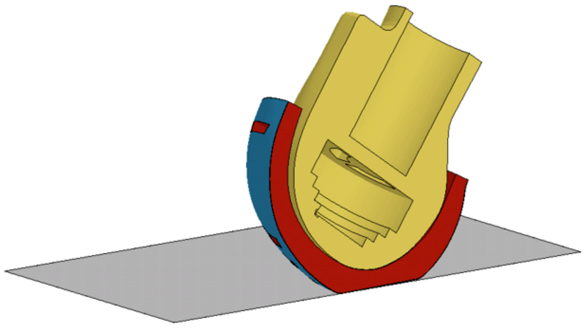
Figure 6. Validation result with kerbstone (Foam density = 60 g/L, high temperature (≈ 50°C)).

3.3. Application of the FE model of EPS foam

The end-application for this methodology is to validate a FE model of a bicycle helmet with the cooperation of Lazer Sport company. Modeling of the bicycle helmet have to be according to the European test standards EN1078 [5]. The impact velocity should be between 5.42 – 5.52 m/s. Impact energy criteria is the acceleration of head <250 g. During modeling, hollow aluminium head forms are used because of their bending stiffness compared to the human skull. The model of the bicycle helmet should consist of polycarbonate cover and EPS foam (Fig. 7).



a) Befor contact



b) After full compression

Figure 7. Predictions of the helmet impacting the crown site on the road.

4. Conclusions

In this research, dynamic compression characteristics EPS foam were quantified at different strain rates and four densities (60g/L, 80 g/L, 100 g/L and 120g/L). The results show the effect of strain-rates on the material properties of EPS. Also, the influence of temperature and density was shown. Density was shown to be the most significant parameter affecting the mechanical properties of EPS foam during dynamic compression.

Compression tests was conducted for obtaining the material properties of EPS foam as well as to develop a material model using LS-Dyna. The most important properties to be included in the material model are the density and the stress-strain curves, quantified experimentally. The stress-strain curves were found to be dependent on the strain rate. As the strain rate increases, the stress-strain curves become stiffer.

Dynamic compression tests were also simulated. Results were validated with experimental data and show that the material model was capable to reproduce the stress strain curve with good accuracy. Therefore, the material parameters are capable of accurately predicting the load and deformation of EPS foams. The results obtained from the validation of the model are in a good agreement with the experimental ones.

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