

Achieving a more Accurate Prediction of a Polymer Snap Deformation Pattern

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Abstract:

A variety of polymers are used extensively for both medical applications and consumer products. Most of these polymers exhibit time-dependant behavior which varies significantly with environmental conditions.

Injection molding technologies generally offer application design freedom and options for several functions build into each component. Meanwhile analysts are often faced with the difficulties of predicting the response of the final product.

Some of the key challenges are:

- *Defining a material test protocol that captures the loading modes which the component materials are subjected to.*
- *Exploration of different measurement methods and their limitations.*
- *Fitting the material model with test data for general purpose or customized use.*
- *Evaluating available Abaqus material models for different load cases.*
- *Testing tailored UMAT models as an alternative.*
- *Benchmark development for numerical model validation.*

From simple geometry loading to virtual prototyping, this paper exemplifies the stepwise progress towards a successful match between load case, measurement setup and numerical model validation. It also deals with the gaps at the current numerical model availability and proposes optional enhancements.

Keywords: Polymer material modeling, Deformation, Bending, Constitutive Model, Creep, Viscoelasticity, Viscoplasticity, Plasticity, Polymer, Residual Stress, Springback.

1. Introduction

Analyzing injection molded components is demanding with respect to both material input data, numerical implementation as well as data interpretation and establishment of proper material failure criteria. For each load case one must consider the model ability with respect to capturing the time, rate, mode and thermal constraints of the problem. This consideration started for this investigation with material data and measurement requirements.

2. The Problem

The snap fit case of this paper (Figure 1) is designed as a single cycle loaded assembly snap. Thus limited post yield loading might occur in the outer range of the tolerances. The analysis should output the assembly reaction force as well as the final position of the snap. The latter is especially important, if a **import* analysis is to be made for e.g. drop test simulation.

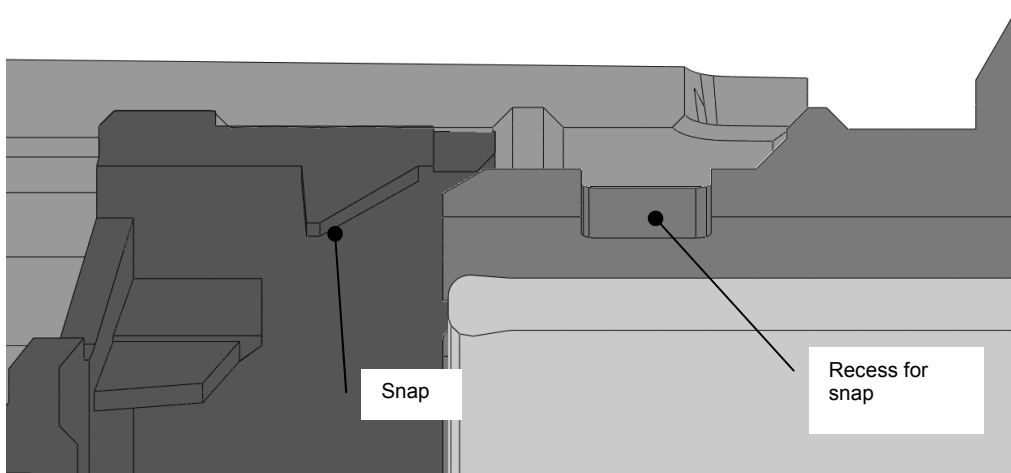


Figure 1. Snap fit Case Study

3. Producing Reliable Data

Raw material vendors most often supply data according to ISO/ASTM standards at only a single temperature level which is insufficient for many load cases and designs. A customized material measurement protocol was made for a more comprehensive coverage.

There are several challenges within polymer material measurement. It is well known that the injection molding process influences the mechanical properties and induces residual stresses. In our setup we developed a 1.5 mm thick dumbbell geometry (Figure 2) which could be molded with parameters similar to those of the application component.

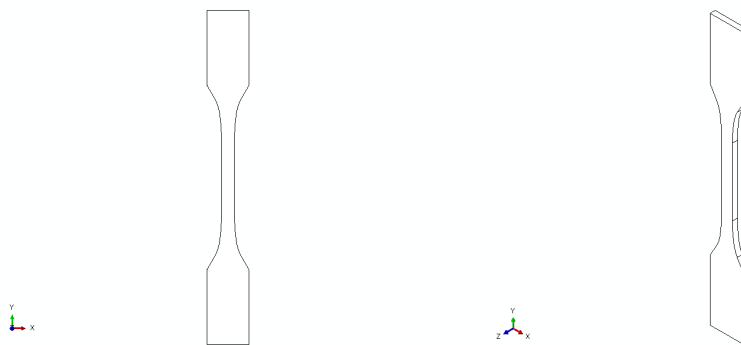


Figure 2. 1.5 mm thickness dumbbell test specimen developed for the material measurement.

The large strain level and rate as well as cyclic loading of the snap-on case required thorough protocol planning. Some of the main lessons were:

- Compensation for clamping induced stresses before extensometer mounting was mandatory.
- For materials that neck only pre-yield straining was predicted accurately using an extensometer.
- Compression test specimen are difficult to constrain in a consistent manner (Digital Imaging strain level measurement is more independent of constraining).
- Digital Imaging Correlation (DIC) technology was incorporated to capture high rate and post yield axial and transversal strain monitoring.
- Monitoring the Poissons' ratio throughout the straining is important.

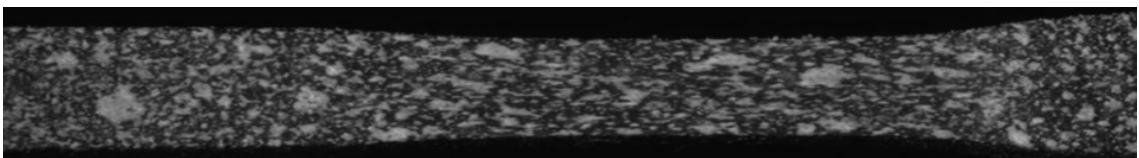


Figure 3. Necking of dumbbell measured by DIC and Speckle Pattern

4. Material measurement extent and Abaqus model benchmarks

4.1 Material Data

The minimum number of different test series required to characterize the bending stress response and rate of the snap was determined by comparing a simple one point bending test with a numerical model. A study starting with simple single upload straining at different rates was performed with a stepwise increase in loading complexity. The resulting programme included:

- Tensile/compression at different rates (single upload)
- Cyclic tensile testing at different rates
- Relaxation at different strain levels

Figure 4 depicts an overview of some of the test schemes of the study.

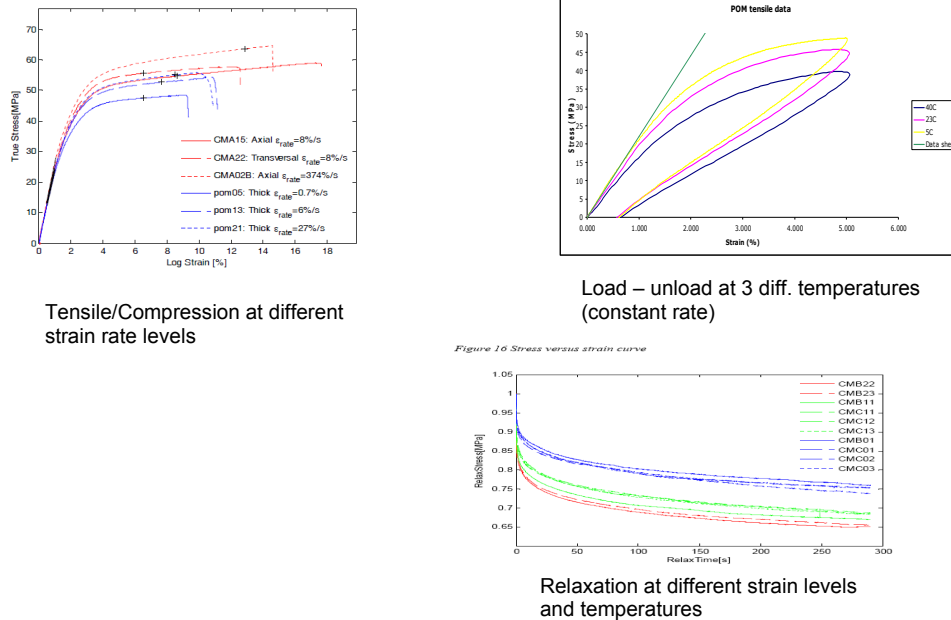


Figure 4. Material test data used for model fitting

4.2 Customized Benchmark Specimen

Next, a dedicated test specimen was machined from a 1.5 mm thickness plate. The chosen geometry shown in Figure 5 contains both shear, compression and tensile stresses when pulled in a standard tensile test bench.

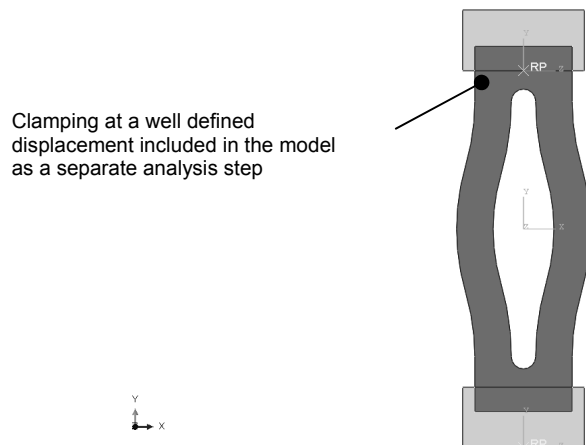


Figure 5. Benchmark test member (machined out of a 1.5 mm injection molded plate)

An Abaqus/Standard model including both clamping to a well defined displacement, zero setting and pulling was then made. The key output to be benchmarked was the reaction force of the model and the bench load cell signal.

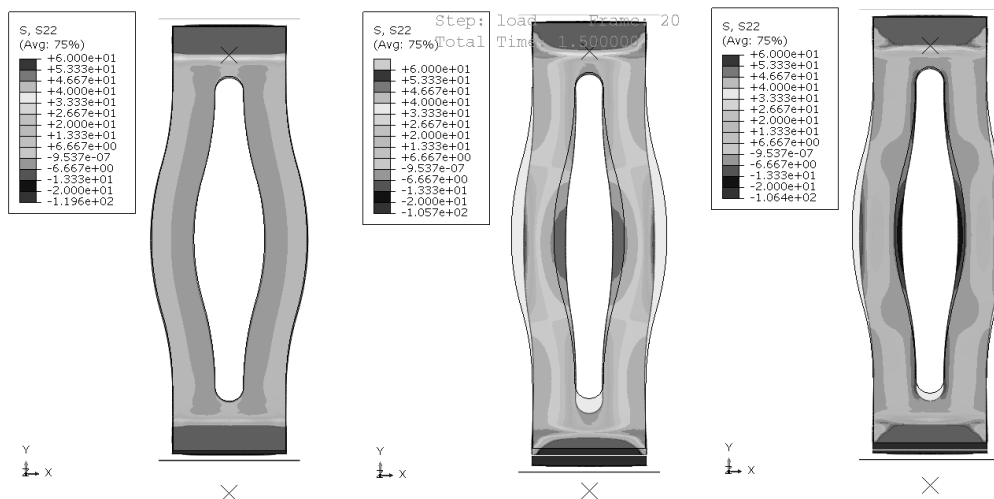


Figure 6. Clamp induced/load/residual stresses of the benchmark member

4.3 The Device Member Benchmark

An injection molded component from a medical device was chosen to benchmark the various material models. The component, called the ratchet, is shown in figure 7. The ratchet has 2 arms; a suitable plate is used to bend one of the arms 4 mm and back again, both as an experiment and as a numerical model in Abaqus using various material models.

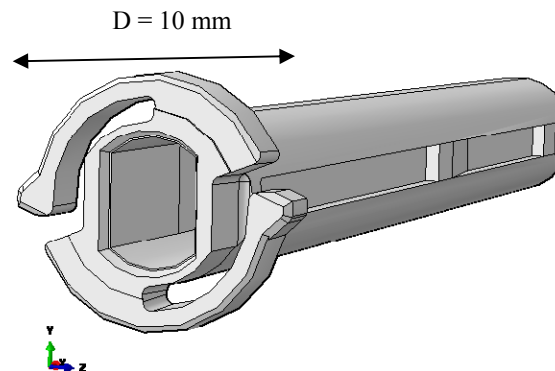


Figure 7. The device member component used for benchmarking.

5. Abaqus Material models tested

The material response during cyclic loading (uni-axial tension) is shown in Figure 8. It shows numerous cycles, the same specimen is loaded to the strain levels (2,4,6,...) % and after each level it is unloaded, before it is reloaded to the next strain level. The behavior we are primarily interested in is the permanent set, as a function of imposed strain.

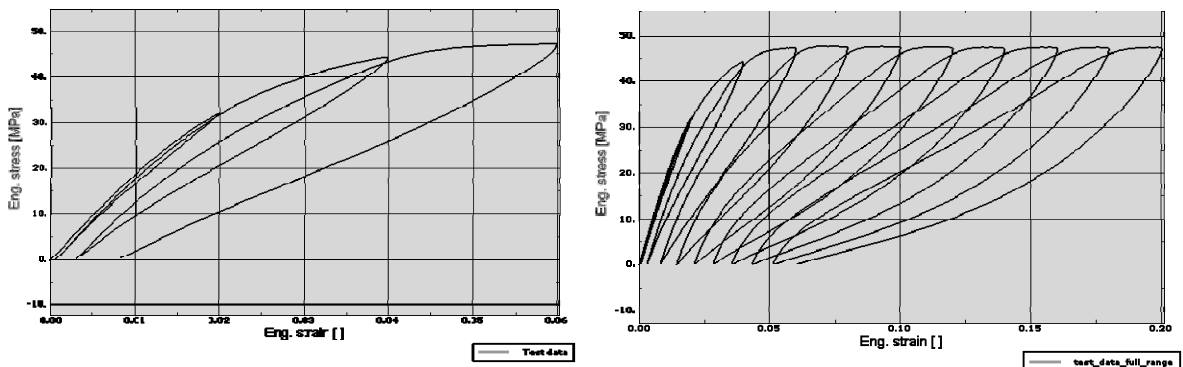


Figure 8, Left: Cyclic loading in uni-axial tension. Right: More cycles added with an increasing strain

From the figures we see:

1. Plasticity, it seems as if a permanent set is generated when the imposed strain is approximately 4 percent.
2. Hysteresis, large hysteresis loops are generated especially for large strain levels.
3. The unloading curve differs from the re-loading curve.
4. The primary curve shows almost perfect plasticity.

It is hard to capture this behavior using the build-in material models in Abaqus.

5.1 Metal plasticity

What people often do is to use simple metal plasticity (**plastic*) to model the non linear thermoplastic behavior. It is obvious from the above figure, that the plasticity thus will be grossly over predicted even for relatively small strain amplitudes.

5.2 FEFP material model

Another option is to use the FEFP model, i.e. non-linear elasticity combined with metal plasticity and the Mullins effect. Referring to figure 8, again we see that this material model will also fail to capture the behavior accurately, e.g. the un-loading and re-loading response differ for the material. But is the model able to capture the permanent set? A nice plug-in¹ to calibrate the FEFP model exists. In the answer ID it is written:

“An Abaqus/CAE plug-in application for this purpose is attached below. It is meant to facilitate the computation of Abaqus material parameters from experimental data collected from cyclic loading tests of filled elastomers or thermoplastics. The plug-in allows you to examine and edit such test data and automatically create the necessary Abaqus material model options - including hyperelastic, Mullins effect, and plastic property specifications.”

It sounds promising and the material class thermoplastics are explicitly mentioned.

Adding some higher strain levels to the cyclic uni-axial tension test data shown on figure 8 and feeding them into this plug-in, it is able to separate the (a) elastic portion, (b) the plastic portion and (c) the Mullins portion, and generating the FEFP material model. Some difficulties and challenges occurred during this:

1. The plug-in does not choose the energy potential for the hyperelastic portion of the response, you have to choose that yourself. In our case, it turned out that none of them are able to capture the non-linear behavior for the relatively small strain levels of

¹ Refers to answer ID 3522 on the SOSS

thermoplastic², see figure 9 left. The only serious options are the Mooney-Rivlin and the Marlow model. But as can be seen from the figure the first mentioned goes unstable when the strain reaches 5%. So the only one left is the Marlow model which can fit the test data exactly. However, using this potential the stress goes out of bounds in compression which is a problem, if the application involves bending. The evaluated Marlow model can be seen in figure 9 right. Please note the plausible behavior in tension and the stress going out of bounds in compression.

2. The slightly softening primary curve. When the stress starts to decrease, the primary curve stops and the plug-in does not include the cycles above this point.
3. Abaqus has a hard time fitting the Mullins effect parameters: beta, m and r, especially, if the data consists of multiple cycles. It is often necessary to manually specify one or more of these and thereby minimizing the parameter space for the fitting to converge.

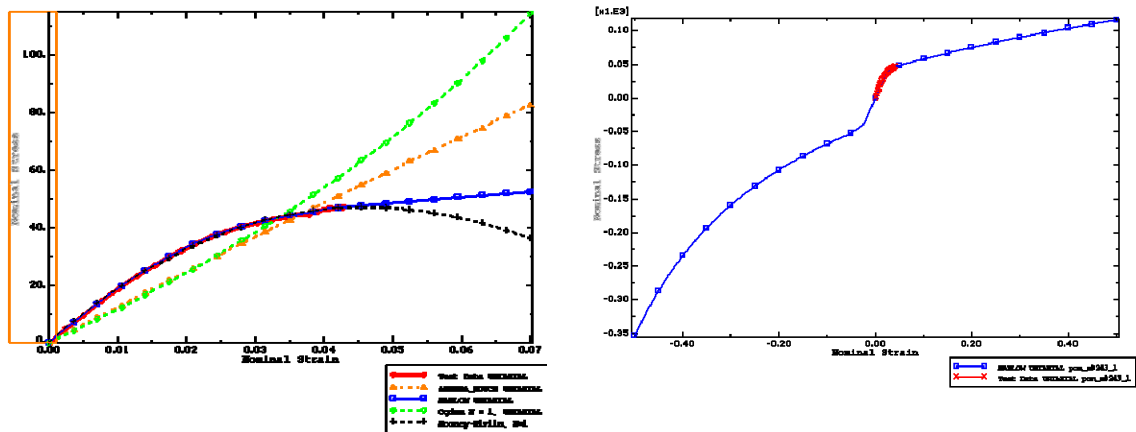


Figure 9. Left: The agreement between various low order strain energy potentials and the test data. Right: The agreement between the Marlow potential and the test data, plotted in a larger strain range including compression.

On top of that it is **not possible** to include the viscous dependency of thermoplastics into the FEFP model.

5.2.1 One element test

The agreement between test data and the fitted FEFP model used in a one element virtual test is shown in figure 10. The material model is fitted to the test data, because of the fitting problems stated above, only one un-loading curve is used namely 6%. So for the model the same fitted

² The hyperelastic models are tailored to the behaviour of elastomers where the stress strain curve becomes non-linear for a much larger strain level than it does for thermoplastics.

material model is used but tested using the various strain levels (4, 6) %. The figure shows a fairly good agreement between the model and the test data, for these relatively small strain values.

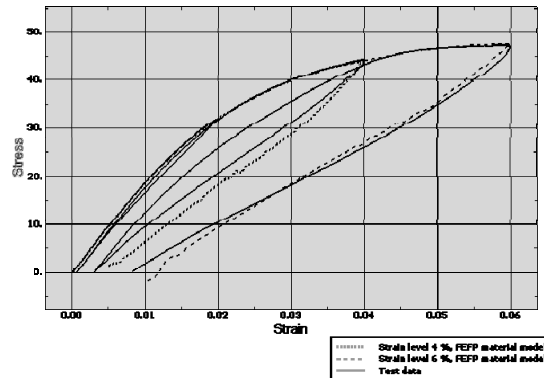


Figure 10. The agreement between test data and the fitted FEFP material model (fitted to the unloading curve for 6% straining)

6. Alternative Material model: The Three Network Model

Better prediction of the viscous response of the material was pursued using the Three Network Model of the PolyUMod library by Jörgen Bergström. The model consists of three non-linear springs with different moduli and two dashpots with different flow resistances.

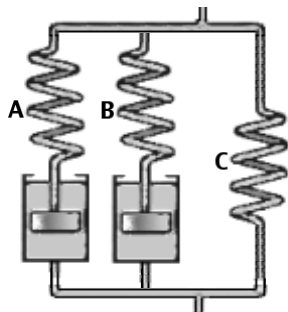


Figure 11. Spring and dashpot representation of the Three Network Model

The MCalibration application was used to fit selected sets of experimental data. So far the model has been tested for both crystalline and amorphous thermoplastic grades. For the cyclic load case the lessons were:

- Acceptable ability to fit the hysteresis at different strain levels for similar strain rate ranges
- Problematic fit to cyclic loading at varying strain rate ranges
- Captures the non-linear viscoelasticity at relaxation quite well

- The larger the slope difference between up- and un-load, the larger the deviation between experimental and model prediction.

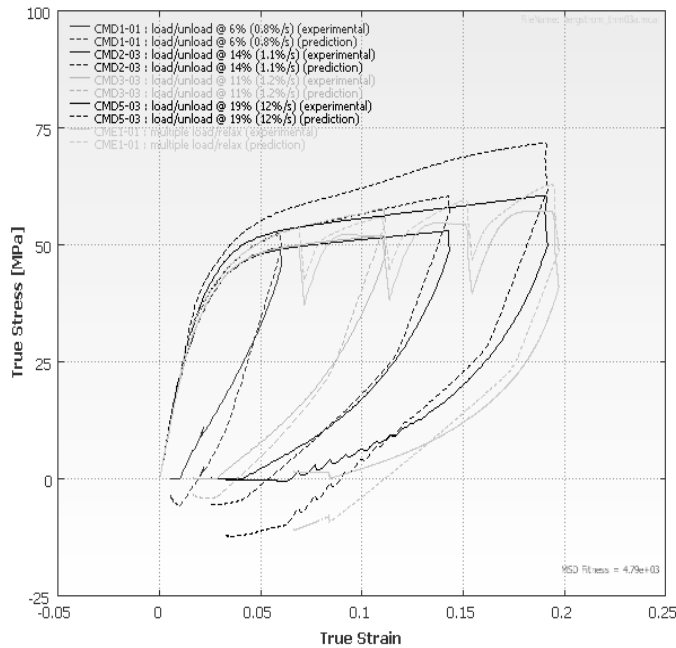


Figure 12. Fitting the Three Network Model parameters to different cyclic load schemes

7. Benchmark Results

7.1 Results from the Customized Benchmark

The customized benchmark of section 4.2 was used to benchmark the efficiency of the Three Network Model (TNM) vs. the **Elastic *Plastic* model which is the most commonly used internal model for such analyses. The resulting reaction force shown in Figure 13 indicates a better prediction of the final displacement using the TNM but a better prediction of the upload force/displacement using the **Elastic *Plastic* model

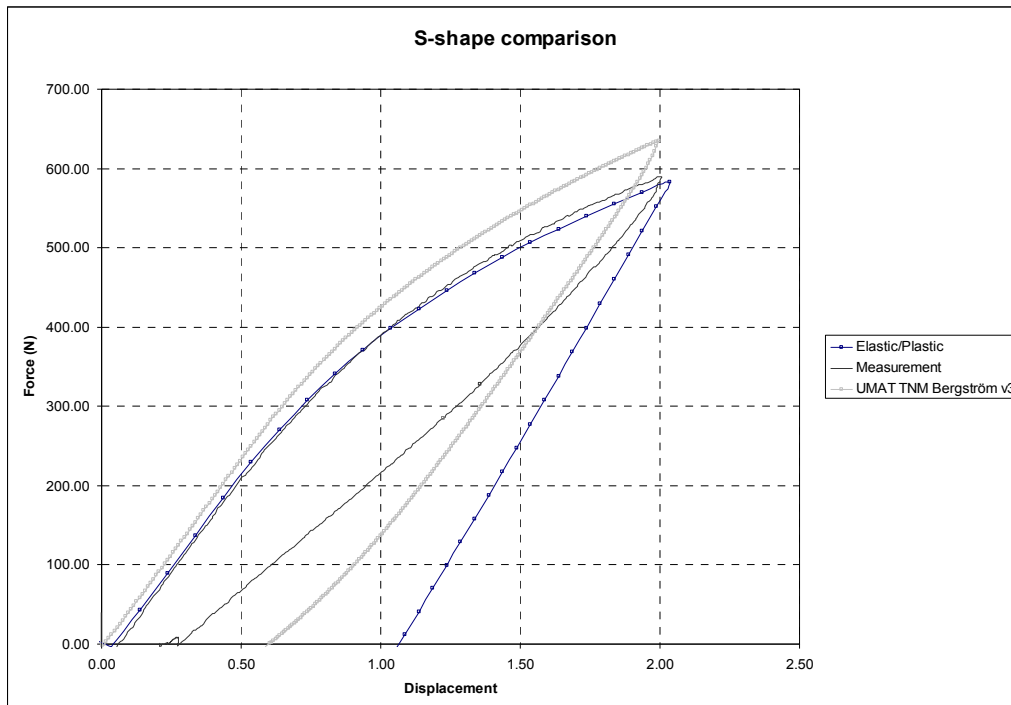


Figure 13. Benchmark test reaction force vs. displacement comparison

7.2 Results from the Device Member Benchmark

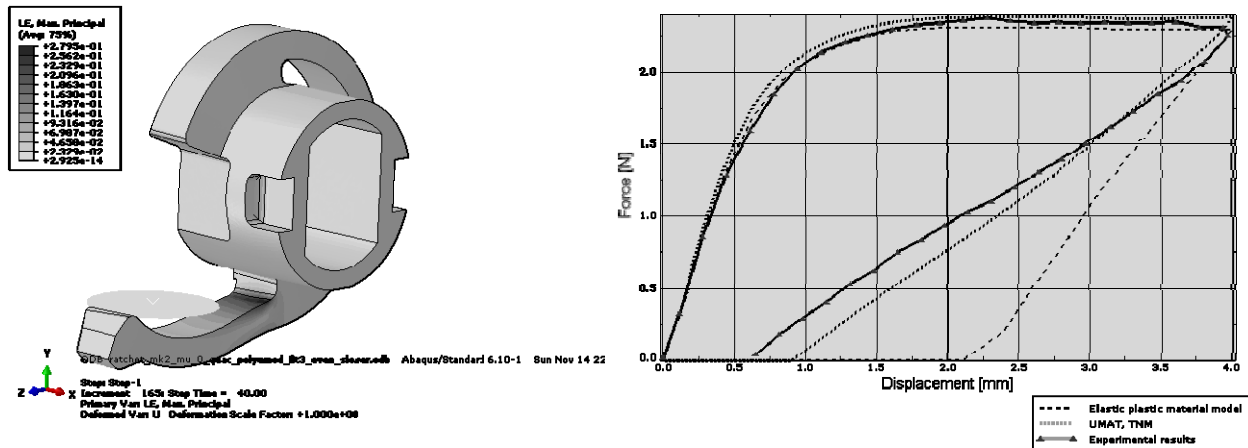


Figure 14. Component loading (left) and resulting test reaction force vs. displacement comparison (right)

Result for the device member component, described in section 4.3 is shown in figure 14.

The level of deformation of the ratchet arm can be seen from figure 14, the strain (max principal) measures up to 30% in the root of the ratchet arm. The load displacement curve of the experiment and based on the model using the elastic plastic material model and the TNM is plotted in the graph in figure 14. As expected, the plasticity is grossly over predicted using the elastic plastic material model, but the up-load curve is very well captured. This is quite impressive based on the load case, primarily bending and the level of deformation. With the three network model, using equivalent loading speed as for the experiment, the unload behavior is more well-captured - and also the up-load curve agrees well with the experiment.

Using the FEFP material model the analysis does not converge, because of the described problems above related to the Marlow model prediction in compression.

8. Final Device Result

The device assembly analysis described in section 2 was analyzed with an **elastic *plastic* and a Three Network Model (TNM) respectively. The aim of the analysis was to quantify the impact of the more refined TMN model on the analysis result (the reaction force and final deformation).

The below figure shows the difference between the predicted post-assembly deformation state of the snap connection which is obviously over predicted by the **elastic *plastic* model (actual deformation is app. 0.1 mm).

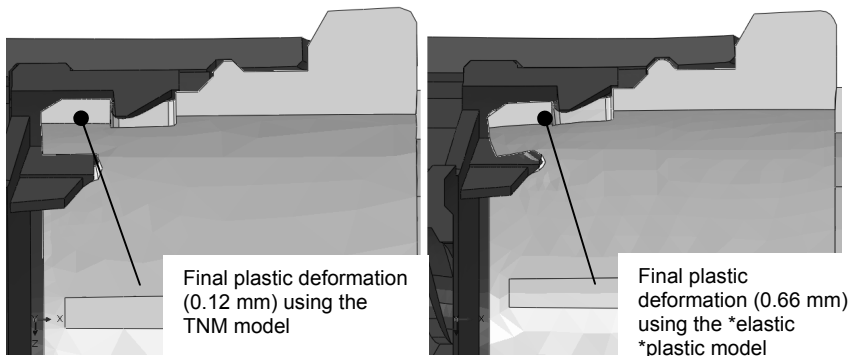


Figure 15. Final snap deformation using the TNM model (left) vs. the **elastic* plastic* model (right)

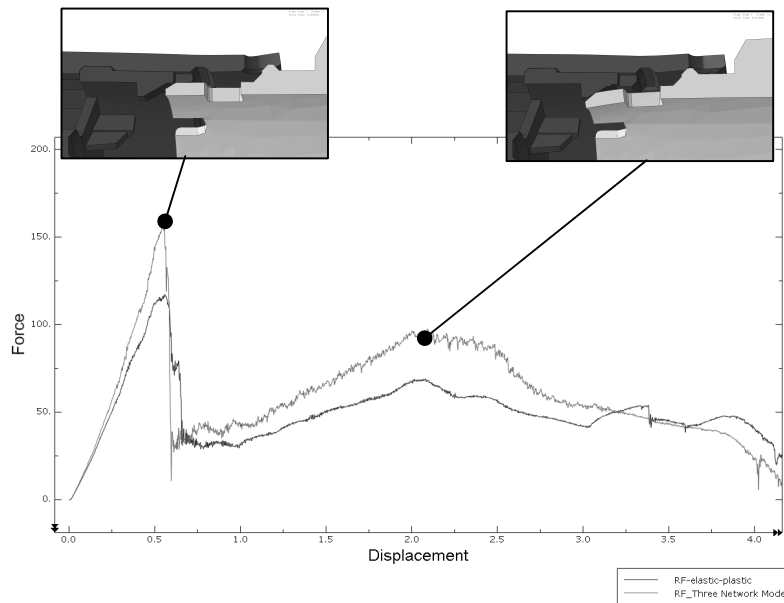


Figure 16. Reaction force comparison (upper curve: the TNM model response)

Plotting the reaction force reveals a quite significant difference between the models which can be explained by the rate dependant nature of the problem. The TNM model prediction matches the actual force peak of app. 150 N much better then the **elastic *plastic* model (which could be improved by including rate dependency).

However the better prediction of the TNM model has a rather high computational cost (mainly Explicit):

- 12 hrs using the **elastic *plastic* model (8 cpus)
- 6 days 2 hrs using the TNM model (~ x12)

9. Conclusion

The benchmarking of the Abaqus-available models has shown a rather good ability to predict the cyclic material response of the chosen thermoplastic in pure tension at a fixed strain rate.

Compared to the current available material models of Abaqus, a better prediction of the rate dependant cyclic material response has been obtained when the non-linear viscous response is included in the material model. Yet a more accurate modeling of the viscoelastic/viscoplastic residual strain level after loading is still much desired. The Three Network Model provided a much better prediction of the final snap deformation. Nevertheless, no satisfactory fit to cyclic data – especially beyond yield - was obtained. The larger the difference between the upload and release tangent stiffness, the more problematic the fit became. For future improvements – an even better fit to the true cyclic response of thermoplastics and increased computational efficiency are much desired.

10. References

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2. Ward I. M., Sweeney J. "Mechanical Properties of Solid Polymers", Second Edition, John Wiley & Sons 2004
3. Bergström Jörgen "PolyUMod – A Library of User Materials for ABAQUS" Version 1.4.2, Veryst Engineering 2010

11. Acknowledgments

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