Dynamic Compression Tests of a Polyurethane Flexible Foam as a Step in Modelling Impact of the Head to the Vehicle Seat Head Restraint

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Flexible polyurethane foams are commonly used materials in automotive applications, especially for internal cockpit parts and seats. During accidental impact, passenger's head has to be stopped by the headrest. Because padding material of a headrest has a significant influence on a head deceleration, mechanical properties of two types of polyurethane foams with a certain range of densities and components proportion have been studied. Dynamic impact tests have been carried out. Results are presented below. Analytical constitutive model of compression has been proposed, which assumes that density, components proportion and strain rate are separable functions. The model has been verified by experimental results of static tests. Impact tests have been conducted due to two objectives: to investigate impact behaviour of examined material and to validate numerical solution based on the method of lumped mass.

Keywords: *polyurethane foam, constitutive model, energy dissipation, impact simulation.*

1. INTRODUCTION

Flexible polyurethane foams are commonly used materials in automotive applications, especially for internal cockpit parts and seats. During accidental impact passenger's head has to be stopped by the headrest. As it is shown in Figure 1, padding material of a headrest has a significant influence on a head deceleration [1]. The primary function of a headrest is to support and cushion the head, protecting an occupant from injury in a front and a rear-end collision (Fig. 2). The head-rest should be able to absorb the kinetic energy of the head, exerting possibly low force, which would not cause damage of the brain or skull. A maximum tolerable acceleration (deceleration) depends on the time, over which it is applied. For example, according to ECE Regulation No. 17 [2] and EU Directive No. 74/408/EEC [3], continuous deceleration of a head (artificial headform during the test) over 80 g should be no longer than 3 ms.

Different criteria, which define a tolerance of a human head (mainly brain) against acceleration have been elaborated by different researchers [1]. One of the first defined criteria was Wayne State Tolerance Curve (WSTC) [4] which has been shown in Figure 3. It presents acceptable deceleration of a head related to the time of deceleration impulse. The most commonly used criteria is a Head Injury Criterion (*HIC*) of the following form [2,3]:

$$HIC = \left[\frac{1}{T_2 - T_1}\int_{T_1}^{T_2} a(t)dt\right]^{2.5} (T_2 - T_1) \qquad (1)$$

where: $a(t)$ is the acceleration of a head center of mass, T_1 and T_2 are initial and final instant of impact, respectively. It has been proved that if *HIC* exerts 1000, death is probable.

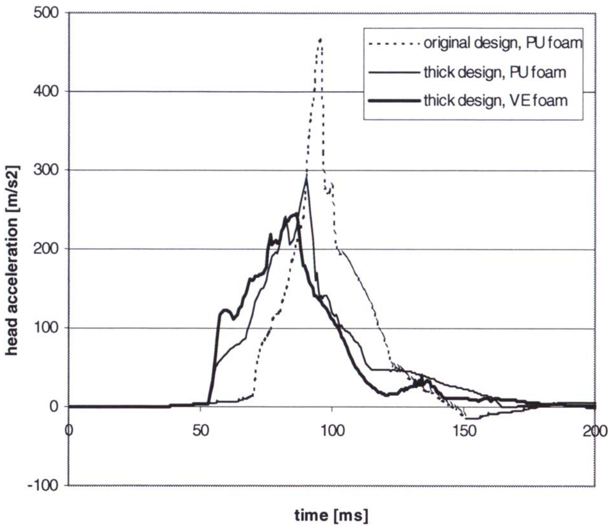

Figure 1. Head deceleration for three different foam materials [1]

In order to fulfil requirements mentioned above a clear understanding of a foam response to an impact compressive force is necessary, as well as the energy – absorption diagram of the foam has to be derived. The paper presents results of experimental investigations into flexible polyurethane foam (FPF) response to dynamic compressive force. On the wider front, presented results

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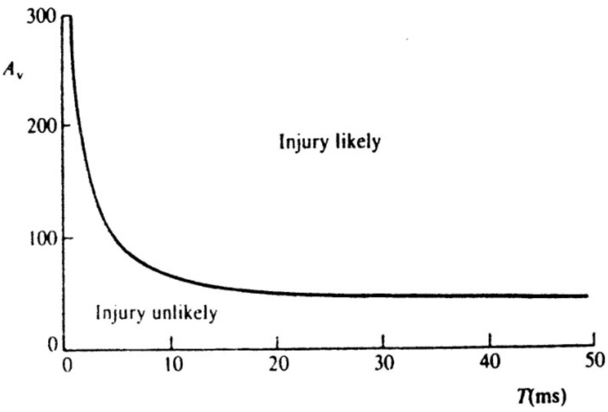
are a part of the project, the aim of which is to elaborate a theoretical model of FPF energy absorber, applicable in design process of the head-rests. Nowadays, such a process is based on experimental data only. Results of those experiments cannot be generalized and experimental tests to be performed are very expensive.

Figure 2. Impact of a head to a head restraint during bus crash test



A_v – average deceleration [g]; T – time of impact [ms]

Figure 3. WSTC curve [4]

2. MATERIAL PROPERTIES OF FPF

2.1 Results of preliminary static tests

Padding of vehicle seats and headrests are commonly produced by technology of pouring mixed foam components into shape mould. For this technology 3 main factors determine mechanical properties of foam parts: raw material type, proportions of 2 main foam components and density, which is regulated by quantity of raw material poured into mould.

Therefore, foam specimens have been prepared from 2 types of raw materials, in various densities and various 2 main components proportions (Tab. 1).

The first step was to carry out static tension and compression tests to identify stress – strain characteristics in relation to density, components proportions and material type.

Stress-strain diagrams (in the whole range of loading – in tension and compression) are shown in Figure 4. According to these results, it can be confirmed that there is a strong dependence of stress – strain relations upon technological parameters (density, components proportion). So we can presume also deceleration – time dependence on these parameters in dynamic tests. There can also be observed (Fig. 5), typical for foam materials, the shape of compression curves. Three regimes of material response are observed: linear elasticity, long, flat plateau and finally – densification of material, causing sharp stress raise [5-7]. FPF, deformed even largely, (in the third regime), returns back completely to initial dimensions.

Table 1. Tested specimens material data (components proportion 45 means 100:45 proportion ratio between 2 main foam components)

Type of material					
2 (MDI)			1 (TDI)		
No. of spec.	Foam density [g/dm^3]	Components proportion	No. of spec.	Foam density [g/dm^3]	Components proportion
1	73	55	9	72	50
2	73	50	10	72	45
3	73	45	11	72	40
4	73	40	12	72	35
5	70	55	13	65	50
6	67	55	14	63	50
7	60	55	15	58	50
8	53	55	16	50	50

It is obvious that foam energy absorber should work only in the range of first and second regimes. Sharp stress raise in the last regime could cause large decelerations of impacting body.

2.2 Theoretical material model

Analytical constitutive model of compression has been proposed, which assumes that density, components proportion and strain rate are separable functions [7,8]. The following interpolation function was derived:

$$\sigma = f_0(\varepsilon)\cdot G(\rho)\cdot H(i)\cdot M(\varepsilon,\varepsilon')$$
$$f_0(\varepsilon) = 9.5\varepsilon - 0.5\varepsilon^2 + 1.5\cdot 10^{-2}\varepsilon^3 - 10^{-5}\varepsilon^4 + 1.05\cdot 10^{-6}\varepsilon^5$$
$$H(i) = 0.05i - 1.56$$
$$G(\rho) = 0.0007\rho^2 + 0.0998\rho - 2.613$$
$$M(\varepsilon,\varepsilon') = 1 \tag{2}$$

where: f_0 is a "shape" function, G is density function, H is components proportion function and M is a strain rate function. Sherwood [8] has proposed similar interpolation function. At this step, M was not derived yet because tests were static only. The model has been verified by experimental results of static tests [7]. The comparison of the interpolation function (2) with results of experiments is shown in Figure 6.

The proposed theoretical model is in good agreement with experimental results, particularly in the two first phases of the compression diagram: linear elasticity and plateau.

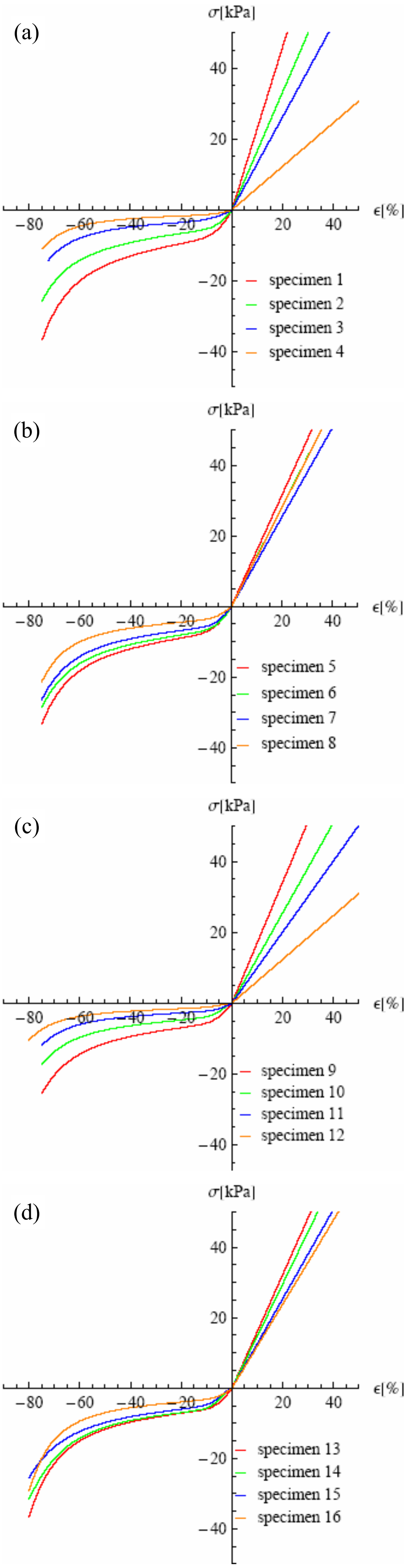


Figure 4. Cumulative diagrams of tension and compression tests results for all specimens: (a) raw material type 2, different components proportions, (b) raw material 2, different densities, (c) raw material 1, different components proportions and (d) raw material 1, different densities

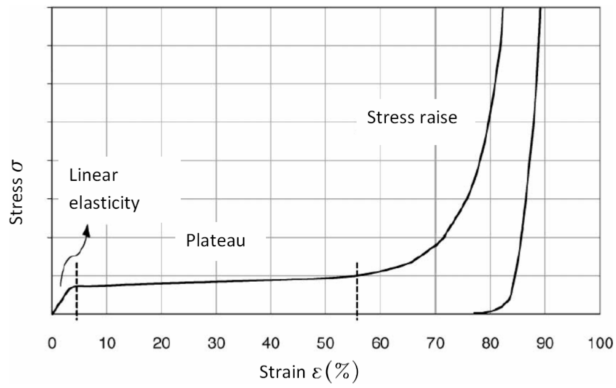


Figure 5. Three regimes of compression curve [6]

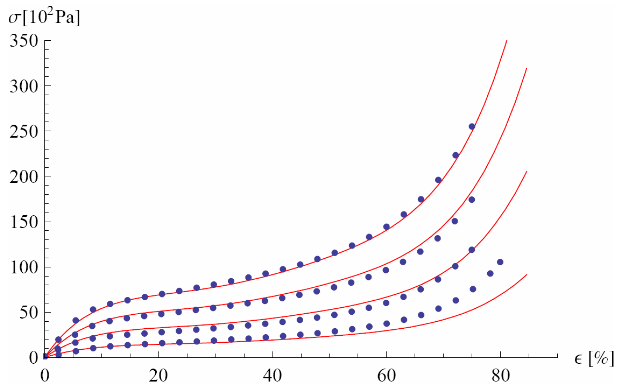


Figure 6. Compression curves for different specimens (continuous line is interpolation function and dark points are experimental results)

3. ENERGY ABSORPTION IN THE FPF PROCESS OF DEFORMATION

Quantity of energy W, absorbed by a foam during compression deformation process is area under the $\sigma - \varepsilon$ curve between this curve and ε axis, according to (3), where the upper limit of integration is the maximum strain achieved.

$$W = \int_0^{\varepsilon} \sigma(\varepsilon)\mathrm{d}\varepsilon \tag{3}$$

When building σ – W diagrams for the tested specimens (Fig. 7) it can be seen, that if we assume some quantity of energy W, which should be absorbed, there are some optimum parameters like density or components proportions for which the assumed condition is fulfilled for a lowest stress level [6]. In practise, it could allow to choose foams which absorb the assumed quantity of impact energy with the lowest decelerations acting on impacting body, e.g. human head.

Similarly, the parameter called effectiveness (4) is helpful to determine ability to absorbing energy of impact [6].

$$\mathrm{E_f} = \frac{\int_0^{\varepsilon} \sigma(\varepsilon)\mathrm{d}\varepsilon}{\sigma_{\max}} \tag{4}$$

$\sigma_{\max}$ is the maximum stress achieved in a test.

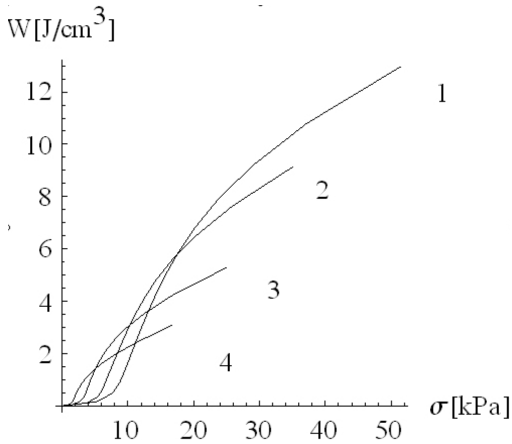


Figure 7. Energy absorption diagram for compression – different specimens and various components proportions

This parameter allows to determine if the foam has been used the most effectively in the one specific application. In practice, the maximum of this parameter is achieved at the end of plateau regime (Figs. 5 and 8). So, the maximum of effectiveness, E_f is equal to the maximum of deformation work done while still small stress value. Diagrams of parameter E_f for some specimens are shown in Figure 8.

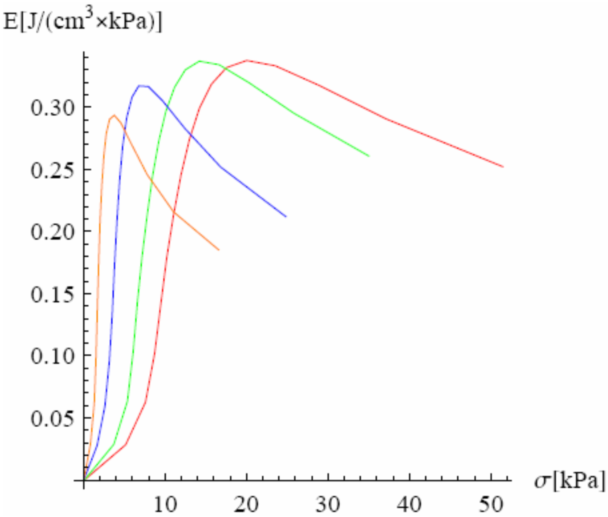


Figure 8. Effectiveness diagram for compression – different specimens and various foam densities

4. LUMPED MASS MODEL OF THE FPF SUBJECTED TO IMPACT DYNAMIC LOAD

On the basis of the static tests results, theoretical 2D model of energy absorber has been proposed. It uses the lumped mass model [9], which divides a foam specimen into small finite elements (Fig. 9). For each of these elements equations of motion are derived (5)

$$m\ddot{x} = \sum_{k=1}^{4} T_x^{(k)} = \sum_{k=1}^{4} \left(\sigma_{11}^{(k)} \mathbf{n}_x + \sigma_{21}^{(k)} \mathbf{n}_y^{(k)} \right) s_k$$

$$m\ddot{y} = \sum_{k=1}^{4} T_y^{(k)} = \sum_{k=1}^{4} \left(\sigma_{12}^{(k)} \mathbf{n}_x + \sigma_{22}^{(k)} \mathbf{n}_y^{(k)} \right) s_k \qquad (5)$$

where: m – lumped mass element; x and y – coordinates of element; $\mathbf{n}$ ($\mathbf{n}_x$ and $\mathbf{n}_y$) – unit normal vector of an element face, T_x and T_y – sum of force components acting on element faces. Forces T_x and T_y are calculated from positions of elements, using finite strain theory together with the proposed material model (2).

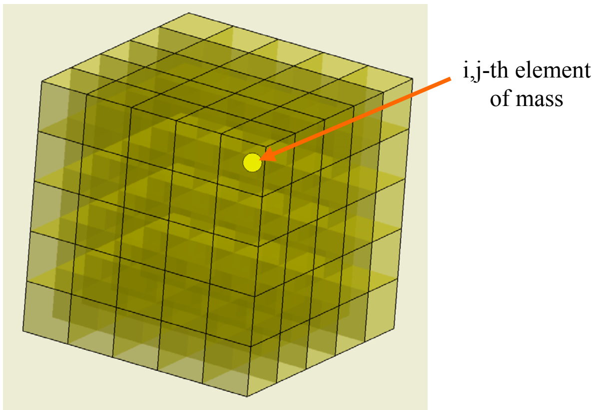


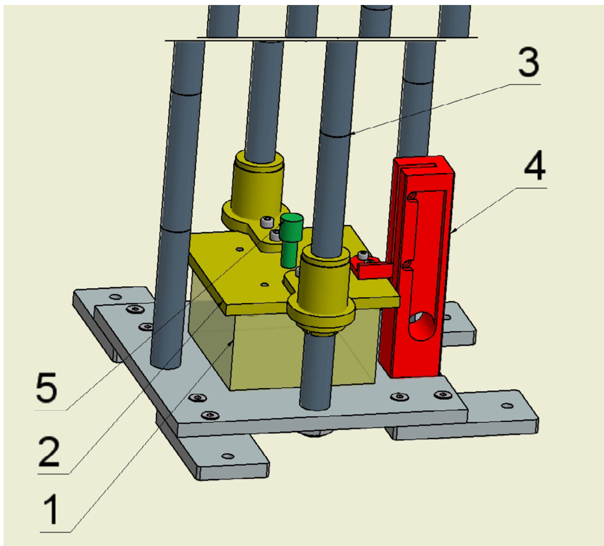
Figure 9. Specimen divided into i × j elements

According to the above model, computer programme was composed which simulates impacting of a rigid plain body to the FPF specimen. The original contact algorithm between specimen and impactor was created. To solve the equations of motion, Runge-Kutta integration scheme of order 4 was implemented.

5. FPF IMPACT TESTS

5.1 Experimental stand

To verify the above numerical model a series of dynamic compression tests were carried out on the special experimental rig shown in Figure 10. The impactor falls from a certain height and hits a specimen. The velocity of impactor is measured by optical device just before the contact with a specimen. Deceleration of the impactor during foam deformation is measured by accelerometer and is recorded by a computer system. The exemplary test record is shown in Figure 11. Subsequent peaks of deceleration value are caused by rebounding of the impactor. Only the first deceleration wave is analyzed because of its highest values. Similar specimens as used



1 – foam specimen; 2 – impactor; 3 – impactor guides; 4 – velocity measure device; 5 – accelerometer

Figure 10. Impact test rig

for static tests were tested dynamically. Four impact velocities for each specimen were applied by dropping an impactor from appropriate heights. The impact velocities from 1 to over 5 m/s were obtained.

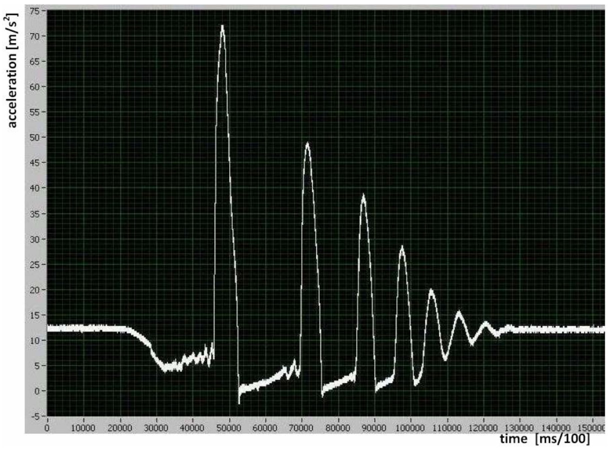


Figure 11. Impact record – deceleration [m/s^2] vs time [ms]

5.2 Results of impact tests

The exemplary results of impact tests are presented in Figures 12-14. It has been confirmed that deceleration profile strongly depends on material parameters.

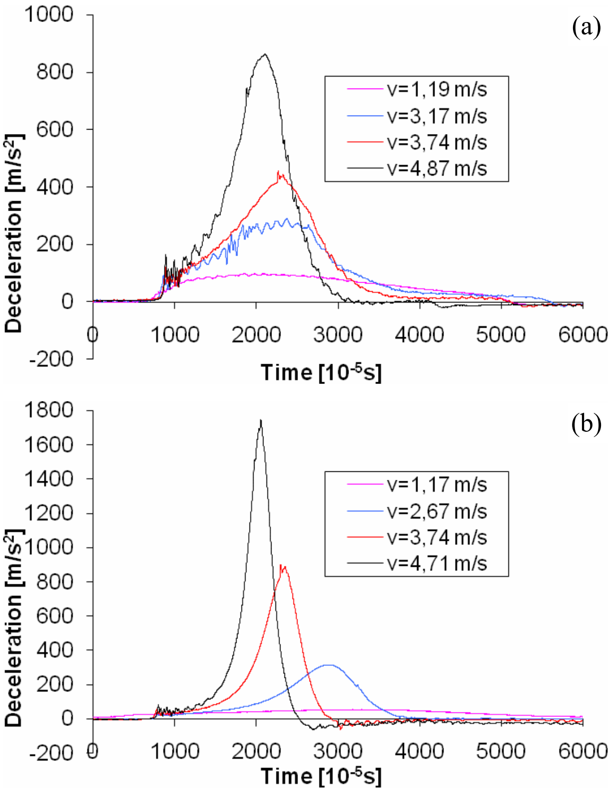


Figure 12. Deceleration vs time for various impact velocities – results for specimens of the same densities and various components proportions: (a) specimen 2 and (b) specimen 4

This dependence is clearly shown in Figures 13 and 14 where for similar impact velocities curves for specimens of different parameters are presented.

For the assumed ranges of densities and components proportions influence of change in component proportion is stronger than density.

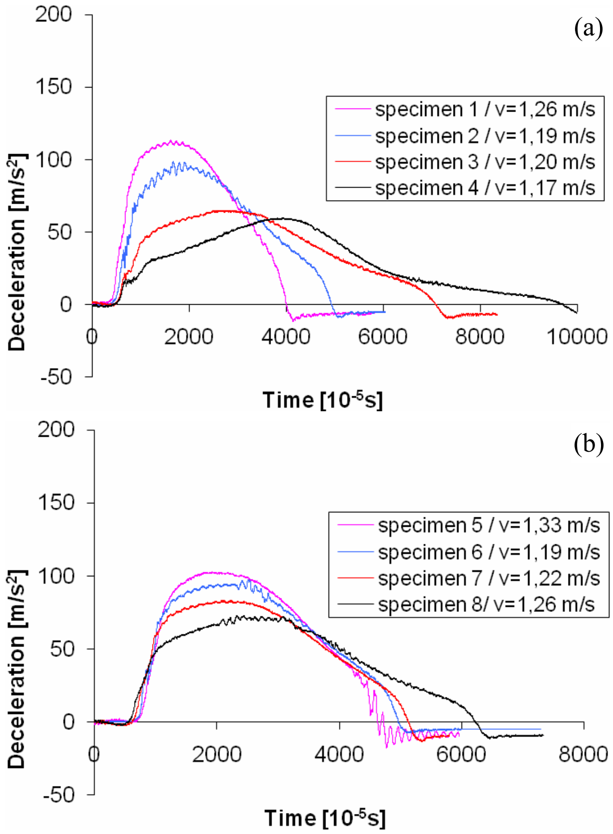


Figure 13. Deceleration vs time for impact velocities about 1.2 m/s: (a) results for specimens of the same densities and various components proportions and (b) results for specimens of the same components proportions and different densities

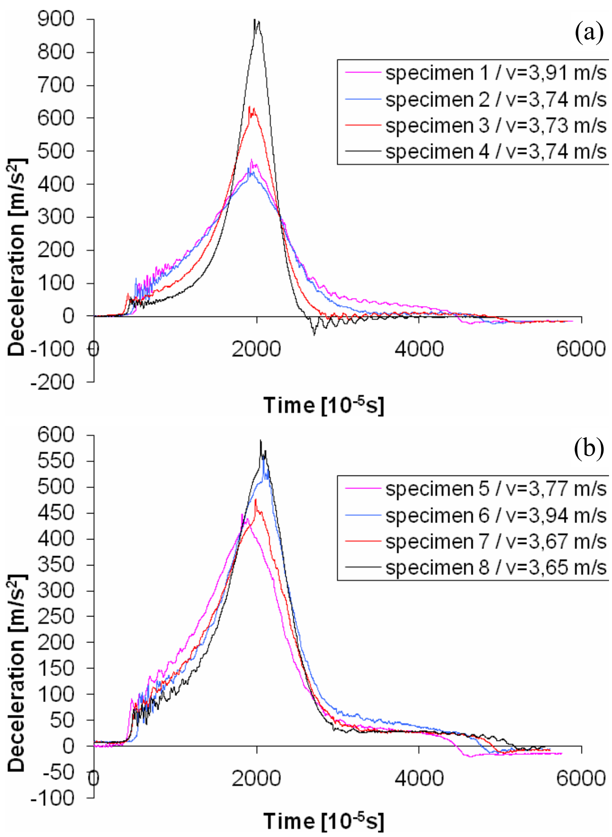


Figure 14. Deceleration vs time for impact velocities about 3.7 m/s: (a) results for specimens of the same densities and various components proportions and (b) results for specimens of the same components proportions and different densities

5.3 Comparison of static and dynamic tests results

In order to determine the dependence between stress value and strain rate, common stress – strain diagrams were created for dynamic and static tests results. Deceleration – time curves of impact tests have been calculated to transform it into stress – strain curves and placed together with static tests curves. Figure 15 presents the exemplary results for one of the specimens. It can be seen that stress value of plateau regime is about two times lower for static test (red line) than for dynamic. However, for all impact velocities, stress values are similar. The same results were obtained for other specimens. Currently, the studies are in progress to find a form of M (ε, ε') function of material model (2).

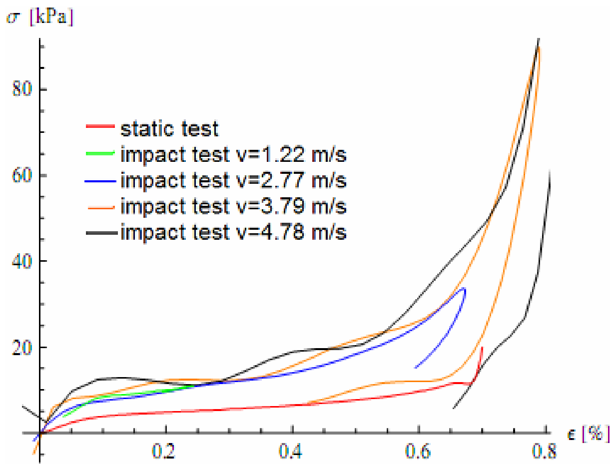
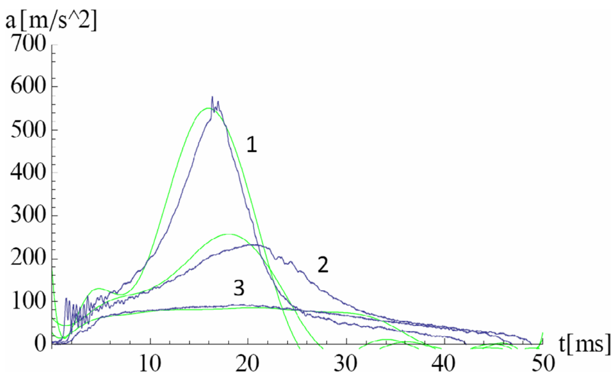


Figure 15. Stress – strain diagram for dynamic and static tests, specimen 10 (red line is a static test curve, other curves are for dynamic tests with four impact velocities approx. from 1 to 5 m/s)

6. VERIFICATION OF NUMERICAL MODEL BASED ON IMPACT TESTS RESULTS

Nowadays, work is in progress to improve numerical model (Section 4). Exemplary, one of the first results of model verification is presented in Figure 16.



1 – 3.92 m/s; 2 – 2.92 m/s; 3 – 1.25 m/s

Figure 16. Numerical calculation results (green, lighter lines) and impact tests results (blue, darker lines) for three different impact velocities, specimen 9

7. CONCLUSIONS

There is a significant influence of polyurethane flexible foam parameters like density and foam's components proportion upon the deceleration profile during impact. The velocity of the impact is a main parameter which should be known to correctly design foam impact absorber. Maximum peak of deceleration which is of great importance for survivability of a passenger during accidental crush of a vehicle depends on the foam parameters.

The proposed material model derived from static tests results should be improved by strain rate function based on impact tests results.

Numerical algorithm can be used to simulate impact, however successive improvements are needed.

Results presented here are a part of larger research programme. Results of further research (comparison with numerical solution) will be presented in separate publication.

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ИСПИТИВАЊЕ ПОЛИУРЕТАНСКЕ ЕЛАСТИЧНЕ ПЕНЕ НА ДИНАМИЧКИ ПРИТИСАК КАО ЈЕДНЕ ФАЗЕ У МОДЕЛИРАЊУ УДАРА ГЛАВЕ У НАСЛОН ЗА ГЛАВУ У ВОЗИЛУ

Марчин Јанковски, Мариа Котелко

Еластичне полиуретанске пене су материјали који се најчешће користе код моторних возила за делове и седишта у простору за возача. Наслон за главу треба да заустави покретање главе уколико дође до случајног удара. Проучавана су механичка својства две врсте полиуретанске пене са одређеном густином и односом компонената зато што материјал за ватирање наслона за главу игра значајну улогу код успоравања кретања главе. Извршено је испитивање на динамички удар и резултати испитивања су приказани у раду. Предлаже се аналитички конститутивни модел који полази од претпоставке да су густина, однос компонената и брзина деформације независне функције. Модел је верификован експерименталним резултатима статичких испитивања. Циљ испитивања удара је био двострук: да се истражи понашање испитиваног материјала на удар и да се докаже вредност нумеричког решења заснованог на методи грудвасте масе.