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

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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.

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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:

\[
HIC = \left[ \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a dt \right]^{2.5} (t_2 - t_1) \quad (1.1)
\]

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
fall experiments of a head form according to formula 1.2
\[ \text{HIC}(d) = 0.75446(\text{HIC}) + 166.4 \] (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.

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 $50 \times 50 \times 50$ 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](image)

| Density (g/l) | Elasticity modulus (MPa) | Plateau stress (MPa) | Poisson’s ratio |
|--------------|--------------------------|---------------------|----------------|
| 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           |
measurement was done using optical deformation analysis in the marked fields.

Besides the stress–strain-curves, only the starting shear modulus was evaluated from the shear tests. The results are shown in Table 2 for a testing velocity of 0.5 mm/s at room temperature.

Relaxation tests are very important for certain types of cellular materials in order to model their viscoelastic behavior.

In the performed relaxation experiments the specimens were compressively loaded to achieve predefined deformations and the time-dependent force-reaction was measured.

These experiments were performed in a climate chamber. The specimens were loaded with 5% engineering strain per step and the reaction force was measured over 24 h. As an example, the force reaction at 30% strain at 21 °C of a foam with density of 80 g/l is shown in Fig. 5.

Even after 24 h the curve shows further relaxation. As already mentioned, the unreinforced foams have mechanical properties superior to those of the rigid plastics. However, foams have very high percentage of voids at the same time and they are suitable for low stress applications only. When fibers are inserted into the foamed material, this leads to a density comparable to that of the unreinforced foam, giving a higher strength-to-weight ratio.

In Fig. 6 the electron microscopy of glass mat reinforced polyurethane foam is given. It can be seen that the fibers appear to be in bundles in this case. In the case of short fibers, however, they are spread and reinforce each cell separately.

| Density (g/l) | Shear-modulus (N/mms) |
|--------------|------------------------|
| 20           | 1929                   |
| 40           | 4885                   |
| 60           | 8543                   |
| 80           | 9375                   |

Table 2
Starting shear modulus at a deformation speed of 0.5 mm/s

![Fig. 3. Force–displacement-diagram of EPP with a density of 40 g/l at 80 °C at different loading velocities.](image)

![Fig. 4. Specimen during a shear test.](image)

![Fig. 5. Force–time relaxation curve.](image)
Glass fibers are used for reinforcement. Glass fibers increase the strength of the cellular structure, adding back the strength normally lost when unreinforced plastics are foamed. In Fig. 7 the comparison of stress–strain-diagrams of glass fiber reinforced polyurethane foam and non-reinforced foam are given for a fiber content of 26%.

3. Material modeling for finite element analysis

To evaluate the impact response of the components in the interior of a vehicle, it is very important to understand in a quantitative manner how the components made from the studied materials might perform in the crash environment.

Reduction of cost and time-consuming prototype tests by pre-designing the automotive components virtually is a key factor for automotive industry. The use of FEM codes, such as Abaqus, LS-Dyna, PAM Crash, etc. enables the achievement of virtual development of automotive components, through finite element analysis (Fig. 8).

Three types of data are required to perform the dynamic FEM simulations: geometric definition, material properties and boundary conditions (loads) definition. Among these data the material properties are the most difficult to categorize and it needs a lot of experimentation to describe them accurately.

Because of the difference in deformation mechanisms of different foams like cell wall cracking or cell wall bending, it would be very expensive to simulate all possible forms of behavior with one model. It is more reasonable to model different foams with different material models. Meanwhile, the successful simulation results must deviate from the experimental ones by less than 5%.

4. Simulation of automotive components

To determine the deformation and energy absorption properties of the automotive components impact tests were carried out on the falling tower of the IVW. The testing conditions were taken to correspond to the extended standard FMVSS 201 [1].

A semispherical impactor with a mass of 6.5 kg, which corresponds to the free-flying headform, hits the component.
with the required testing velocity (See Fig. 9). An acceleration-sensing device is integrated into the impactor and a high-speed camera is used to record the tests.

In Figs. 9 and 10 the impact tests and finite element simulation on an integrated rib absorber are shown. Transverse energy absorbing ribs are incorporated into the back of the reinforced plate. Crushing of the ribs induces plastic deformation in the material that results in energy absorption through plastic flow. Since in reality, the ribs have variable thickness, being much thicker at the contact part with the plate than at the top, this fact also has to be taken into account while building a model in FEM. Shell elements have been taken to build the model in PAM Crash. The shell elements enable an easy description of the variable thickness, giving it as a parameter in the model. Use of shell elements also reduces the simulation time, which is very important in the case of large
automotive components; such as A-rails, doorframes and other interior trim parts.

The acceleration versus time and displacement versus time diagrams, given in Fig. 11, show a close agreement between experimental and simulation results.

5. Conclusions

Crashworthiness simulation has been a major factor in enabling automotive manufacturers to achieve a 30–50% reduction in development time and costs over the past years. Today, this technology is considered a mature and proven design tool for the development of conventional automotives. Only minimal prototype testing is needed, usually at the end of the design phase, for the purpose of confirming the simulation-based design. And it is not always necessary to perform simulations for the whole vehicle each time. Component analysis becomes more and more essential.

The design of the structural parts of the inner trim and roof often involves energy-absorbing polymeric foams and their reinforced versions. The mentioned foams have proved to be the best for this purpose and are widely used in automotive industry to prevent injuries to the occupants in the event of front or side collisions. The use of foamed materials results in a significant improvement of the passive safety of the vehicle, owing to their excellent energy dissipation properties. In addition, they are relatively cheap and allow great design flexibility, as they are easily modeled in complex geometric parts.

The interior components of the vehicles, which are modeled and simulated at the Institut für Verbundwerkstoffe GmbH have shown to completely satisfy the requirements of FMVSS 201. The new lightweight materials are characterized and the optimal fabrication parameters, needed to comply with the mentioned standard, are revealed. With the help of the crash simulations many time and cost consuming tests have been saved.

Acknowledgements

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References

[1] Code of Federal Regulations- Transportation. Standard No. 201: Occupant protection in interior impact. 49 CFR § 571.201, 08.04.1997.
[2] J. Schluppkkotten, R. Paßman, M. Streit, M. Holzner, M. Maier, Integration innovativer Werkstoffe in die Fahrzeugberechnung- Numerische Simulation polymerer Schaumstoffe VDI Berichte 1411’ Berechnung und Simulation im Fahrzeugbau’, VDI Verlag GmbH, Düsseldorf, 1998, pp. 173–191.