# Selecting Material Models for the Simulation of Foams in LS-DYNA

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**Summary:**

Foams are multi-phase materials that exhibit dramatically different properties that depend on the matrix material as well as the pore microstructure. This additional degree of freedom from the presence of the gas phase makes material modelling for foams a difficult matter. LS-DYNA offers a variety of material models, each with capabilities designed to capture the unique behaviour of a different types of foam. The selection of the correct material model depends to a large extent, on the observed behaviour of the foam during the test. Other factors will include the actual situation under simulation, which becomes important for highly non-linear materials, where a single material model often cannot capture all the dependencies, forcing a localized material calibration. The material calibration itself is not easy because of the lack of set procedures for characterization. Previous research has devoted a lot of effort to enhancing these material models to improve their capabilities as well as to make them easier to use.

In our current work, we seek to lay down a framework to help us understand the different behavioural classes of foams. Following a methodology that we previously applied to plastics, we will then attempt to propose the right LS-DYNA material models that best capture these behaviours. Guidelines for model selection will be presented as well as best practices for characterization. Limitations of existing material models will be discussed.

**Keywords:**

Material model calibration, foams, impact, crash

## 1 Introduction

Foams are used in a variety of applications in ranging from the absorption of energy, the protection of components and in comfort situations. For these purposes, a variety of foams have been designed with widely varying properties tailored specifically to each end use. In fact, this variability is one of the key factors contributing to the complexity of foam modelling.

Foams are created with two important variables: the matrix material and the morphology of the gaseous phase. There are two generic morphologies; open cell and closed cell. Foams are often characterized based on the percentage of open cell fraction or the closed cell fraction. Additionally, the pore size plays a role in the behaviour, controlling the rate at which the gas exits the foam when it is compressed. Careful tuning of these parameters gives a range of behaviours that can tailor the foam to different applications.

The matrix can be made from a variety of material, rigid or flexible. Rigid materials typically result in crushable foams. Crushable foams undergo deformation by ductile plasticity or brittle means. In ductile behaviour, the foam walls undergo plastic deformation with little or no recovery. Classic examples are metallic foams. The cell walls in brittle foams fail, on the other hand, and there is no recovery. Rigid polyurethane foams fail in this manner.

Flexible materials are also used in foams. Common materials are plastics and rubber. Elastomeric foams are highly flexible, with high levels of recovery. The recovery may be instantaneous or over a period of time. Flexible polyurethane foams are typical of this class. Dense foams based on rubber are also made. Elastomeric foams tend to be open cell in nature. Polystyrene, polyethylene and polypropylene are used in closed cell applications. Polystyrene tends to produce rigid foams while polyethylene and polypropylene produce flexible foams of highly varied consistency based on the morphology. Specific to plastics, is the case of bead foams where the raw material in the form of un-foamed beads is allowed to foam and fuse together in a heated mould to produce the desired product.

It is important to state here, that the above description may be somewhat simplistic in the current landscape of foam materials. Manufacturers today have achieved a high level of sophistication in fusing the well-defined characteristics explained above. Matrix modification may lend a level of recovery to crushable foams. Recovery can be time based by playing with pore morphology. The open to closed cell ratio is tuned to control the elastic nature of the foam compared to its deformation.

In this paper, we use this basis as a means to attach behaviours to the classification outlined above. This permits us to examine the possibility to create a framework for the material modelling of these materials. Our work follows that of Sambamoorthy and Halder [1] who presented an excellent starting point in 2001. We have applied a more rigorous experimental method for the test data coupled with a methodology that we previously applied successfully to the characterization of plastics [2].

## 2 Foam Behaviour

The most common mode of deformation in foams is by compression. Foams are usually not strong in tension or shear and are rarely intentionally subjected to deformation in these modes. Nonetheless, these modes can occur in foamed components as a consequence of their geometry.

Generically, there are three zones in the compressive stress-strain relationship of foam (Figure 1): an initial region (Zone 1) that 'yields' to a flat plateau compaction region (Zone 2) followed by the densification zone (Zone 3). In the initial region, foams may have some stiffness due to the strength of the matrix material itself. Following the yielding, the gaseous component is affected. In open cell foams, the gas exits the foam through the open pores or channels. In closed cell foams, the gas is compressed. Now, the gas pressure may get high enough to rupture the cell wall thereby releasing the gas to the atmosphere. This results in permanent rupture to the cell and irrecoverable damage to the foam material. On the other hand, if the matrix is strong enough, the cell remains intact but collapses completely. When all the cells have either ruptured or collapsed, densification begins where the foam begins to behave much like the matrix material in its stress-strain relationship.

This behaviour is observed by and large by foams except that the relative size of each of these regions will vary depending on the matrix and morphology.

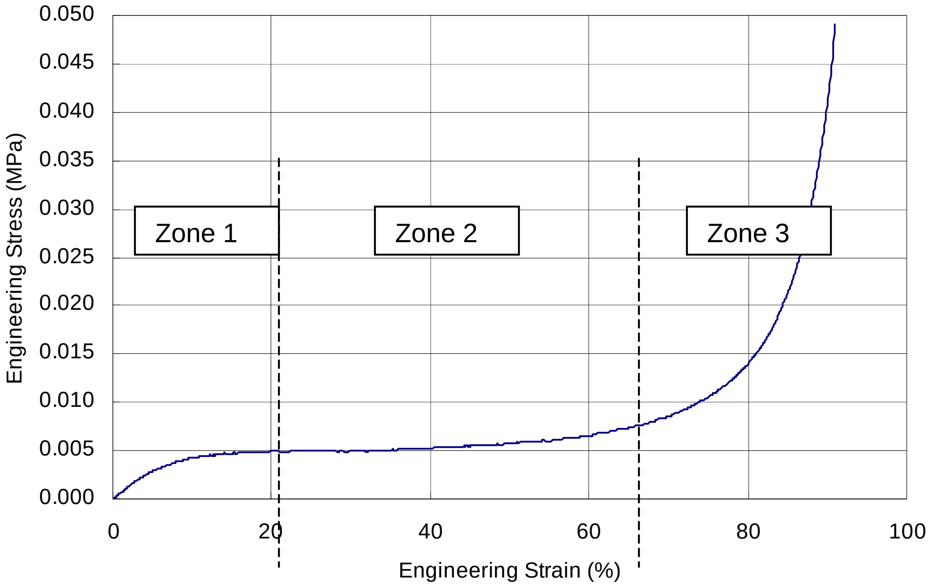

*Figure 1 Three deformation zones typically observed in foams*

## 3 Experimental work

In this study, we chose three foams with an objective to highlight the range of differences that can be observed in foam behaviour. Each foam was tested for rate dependent compressive behaviour covering a strain rate range of 0.01 to 100/s. This is because yield stress is found to have dependencies that vary with the logarithm of strain rate. The wide range of strain rates is intended to provide a clear picture of the rate dependency of yield of the material. In previous work, we made important observations regarding the rate dependency of plastics based on this same methodology.

All materials were tested to large strains to take the material into the Zone 3 densification region. Measurements were made on a BOSE Enduratec ELF 3200, a high rate, low force, low inertia instrument. No extensometry was used. Test specimens were right cylinders approximately 12.5 mm diameter and 12.5 mm thick. For the purpose of this study, specimen size effects were neglected. Minimal corrections were applied including slack, toe correction and smoothing in selective cases.

### 3.1 Polyurethane Foam Characterization

A commercial grey open cell polyurethane foam (density 27kg/m$^3$) was used. Such foams are commonplace in insulating and cushioning applications including packaging, seats and beds, electronics packages, including the egg carton profile foams used to transport circuit boards. The open cell and large pore characteristics mean that the material recovers quickly when the compressive load is removed. Time based (visco-elastic) recovery effects are not significant when compared to the so-called “visco-elastic” foams that are being designed today. Data are presented in Figure 2.

All three regions of stress-strain behaviour are evident in this data. The data at the highest 100/s strain rate appears to cross over at high strains. This behaviour is suspected to be an experimental artefact rather than an expression of the true nature of the material. We believe this to be so from the substantial self-consistency of data at the lower strain rates.

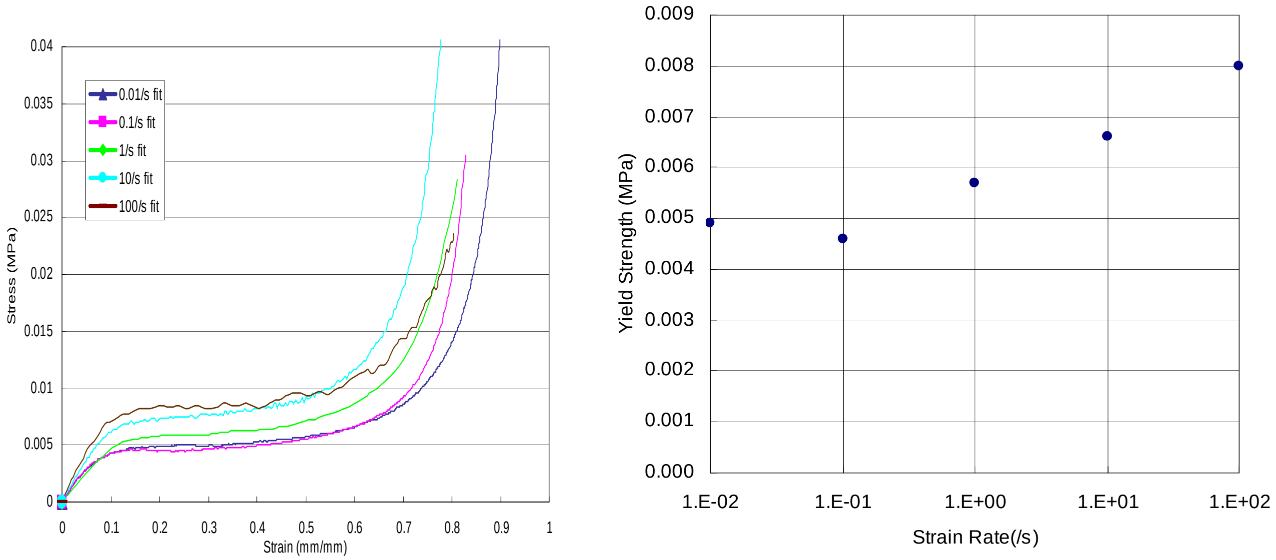

*Figure 2 Rate Dependent data for a polyurethane foam*

This foam demonstrates a measurable level of rate dependency of yield, changing about 50% over 4 decades of strain rate. The initial modulus is rate dependent. Unlike plastics, the dependency is non-linear in log strain rate, with an initial plateau that progresses to a steep rate dependency at higher strain rates. The phenomenological explanation lies with the understanding that at low strain rates, the gas can escape through the pores fast enough that it does not impact the stress-strain characteristic. At high strain rates, the behaviour is stiffer as the gas exercises a cushioning effect from not being able to escape during the time scale of the event. In corollary, it would be logical to note that controlling the pore geometry would permit the design of foams with more, or less rate dependency.

## 3.2 Expanded Polyethylene Foam

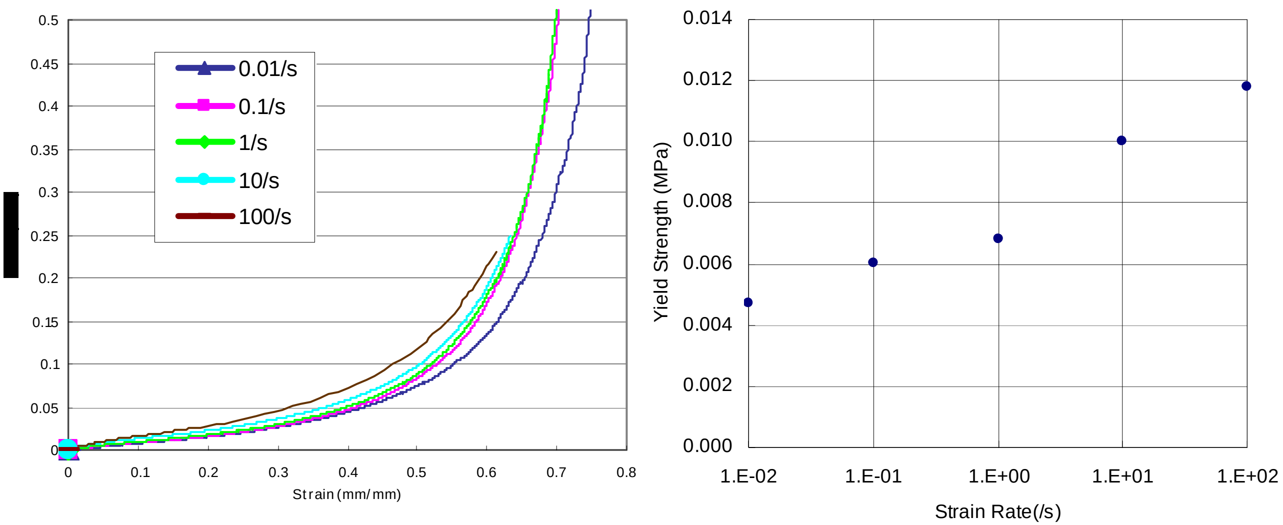

*Figure 3 Rate Dependent data for a polyethylene foam*

EPE foams are closed celled foams. These foams are available in three forms: bead foams, laminated sheets and as monolithic foamed structures. These foams are commonly used in energy absorption applications, primarily in packaging. The particular sample used is foamed as sheets 5-6 mm thick, which are then sandwiched together to form the desired shapes. The sample had a density of 21 kg/m$^3$ available as a 2 layer 12 mm thick sheet. Data are presented in Figure 3.

With this foam, the initial Zone 1 behaviour is not so evident. Instead the material appears to show a monotonically increasing stress-strain relationship not unlike that seen with hyper-elastic materials. There is no plateau but the densification region is clearly visible. The analogy to hyper-elastic behaviour is somewhat understandable. The gas phase has no opportunity to escape rendering it an integral part of the material and its behaviour. Consequently, there is no plateau as seen with the open cell foams. Note however that the high compressibility would make a hyper-elastic model to be an unsuitable choice to describe such behaviour. We noted that at high compression strains, some of the cells failed audibly during the test, pointing to the onset of damage.

The rate dependency of the yielding behaviour of this foam was observed to be high, but relatively linear with the logarithm of strain rate, behaviour previously shown to be commonplace with polymers [1]. As expected, the non-linear behaviour observed with the open cell foam was not observed.

### 3.3 Expanded Polystyrene Foam

EPS foams are used in protective applications. They are often seen in helmet liners, component and product packaging. They are easily damaged but have high energy absorption capacity and are not suitable for multiple impacts. Based on the selection of matrix material, they may be completely rigid or have a small elastic component. They are available as bead foam or a solid foamed product. The foam selected for this study was a bead foam with a small elastic component, and a density of 16 kg/m$^3$. Data are presented in Figure 4.

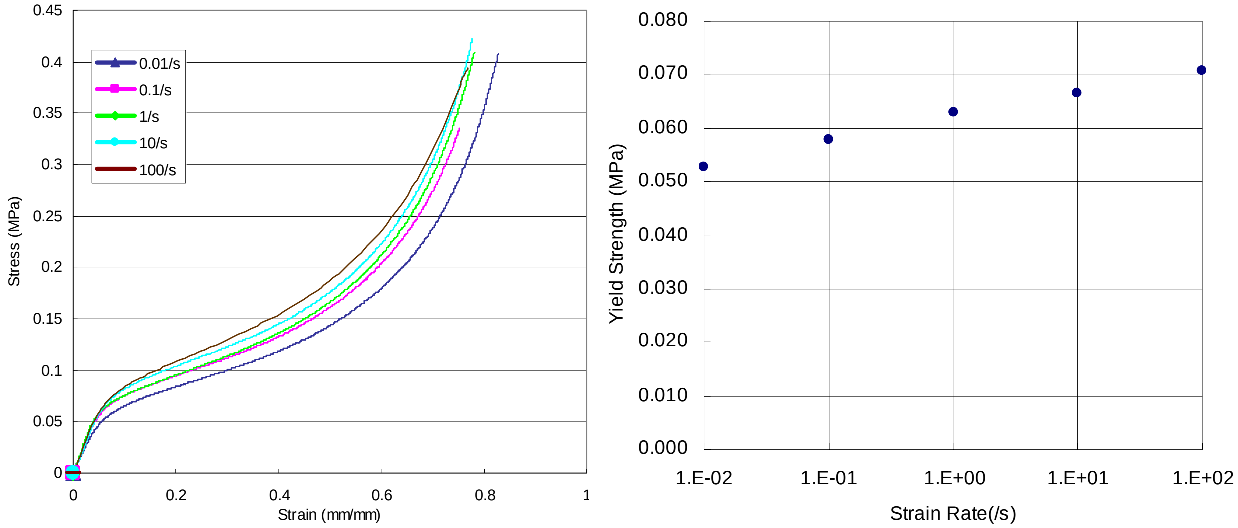

*Figure 4 Rate dependent data on a crushable EPS foam.*

All three deformation zones are observed with this material. The Zone 2 compaction behaviour is not the same as that seen with the polyurethane foam. This might be attributed to the fact that compaction occurs by the destruction of the cells, resulting in substantial and permanent damage. Nonetheless, the matrix material in this formulation had some level of elasticity, resulting in some degree of recovery after the event.

The rate dependent behaviour was observed to be linear with the logarithm of strain rate. The effect, about a 40% increase over 4 decades of strain rate, is comparable with that of most plastics.

## 3.4 Material Modelling Strategies

While a large number of models are available, because of the complex and highly varied behaviour of foams, material model selection is not a simple matter. Often, the models are limited in one way or another preventing the full expression of all relevant behaviours. Hence, pragmatic choices must be made, understanding both the material and its behavioural characteristics. Additional layers of complexity, such as recovery and time-based visco-elasticity can be layered upon subsequently to add richness to the material model. Lastly, some material models, while being extremely well suited to a particular material are unusable because of the complex material model calibration procedure involved.

Soft, open cell, polyurethane foams lend well to the MAT_LOW_DENSITY_FOAM (MAT57) material model. In its simple form, the model incorporates only one loading curve, but it can be augmented to handle loading as well as unloading behaviour. Because such foams do not easily undergo damage, the recovery is complete. The recovery path is however different (see Figure 5). In cases where it is important to follow the recovery path diligently, it may be useful to instantiate the HU and Shape parameters of the model. For the behaviour observed above, the LS-Dyna Theory Manual [3] provides a starting point of 0.01 for the hysteretic factor and about 6 for the shape factor. The values can be tuned using LS-OPT. The handling of rate dependency in this model is not as convenient as with MAT_FU_CHANG (MAT83) because it is handled via a visco-elastic term. A one-term Prony Series can be described with the help of a reference modulus and a decay constant. In the next phase of our work, we will examine enriching the calibration to include these additional parameters.

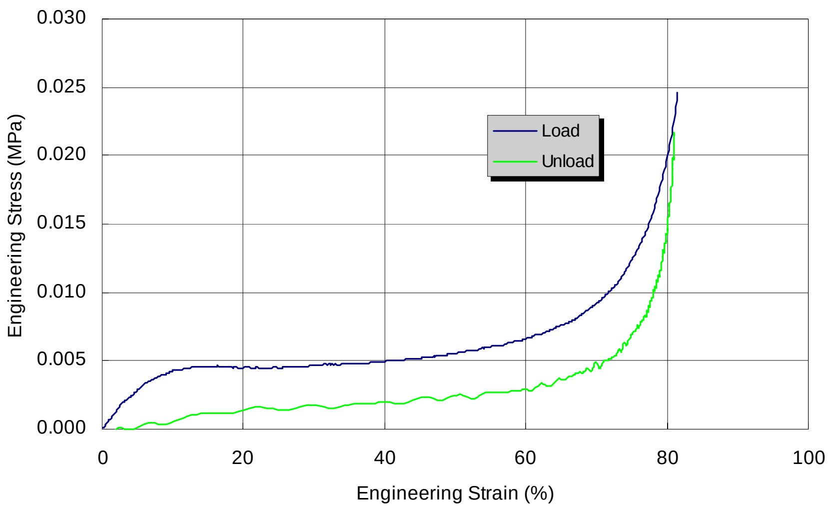

*Figure 5 Load-recovery data for a polyurethane foam*

The EPP foam is neither crushable nor totally recoverable. Neither MAT_CRUSHABLE_FOAM (MAT63) nor MAT57 are logical choices; MAT83 proves to be reasonable choice. Because of the work of Hirth et al, [5,6] to simplify the calibration to accept rate dependent stress-strain data as an input, this model is frequently used for a wide variety of foams. Here, rate dependency is easily captured but unloading is not represented. The model appears to be fairly simplistic in handling concepts of damage and in cases where a better representation is desirable MAT179 may pose a suitable replacement. It is important to note additionally that the EPP foam showed minimal Zone 1 behaviour. According to Sambamoorthy [1], the model should not be used when the data shows hyper-elastic trends such as the EPE foam characterized here.

The MAT63 model is useful when there is no recovery and could be a logical candidate for the EPS foam, which undergoes considerable damage under impact. Stress v. volumetric strain is input. Since Poisson's Ratio is zero, volumetric strain is easily obtained from uniaxial strain. The EPS foam tested does exhibit rate dependency. For this reason, MAT_MODIFIED_CRUSHABLE_FOAM MAT 163 is better choice. The model is fairly simple to calibrate, requiring simply the input of the rate dependent stress-strain data. The model could handle the limited amount of elastic recovery that would occur with this kind of material.

## 4 Conclusions and Future Work

A wide variety of material models are available for foams. Some of these are designed to capture important characteristics of particular types of foams. Where it is important to reproduce these behaviours in simulation, an effort must be made to calibrate such material models for the best results. The Fu-Chang material model is a good general purpose starting point but more appropriate material models can be exploited for particular types of foams. In future work, we would like to refine this concept further with the characterization of additional foams with well identifiable behavioural characteristics and to link them to material models that are best suited to describe them. Robust calibration methods will be evolved to ensure that the models capture the desired characteristics with fidelity.

## 5 Literature

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