Modelling of Hytrel® Thermoplastic Elastomer Material for High-Strain Cyclic Loading

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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.*

1. Introduction

The Jounce bumper, or spring assist, is an important and active part of a vehicle's shock-absorber system, which serves not only to protect the coil spring and damper but also improves vehicle ride and handling and influences the level of comfort by absorbing small movements, such as irregular road surfaces.

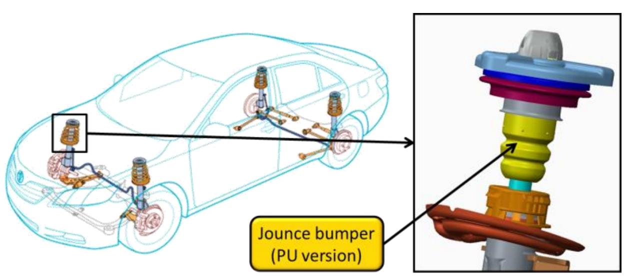

Figure 1: Car suspension and Jounce bumper (Donis, 2015)

Currently made from natural rubber or PU foam, DuPont has developed a new innovative solution using blow-molded Hytrel® thermoplastic elastomer (Donis, 2015), using the same manufacturing process as for CVJ boots. To support the (patented) design of the shape needed to obtain the required response (Székely, 2012; Székely, 2014), a simulation procedure has been developed to predict the load-displacement curve. The subsequent compression response after initial loading, which is different from the initial response curve due to the material behavior typical of elastomers, is important for the design.

To that aim, a material model for large displacements (part compression of 80%) and large elastic deformations (up to 100% strain), including plasticity and loss of stiffness is required. Abaqus allows the combination of hyper-elastic models including Mullins' effect and permanent set, which provides the fundamental behavior of the material. However, Hytrel® thermoplastic elastomer behavior is somewhat different than most elastomers, with a particularly high permanent set. This paper describes the challenges, limitations and success encountered when applying this material model to the behavior of Hytrel® in a Jounce bumper application.

2. Material behavior

To understand the needs and requirements of the material model, it is important to understand the application and its behavior the numerical analysis aims to predict. In this section we will therefore first describe the function and behavior of the component followed by showing the cyclic tests on the material before describing the material model requirements.

2.1 Application considerations

As stated above, the Jounce bumper or spring assist is a part of the suspension system and therefore continuously under cyclic (compressive) loading. Figure 2 below shows a generic load-compression requirement for a Jounce bumper. The response serves 3 distinct functions.

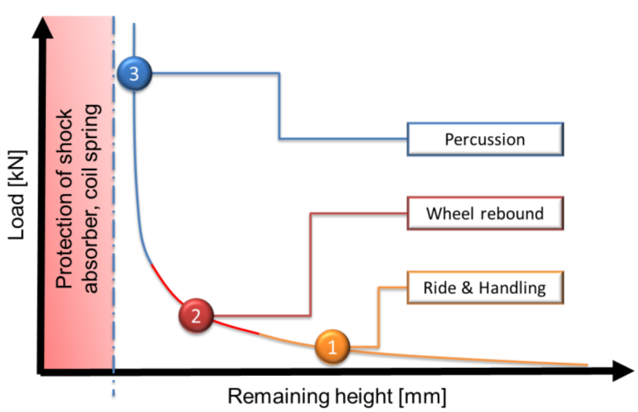

Figure 2: Jounce bumper load-displacement OEM requirement (Donis, 2014).

The first part of the response (shown in orange) contributes largely to the comfort and behavior (ride and handling) of the vehicle. The second (red) part of the curve controls the wheel rebound for large displacements. The third and final part of the response (percussion) serves as a displacement limiter, with an almost vertical increase of the reaction force. This prevents too large deformation of the shock absorber system in compression, which could lead to damage or failure of the suspension.

All current solutions, whether made from PU foam or natural rubber, do not follow the same path in unloading as in loading. Also, the part, due to its high compression ratio, will be subjected to plastic deformation in the first few loading cycles, after which the part response is stabilized. The new Hytrel® Jounce bumper solution also shows this behavior, as shown in Figure 3 below, and it is the stabilized response which is sought in the design of the Jounce bumper.

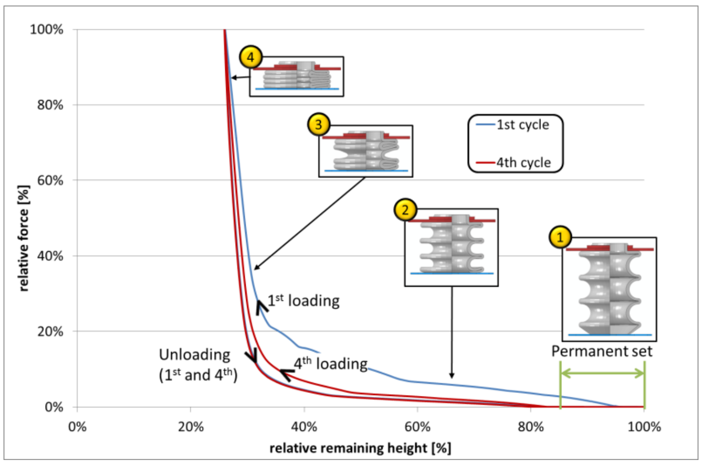

Figure 3: Example of Hytrel® Jounce bumper cyclic loading test curve.

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 show the deformation of the component and how the changing stiffness is achieved. From state (1) of the Jounce bumper in the unloaded condition, the initial stiffness is obtained from the folding of the bellows (2). At a certain point the stiffness increases significantly when the different convolutes start to touch themselves (3) until the part is completely folded (4) at which point it becomes almost incompressible.

It is clear from the response curves shown above that during the conditioning of the part, the material undergoes significant change with plastic deformation and a reduction of the stiffness.

The material test data should show this behavior and allow a suitable material model to be constructed which will sufficiently accurately predict the part performance.

2.2 Cyclic material tests

Although the main deformation mode of the Jounce bumper is the bending of the blow-molded structure, causing simultaneously tension and compression, obtaining material properties from bending samples is difficult. Compression testing of test bars or other samples does not allow us to obtain material data up to the required strain levels (80% or more) due to buckling of the samples. Technically, the only reliable test data which can be obtained is tensile testing, which can be done to 100% strain or more.

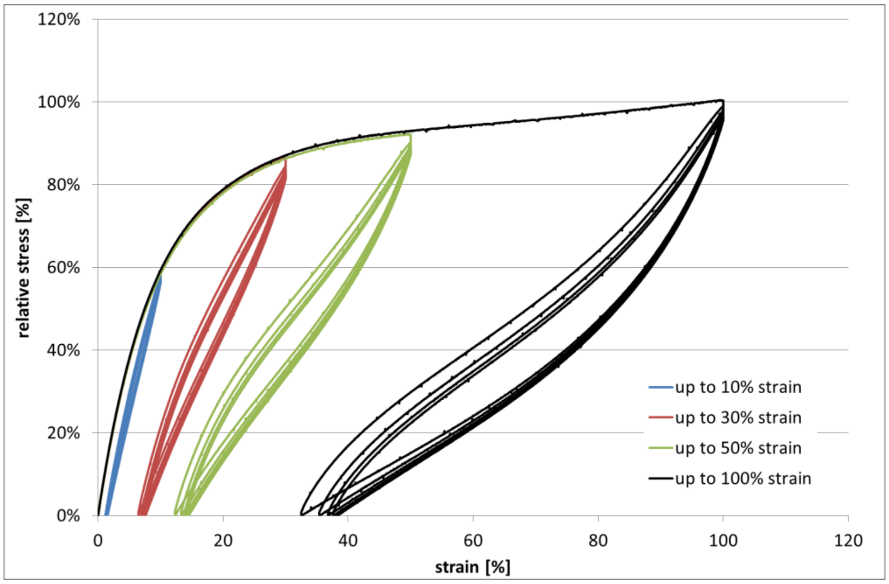

Figure 4: Cyclic loading data on Hytrel® specimen samples

In addition to the traditional single-stroke testing, the material samples are cyclically loaded from 0% up to a pre-defined strain level. At this point the sample is unloaded and re-loaded to the same nominal strain several times. The results of such testing are shown in Figure 4.

The resulting stress-strain curves show the material behavior to be taken into account for a suitable material model: hyper-elasticity due to the large strains, reduction of stiffness with increasing deformation and as well as plasticity.

3. Material modelling

In order to model the material behavior described in the previous section, full advantage is taken of the capability in Abaqus to combine material properties and models. In this specific case, the base model is hyper-elastic, whereby the material evaluation option allows for the selection of the most suitable model. To account for the loss of stiffness, the sub-option for damage of elastomers, the so-called Mullins' effect, is added. And to include the permanent set of the material, standard isotropic plasticity is super-imposed (Abaqus, Version 6.14).

3.1 Hyper-elastic model in Abaqus

To determine the suitability of a hyper-elastic model and its corresponding material parameters, Abaqus/CAE allows the input of one or more nominal stress-nominal strain curves. Using the material evaluation option, different models can be compared and their numerical stability limits are shown. Figure 5 shows the tension and compression curves for 3 different common hyper-elastic material models and compares them to the input test data: Marlow, Ogden (N=3), Mooney-Rivlin (polynomial with N=1) and a general Polynomial (N=2).

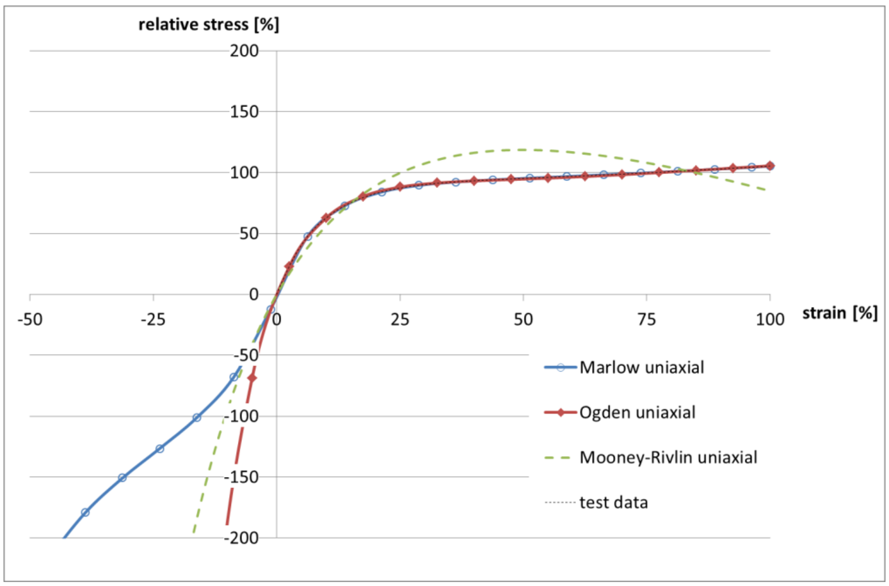

Figure 5: Evaluation of various hyper-elastic models – uniaxial response

Test data is only in tension and is not clearly visible in the graph above, as it falls exactly onto the Marlow and Ogden uniaxial curves. It is clear from the graph above that the Mooney-Rivlin material model does not give a response which corresponds to the behavior of the Hytrel® in tension beyond 20% strain. The second order polynomial (not shown) and Ogden models are stable in tension beyond 100% strain, but unstable in compression at 20% strain or even less, which is well below the maximum compressive strains observed in the application.

The only model which is stable at all strains and conditions is the Marlow model, which will be used for this material.

3.2 Calibrating the non-elastic model parameters

Material model parameters can be obtained using the plug-in for determining the properties to create a rubber-like material. This plug-in can be found at the Simulia support site (3DSWM). Providing the primary curve with loading and unloading at various strain levels should give the suitable material model. Users familiar with this plug-in may be familiar with some of the problems described below.

The latest version of the plug-in for Abaqus version 6.14 (plugin_1_3_1), which was uploaded in January 2016, addresses the issues described below.

3.2.1 Permanent set

Permanent set is included as a plasticity model and takes the true yield stress and true plastic strain as input. As the hyper-elastic curve specified in the hyper-elastic material model definition defines the ***elastic*** response of the curve, the provided curve should be corrected, such that the resulting total stress-strain response corresponds to the test data.

$$\epsilon_{total} = \epsilon_{elastic} + \epsilon_{plastic}$$

Failure to do so will lower the effective stress response of the material. More detailed information on the actual implementation can be found in the knowledge base (Simulia, 2015). With the nominal stress-strain response being very flat in the large strain region, this will cause instability with reducing stress for increasing strain, as shown in the figure below (green dashed line).

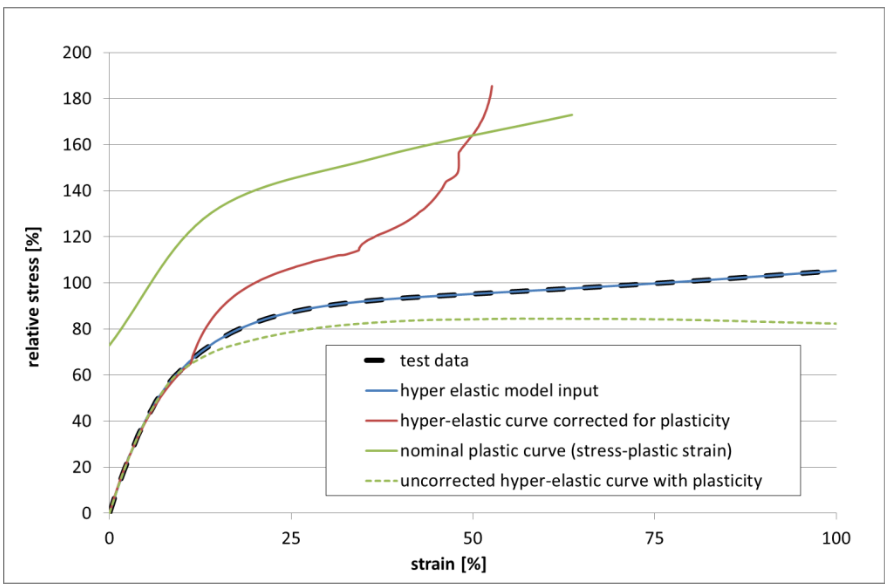

Figure 6: Stress-strain response of hyper elastic curve with and without plasticity

The continuous green curve starting at 75% relative stress is the nominal yield stress-nominal plastic strain defining the permanent set. The twisting red curve going up to 190% relative stress is the corrected input for the hyper elastic curve. Both combined give the stress-strain response corresponding to the actual test data.

3.2.2 Mullins' effect

Mullins' effect using the plug-in or calibration tool in Abaqus/CAE tended to calibrate the response towards the ***unloading*** path of the stress-strain response. However, in the application concerned, we are mainly interested in the ***re-loading*** of the component. Manual calibration was needed to improve the results to better correlate to the measured data. The Mullins' effect is determined as described in the Abaqus User's Manual, Section 22.6.1 and is controlled by the parameters m, r and β. The parameter m controls the initiation of damage, while r and β control the shape of the unloading/reloading curve. It is important to note that the hysteresis effect seen in the measured stress-strain curve is not included in the model. The parameters therefore need to be calibrated towards the re-loading curve.

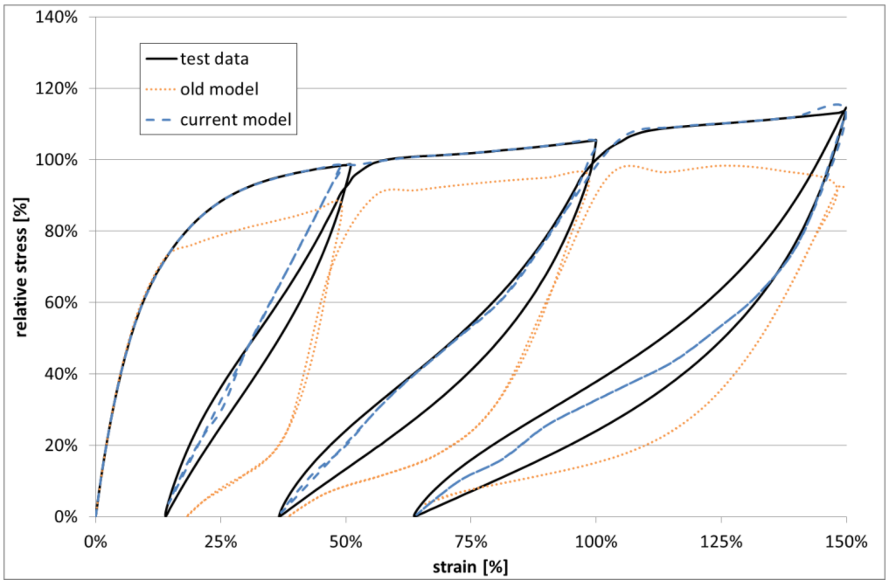

Figure 7: Calibrated material model with plasticity and Mullins' effect

The figure above shows the standard calculated material response of the old and the new version of the plug-in. The initial model (orange dotted line) shows the reduced (uncorrected) hyper-elastic response due to the plastic strain, as well as the low stiffness of the unloading/reloading curves. This required not only a correction of the provided hyper-elastic curve, as described above, but also a manual calibration of the Mullins' effect parameters m and β to better fit the reloading curve. The model generated with the current plug-in does both of these corrections, to obtain a stress-strain response (blue dashed line) closely matching the measured test data (black line).

4. Application to Jounce bumper analysis

The design of a Hytrel® Jounce bumper is governed by various design variables, such as the thickness profile, which controls the percussion, the bellow shape and number, which control the wheel rebound, and the shape of the lip, which controls the ride and handling, as well as the inner and outer diameter. Finite element analysis is used to support the design before the mold is cut, and afterwards to help improve the response behavior by changing the process parameters which influence the final shape and response.

As stated in the introduction, the component 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 of the Jounce bumper. It is this conditioned state which is of importance for the part design. The results shown in this paper are based on the measured geometry of a blow-molded Hytrel® Jounce bumper in order to eliminate any possible deviation due to geometry and/or wall thickness difference between the numerical analysis and the test results.

For reasons of stability, the explicit dynamic solver is used. Although the large deformations can be handled by the implicit solver, the behavior of the bending lip can in some cases cause instability in the implicit analysis. Also the model contains two self-contact definitions, for the inner and the outer surface of the Jounce bumper, which reduces the efficiency of the parallel solver. The explicit solver is therefore not only more stable, but more computationally efficient.

As both the geometry and the loading conditions of the test case are symmetric around the central axis, an axisymmetric model is used, thereby significantly reducing the analysis time.

4.1 Validation of the 1st compression cycle

The material model should first be able to reproduce the initial loading curve, where the influence of the permanent set and Mullins' effect are minimal. The figure below shows the results for a purely hyper-elastic model and the full model, both showing good correlation.

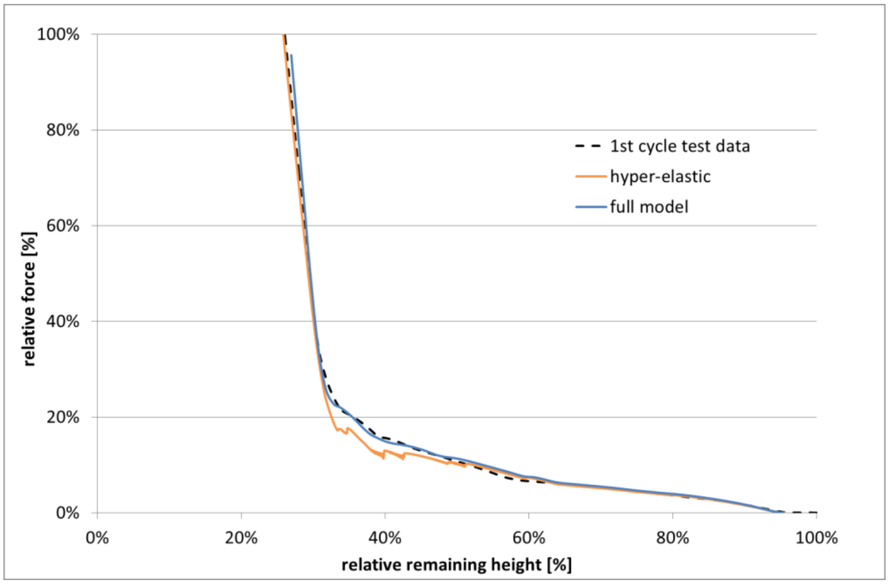

Figure 8: Load-displacement curves for test data (dashed), hyper-elastic (orange, below test curve) model and full model (blue, on top of test curve)

Both curves show a good correspondence to the test results, but with the purely hyper-elastic model showing some instability and noise in the response curve, taking it away from the measured graph. It seems that the full model apparently dampens the material behavior, which results in a reduced step time (the full model requires about 5% more increments than the hyper-elastic model) and a more even compression of the convolutes. This is shown in the image below at 65% compression.

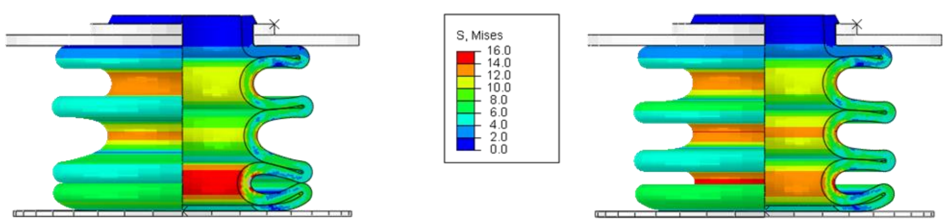

Figure 9: Deformed state at 65% maximum compression for pure hyper-elastic model (left) and full material model (right).

The various deformed states, at different stages of the compression curve, show the high deformation levels reached in the part as well as the corresponding permanent set (plastic deformation). This confirms the need stated in the previous section for a hyper-elastic material model which is stable and accurate beyond 20% strain in both tension and compression.

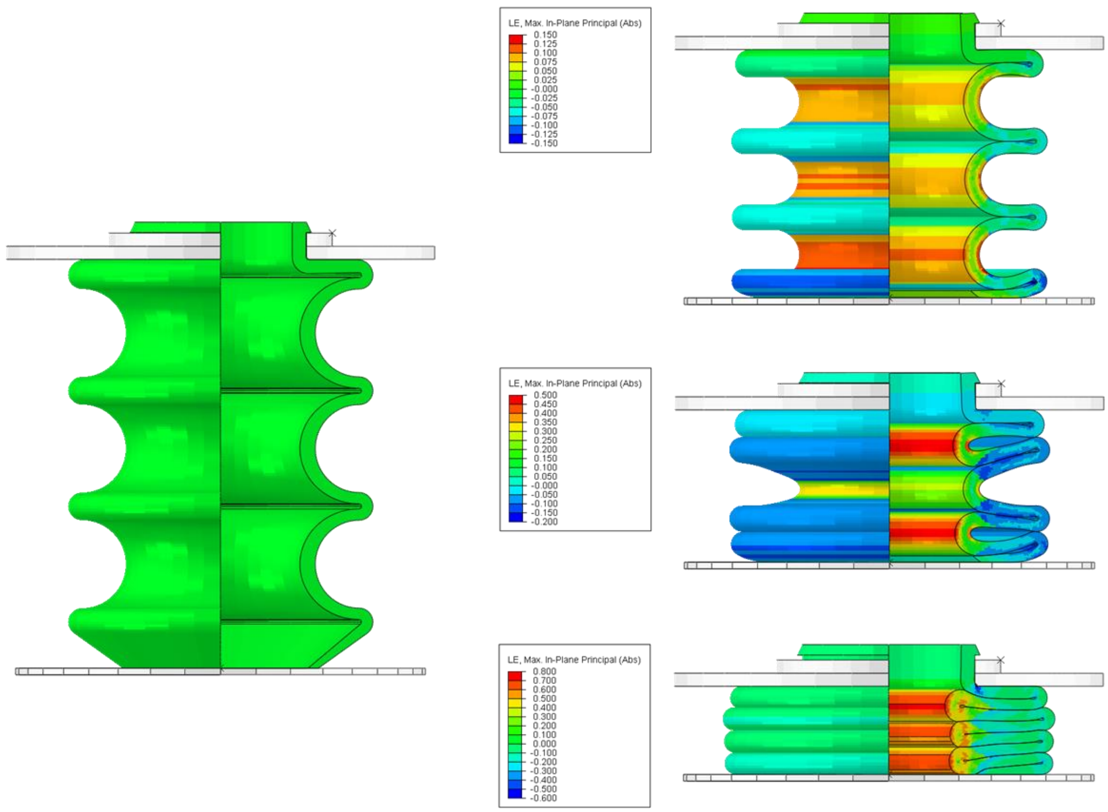

Figure 10: Strains in the Jounce bumper at various stages of compression

4.2 Validation of the conditioned state

The main objective of the numerical analysis is the prediction of the conditioned part shape, especially its conditioned length, as well as its response. The permanent set largely determines the conditioned shape, while the calibration of the Mullins' effect influences the response curve, particularly the first 20% of the load, which corresponds to about 80% of the total compressive displacement.

The numerical analysis uses 3 steps. The first step compresses the "as molded" or "as designed" 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 (last) step compresses the Jounce bumper again to calculate the component response in its conditioned state. Subsequent unloading and reloading of the part does not show any significant difference in the numerical analysis compared to the second compression step and are therefore not considered in the simulation.

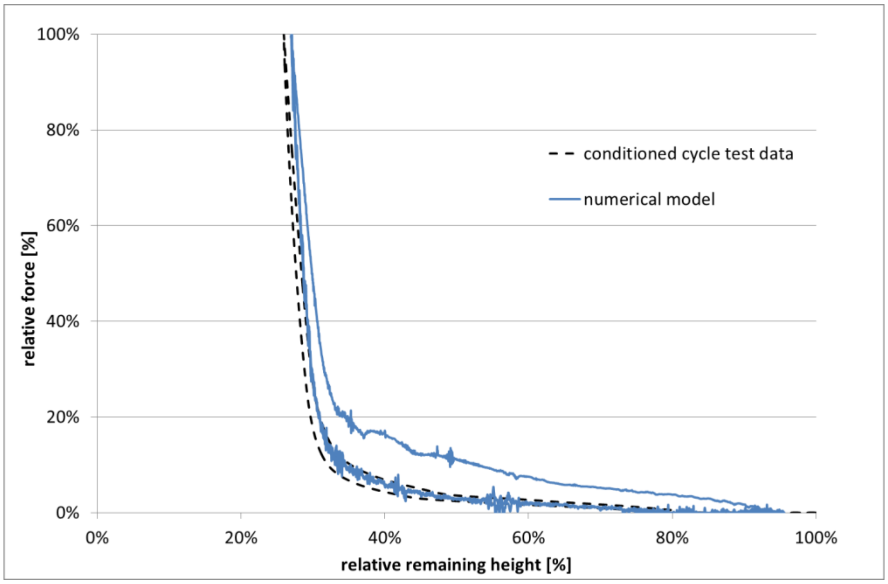

Figure 11: Numerical analysis vs test data for conditioned Hytrel® Jounce bumper.

The manually calibrated model and the material model parametrized using the latest plug-in give virtually identical results. As the material model does not include hysteresis, the unloading and re-loading curve are not distinguishable in the graph above, although small differences can be seen up-close, especially in the low load level region (10% of maximum load, or less). Also the re-loading curve will give a more accurate prediction of the modified (static) height of the Jounce bumper.

The current plug-in now provides directly a suitable set of model parameters which need little to no correction to obtain acceptable numerical results compared to the test data. The predicted conditioned response curve is only slightly below the actually measured test data up to 20% of the maximum load. The material model allows a good prediction of the behavior of the Hytrel® Jounce bumper, including the prediction of the final conditioned part shape.

5. Summary and conclusions

DuPont has developed a new Jounce bumper, or spring assist, for automotive suspension systems, based on the Hytrel® thermoplastic elastomer, using a blow-molded shape for optimal performance at reduced cost compared to existing systems based on PU foam. In order to support the design of these components, a finite element analysis procedure has been developed using a hyper-elastic model with permanent set and Mullins' effect to describe the material behavior.

The latest release of the plug-in available for Abaqus/CAE allows for direct calibration of the material parameters, reducing the time needed previously to compensate for the plastic strain on the normal strain measured, as well as the calibration of the parameters for the Mullins' effect to accurately predict the re-loading behavior. This unique capability of Abaqus is essential for the analysis of the Jounce bumper.

This material model is used in an axisymmetric explicit dynamic analysis to simulate the initial maximal cyclic loading (so-called conditioning) in order to predict the operational response curve, which is significantly different from the initial compression loading curve, as well as the conditioned geometry of the Jounce bumper. Evaluation of the model and analysis procedure has been performed based on actual measured geometry and corresponding tests, showing good predictive accuracy.

The possibilities offered by accurate simulation has created a demand for more fine-tuning of the design to optimize the ride and handling behavior of the suspension system, which demands even better accuracy of the material model, including the capture of the hysteresis effect not included in the current model, the inclusion of visco-elastic behavior and the dependency on the strain rate. Current implementation is based on tensile test data generated at approximately the same deformation rate as observed in the (standardized) test conditions, which do not necessarily reflect the behavior in the actual car driving environment. Work has started on a new material model, using the state-of-the-art possibilities in Abaqus, to further improve the predictive capabilities for this application.

The material model described in this paper is now extended to other Hytrel® grades and new applications which use the large strain deformation of the material, but demand numerical analysis support for its design.

6. Acknowledgements

I would like to thank the following people who are part of the Hytrel® Jounce bumper team and who contributed to the results in this paper: Thierry Donis, Hytrel® Jounce bumper application leader; Peter Székely, principal investigator Hytrel® and Jounce bumper expert; Damien Van Der Zyppe, technical consultant and Hytrel® Jounce bumper design expert, Fabrice Giaume, technical program leader; Daniel Miguel, laboratory technician and material tests; Bryan Morris, design; and Ruth Jackowiak, Ossberger blow-molding expert.

From Simulia I would like to thank Tod Dalrymple for his valuable advice on material modeling and updating the plug-in.

And anybody else I may have inadvertently forgotten – for which my apologies.

7. References

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8. Appendix: Material Input

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*Material, name="DuPont Hytrel(r) 8724 - normalized stress"
*Density
 1.16e-09,
*Hyperelastic, marlow, poisson=0.48
*Uniaxial Test Data
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 0.10213, 0.0101232
 0.19036, 0.0201231
 ...
 *Mullins Effect, TEST DATA INPUT
*Uniaxial Test Data
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  1.78485,   0.520572
...
*Uniaxial Test Data
   1.44254,   0.461447
   1.33444,   0.454373
...
*Uniaxial Test Data
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  1.00186,   0.305473
...
*Plastic
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 1.48648, 0.131079
 2.10820, 0.312251
 2.82989,  0.49251
 20.5762,   4.9251
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