Modelling of Foams using MAT83 – Preparation and Evaluation of Experimental Data

Authors:

Enver Serifi, Universität Stuttgart
Andreas Hirth, DaimlerChrysler AG
Stefan Matthaei, DaimlerChrysler AG
Heiner Müllerschön, DYNAmore GmbH

Correspondence:

Heiner Müllerschön
Industriestr. 2
D-70565 Stuttgart
Germany

Tel: +49-(0)711-4596000
e-mail: hm@dynamore.de

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ABSTRACT

Foam materials are widely used in automotive industry such as energy absorbers and comfort enhancers. Because of high energy absorbing capability of foams, they became very important in vehicle crashworthiness.
So in this manner, FE modelling of foam materials also becomes important. Although foam materials are very promising materials, not that much study has been done about foams comparing to other commonly used materials like steel, etc. Some different approaches are available to define the behaviour of foam materials. One micro-structural approach to define the mechanical behaviour of foam materials, considers the foam material as a cubic model and uses the standard beam theories with solid-fluid interaction to describe the in- and out-flow of fluid inside the foam material (see Gibson and Ashby [1]). There are also macro-structural approaches those consider the foam material as a continuum with solid-fluid interaction in order to describe the in- and out-flow of the pore-fluid in the foam material (e.g. Ehlers [2]).
In contrast to such quite sophisticated models, in LS-DYNA for practical engineering purposes the foam model `*MAT_FU_CHANG_FOAM` (MAT83) is available. The main assumption of MAT83 is, that Poisson's ratio is equal to zero for foams and therefore no coupling between the material axes is present. This leads to a one-dimensional material law, where experimental curves of uni-axial test can be used directly.

The aim of this work is to provide a method and to develop a computer program in order to generate reliable input data for the simulation of EPP foam with MAT83 in LS-DYNA. Experimental raw data have to be prepared and extended respectively. In addition, suitable density laws have to be developed in order to provide LS-DYNA input data for intermediate densities, where no experimental data are available.
To verify the reliability of the results, simulations with the generated curves are compared to an independent experimental database and to some real experimental applications.

INTRODUCTION

EPP foam is a strain rate dependent, reversible foam. In order to model an EPP foam with MAT83 in LS-DYNA, essentially uni-axial compression load curves with different strain rates are needed. In case available, hydrostatic curves, to be used for calculating the volumetric part of the stress and strain, and tensile curves, to be used for tension calculations, may also be introduced. But because of lack of enough experimental results for every type and density of foam, one has to generate these missing curves numerically using the existing databases available only for some densities.
For this project there are two different databases available. The first one consists of experimental results for 4 different densities of EPP foam with different loading cases. The second one is for only one density (55 g/l) with more detailed experimental results like more strain rates etc. and includes more recent experimental data.
Our aim is to calculate the stress-strain values, for densities not available in experimental results using the first database. This calculated stress-strain values are used for the LS-DYNA MAT83 input card. In order to generate reliable load curves, a computer code is written.

This computer code,

- reads in the experimental results,
- extends the curves in the densification region,
- averages the repeated experimental curves to one final curve,
- generates a general density law to calculate stress-strain values for user-defined densities,
- writes a material MAT83 input card automatically.

By using the generated material input data for MAT83, simulations of existing experimental applications were performed and compared.

Properties of MAT_FU_CHANG_FOAM (MAT83)

The material model MAT83 is a one dimensional material law due to the assumption of zero Poisson's ratio. It is based on unified constitutive equations for foam materials by Fu Chang (1995). Rate effects can be modelled in low and medium density foams. The main advantage of MAT83 is, that the user can input experimental results of uni-axial compression directly. If available direct input of tension and hydro-static experimental results is also possible. For the modelling of reversible foams, MAT83 is widely used. The main reason is probably because there is no need to define complex material parameters.

In case only uni-axial compression load curves with different strain rates are defined, LS-DYNA interpolates linearly between the strain rates to calculate stress-strain values for the applied strain rate. For strain rates above the highest strain rate, no extrapolation is made. LS-DYNA simply takes the stress-strain values of the highest strain rate, assuming that the stress is constant above the highest strain rate.

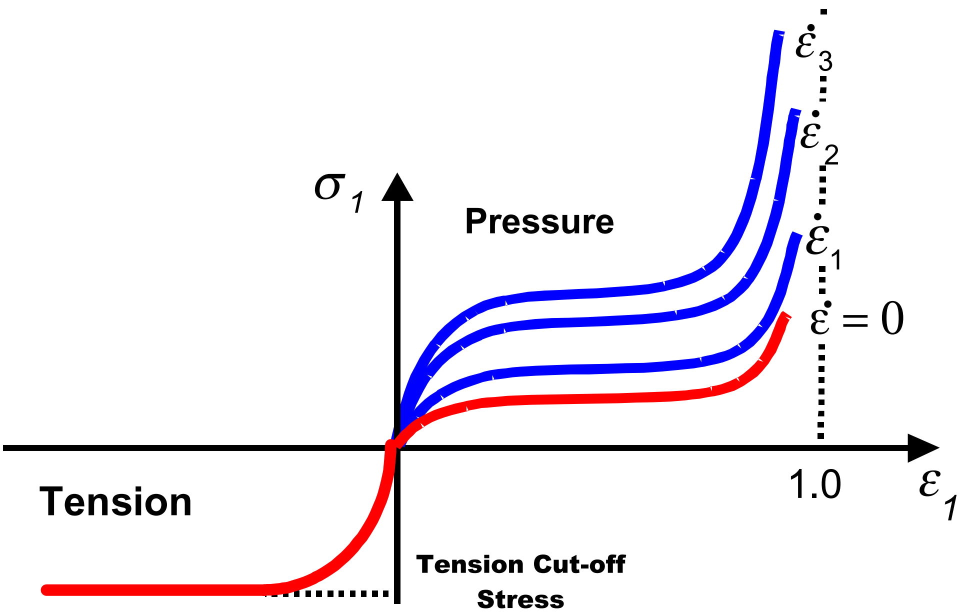

Figure 1: LS-DYNA interpolates linearly between the strain rates and keeps the stress value constant after the highest strain rate.

The definition of tensile load curves is optional. If tensile load curves are not available, a Young's modulus for the foam material for tension has to be introduced. The stress-strain relation is then linear elastic for tension. If available, tensile load curves are introduced as the negative values of uni-axial compression load curves. In MAT83 material model, strain rate dependency for tension is not considered. The user has to add to all load curves for the different strain rates the quasi-static tension values.

The possibility of using engineering strain rates instead of true strain rates is an important improvement in MAT83. It is much easier to keep engineering strain rate constant than to keep the true strain rate constant in an experimental set up.

MAT83 allows only the input of loading curves. Unloading curves may not be introduced as input. The minimum strain rate load curve is used for unloading in simulations with MAT83. This makes the simulations behave stiffer than real cases.

The optional tri-axial load curve is requested by the users as the volumetric stress value for the same volumetric strain is 2~3 times higher in tri-axial loading than in uni-axial loading. The tri-axial load curve, introduced in MAT83, is not rate dependent. Only hydrostatic load curves can be introduced. So, it may happen that for high strain rates, stress values of uni-axial compression may be higher than hydro-static compression stress values. Such cases shall be carefully examined, and if necessary using tri-axial load curve for these cases shall be avoided.
In MAT83 card, if an optional hydrostatic load curve is defined, stress is then calculated as:

$$\sigma_{11} = \sigma_{11} * \alpha + (1-\alpha)\, P_{LC} \;,$$
$$\sigma_{22} = \sigma_{22} * \alpha + (1-\alpha)\, P_{LC} \;,$$
$$\sigma_{33} = \sigma_{33} * \alpha + (1-\alpha)\, P_{LC} \;,$$

$$\alpha = \sqrt{\frac{2}{3}\left[\left(\sigma_{11} - \frac{1}{3}tr[\underline{r}]\right)^2 + \left(\sigma_{22} - \frac{1}{3}tr[\underline{r}]\right)^2 + \left(\sigma_{33} - \frac{1}{3}tr[\underline{r}]\right)^2\right]} * \frac{1.5}{\sigma_{\max}}$$

Equation 1: This formulation is used to calculate the influence of tri-axial load curve in LS-DYNA.

This formulation is only to satisfy the boundary conditions of uni-axial and tri-axial loading cases. As seen from the formulation, in case of uni-axial loading, α is equal to one, so values only from uni-axial load curves are taken. And in case of tri-axial loading, α is equal to zero, so values only from tri-axial load curves are taken.

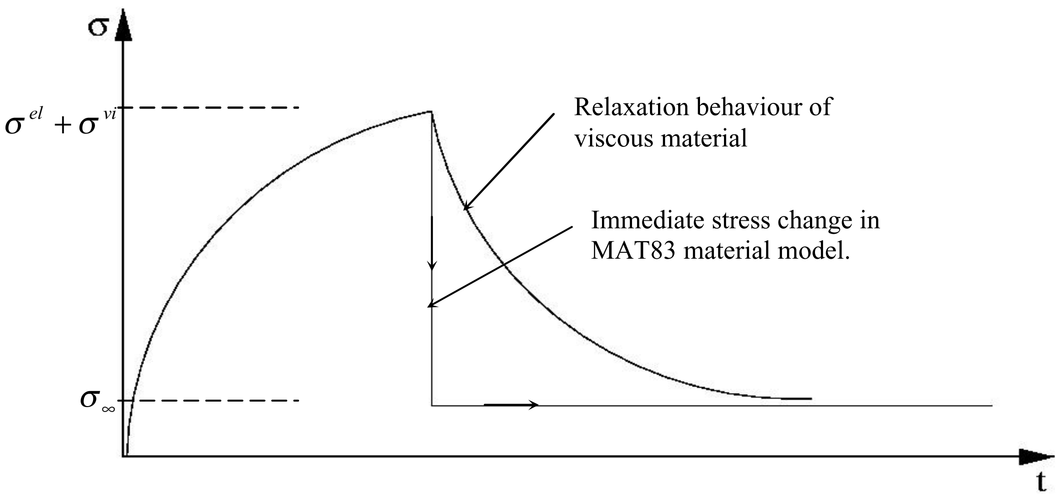

Figure 2: Difference between real physical behaviour of viscous material and relaxation behaviour of MAT83.

The relaxation behaviour of foam materials is not well-defined in MAT83. As MAT83 uses only the load curves from the material card, during relaxation the stress value immediately drops down to the stress value of min. strain rate load curve at the same strain value (Figure 2). This causes an unrealistic relaxation behaviour in simulations.

Preparation of Experimental Data

In this project, a computer code is written in order to create a general density law. This density law is used to calculate stress-strain values for the user-defined densities. The code reads in the experimental data from the first database and at the first phase it prepares these data for further use in the code. Preparation of experimental data is done in three steps;

a) Cleaning

This part intends to put the raw experimental data in a format that makes the calculations easier. The computer code simply;

- reads in the experimental data,
- removes singularities from displacement and force values, shifts negative displacement values to positive region and removes the negative entries of force values.
- smoothes the curve by averaging each data.

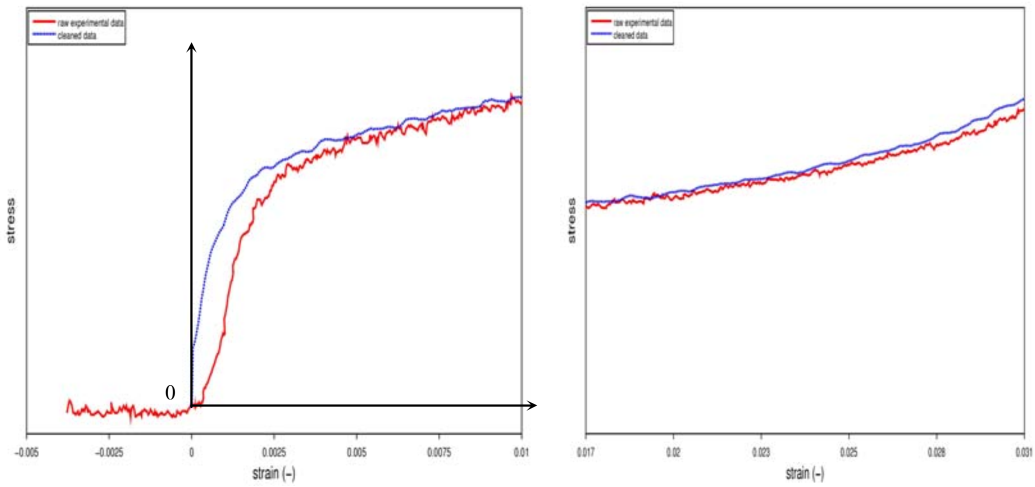

Figure 3: Raw and cleaned experimental data.

b) Extension of Curves

It is not easy to have reliable results at high compression ratios for a uni-axial or a tri-axial compression. Although data up to the densification region is quite reliable, because of the experimental set-up, one shall avoid using unreliable data in densification region. This limit where reliability ends can be decided visually.
But one still needs the data in densification region. This part of the computer program aims to have numerical stable load curves that are extended in the densification region. The code works as:

- using the hyperbolic function below, generate a general density law to calculate stress-strain values for user-defined density in densification region, (eqn. from Paul Du Bois[6])

$$\left.\frac{\partial\sigma}{\partial\varepsilon}\right|_i = \left(\left.\frac{\partial\sigma}{\partial\varepsilon}\right|_{laststrain}\right)\left(\frac{1.0 - laststrain}{1.0 - \varepsilon_i}\right)^n$$

$$\sigma_{i+1} = \sigma_i + \left.\frac{\partial\sigma}{\partial\varepsilon}\right|_i \Delta\varepsilon$$

Equation 2: Hyperbolic function used for curve extension

- use the assumptions and constraints listed below for the extension of the curve,
  - ♦ young's modulus of foam material at zero void ratio is equal to matrix material's young's modulus,
  - ♦ extension of the curve, using a hyperbolic function, continues till zero void ratio,
  - ♦ curve extension after zero void ratio till 99%, is performed linearly, assuming the matrix material is linear elastic.
- further extension of the curve at 99% is an almost vertical tangent to assure numerical stability. This is to avoid a compression of 100% or even higher.

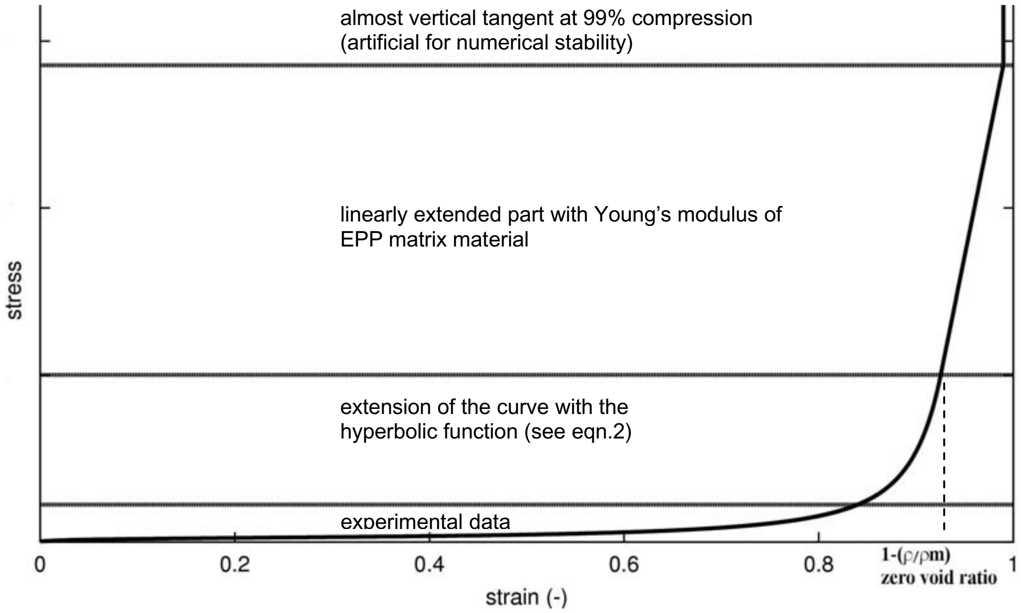

Figure 4: Curves are extended with the steps described above

Curve extension is applied only to uni-axial and tri-axial load curves.

c) Averaging

To be able to calculate a density law, these repeated experimental curves shall be reduced to one curve representing each density at each load case. The code averages the curves linearly to find a final curve.

Density Law

The aim of this part of the code is to generate a density law that will be used to calculate stress-strain values for user-defined densities.

- For uni-axial and tri-axial compression load curves, the least squares method is used to generate a density law, using an exponential function. A curve is fitted through 4 experimental density-stress values for each strain value (at least 4000 strain values). Later, to increase the range of this density law, 2 artificial points are introduced. The co-ordinates of the first artificial point is half value of the stress value of first experimental point at 15 g/l. The second one is 2.5 times of the last experimental point at 100 g/l. Adding these artificial points avoids crossing of the density-stress curves outside of the density region 30-80 g/l.
- For tensile load curves interpolation/extrapolation of the curves is done linearly. There is no special method used to calculate tensile stress-strain values for unknown densities.
- Using the evaluated density functions, the material input card for a specific density for MAT83 is generated.

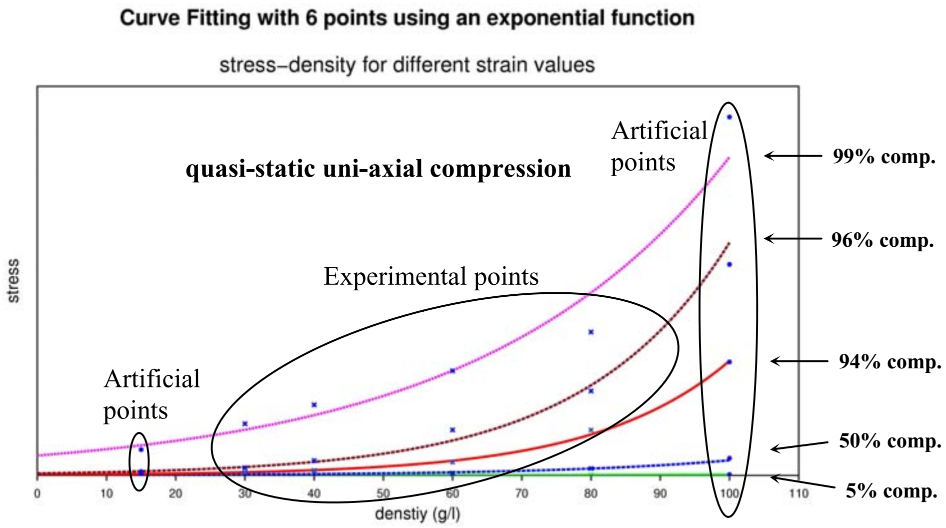

Figure 5: Curve fitting using an exponential function

This code is working only up to a density of about 130 g/l. The reason for this limit is, the experimental results are only available up to 80 g/l for EPP foam in this database. If results for higher densities would be available, the upper limit of reliable results could be extended.

Strain-rate dependency of EPP foam

In a second database dynamic uni-axial compression tests are available, but only for EPP foam with a density of 55 g/l. These tests are not used for the generation of the LS-DYNA material cards.

The tests for the second database are not performed at the same strain rates. That is, why no one-to-one comparison between the simulation results could be carried out. Instead, all strain rates for some specific strain values were compared to check if the code's output is lying within the range. Below, is a graphic showing the relation between stress and strain rate for different strain values.

As seen in the graphic below, the stress value tends to remain almost constant after 80 1/s ~ 90 1/s strain rate. LS-DYNA interpolates linearly between each strain rate to calculate the stress for the applied strain rate. But when a strain rate above the highest strain rate is applied, simply the stress values for the highest strain rate are taken. So, a shift of the highest strain rate from 135 1/s to 85 1/s in LS-DYNA represent the physical limit of strain rate dependency, as shown in Figure 6. This means the tri-linear curves in Figure 6 are used.

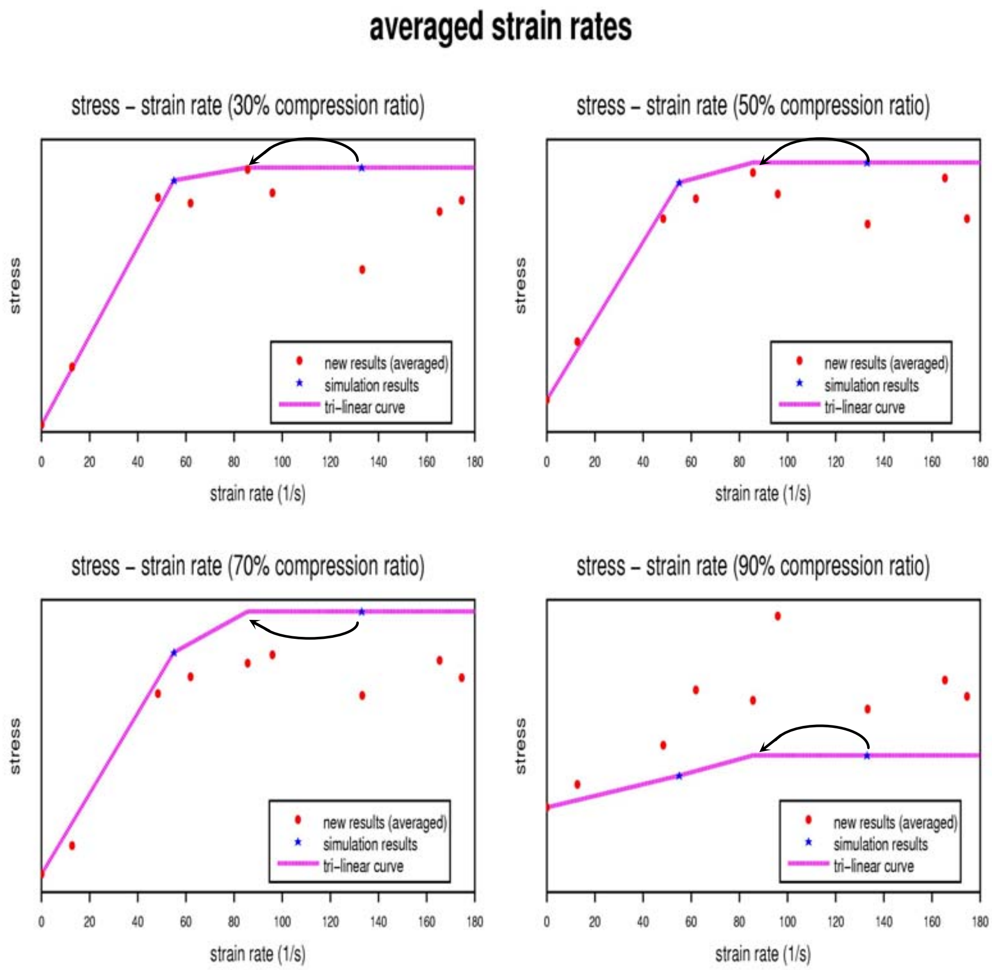

Figure 6: Strain rate dependency of EPP foam for specific compression ratios: * results of simulation • experimental results

Verification of Results

Verification of results is performed by comparing the models, prepared by using the calculated load curves, to real applications like uni-axial compression tests, shear tests and a drop-tower experiment. The second database, which is not used by the computer code for creating the density laws, is ideal for this comparison.

Quasi-static uni-axial compression curves:

Below, the comparison of quasi-static uni-axial compression curves is shown. The comparison is made between the simulation results and the results from an independent experimental database, the second database. As seen in Figure 7, both curves are exactly matching up to the point where the experimental curve ends.

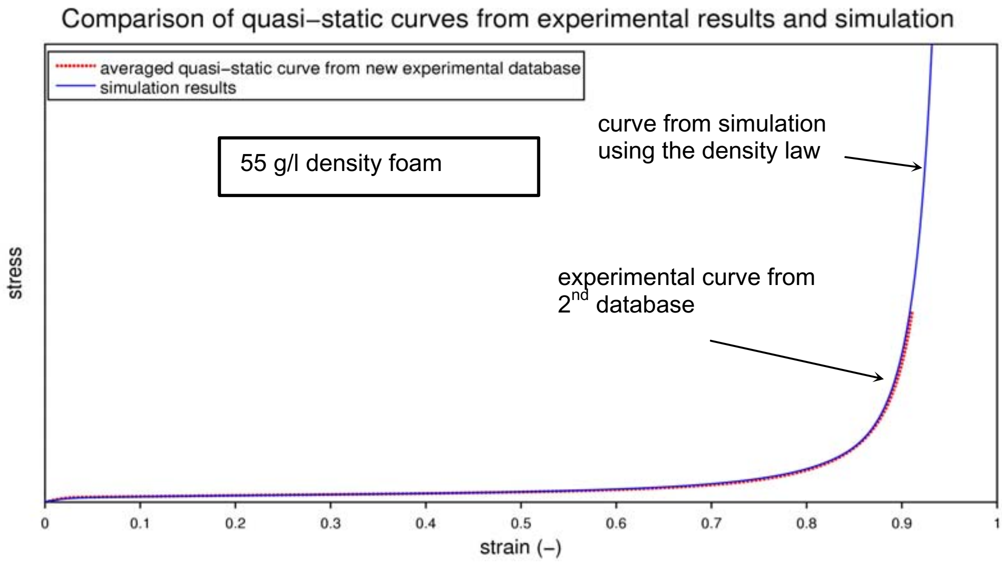

Figure 7: Comparison of quasi-static curves

Simulation of a sphere-drop test:

A simulation using the material card generated by the code for an intermediate density is also compared to a sphere-drop experiment in LS-DYNA. This is a non-homogenous deformation and in this application compression, tension and shear is involved. As seen in the results, while the loading part is quite similar, the unloading part is behaving much stiffer than the real application. The reason is, in MAT83 only loading curves are defined. The lowest strain rate load curve, quasi-static load curve so to say, is used as unloading curve. This relatively unreal assumption for unloading makes the model behave stiffer (as it is described in the chapter *Properties of MAT_FU_CHANG_FOAM*).
In some dynamic applications, where unloading is also important, some engineers define the dynamic unloading curve as quasi-static load curve, to avoid this stiffer behaviour. This assumption helps to model a more realistic unloading behaviour in dynamic unloading with MAT83. However, this only works for dynamic cases. In case of quasi-static loading, the real quasi-static load curve must be introduced to avoid too soft behaviour.

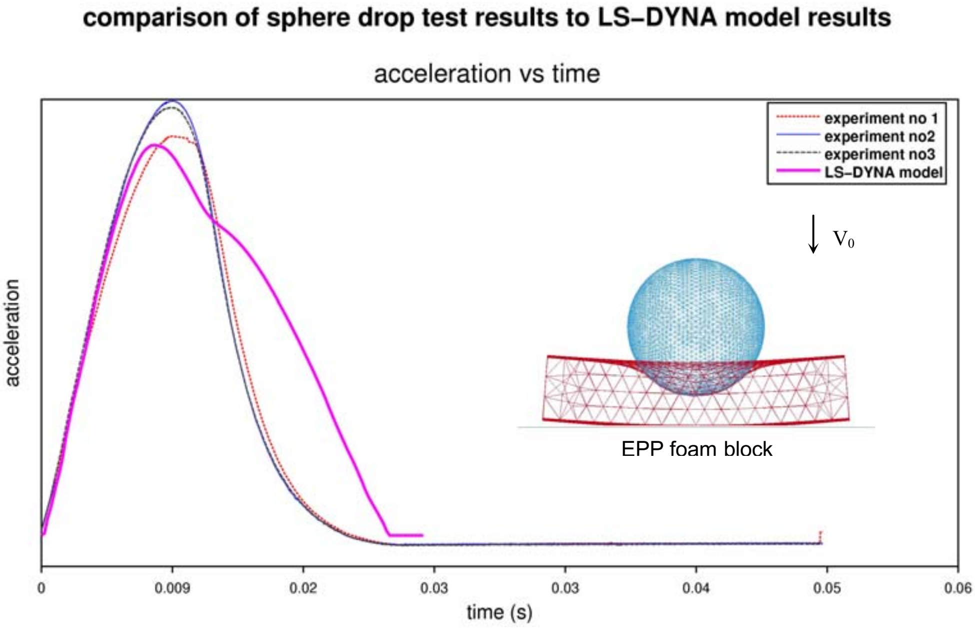

Figure 8: Comparison of a sphere drop model to a real sphere drop application results

Simulation of Shear Loading:

In MAT83, direct input of uni-axial compression, hydro-static compression and tensile is allowed. There is no option for direct shear load curve input in MAT83. Yet, using the available loading curves, shear can also be modelled. Below, results from a shear loading modelled in LS-DYNA compared to a real application is shown. As seen from the graphics, up to the failure point of the real application, the results from real application and LS-DYNA model are quiet similar. The difference between real application and LS-DYNA model after rupture occurs is, no failure criteria is introduced in LS-DYNA model. The large elongation of the elements is the result of keeping tensile load constant at highest tensile stres (Figure 10). At this point no additional tensile resistance is available (Figure 11).

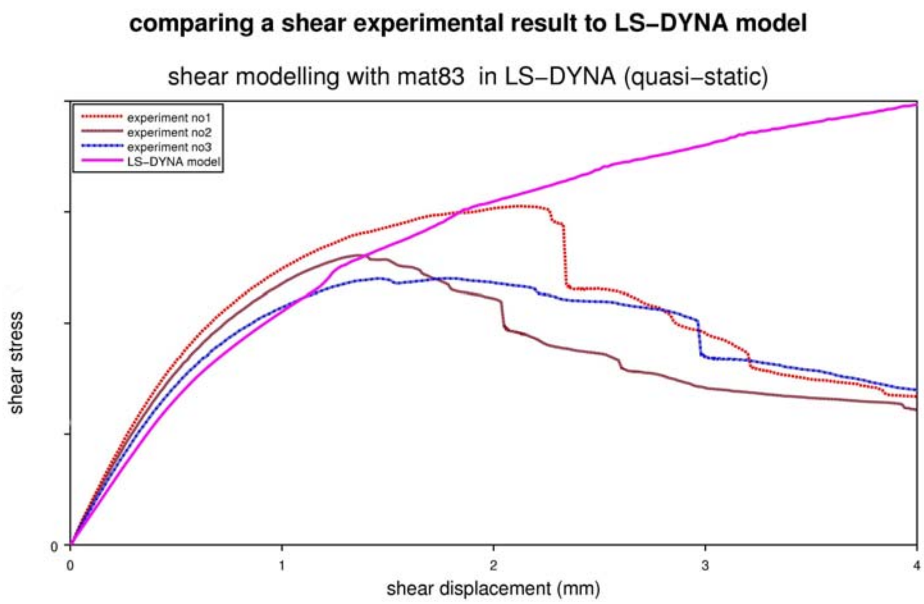

Figure 9: Comparison of a shear model with real shear results

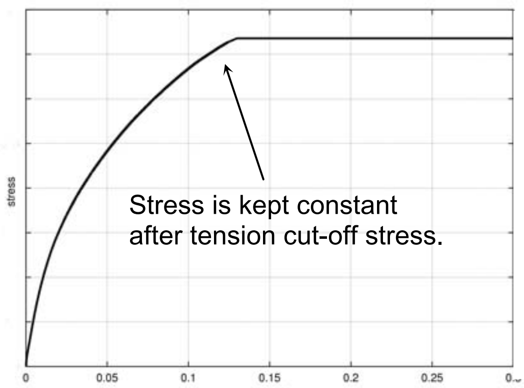

Figure 10: Tensile load curve introduced in the LS-DYNA material card.

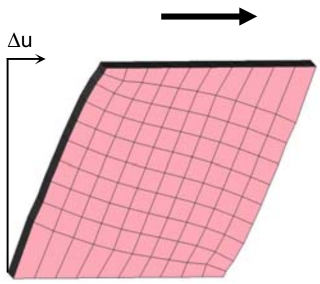

Figure 11: Elongation of elements under shear load

But modelling shear and tensile also has some limits. In MAT83, tensile loading has no strain rate dependency, which means whatever the loading speed is, the response of MAT83 for tensile is more or less the same. And as the main component of shear is tensile loading, the strain rate dependency of shear also can not be modelled. The code is generating tensile load curves only for quasi-static case. So, reliable results can be achieved only for quasi-static tension and quasi-static shear with the code's output. If one wants to model tensile or shear with different strain rates, these tensile load curves shall always be modified in order to cover the different strain rates. One has to be careful about results of shear or dynamic tensile loading modelled in LS-DYNA, using the code's output.

Summary and Conclusions

The purpose of this work was to develop a computer code in order to supply load curves for different densities to be used in FEM calculations of EPP foam. This computer code reads in the raw experimental data, processes it (removes singularities, reduces to one final curve for each density, etc.), extends this final curve in the densification region for uni-axial and tri-axial compression and then creates a general density function which is used to create load curves for MAT83 input deck. As seen from the results of comparisons between models and real applications, numerically generated load curves, that demonstrate the behaviour of foam material with a density lying within the range, is reliable. This saves a lot, for engineers who are working with different densities of EPP foam and don't have that big databases including all the densities they use.
But one has to be careful about results from the code's output and MAT83. This means, both has strong and weak sides explained above. Taking into consideration these properties will reduce the probability of bad designed models.

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