# State of the Art Hytrel® material modeling development for the design of Jounce Bumper

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***Abstract**: This paper describes the behavior and subsequent constitutive modelling of a Hytrel® thermoplastic elastomer (TPC-ET) for a so-called Jounce bumper, which is a part of the vehicle's shock absorber system. This component is subjected to large deformations (up to 100% strain) with significant permanent set and loss of stiffness. The objective of the analysis is to predict the component behavior after cyclic loading to obtain the load-displacement response curve of the Jounce bumper in operational conditions. The possibilities and limitations of the hyper-elastic model, including permanent-set and Mullins' effect are discussed and numerical results compared to the test data from an actual component.*

***Keywords**: Constitutive Model, Mullins' effect, Hyperelasticity, Polymer, Plasticity, Suspension, Parallel rheological framework, Viscoelastic, Jounce Bumper*

## 1. Introduction

A jounce bumper (Figure 1) is part of a shock absorption system found on automotive vehicles designed to absorb impact and dampen noise, vibration, and harshness (NVH). The features and benefits are:

- Cost savings. in particular, through the adoption of Ossberger process manufacturing and a thermoplastic design including multifunctional integration as a dust cover,
- Constant deflection at high loads. Including, even when subjected to various ageing conditions including fatigue tests,
- No significant lateral expansion under compression stress. No need of saturation cup,
- Excellent performance at very low temperature. Non-significant moisture absorption, even under wet conditions.
- Durable fastening.

While keeping usual features of automotive jounce bumpers, such as:

- Low compression set,
- High energy absorption with progressive response,
- Low impact noise,
- High abrasion resistance,

- High chemical resistance (ozone, oils, greases, aliphatic hydrocarbons, hydrolysis, zinc chloride).

**Figure 1. The jounce bumper is part of a vehicle's shock absorption system designed to absorb impact and dampen noise, vibration and harshness transformation option**

The Hytrel® jounce bumper design helps automakers and suppliers realize significant cost reduction when replacing the incumbent foam polyurethane (PUR). The modeling approaches developed thus far do not provide sufficient accuracy, especially concerning the local stiffness variation due to initial compression and permanent set. A more precise modeling approach, capable of describing the full load-displacement curve, is needed to meet the increased design requirements

State-of-the art material modeling is needed to address the increased requirements described above. The parallel rheological framework (PRF) provides such capabilities, but is difficult to characterize using traditional material model calibration methods. The use of a parameter optimizer, such as Dassault Systèmes' Isight or PolyUmod M-calibration , allows for semi-automatic generation of the material model parameters.

## 2. Material Properties and Characteristics

Hytrel® is a modified thermoplastic elastomer that delivers better mechanical performance, excellent shape recovery, and balance between stiffness and low temperature properties, particularly under high strain conditions. To develop a strong and accurate material model, it is important to determine and understand the material behavior under states of stress and strain like those the part will be experience in application

All current jounce bumper solutions do not follow the same path in unloading as in loading. The part, due to its high compression ratio, will be as well subjected to plastic deformation in the first few loading cycles, after which the part response is stabilized. The Hytrel® Jounce bumper solution also shows this behavior, as shown in Figure 2 (Volgers, 2016) below, and it is the stabilized response which is sought in the design of the Jounce bumper.

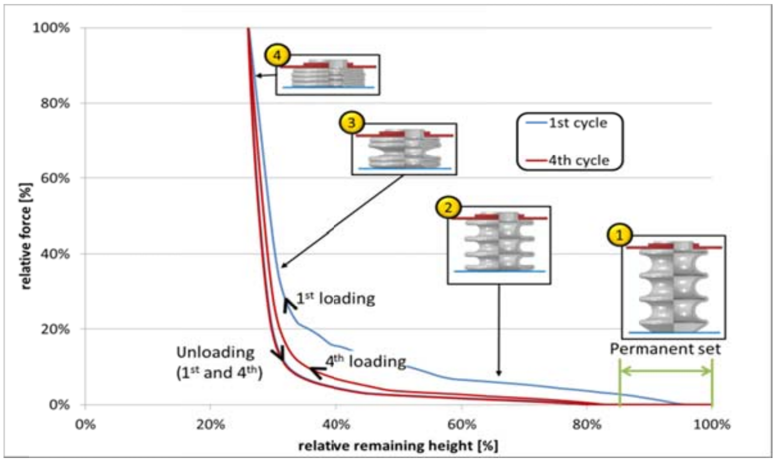


**Figure 2: Example of Hytrel® Jounce bumper cyclic loading test curve.**

The upper (blue) curve corresponds to the 1st loading curve of the Hytrel® Jounce bumper after manufacturing. The lower (red and blue) curves are virtually identical and correspond to the unloading response. The (red) curve in the middle is the compression curve after 4 loading cycles, after which the response is stabilized, and which is the prediction objective of the numerical simulation. The curve also shows a delayed onset of the reaction force after loading, which is the permanent set and determines the final part length. This is called the “conditioned state” of the Hytrel® Jounce bumper. The images of the corresponding Hytrel® Jounce bumper in Figure 2, show the deformation of the component and how the changing stiffness is achieved.

The first step for the modeling of any material is the generation of material property data through standard material tests. A testing program was developed which captures the behavior of the material under cyclic loading. The following experiments were conducted:

- Tensile
- Compression
- Shear

Each of these tests provides important parameters that are required to calibrate the material model needed to simulate the jounce bumper performance. The extensive material testing allowed for full characterization of the material behavior and the selection of suitable material model and their corresponding material model parameters. Following initial material characterization and evaluation, cyclic testing was performed on a Hytrel® Jounce Bumper to further understand the material behavior with the objective of more accurately predicting the performance of a part.

# 3. Material Testing

## 3.1 Tensile Test

The tensile test was conducted following the ISO 527-2 standard, Plastics –Determination of Tensile Properties. Tensile coupons were subjected to four different loadings:

- Monotonic load
- 1-cycle multilevel cyclic load
- 5-cycle multilevel cyclic load
- Stepped load

Figure 3 shows the tensile stress-strain response for the 4 different loadings, monotonic load, 1-cycle multilevel cyclic, 5-cycle multilevel cyclic and stepped load for specimens subjected to a maximum fixed strain of 100%. Stress softening and an associated permanent set, or plastic deformation, can be observed after subjecting the specimen to loading–unloading cycles. This stress softening is also commonly referenced as the Mullins effect.

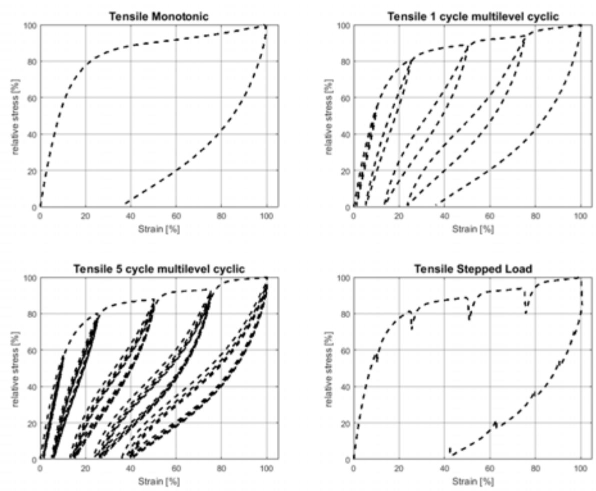


**Figure 3: Tensile Stress-Strain Response for Hytrel® for different loadings**

## 3.2 Compression Test

Uniaxial compression was performed on pucks of three different specimen diameters. Samples had an aspect ratio of diameter/thickness (d/t) of 4, 2 and 1. Samples were compressed between two large rigid platens. Strain was measured by a laser extensometer, using the measured sample thickness as the starting gage length.

These experimental measurements are not ideal because they are influenced by boundary conditions and specimen cutting technique (Diehl, 2010). With nearly incompressible elastomers, data distortion can occur because of the interaction of high bulk modulus, sample geometry aspect ratio, and sample clamping. Compression test on pucks does not satisfy the ideal uniaxial compression state assumed by calibration and finite element analyses software. The experiment will have some amount of non-uniform transverse deformation caused by the interaction of the sample and the loading platen, which can distort the measured load and calculated stress by large amounts compared to what an ideal uniaxial test would produce. To reduce friction between specimen and platen test specimens were lubricated with vacuum grease. Near frictionless surfaces reduce non-uniform bulging of the specimen during testing.

Compression coupons were subjected to four different loadings:

- Monotonic load
- 1-cycle multilevel cyclic load
- 5-cycle multilevel cyclic load
- Stepped load

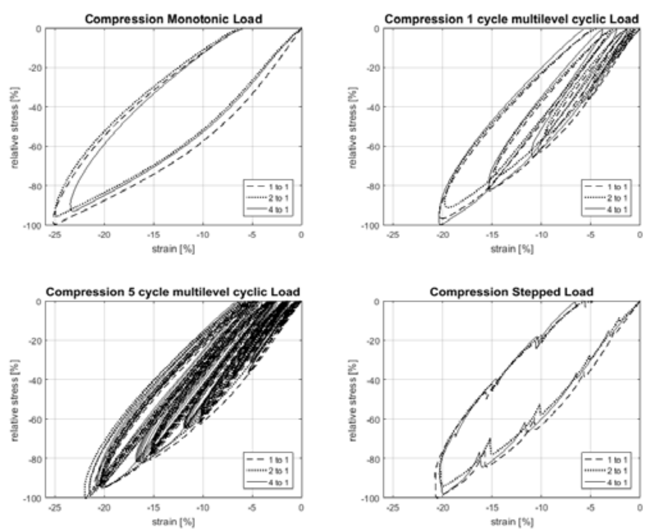


**Figure 4: Compression Stress-Strain response for Hytrel®**

Figure 4 presents the “apparent” stress-strain data for the puck compression test of three specimens with different aspect ratios. The apparent stress is calculated by dividing the applied compressive force by the original cross sectional area of the sample diameter (d). The data is labeled “apparent” because the strain and stress states in each specimen are non-uniform and unknown due to boundary condition effects. There is not a significant difference that can be observed on the stress-strain response between samples with aspects ratio of d/t of 4, 2 and 1, which therefor can be concluded that the boundary effect based on the different puck sizes is small and for this study can be ignored.

### 3.3 Double Lap Shear Test

The double lap shear test was conducted on rectangular samples 25 mm long x 10.2 mm wide x 4.15 mm thick. Samples were clamped in a fixture. Typical gage length on the tested portion of the sample was 1.4 mm. Strain was measured using a laser extensometer. The laser tracked the displacement of the top fixture clamp in relation to the bottom fixture clamp.

Shear coupons were subjected to four different loadings:

- Monotonic load
- 1-cycle multilevel cyclic load
- 5-cycle multilevel cyclic load
- Stepped load

Shear stress-strain data for the double lap shear test is presented in Figure 5. The data looks reasonably linear, and no Mullins effect can be observed for specimens subjected to 20% strain.

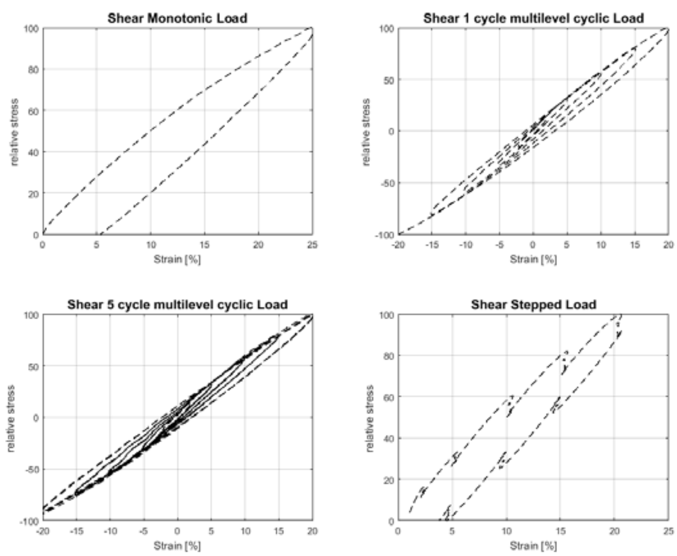


**Figure 5: Shear Stress-Strain Response for Hytrel®**

## 4. Material Modeling

The ultimate objective for material modeling is to provide customers with the necessary know-how and capabilities to analyze and design parts and components using Hytrel®. Abaqus is the global finite element analysis software used in DuPont for structural analysis, and because of its excellent material model capabilities, it is well recognized in the industry. State of the art material modeling is needed to accurately predict the response of a jounce bumper load-displacement curve.

An ABAQUS hyper-elastic model material model for the Hytrel® Jounce Bumper was developed, which was based on Marlow energy potential and including Mullins effect and permanent set. Despite the complexities during calibration of the model due to large permanent set observed in the material and the material stress softening during loading and reloading, acceptable results were obtained with a good estimate of the jounce bumper remaining height and permanent set. This model was capable of predicting the overall behavior, but it did not provide sufficient accuracy, especially concerning the local stiffness variation due to the initial compression and permanent set. (Volgers, 2016).

The Parallel Rheological Framework (PRF) model in Abaqus has been identified as the most promising material model to predict the complex behavior of an elastomeric material such as Hytrel® (Odgen, 1999). The PRF material model is intended for modeling polymers and elastomeric materials that exhibit permanent set, nonlinear viscus behavior, and undergo large deformations.

### 4.1 Calibration of material properties

The goal is to determine the 21 parameters, or coefficients, needed for the PRF model to describe the nonlinear viscoelastic behavior with stress softening and permanent set. Simulations of the different tensile, compression, and shear tests were conducted to calibrate the material model.

The following step-by-step methodology was used, which can be used for other material model development.

1) Calibrate model with data from 1-cycle response (or monotonic), where maximum strain is maximum strain of whole test. Calibration of elastic constants, which are 6 parameters.

2) Calibrate model with data from 1st cycle behavior from each load level. It captures short term and long term material response.

3) Calibrate model with data from 1st 3 cycles behavior from each load level. It captures short/ long term material response and damage.

4) Calibrate model with data from all cycles and all load levels. In this step, weight setting adjustments and final tuning of the model occurs.

The calibration process was conducted in four parts, as described below.

In Part I, PolyUMod® MCalibration was used to obtain version 1 of a calibrated material model. MCalibration took tensile test data and determined the best fitting material parameters for the PRF material model. MCalibration was executed through the step-by-step calibration procedure described above.

In Part II, PolyUMod® material model version 1 was calibrated and fine-tuned using compression test data, which generated version 2 of the material model.

In Part III, material model version 2 was further calibrated and fine-tuned using double shear test data. A direct Abaqus finite element simulation was used for this calibration because of the complexity of a double lap shear experiment, which cannot be represented well with a PolyUMod® one Element model. This calibration generated material model version 3.

In Part IV, a validation of material model version 3 was performed using tensile and compression data. Minor fine-tuning was done on the stress softening and nonlinear viscoelastic parameters, and material model version 4 was obtained. The shear test model was then validated with material card version 4, and no further changes where implemented.

### 4.2 Material Model Development

Several hyperelastic and viscoelastic material were explore via PolyUMod.

The hyperelastic materials are described in terms of “strain energy potential”. There are several strain energy potential forms available in Abaqus to describe the hyperelastic behavior of a material. Three of them were explored, which are the Mooney-Rivlin , the Ogden and the Yeoh, As a general guidelines these three model are applicable to up to 90-100% strains. The Yeoh form is a three term model which captures inflection point in the engineering stress-strain curve. The Mooney-Rivlin and Ogden forms available in Abaqus are two-term model which have a single curvature. The three term Yeoh model provided the best fit due to the capability to predict an inflection point which can be observed in the Hytrel tensile test data.

The PRF allows definition of nonlinear viscoelastic-elastoplastic model consisting of multiple networks connected in parallel. The number of viscoelastic networks, N, can be arbitrary, however, at most one equilibrium network is allowed in the model. It uses a multiplicative split of the deformation gradient and a flow rule derived from a creep potential to describe the viscous behavior. Three available flow rules in Abaqus were explored, which are the Power law model, the Power-law strain hardening model and the Bergstrom-Boyce (BB) model. The material model development started with a 3 network model using the three different flow rules defined above. All three flow rules presented promising fit on the loading portion of the stress-strain curve but on the unloading portion the Power law strain model deviated significantly from the Hytrel® behavior. Therefore the material development exploration continued with two of the flow rules; the BB model and the Power-law strain hardening model. The three network models were not as accurate beyond 50% strain during the tensile test reloading and unloading , due to a significant inflection point which good not be softened. A 4 network models with the two different flow rules, were explored. Both of these models predicted similar results matching the tensile multi cycle data quite well. The author decided to proceed with one of this two promising models, to further develop and implement stress softening and permanent set in the model.

The 4 network model with "strain" flow rules and Yeoh viscoelastic behavior was then further develop including plasticity and Mullins effect, which was calibrated using multi cyclic compression, shear and tensile test data.

Example of Material card parameters defined in model:

*Density

*Hyperelastic, Yeoh, Moduli=Instantaneous

*Mullins effect

*Plastic, hardening=isotropic

*Viscodlastic, Noninear, NetworkId=1, SRation =  , Law=strain

*Viscodlastic, Noninear, NetworkId=2, SRation =  , Law=strain

*Viscodlastic, Noninear, NetworkId=3, SRation =  , Law=strain

### 4.3 Implementation and Validation of Material Parameters

Final results of material model predictions are presented here, which were obtained through the processed described above (Part I, II, III, and IV).

Figures 6 and 7 show comparison between tensile experimental data and model prediction. The results show that the response using an Abaqus PRF material model.has been capture well, up to 60-70% strain.

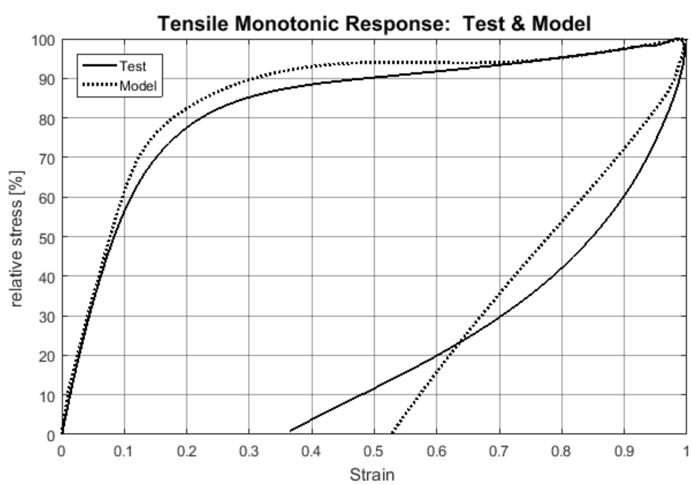


**Figure 6: PolyUMod® MCalibration simulation (dotted line) against Hytrel® monotonic tensile test data (solid line)**

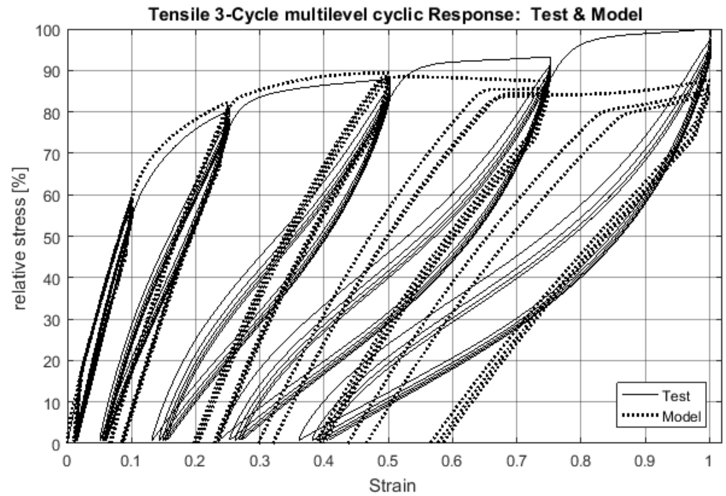


**Figure 7: PolyUMod® MCalibration simulation (dotted line) against Hytrel® 1st 3-cycle of multilevel cyclic tensile test data (solid line)**

Figures 8 and 11 show comparison between experiment and model prediction. The comparison show that the model response has been capture well using an Abaqus PRF material model.

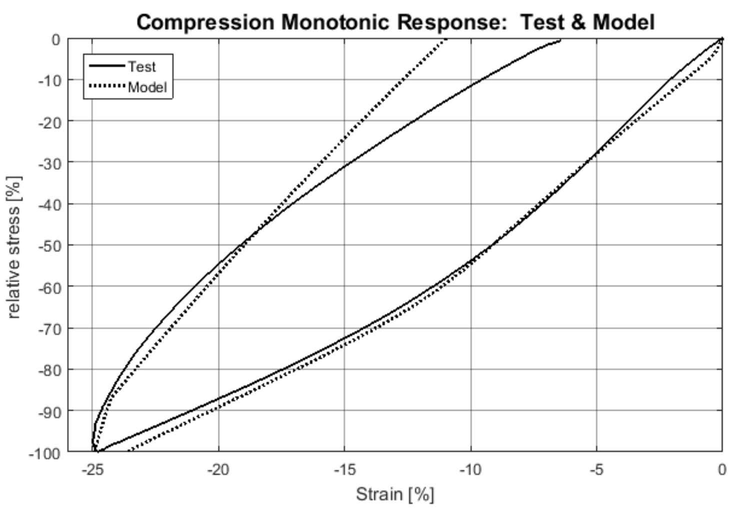


**Figure 8: PolyUMod® MCalibration simulation (dotted line) against Hytrel® monotonic compression test data (solid line)**

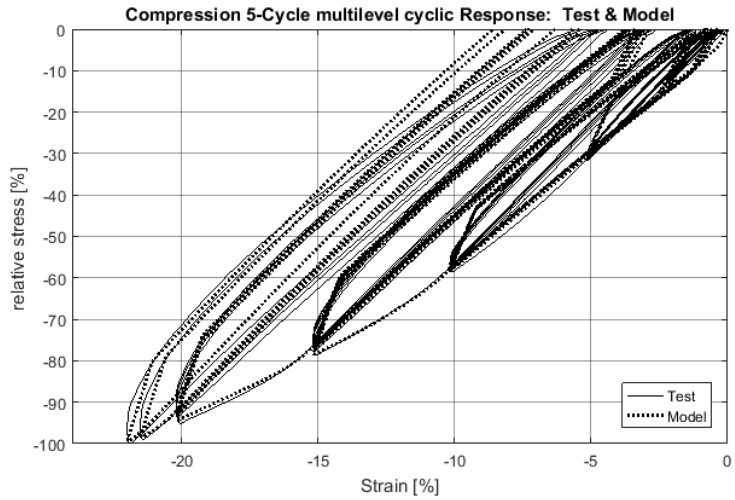


**Figure 9: PolyUMod® MCalibration simulation (dotted line) against Hytrel® 1st 3-cycle of multilevel cyclic compression test data (solid line)**

Comparison of shear experimental stress-strain data and model prediction are presented in Figure 10 and 11. The PRF material model matches closely the measured data.

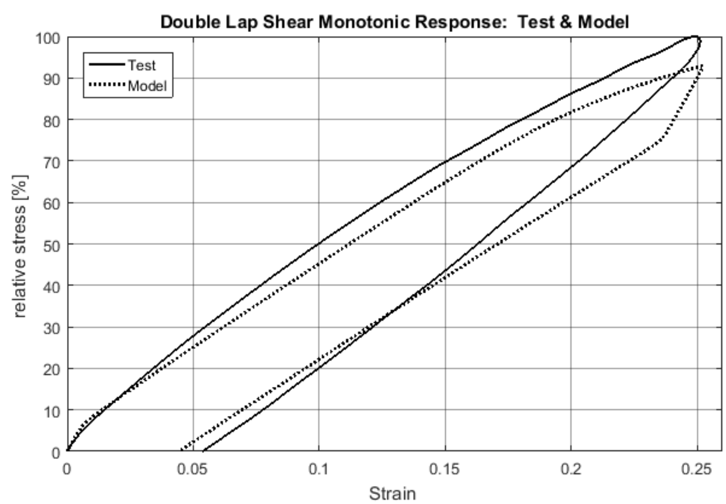


**Figure 10: PolyUMod® MCalibration simulation (dotted line) against Hytrel® monotonic shear test data (solid line)**

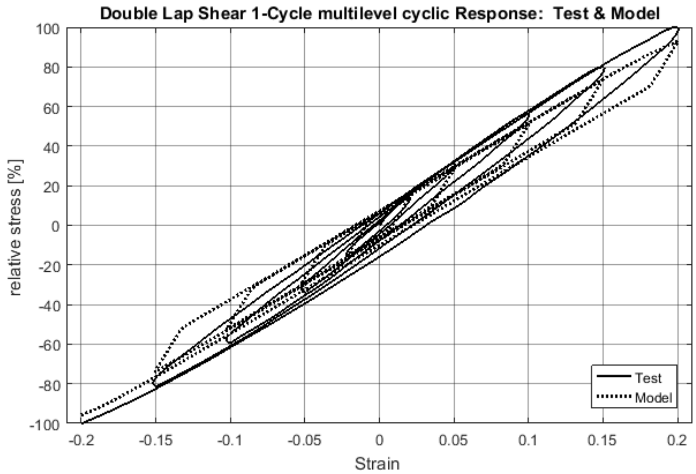


**Figure 11: PolyUMod® MCalibration simulation (dotted line) against Hytrel® 1-cycle of multilevel cyclic shear test data (solid line)**

### 4.4 Jounce Bumper Application

The jounce bumper shape and response is different from the shape and response of the part as molded. Loading the component 2 to 4 times will stabilize the part behavior and is called conditioning the Jounce bumper. It is this conditioned state which is of importance for the part design.

As both the geometry and the loading conditions of the test case are symmetric around the central axis, an axisymmetric model is used (see Figure 12).

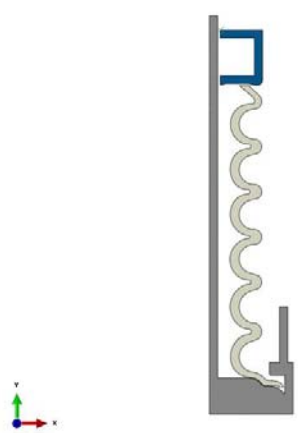

**Figure 12: Abaqus Hytrel Jounce Bumper Axisymmetric Model**

The numerical analysis uses 4 steps. The first step compresses the “as molded” geometry to the maximum compressive load (conditioning). The second step unloads the Jounce bumper by moving the striker back to its original position. The third step compresses the Jounce bumper again to calculate the component response in its conditioned state. The fourth step unloads the Jounce bumper by moving the striker back to its original position.  Subsequent unloading and reloading of the part does not show any significant difference in the numerical analysis compared to the second compression step, as can be observed in Step 4.

### 4.5 Material Validation

The material model should be able to predict the initial response of the part (1 cycle), as well as the response of the conditioned part (cycle 2 and beyond).  The initial response, cycle 1 of test data and simulation, are plotted in Figure 13.  Subsequent cyclic load-displacement response of conditioned part is presented in Figure 14.  Figure 14 shows the 1st 3 cycles of the test compared to the Abaqus model prediction. A close-up view of the loading and unloading responses is presented in Figure 15.  There is a good correlation between test and model.

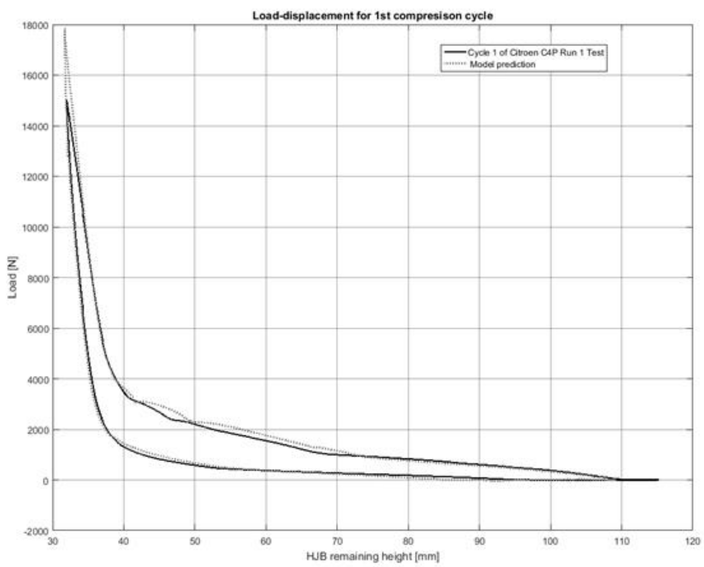


**Figure 13: Jounce bumper Load- displacement response for 1st cycle compression test (solid line), Abaqus prediction (dotted line)**

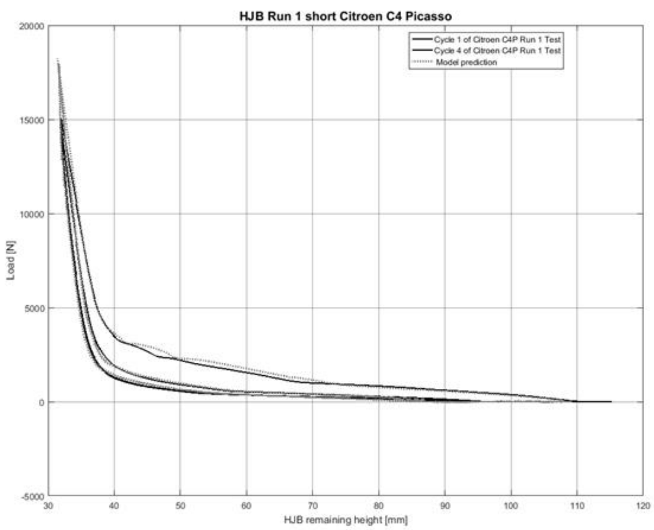


**Figure 15: Load- displacement response for multiple cycles, Jounce bumper test data (solid line), Abaqus prediction (dotted line)**

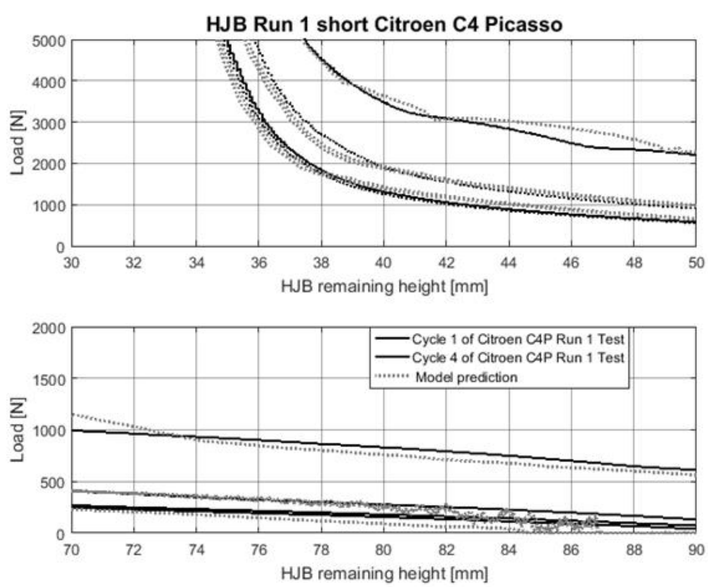


**Figure 16: Close-up view of Load- displacement response: test data (solid line), Abaqus prediction (dotted line)**

## 5. Summary and Conclusions

DuPont successfully developed a Hytrel® material model that can predict the initial maximal cyclic loading, commonly referred to as "material conditioning", as well as the operational response of a jounce bumper. The material model was calibrated with Hytrel® multi-cycle tensile, compression, and shear test data and validated with a jounce bumper subjected to cyclic loading. The material model accurately predicts the response curve from 0 N to 1000 N loading, with the aim to improve the ride behavior of the suspension, which was not accurately predicted in previous models.

Based on learnings from the development of this material model, we recommend first using PolyUmod® 1D element simulation of material testing for the calibration of the material parameters, and then fine tuning the parameters with ABAQUS test and component simulations. This approach significantly reduces the time and cost of material model development.

## 6. References

List references in alphabetical order based on the lead author's last name. List all authors' names, unless there are more than six authors.

Do not cite references by number. Use the name of the lead author, followed by a comma and the date of publication, enclosed in parentheses; for example, "(Crisfield, 1982)."

Capitalize titles of papers and journals as shown below. Some examples of references follow:


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