Science and Technology of Advanced Materials 6 (2005) 883–888
www.elsevier.com/locate/stam

Modeling and testing of energy absorbing lightweight materials and structures for automotive applications

C. Fremgen, L. Mkrtchyan, U. Huber, M. Maier *

Institut für Verbundwerkstoffe GmbH, Erwin-Schrödinger-Str., Geb. 58, 67663 Kaiserslautern, Germany

Received 4 March 2005; accepted 30 July 2005
Available online 2 November 2005

Abstract

As a consequence of the increasing demands in automotive industry concerning crashworthiness and passive safety, the concern for energy management and safety demands also increases. The goal of energy management is to reduce the forces and stresses on an occupant or a pedestrian during a crash event; in some cases it may be possible to reduce the forces by a factor of two. This requires usage of new advanced materials in automotive components. Energy absorbing foams and other lightweight materials like plastics and polymer composites are increasingly used in automotive industry. Hence, extensive study of energy absorbing behavior of these materials as well as the automotive components is needed for further improvements in numerical modeling and crash simulations. The paper enlightens recent advances in investigation of mechanical properties and energy absorption ability of the mentioned lightweight materials as well as modeling with finite element codes for crash simulations.

Keywords: Crashworthiness; Safety; Material modeling; Simulations

1. Introduction

Safety of transportation vehicles, especially passenger cars, has to meet permanently increasing demands. Developments in active and passive safety systems in vehicles have already led to high standards. Nevertheless, passenger as well as pedestrian protection in various crash situations still remains to be a weak point in automotive industry.

The main concern of passive safety is the fact that during an accident most of head interactions of vehicle passengers result in head impact to either the upper interior or A-pillar and roof rails of the car. During a side impact of a vehicle the door is pushed into the occupant, and energy management of the chest constitutes a major concern in this case.

In case of a pedestrian accident normally the upper body and head strike the bonnet top, the scuttle (area between the rear of the bonnet and the bottom of the windscreen), the windscreen or windscreen frame. Hence, improvement of these automotive parts is crucial with respect to pedestrian safety.

Taking into account the necessities coming from ergonomics as well as legislative requirements (free motion possibility for the head, binocular angle for the traffic view etc.), additional demands must be put on the components and instrumental panels of the cars. The requirements mentioned above were reflected in the American National Highway Traffic Safety Standard: FMVSS 201U [1].

The mentioned revised standard FMVSS 201U is fulfilled, if the corrected HIC (d) value (Head Injury Criterion) during the head impact is smaller than 1000.

HIC is determined from the deceleration–time diagram in the time interval, during which the head is decelerated after impact with the inner trim or roof components. The corresponding time interval can be determined and may not be larger than 36 ms, according to the following formula:

$$\mathrm{HIC} = \left[\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} a\,\mathrm{d}t\right]^{2.5}(t_2 - t_1) \quad (1.1)$$

In formula 1.1 the modulus of the resultant triaxial acceleration vector and $[t_1, t_2]$ is the time interval that cannot exceed 36 ms. Different anatomical as well as mechanical prerequisites can change the HIC value. Consequently, a modified index HIC (d) has been introduced, based on the free

* Corresponding author. Tel.: +49 631 201 7301; fax: +49 631 201 7199.
E-mail address: maier@ivw.uni-kl.de (M. Maier).

1468-6996/$ - see front matter
doi:10.1016/j.stam.2005.07.007

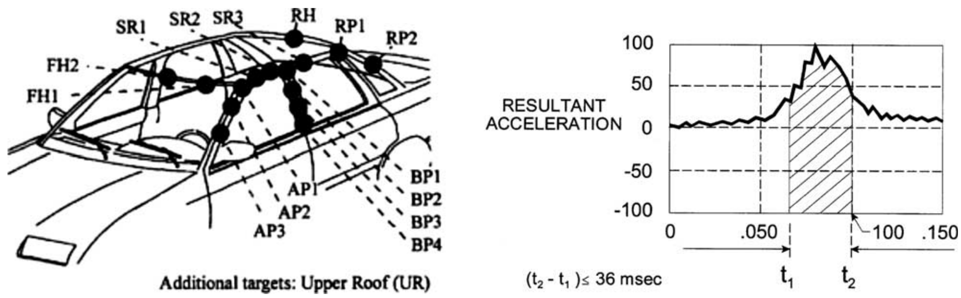

Fig. 1. Impact points for head impact test in a vehicle and acceleration (g) time interval (ms) for HIC calculation.

fall experiments of a head form according to formula 1.2

$$\mathrm{HIC}(d) = 0.75446(\mathrm{HIC}) + 166.4 \tag{1.2}$$

Fig. 1 demonstrates the areas of the vehicle interior, which are mostly hit during the accidents. These areas must be designed in such a manner that they comply with the head injury criterion in the event of an impact of the occupant's head.

To make sure the admissible HIC (d) limit does not get violated, it is required nowadays that the maximal contribution in preventing the head injuries during impact should be taken over by the interior components themselves. These components should be able to wind the kinetic energy of a hitting mass and keep small the negative accelerations.

This leads to the demand of usage of new enhanced materials for automotive components.

2. Energy absorption behavior of polymeric foams

An optimum energy-absorbing material, which must be used for interior components of automobiles, needs to dissipate the kinetic energy of the impacting body while keeping the force on it below some limit, thus, resulting in a no-dangerous deceleration of the head of the occupant [2].

In order to obtain an optimized construction, extensive experimental investigation of these materials is needed. Their mechanical behavior must be well understood and be predictable for dynamic applications.

Most of the foams are strain rate-dependent and this fact should also be taken into account while modeling them with finite element methods.

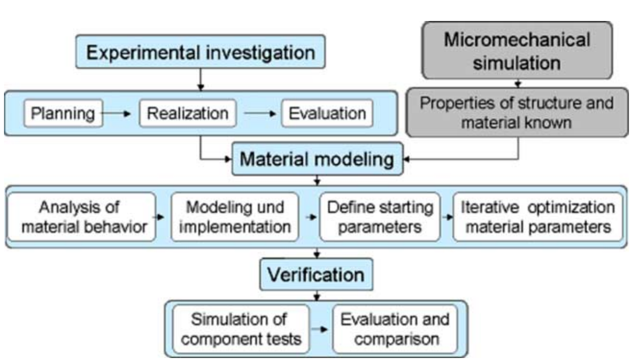

Fig. 2. Procedure for the optimized material modeling process.

To enhance the predictability of these cellular materials a method has been developed at the Institut für Verbundwerkstoffe GmbH to achieve optimized parameter fitting of any material model starting from the material itself. The flowchart shown in Fig. 2 enlightens the procedure for the optimized material modeling as proposed at the Institut für Verbundwerkstoffe GmbH:

Compression tests have been performed to investigate the compression behavior of polypropylene foam. These experiments were carried out with specimens with an original dimension of $50\times50\times50\ \mathrm{mm}^3$, which were compressed to 95% of their initial height. In these tests, strain rate, density, temperature and the influence of time onto the mechanical behavior of the EPP were taken into account (Table 1).

Using optical deformation analysis the Poisson's ratio, the elastic modulus and the stress–strain behavior of the tested specimens have been evaluated. These evaluations took into account the parameters mentioned above. As an example the force-displacement-diagram of a specimen with a density of 40 g/l at 80 °C with different deformation velocities is shown in Fig. 3.

The evaluation shows the following results for elastic modulus, Poisson's ratio and stress at 40% compression at 80 °C and a crosshead velocity of 1 m/s at the initial strain-rate $\dot{\varepsilon} = 20\ 1/s$ (Table 1).

To evaluate the mechanical behavior under different types of loadings, also shear tests have been performed up to the failure of the specimen. In these investigations the use of optical deformation analysis was essential since the loading did not allow the generation of a homogeneous state of stress. Consequently, only a section of the specimen was loaded and the deformation was locally measured with the help of optical deformation analysis. The specimen geometry (Fig. 4) was formed by cutting a block with the corresponding outer dimensions and then milling radii at the sides. Deformation

Table 1
Results of uniaxial compression tests

Density (g/l)	Elasticity modulus (MPa)	Plateau stress (MPa)	Poisson's ratio [1]
20	1.48	2.10	0.02
40	7.28	1.37	0.02
60	12.31	0.96	0.02
80	16.00	0.48	0.04