Analysis of DuPont Engineering Polymers – Challenges and Solutions

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Abstract: *This paper describes the material behavior for different families of materials of the DuPont product offering, the performance of a selection of different material models for these materials using the extensive possibilities available in Abaqus, and the collaboration between DuPont and Simulia to advance the developments for a more accurate prediction of their behavior. In addition to the topic of modelling, the challenge of resource-effective data generation, state-of-the-art laboratory testing and corresponding data management on a global scale is discussed.*

Keywords: Constitutive Model, Elasticity, Hyperelasticity, Plasticity, Viscoelasticity, Polymer

1. Introduction

Modern application development and design depends increasingly on more accurate predictive engineering methods. Critical in these analysis is the response of the material and its corresponding constitutive behavior. Engineering polymers exhibit extensively complex behavior, where traditional isotropic elastic-plastic models are often no longer acceptable with regards to precision requirements.

DuPont is one of the major suppliers of thermoplastic engineering polymers, providing support and knowledge to its customers regarding best-practice use of its materials. Understanding and developing state-of-the-art material models for its portfolio (e.g. Karim, 2016; Kuhlmann, 2016, Volgers, 2015, Volgers, 2016, Wedgewood, 2014, Zhang, 2016), as well as best-practice use for a specific problem at hand, is key in this effort. These material models should capture the essential behavior of thermoplastic polymers, while at the same time avoiding unnecessarily complex material characterization and lengthy computation times for reasons of efficiency and cost. The goal of this paper is to describe the link between testing and numerical modelling and to seek the best solution depending on the problem at hand.

In addition to state-of-the-art predictive engineering, material testing capabilities and data management must meet the needs of data generation. Obtaining the material properties and parameters for models of constantly increasing detail and complexity requires advanced testing equipment and techniques. The time and cost for non-standard testing to extract advanced properties often exceeds the time and cost for the numerical modelling itself.

This paper begins by describing the general behavior of engineering polymers as offered by DuPont Performance Materials. For reasons of simplicity, only non-reinforced materials are concerned, thereby reducing the complexity considered, particularly fiber-orientation, which is strongly influenced by processing conditions. More specifically, this paper will focus on using data for Delrin® (POM homo-polymer) and Hytrel® (TPC-ET thermoplastic elastomer). Despite these materials being considered significantly different (based on comparing standard ISO data), a case will be made that a similar modelling approach can be used for both types of polymers. Based on these observations, a list of characteristics will be established, which a material model should be capable of capturing for an accurate description of the material behavior.

The subsequent section addresses a selection of material models available in Abaqus and evaluate their performance against the aforementioned criteria. Beginning with the "classical" elastic-plastic model using von Mises plasticity, increasing complexity will be introduced, cumulating with the PRF model for both materials. This review will include reflections on the effort needed to parameterize such models and the influence of the computation time on a representative problem.

The third section discusses the material testing needed for such models in more detail. This includes estimates on both effort and cost, and putting this into perspective from a material supplier point of view with a portfolio the size of DuPont's. The need and difficulty of automating these tasks is described, showing the importance of calibration tools integrated in the pre-processing software, such as Abaqus/CAE.

The closing section consists of a summary and description of development needs from DuPont's perspective for advancing the use of engineering polymers in a wide range of industries with consistently more demanding applications and requirements through close collaboration between DuPont and Dassault Systèmes.

2. General Material Behavior

The selection of a suitable material model is based on the force-deflection response as observed in mechanical tests on specific specimens reported in the form of (nominal) stress-strain curves. Particularly in the case of thermoplastic polymers, the mechanical material response is dependent on various factors, such as temperature, moisture, fiber orientation (for fiber-reinforced polymers), testing speed, aging, etc. For the purpose of clarity, this paper will concentrate on the behavior of two polymer types; Delrin® (a POM homo-polymer) and Hytrel® (a TPC-ET thermoplastic elastomer). The grades considered do not include any fiber reinforcements and are not sensitive to the humidity level of their environment, thereby eliminating two significant factors potentially influencing their performance from the narrative.

2.1 Static Test Data

Basic plastics material data is freely available via the CAMPUS[1] material information system. Its objective is to guarantee comparability between the data of different suppliers through the use of uniform test procedures based on international standards (ISO). From this database, the user can obtain a set of standardized stress-strain curves for a wide selection of polymers. These curves form the basis for any material model. Figure 1 shows the stress-strain curves for Delrin® 100 NC010 and Hytrel® 5555HS at room temperature, 40 °C and 60 °C as found in the CAMPUS database.

[1] http://www.campusplastics.com

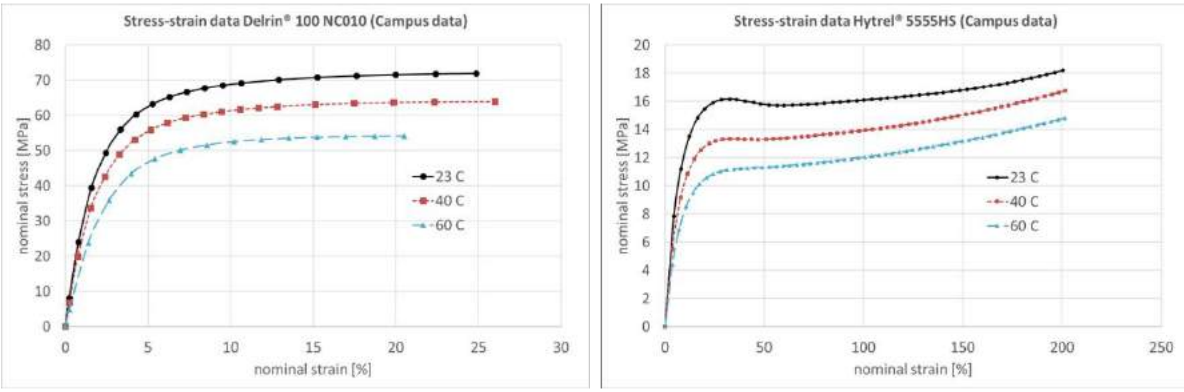


Figure 1. Standard stress-strain curves as obtained from the CAMPUS database.

The stress-strain curves for Delrin® exhibit what is expected of a ductile elastic-plastic material. The Hytrel® curves look like what would be expected from a hyper-elastic elastomer. Both materials are shown to be highly sensitive to temperature, for both initial stiffness and yield.

Engineering polymers are known in practice to perform better in compression than in tension (see e.g. Winkler, 2009, DuPont, 1995). Due to their low stiffness compared to metals, compressive testing is inherently difficult risking premature buckling of the samples, which limits the amount of compression of test specimens.

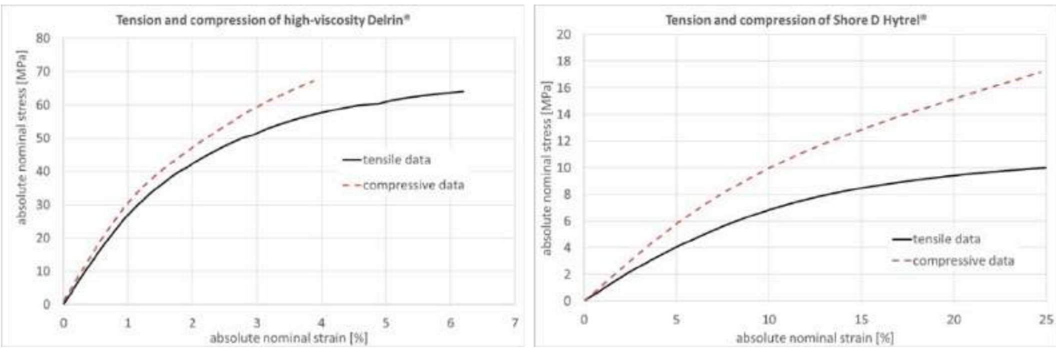


Figure 2. Tension and compression performance of engineering polymers

Figure 2 shows the compressive stress-strain data compared to the tensile stress-strain response for a high viscosity Delrin® (until buckling occurred, left) and a Shore D Hytrel®. Both materials display an increased stiffness compared to their tensile performance.

Typical application use requires the material to remain in its elastic region when subjected to the nominal load at peak temperature in the part. Based on the stress-strain data alone, Delrin® 100 parts are designed not to exceed 2% strain at room temperature, while Hytrel® parts will rarely exceed 20%, with 5-10% a common usage range.

To determine the actual onset of permanent deformation, cyclic testing of tensile specimens have been performed. Results at room temperature for two materials are shown in Figure 3 below.

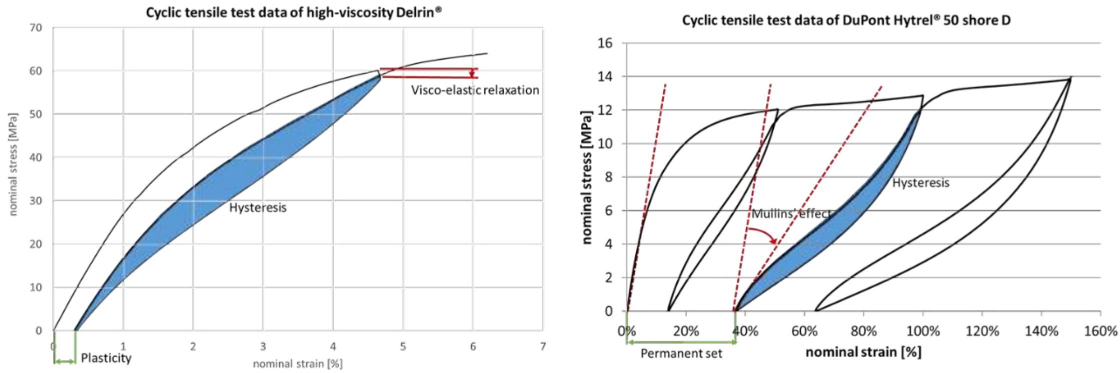


Figure 3. Cyclic loading behavior of thermoplastic engineering polymers

The first thing to notice when considering the cyclic loading response for the Delrin® (left) is the low level of plasticity, even at a total strain of 5%. This clearly emphasizes the non-linear elastic behavior of the polymer. In addition, the data shows a rapid drop in effective stress at the transition from loading to unloading, indicating a strong viscoelastic behavior, which will be discussed in more detail below.

The response for the Hytrel® grade (right) is more what would be expected from a rubber-like material, but with significant permanent set (see also Volgers, 2016). Contrary to the stiffer Delrin®, the thermoplastic elastomer also demonstrates a strong Mullins' effect.

2.2 Viscoelastic Response

Thermoplastic polymer materials are known to exhibit viscous behavior. Figure 4 shows incremental strain loading with periodic stress-relaxation (also referred to as Christmas-tree test). Both Delrin® and Hytrel® show significant viscoelastic behavior.

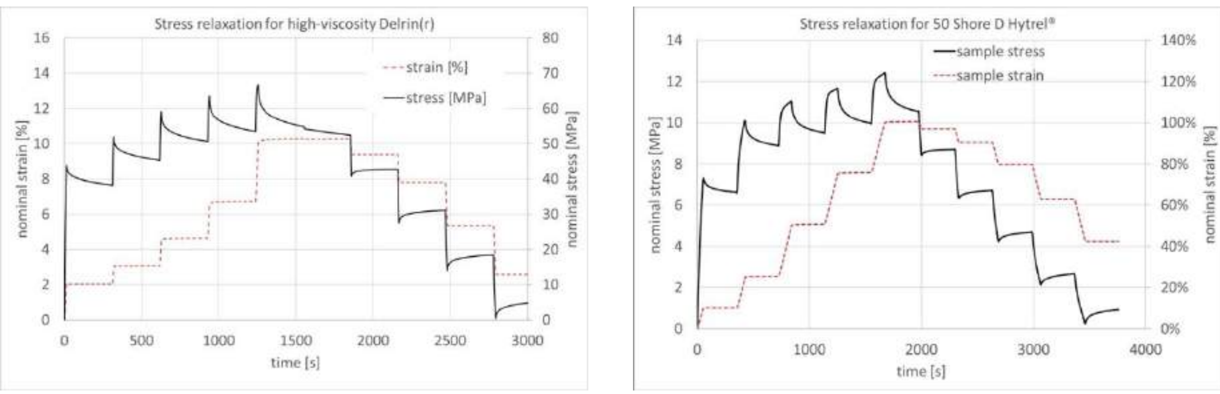


Figure 4. Stress-relaxation curve for a Delrin® grade (left) and Hytrel® grade (right)

Note that the strain levels for the Delrin® are an order of magnitude smaller than for Hytrel®. As a result, the time duration between strain increases is significantly higher for the thermoplastic elastomer. For the Hytrel® grade the stiffness change in re-loading, as shown in the cyclic test data

(Figure 3) due to the Mullins' effect is visible in the Christmas tree loading as a non-linear stress increase, which a pronounced change in slope.

This non-linear behavior is not visible in the strain-increase stages of the step-wise loading of the Delrin® grade, but the viscoelastic stress-relaxation is more pronounced. For both materials, a reduction of the stress level of about 10% occurs within 5 minutes of relaxation.

2.3 Strain-rate Dependency

Given the strong viscoelastic response shown above, a significant strain-rate dependency would be expected. Figure 5 shows the rate-dependency for a high-viscosity Delrin® grade.

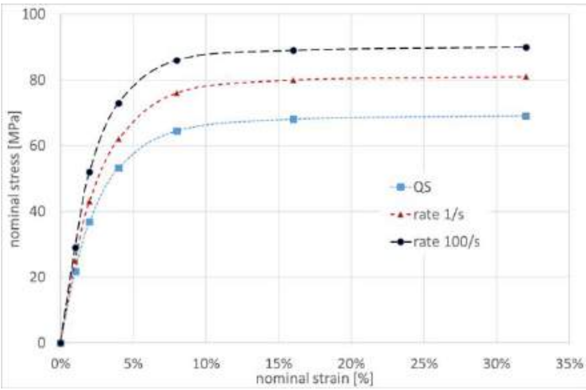


Figure 5. Stress-strain curves at different rates for Delrin® grade.

The initial stiffness is virtually unchanged, but the onset of the non-linear part of the response sees a significant increase in the stress level, giving a 30% increase in its load-carrying capability. A further characteristic of interest for Delrin® is the increase in deformation capacity. This is in fact the result of poor heat conduction, which in this case works in favour of the material (Hellerich et. al., 2010). Further investigations conducted (Winkler, 2009) confirm the above observations.

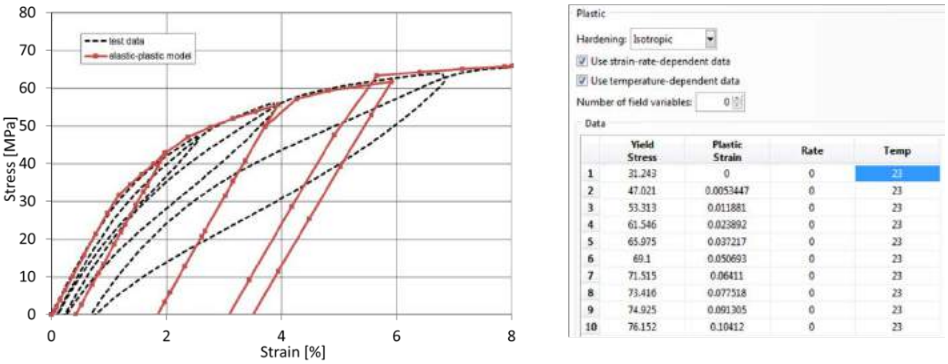
3. Material Modelling

In this section, we will consider various constitutive models available in Abaqus for the modelling of thermoplastic engineering polymers based on the mechanical behavior described in the previous section. We will consider not only their accuracy with respect to the specimen test data, but also evaluate the time needed to calibrate the model itself. It will be shown that increased complexity of the constitutive model will certainly improve its predictive capabilities in general, but this may not always be required, depending on the load case and design requirements.

Due to the limited applicability to most design problems (apart from creep) and the limited space for this article, we will refrain from the evaluation of a purely viscoelastic material model. These effects will be included in the description of the PRF model results.

3.1 "Classic" Approach: Elastic-Plastic Model

The standard and most common approach used for modelling engineering thermoplastic polymers, including the semi-crystalline materials offered by DuPont Performance Polymers, is a basic elastic-plastic material model with isotropic hardening. The material parameters can be determined (including the true stress-plastic strain table) directly from standard tensile test data. Results for simulating the cyclic loading of a Delrin® tensile bar are shown in Figure 6.



	Yield Stress	Plastic Strain	Rate	Temp
1	31.243	0	0	23
2	47.021	0.0053447	0	23
3	53.313	0.011881	0	23
4	61.546	0.023892	0	23
5	65.975	0.037217	0	23
6	69.1	0.050693	0	23
7	71.515	0.06411	0	23
8	73.416	0.077518	0	23
9	74.925	0.091305	0	23
10	76.152	0.10412	0	23

Figure 6. Elastic-plastic material model results for high-viscosity Delrin®

The elastic-plastic model follows the primary curve very well, even after unloading and re-loading, but does not follow the unloading path and strongly over-estimates the plastic strain.

The standard elastic-plastic model has the great advantage of easy characterization. In addition to this, the Abaqus input format allows both the elastic and the plastic properties to be defined at various temperatures, with Abaqus automatically interpolating the behavior between temperature points. Also, the strain-rate can be specified for the plastic yield, which is sufficient for polymers such as Delrin®, where mainly the non-linear part of the stress-strain curve is influenced by the rate of deformation.

A similar argument can be made for a thermoplastic elastomer, specifically if the effective deformations remain relatively low (less than 30%, say).

3.2 Hyper-elastic Model with Permanent Set

A hyper-elastic material model including Mullins' effect and permanent set for Hytrel® has been described in full detail in (Volgers, 2016).

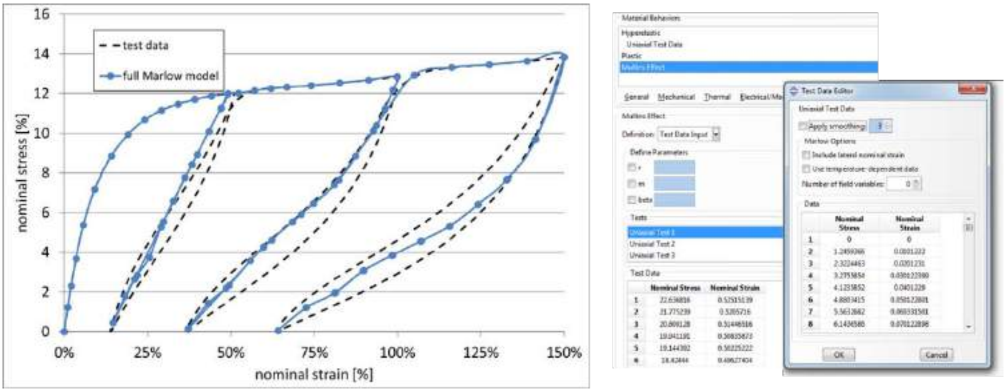


Figure 7. Hyper-elastic model with Mullins' effect and permanent set for Hytrel®

The need for a hyper-elastic material model is rather obvious, given the large deformations the material can be subjected to. However, the material is not fully elastic, as would be expected from an elastomer, but shows significant permanent set. For any analysis to include plastic deformation, this effect can be more significant than the loss of stiffness (Mullins' effect). The current implementation of this model includes both effects quite well and can be calibrated using an Abaqus/CAE plug-in, greatly facilitating the parametrization effort.

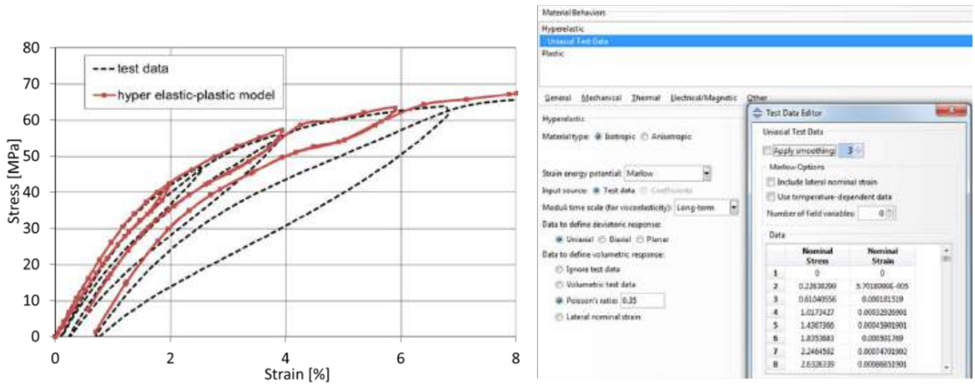


Figure 8. Hyper-elastic material model results for high-viscosity Delrin®

Using the same calibration plug-in, a hyper-elastic model with permanent set can be created for unreinforced engineering polymers which are much stiffer than elastomers. Even when excluding the loss of stiffness, the resulting cyclic loading response is very close to the observed behavior and allows for accurate prediction of the plastic deformation.

3.3 Using the PRF Model

The Parallel Rheological Framework available in Abaqus/Standard and Abaqus/Explicit "*is intended for modelling polymers and elastomeric materials that exhibit, permanent set and nonlinear viscous behavior and undergo large deformations.*" (Abaqus, 6.14). It is comprised of multiple networks consisting of a spring-resistance (elastic-plastic) network for the network 0, followed by a series of spring-dashpot (viscoelastic) networks 1 to N, as shown in Figure 9 below.

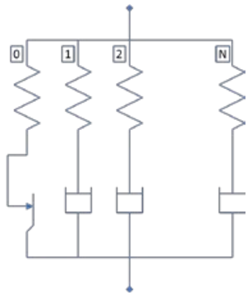


Figure 9: Non-linear parallel Maxwell model

The viscoelastic networks each need a definition of their respective behavior and corresponding model parameters, in addition to determining the weight factors for each of them. This makes calibration of such models complicated and intensive, requiring tools such as Isight or PolyUMod MCalibration, as used by DuPont.

A 50 Shore D Hytrel® grade has been calibrated based on cyclic tension and compression test data, as well as the christmas-tree data, described in section 2.2, with a set of results shown in Figure 10 below, using PolyUMat and Abaqus/Explicit.

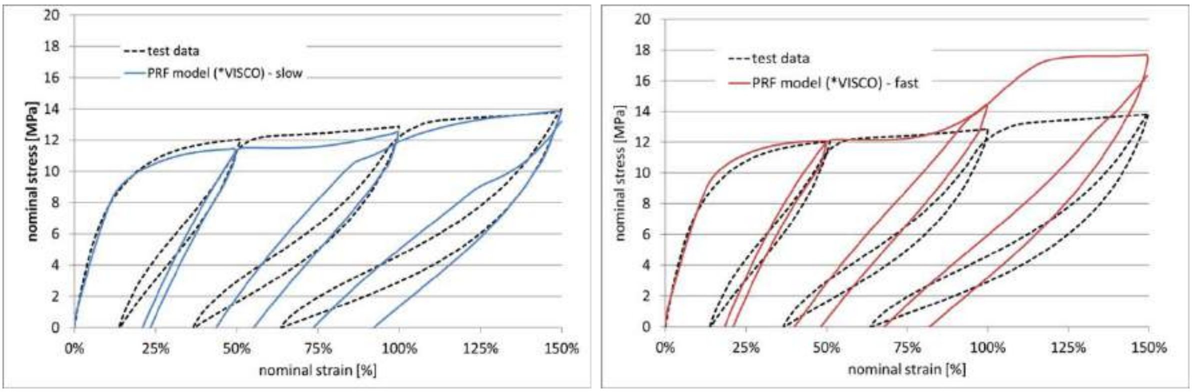


Figure 10. PRF model results with Mullins' effect and plasticity for Hytrel®

The model and its results are described in more detail in (Kuhlmann, 2017). Shown here are simulation results using Abaqus/Standard with the “VISCO” solver. On the left is a 1-element test reproducing the loading-unloading tensile stress-strain curve at very low speeds. One the right is the same 1-element simulation but with increasing loading speeds at each re-loading phase, showing the increasing stiffness response of the material model.

4. State-of-the-art Testing Needs

Material testing is one of the core activities of the laboratories of a supplier like DuPont Performance Materials to support new material developments and its customers in the use and application of these polymers. Tensile testing of materials, either as molded or after environmental exposure (such as air oven ageing, humidity exposure, oil soaking, etc.) following well-defined protocols is performed on a daily basis. With a material portfolio of well over a thousand material grades (more than 200 Delrin® grades, about 150 Hytrel® grades), this testing is highly automated. A robotized traction testing cell is available at the European Technical Centre in Geneva (as shown in Figure 11), which allows for fully automated tensile testing, creating a high output rate of generated data and keeping costs under control.

Figure 11. Automated tensile testing equipment (DuPont ETC, Geneva)

State-of-the-art material modelling requires material testing beyond the standard unidirectional continuous tensile stress-strain curve, with data as described in the previous section. This additional material can no longer be generated fully automatically, since the basic unidirectional continuous stress-strain curve needs to be available before setting up any cyclic and relaxation tests, to determine at what stages the cyclic loading or relaxation should occur.

Additional complexities occur due to the control mechanisms of most tensile test machines, which are either load (or stress) controlled or displacement (or strain) controlled. For cyclic tests, where the goal is to unload the specimen until a zero-stress state has been reached before re-loading, this means that the testing has to be conducted using load-control. However, with the non-linear part of the nominal stress-strain curve being relatively flat, a small variation in applied load, or fractional variation in material properties (well within the standard variation) will result in significant change in strain where unloading will take place. Using displacement (strain) control would allow a much more accurate and repeatable start of the unloading, but since the plastic deformation is not known in advance, this will result in the re-loading commencing either before the zero-stress state has been reached, or after the material has been subjected to compressive loading.

For more consistent cyclic stress-strain data, a mixed-mode control is needed. Not all testing machines allow such modes, and most which do require special software, and would need special programming. Such capabilities, as available at the DuPont American Technical Center in Wilmington (DE), allow for the creation of more automated testing for specific grades of material to generate consistent and comparable cyclic stress-strain data.

5. Discussion on Testing vs Modelling

It is generally assumed that increased complexity of material modelling will result in increased accuracy of the numerical simulation results with respect to actual structural behavior. In this section, the authors will argue that this is not necessarily the case and can actually lead to false security. To better understand the argument one has to look at the error and variation in the material testing data and compare this to the material model calibration. We will use the determination of the elastic modulus to illustrate this point. A further point of consideration is the amount of effort needed in both testing and model calibration with increased complexity, which will also be addressed.

The authors postulate that increased model complexity and corresponding effort is mainly useful for a more accurate description of the material behavior and not necessarily for a more accurate structural response prediction. The choice of model should therefore be determined by the type of material behavior the analysis intends to capture, and not by the accuracy of the numerical prediction as such.

5.1 Error in the Determination of the Elastic Modulus.

A few years ago (Winkler, 2009), one of the authors had been conducting a large-scale material program on injection molded plastics, which among others included a substantial monotonous tensile testing on DIN-EN-ISO-3167 specimens. The primary material parameter usually deduced from such tests is the Young’s modulus, or modulus of elasticity (although based on the results shown above it can be argue that this parameter does not really apply to thermoplastic polymers). It is often used to give engineers a common denominator around which a stiffness discussion on the material can be conducted. The values reported in data sheets and CAMPUS as supplied by plastics manufacturers, such as DuPont, are of extremely high statistical quality as far as the mean and standard deviation are concerned. Two things however, are commonly set aside and never really presented. First, the error in the actual deduction in the parameter; and secondly the discrepancy between published stress-strain data and the elastic modulus in the data sheet.

For the correct calculation and simulation of load conditions the true stress and strain are the decisive quantities. During data acquisition the forces recorded in the testing will be related to the initial cross-section. For larger deformations one will therefore see a systematic error occur in the calculated stresses. Since the deformation of polymers does not take place under constant volume conditions, the cross-sectional change must be taken into account using Poisson’s ratio. Poisson’s ratio in polymer materials is on average 0.35 and increases for highly elastic Polymers (i.e. elastomers) up to almost 0.5 (Gaussian networks). In the metrological detection of characteristic material parameters, the results are greatly dependent on the tolerances of the measuring equipment. We can therefore speak of a certain tolerance range of material characteristics. This range can be described by a measure of uncertainty, U, which in the following will be assessed for Young’s modulus for a non-reinforced injection-molded engineering plastic.

The following relationships constitute the starting point:

$$E = \frac{\sigma}{\epsilon} \text{ with } \sigma = \frac{F}{A} \text{ and } \epsilon = \frac{\Delta L}{L_0}$$

Referring to the cross-section according to DIN 527-1, the correction by means of transverse contraction results in:

$$A = b_0 \cdot c_0 \cdot (1 - 2\nu\epsilon + \nu^2\epsilon^2)$$

Thus, from:

$$E = \frac{F}{b_0 c_0}(1 - 2\nu\epsilon + \nu^2\epsilon^2)\frac{\Delta L}{L_0}$$

The uncertainty of the modulus can be explicitly stated as:

$$U_E = \sqrt{\sum\left(\frac{\partial f}{\partial x_i}u_{x_i}\right)^2}$$

To give the equation some practical meaning, the uncertainty for a polyamide will be calculated. The individual parameters and their respective uncertainties are listed in the table below.

Table 1. Testing parameters and their uncertainties for a polyamide (Winkler, 2009)

Parameter	Designation	Unit	Magnitude	Uncertainty [abs]	Error [%]
F	Tensile force	N	847.97	± 20	2.36
c_0	Thickness	mm	4.030	± 0.10	2.48
b_0	Width	mm	10.01	± 0.10	1.00
ν	Poisson's ratio	-	0.35	± 0.05	14.3
ΔL	Change in length	mm	0.54	± 0.06	11.1
L_0	Gauge length	mm	80.00	± 0.20	0.25

The authors would like to point out that these values stem from a state-of-the-art high precision static testing machine from Zwick, and the specimens were manufactured to a very tight specification. This is certainly not a generic situation for contemporary engineers. In fact, the authors consider the boundary conditions for these measurements to be somewhat luxurious.

With the values from the table it is possible to calculate a value for the uncertainty for the elastic modulus of approximately 365 MPa. This corresponds to about 7.5%. It is thus possible to state the tensile modulus for the polyamide as follows:

$$E_0 = 4822\frac{N}{mm^2} \pm 7.5\%$$

Most users do not have access to such accurate testing data, but instead need to rely on the published data from the material supplier, as found in the data sheet and the stress-strain data as found in CAMPUS. When taking a closer look at these, one can find significant differences between the two. Returning to Delrin® 100 as the example, the data sheet will state an elastic modulus of 3000 MPa, with the stress-strain data as shown in Figure 12 below left.

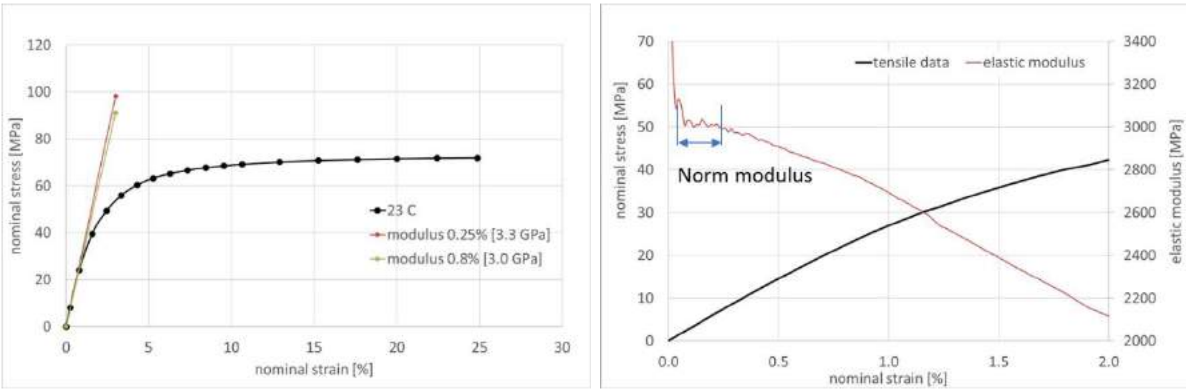


Figure 12. Elastic modulus from CAMPUS stress-strain data and per norm

According to the ISO-527-1 norm, the elastic modulus is determined by the slope of the stress-strain curve in the strain interval between $\epsilon_1 = 0.05\%$ and $\epsilon_2 = 0.25\%$. Following the norm, one might expect the modulus from the stress-strain curve at 0.25% to correspond to the modulus in the data sheet. However, using this method the elastic modulus is determined to be 3300 MPa, or an increase of 10% compared to the published modulus.

This can be explained by looking at Figure 12 on the right, where the data from the machine, which contains many more data points than are published in CAMPUS, is shown, together with the local (secant) modulus. It can be seen that the small region where the modulus is almost constant is to be found in the strain region as defined by the ISO norm, determining the modulus to be 3000 MPa.

As a result of the error discussion the following conclusion can be drawn with respect to numerical (FEA) and closed (analytical) methods: With a minimum of 5 to 10% error in parameter extraction it becomes non-constructive to fuss about insufficient precision in decimal points. It is thus of utter importance that the measurement technology be kept up to date and that the equipment at hand is continuously calibrated using the most modern means.

5.2 Cost and Effort of Advanced Methods.

The accuracy of advanced, complex material models cannot be separated from the cost and effort needed to characterize the materials, both for testing and numerical model calibration. DuPont is asked daily to provide material data, from standard stress-strain curves to high-speed test data, creep, ageing, environmental resistance, etc. With a portfolio of more than a 1000 material grades, it is evident that not all data is available for all grades.

As described in this paper, increasingly accurate material models also require increasingly complex material test data, as well as time- and resource intensive model calibration. Table 2 provides a brief qualitative overview on the testing and calibration efforts needed for the respective material models described in this paper.

Table 2. Overview of effort for various constitutive models

Constitutive model	Testing effort	Calibration effort
Elastic-plastic	• No prior property knowledge required. • Fully automated equipment.	Semi-automated (Excel)
Hyper-elastic-plastic	• Requires monotonous loading stress-strain knowledge of material type. • Specific equipment/software.	Using Abaqus/CAE plug-in
PRF model	• Needs wide range of testing data. • Preferred set based on shear testing. • Needs specific testing equipment, programming, jigs and samples.	Requires significant effort and external software tools. Not integrated in Abaqus/CAE V6-14

5.3 Selecting a Suitable Material Model for Analysis

The standard elastic-plastic model is by far the most efficient material model available. Its parameters can directly be determined from standard stress-strain tensile test data, which in its turn can be generated automatically. This data is always generated for any of the commercial available grade in the DuPont Performance Materials portfolio. Although it does not describe the actual behavior of the materials considered, it does allow an accurate reproduction of the unidirectional continuous loading of the material, and hence the structural part. This means, that for determining the structural deformation under a continuous load, or the global deformation and reaction forces of a component with a given displacement, the prediction can be sufficiently accurate.

An additional advantage is the numerical stability and computational efficiency of such a model, resulting in total analysis times much shorter than any of the more complex models. However, a key element is that the analysis engineer needs to be aware of its limitations, particularly when trying to determine the plastic deformation, as this will be significantly over-estimated.

The hyper-elastic material model, especially with the inclusion of permanent set and (possibly) Mullins' effect, significantly broadens the scope of applicability to a wide range of structural loading conditions, especially when predicting plastic deformation and unloading behavior. Using the Abaqus/CAE plug-in allows for easy and (relatively) quick deduction of material parameters. Testing could be made more semi-automated, based on the material type and general grade, given additional testing programming effort. Although computation times can increase significantly compared to the standard elastic-plastic model, this model is considered to be a very good compromise between testing and calibration effort and numerical accuracy.

The choice of using a PRF model should only be made when the application requires the analysis of viscous behavior. The material property testing required does not allow for (semi-)automated testing, significantly adding to the workload of the analytical lab. The material model parameter determination is another time and resource intensive step, limiting its general applicability. To increase the use of a PRF models in numerical structural analysis, a more standardized testing procedure should be linked directly to a plug-in or external software tool to facilitate the material parameter determination.

6. Summary

This paper described the general material behavior of unreinforced engineering thermoplastic polymers and various means of modelling this behavior. An evaluation of the different material models available in Abaqus is described. This is linked to the testing effort needed to obtain the data to calibrate the respective models.

Considering the material behavior, a complete constitutive model for engineering thermoplastic polymers should include plasticity, reduction of stiffness (Mullins' effect), rate- and temperature-dependence, viscoelasticity and distinguish between tension and compression. This behavior covers a wide range of polymers, from a stiff Delrin® to a flexible elastomeric polymer such as Hytrel®. There is currently no material model available in Abaqus (or anywhere else to our knowledge) which captures all these phenomena in a comprehensive and pragmatic implementation. DuPont is collaborating closely with Dassault Systèmes by providing material tests data and feedback, in order to advance its capabilities.

Although standard elastic-plastic models are the ones still in majority for the industry due to their simplicity both regarding testing and model parameterization, it has been demonstrated in this paper that they highly over-estimate the permanent deformation and do not capture the loss of stiffness at larger strains. This presents a severe limitation to their applicability. The use of hyper-elastic models with permanent set as available in Abaqus, greatly improves the predictive quality of the numerical analysis.

The current state-of-the art material models, in particular the PRF model available in Abaqus, do manage to describe many of the required characteristics mentioned previously. However, such models require material testing which currently cannot be automated. In addition, material parameter deduction is very resource- and time-consuming, in addition to the aspect of increased computation time for the numerical analysis. Automated calibration tools, similar to the Abaqus/CAE plug-in available for hyper-elastic models, would greatly facilitate its use.

The significant increase in material characterization costs (time and resources) with increasing material model complexity, is a major concern for a material supplier with more than a 1000 grades in its portfolio, who is requested to provide such data, or even to develop grade-specific material models. The authors would like to stress the need to select the most suitable material model based on the analysis needs and obtainable material data instead of an automatic drive towards the most complex and complete model. Close collaboration is helping to provide end-users and customers of both companies the best solutions for their numerical analysis.

7. Acknowledgements

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