Numerical and Experimental Investigations of Polyurethane Foam for Use as Cask Impact Limiter in Accidental Drop Scenarios - 12099

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ABSTRACT

Rigid, closed-cell polyurethane foams are frequently used as cask impact limiters in nuclear materials and hazardous waste transport due to their high energy-absorption potential. When assessing the cask integrity in accidental scenarios based on numerical simulations, a description of the foam damping properties is required for different strain rates and for a wide temperature range with respect to waste heat generation in conjunction with critical operating and environmental conditions. Implementation and adaption of a respective finite element material model strongly relies on an appropriate experimental data base. Even though extensive impact experiments were conducted e.g. in Sandia National Laboratories [1], Savannah River National Laboratory [2] and by Rolls Royce plc [3], not all relevant factors were taken into account.

Hence, BAM who is in charge of the mechanical evaluation of such packages within the approval procedure in Germany, incorporated systematic test series into a comprehensive research project aimed to develop numerical methods for a couple of damping materials. In a first step, displacement driven compression tests have been performed on confined, cubic specimens at five loading rates ranging from 0.02 mm/s to 3 m/s at temperatures between +90°C and -40°C. Materials include two different polyurethane foam types called FR3718 and FR3730 having densities of 280 kg/m³ and 488 kg/m³ from the product line-up of General Plastics Manufacturing Company [4]. Their data was used to adapt an advanced plasticity model allowing for reliably simulating cellular materials under multi-axial compression states [5]. Therefore, an automated parameter identification procedure had been established by combining an artificial neural network with local optimization techniques.

Currently, the selected numerical material input values are validated and optimized by means of more complex loading configurations with the prospect of establishing methods applicable to impact limiters under severe accidental conditions. The reference data base is provided by experiments, where weights between 212 kg and 1200 kg have been dropped from heights between 1.25 m and 7 m on confined 10 cm cubic foam specimens. By presenting the deviations between experimental values and the corresponding output of finite element simulations, the potentials and restrictions of the resulting models are highlighted.

INTRODUCTION

Reliable numerical simulations of the deformation and energy absorption of impact limiters in severe accidental scenarios are challenging due to their highly nonlinear and dynamic response. The corresponding finite element models have to consider a large number of interrelating parameters such as temperature, strain rate and the specific boundary and contact conditions of the components. An implementation of appropriate material models is often compounded by the lack of systematic experimental data that expose major factors influencing the dynamic load-deformation relationships.

Since proper predictions of the behaviour of limiter materials are, however, of utmost importance in safety assessments for licensing casks for transport and storage of high active waste, BAM conducts a research project to overcome these limitations and thus to optimize the design and material selection for such components. A major milestone is to enhance and to develop advanced material models for simulating the behaviour of wood, polyurethane foam and damping concrete in dynamic finite element computations. The data basis needed for parameter identification is provided by comprehensive compression test series with varying specimen dimensions, temperatures, deformation rates, material orientations and boundary conditions. The test programme is divided into three parts, all of them performed at different BAM test sites. The first two of them consisting of displacement-driven tests and guided drop tests are almost completed and their results are currently used to evaluate and improve material models for rigid, closed-cell foams.

EXPERIMENTAL OUTPUT

Displacement-driven tests (DDT)

Displacement-driven compression tests provide load-deformation curves for specified constant deformation rates and thus form the basis for the development and adaptation of adequate numerical material models. They had been conducted on confined and simply supported cubic foam specimens with 10 cm edge length as part of the first stage of the experimental program. Load was applied at rates between 0.02 mm/s and 3 m/s under ambient, cool (-40°C) and warm temperatures (90°C) up to a total compression of 70%. Table 1 gives an overview of the relevant test series, each of them comprising of at least five individual test runs performed on both types of foam (FR3718 and FR3730). The resulting load and displacement measurements had been used to calculate true stress - logarithmic strain relations as well as to determine the corresponding strain rates. In the following, the values given are always arithmetic means as justified by the very slight variations within one test series.
Additional investigations proved that the behaviour neither depends significantly on the angle between specimen foam growth and load axis nor on its edge size. Hence, the results are valid for arbitrary oriented components in all usual dimensions.

Table 1: Test series DDT

no.	loading speed	temperature	boundary condition
D1	0.02 mm/s	+20° C	confined
			unconfined
D2	200 mm/s	-40°C | +20°C | +90°C	confined
D3	3000 mm/s	-40°C | +20°C | +90°C	confined
		20° C	unconfined
D4	0.5 mm/s	-40°C | +20°C | +90°C	confined
D5	10 mm/s	+20° C	confined

Both foam types exhibit a three-zone flow curve consisting of a short elastic range, a plateau and subsequent densification. The width of the plateau zone as well as the stress level depends significantly on foam density, temperature and strain rate.
The influence of the first two factors is illustrated in figures 1 and 2, which compare the stress strain relations for quasi-static loading for both foam types: Specimen stiffness decreases with temperature and increases with the foam density, where these dependencies are nonlinear and correlate with each other as well as with the strain level. Due to the machine capacity limited to 1MN, especially the cooled FR3730 specimens could only be subjected to approximately 50-55% deformation. Further hardening occurs when load is applied dynamically. This effect again is sensitive to the parameters above and can amount to up to 60% load increase for reaching the same deformation state. As an example, the different flow curve levels are given for FR3718 ambient temperature test series in figure 3.

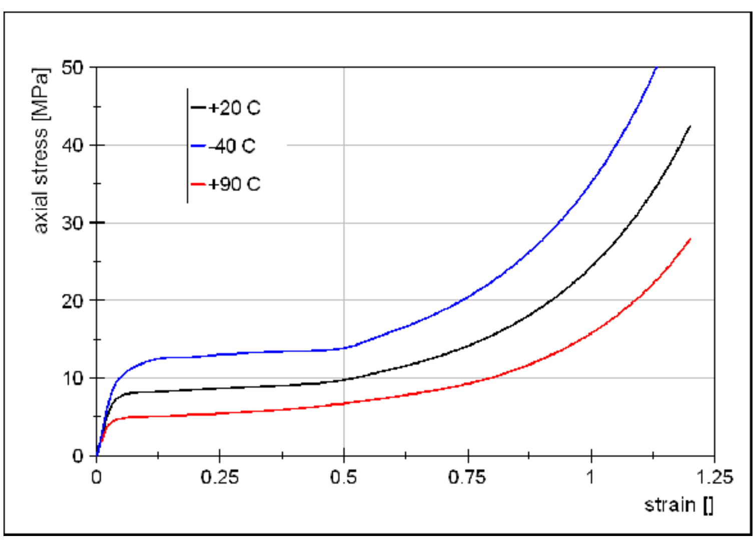

Figure 1: Flow curves of tempered FR3718 under quasistatic loading

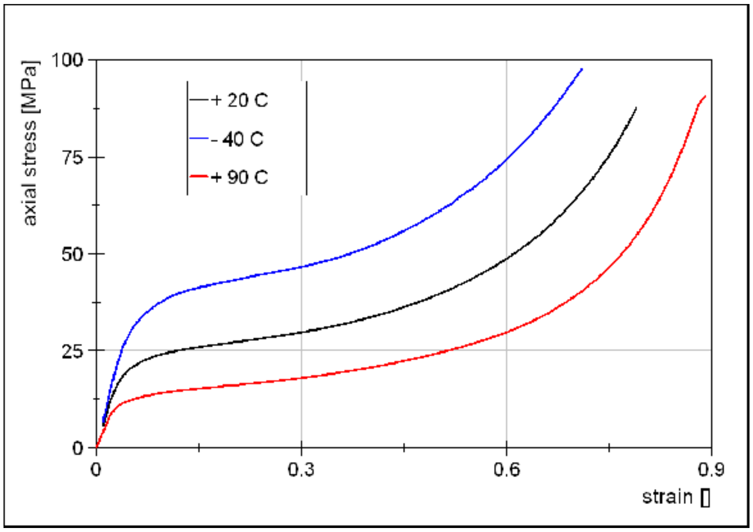

Figure 2: Flow curves of tempered FR3730 under quasistatic loading

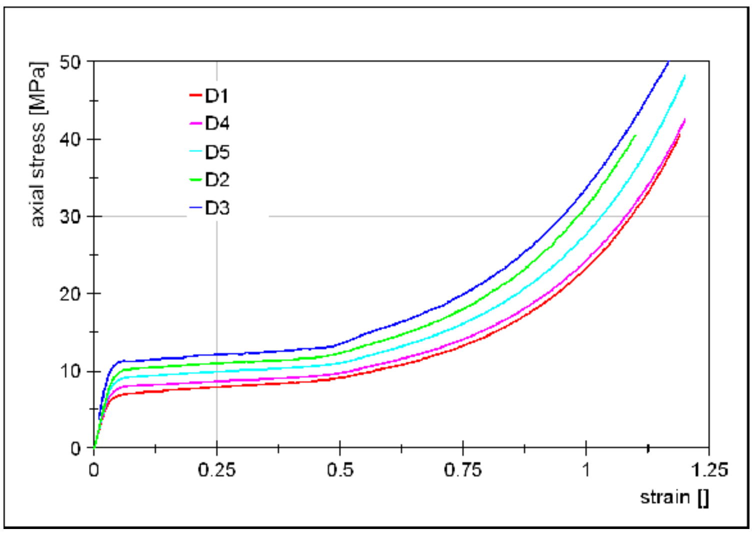

Figure 3: Flow curves of FR3718 under different loading rates

Guided Drop Tests (GDT)

The second stage of the experimental programme focuses on guided drop tests in order to yield a realistic loading course characterised by a high initial loading speed and gradual slowdown. At the BAM test facility in Horstwalde near Berlin weights of up to 1200 kg can be dropped from up to 12 m onto a specimen at a specified position. All samples are confined using the same device as in the first project stage. The stamp is positioned onto the specimen and pushed by the drop weight.

In order to verify the parameter sets that had been determined by means of the first stage results, tests had to be performed where the maximum loading speed as well as the resulting compression is within the limits of the previous experiments again under consideration of the specific temperature range. Additionally, higher deformation speeds are of special interest in order to be able to extrapolate the strain-rate dependency for high dynamic loading as it occur in drops from high heights or if cask components are exposed to bullets or similar kinds of blast energy. Hence, altogether 10 test series consisting of at least 4 runs are designed for each foam type whose configurations are given in table 2. Except for the highest drops (configuration C4) all tests are completed.

Table 2: Test series GDT

<table>
<tr><th>no.</th><th>temperature</th><th>drop height</th><th>drop weight</th><th>foam type</th></tr>
<tr><td rowspan="2">C1</td><td rowspan="2">+20°C</td><td rowspan="2">1.25 m</td><td>570 kg</td><td>FR3718</td></tr>
<tr><td>1200 kg</td><td>FR3730</td></tr>
<tr><td rowspan="2">C2</td><td rowspan="2">-40°C | +20°C | +90°C</td><td>2.50 m</td><td>500 kg</td><td>FR3718</td></tr>
<tr><td>2.00 m</td><td>1200 kg</td><td>FR3730</td></tr>
<tr><td rowspan="2">C3</td><td rowspan="2">-40°C | +20°C | +90°C</td><td>7.00 m</td><td>212 kg</td><td>FR3718</td></tr>
<tr><td>7.50 m</td><td>422 kg</td><td>FR3730</td></tr>
<tr><td rowspan="2">C4</td><td rowspan="2">-40°C | +20°C | +90°C</td><td rowspan="2">8.50 m</td><td>212 kg</td><td>FR3718</td></tr>
<tr><td>422 kg</td><td>FR3730</td></tr>
</table>

Based on the load values measured at the stamp and the stamp displacements, mean true stress – logarithmic strain curves including the unloading path had been calculated. They likewise show a significant dependence on foam density, temperature and strain rate. In Figure 4 the influence of drop height and drop mass is illustrated for ambient temperature tests of FR3730. The amount of potential energy accounts for the final compaction grade, while the stress values for a specific strain level are affected by the drop height and thus by the impact speed. Anyhow, since the resulting strain rates differ only by a factor 2 to 3 between configurations C1 and C3 (Figure 5) whereas dynamic hardening follows rather logarithmic functions, the differences in stress level are not that large. Strain rate effects become more significant when comparing the results with the DDT. Especially for ambient and warm foam specimens the stress curves of GDT are significantly higher, what is shown for FR3730 in 6. The fact that in the same test configuration the 90°C specimens had been subjected to higher deformation due to their reduced stiffness, allow for determining strain rate effects up to technical strain levels of 80%.

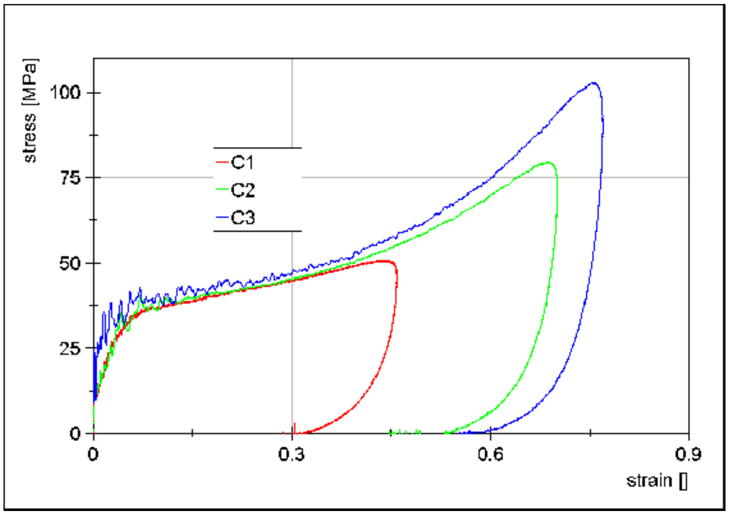

Figure 4: Stress-strain relations for GDT FR3730 at ambient temperature

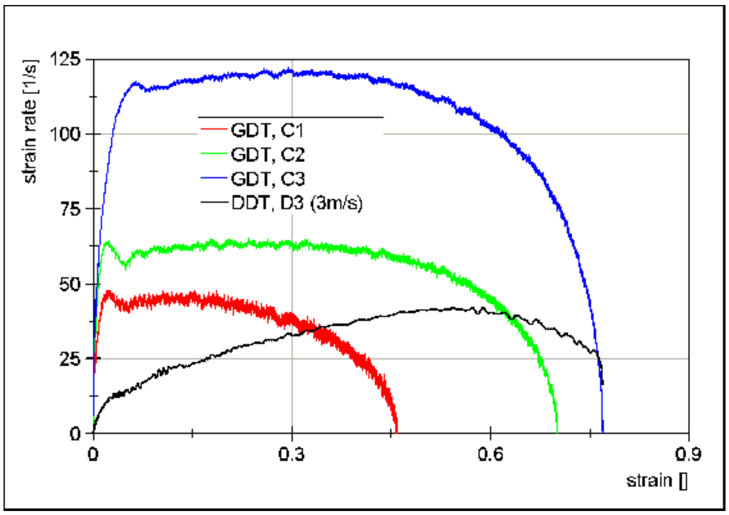

Figure 5: Comparison of strain rates FR3730

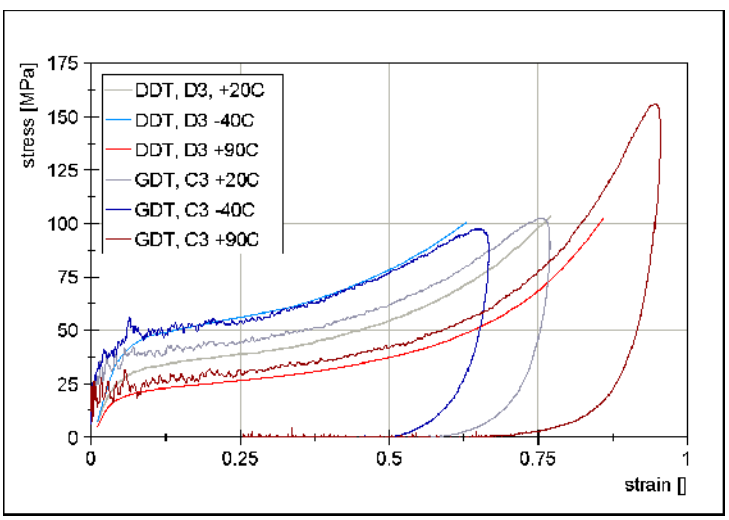

Figure 6: Comparison of GDT and DDT flow curves for FR3730

NUMERICAL MODEL

The research project aims to develop and to adapt adequate material models in order to reliably simulate the behaviour of relevant cask components. With regard to high loading in accidental scenarios and the broad temperature range that might occur, all aforementioned aspects have to be considered in a qualified model. Especially it must account for plateau and densification zones, strain-rate and temperature dependency. Since for a start, the finite element programme ABAQUS was applied for numerical calculations, the standard foam material approach of its material library was evaluated. There is more than one implementation available but by means of sensitivity studies the so called “crushable foam model with isotropic hardening” turned out to be the best for the specific task.

Considering the principally different stress-strain relations, separate input sets had been generated for FR3718 and FR3730. There are also initially individual sets for each temperature assuming adiabatic conditions without any temperature change across the specimen during loading. Anyhow, the last simplification can easily be withdrawn as each parameter can be given as a multi-linear function of temperature. This is important when implementing thermo-mechanical coupling for components which release major quantities of heat under impact loading.

So far, six individual finite element models had been implemented (3 temperatures, 2 foam types) whose basic input yield curves had been adapted by using the results of the quasi-static DDT tests. Furthermore, the dynamic DDT tests results had been deployed to determine strain-rate dependent hardening functions. Unfortunately the standard material concept allows only for multiplying the static flow curve with constant factors, so that here a good agreement between numerical and experimental results could only be achieved for a specific strain range. It was chosen to better approximate the plateau zone as it dominates the behaviour of impact limiters in relevant scenarios. Accordingly, there are only minor deviations in this zone, what is exemplarily shown for FR3718 tests at ambient temperatures (Figure 7).

When applying the resulting material parameter to simulate GDT, the gap between calculation and experimental behaviour increases. Since the latter tests come much closer to real loading conditions, there is a need to substantially enhance the standard foam model by incorporating strain level dependent hardening functions. This work is currently being done as well as implementation of shear failure in order to better simulate the boundary region in penetration tests.

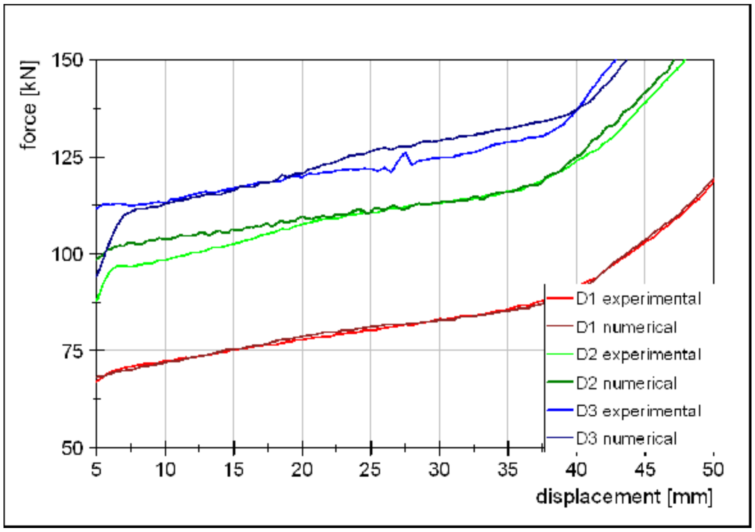

Figure 7: Comparison of numerical and experimental load-displacment curves for FR3718 (DDT, ambient temperature)

CONCLUSIONS

Systematic compression tests on polyurethane foams had been performed at BAM test site within the framework of a research project on impact limiters for handling casks for radioactive waste. The experimental results had been used to adapt numerical models for simulating the behaviour of different foam types at different temperatures. The loading speed, however, turned out to have a major influence on their flow curves that can not be captured by simple strain-rate dependent multipliers. Especially for guided drop tests that come close to real accidental scenarios there is a significant gap between experimental and numerical results even when applying such advanced material models. Hence, the extensive data base is currently deployed for expanding the standard algorithms to include adequate dynamic hardening factors.

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