Simulation creep behavior of plastic parts during complex thermo-mechanical loading

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Abstract: The paper describes using of Abaqus for evaluating the behavior of car plastic parts which are exposed to high temperature and self weight (plus another load) for long time. Car plastic parts (inside and outside) are subjected to complex loads – temperature, vibration and environmental conditions. It is a challenge to prepare simulations which correctly describe the complex behavior - temperature dependent, time dependent of stress-strain behavior. To capture visco-elastic behavior we chose a creep description of the material. We discussed choosing suitable material in Abaqus for the description of creep behavior. Base on measurements (of specific load cases), we define a process for defining material Abaqus cards. And finally we describe the results validation of simulation on real parts. There were some specific requirements to evaluation of result – effectively measure the change of gaps between parts in dependency on position of measurement lines which have to be solved.

Keywords: Viscoelasticity, Creep, Power Law

1. Introduction

The automotive industry is increasingly using plastic materials. The essential parts such as bumpers, inner door trim, dashboard, etc... Temperature has an important effect on the mechanical behavior of plastics and at the same time due to the large thermal expansion occurs to large temperature deformations. Standard elastic-plastic material model is not sufficiently accurate during long term loading at higher temperature conditions. For realistic results is necessary to add a model of creep. The simulation of this specific phenomenon will be discussed in this article.

1.1 Requirements for plastic parts

The plastic parts need to be designed according these criteria:

- Dimensional stability at higher temperatures - reduce curling, buckling.
- Stability of gap between parts - the opening and closing of visible gaps between parts.
- Residual deformation after thermal and mechanical load.
- Dynamic stiffness for vibration.
- Good behavior during crash.
- Stiffness, Strength, Durability.

The requirements have to be taken account during designing, simulation and testing. The criteria and conditions are specified by manufacturers.

The IDIADA has organization has worked to improve the methodology of simulation of plastic parts systematically. One of many topics are the simulations of outdoor plastic parts like a front and rear bumpers during thermal-structural loading and thermal-vibration (Table 1.).

Table 1. Range of analysis solve by Abaqus

	Quasi -static loading (force, gravity)	Environmental load (temp. load)	Vibration
Abaqus Standard nonlinear static	temperature – mechanic		
Abaqus Standard NVH analysis		temperature – vibration	

This article deals only with temperature-mechanics simulations, where it is necessary to evaluate the creep effect. (Figure 1.).

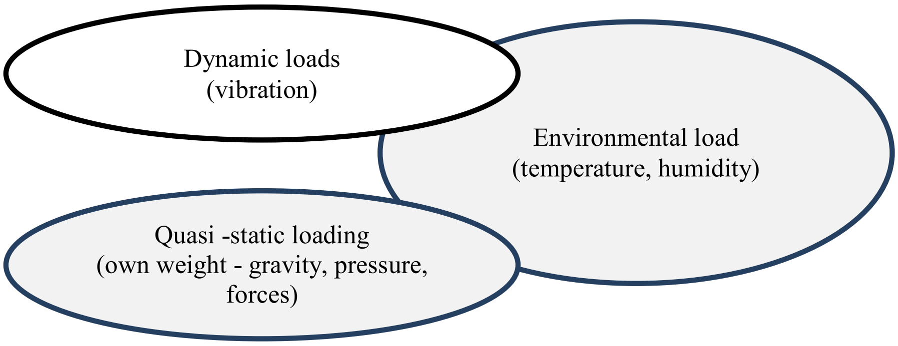


Figure 1. Cylindrical transformation option.

1.2 Creep in thermal-structural analysis

Polymer materials exhibit creep - time dependent behavior at room temperature. The stress and strain have to be defined as functions of time. In the most general form they can be thought of as a three-dimensional surface. The stress-strain-time relationship, or constitutive law, can be determined by loading a polymer specimen with constant stress (creep) or constant strain (stress relaxation or isometric). We can also construct an isochronous curve by cross section of the surface with constant time levels as shown in Figure 2.

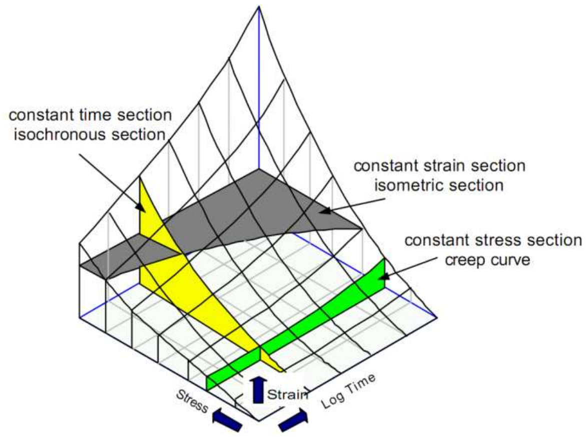


Figure 2. Stress – strain – time surface [1].

When a plastic material is subjected to a constant load, it deforms continuously (Figure 3.).

The primary region is the early stage of loading when the creep rate decreases rapidly with time. The primary stage is not so important in our simulation.

Then it reaches a steady state which is called the secondary creep stage followed by a rapid increase (tertiary stage) and fracture. This phenomenon of deformation under load with time is called creep.

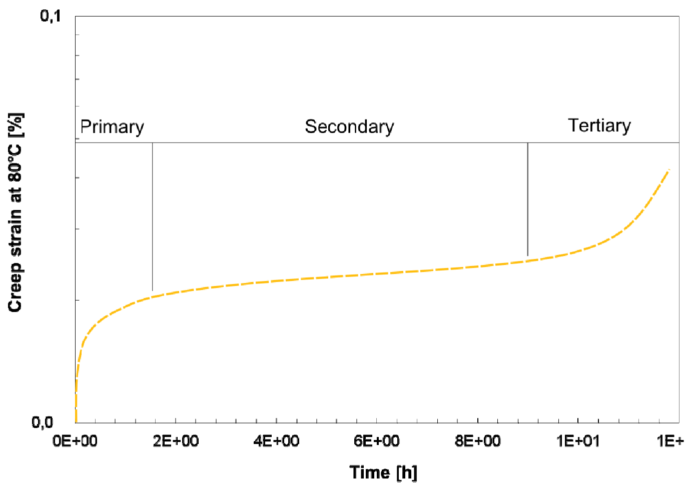


Figure 3. Creep curve for PP type material.

2. Methodic of simulation – material model

From the point of view of the material we use a visco-elastic-plastic model (Figure 4). For higher temperature, the plasticity section is rigid so the deformation is realized only by the visco-elastic section. Plastic strain can take part only at lower temperature – this serves as an indicator of high levels of stresses for evaluating the risk of brittle break. The viscous section at lower temperatures is rigid; in this regime creep is negligible.

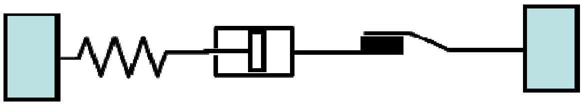


Figure 4. Visco-elastic-plastic rheology model.

The simple Maxwell like model in combination with plasticity is suitable only for a narrow area of simulation plastic parts:

- Narrow range of temperatures (from -40C to 80C) for filled PP materials.
- Longer time of applying forces, temperatures. We are able to simulate mainly secondary creep
- The stress is bellow yield stress for higher temperatures.

Simulation of creep in Abaqus is realized by the combination of keywords *CREEP, *PLASTIC and *ELASTIC.

Unfortunately it is not possible to use this for our shell-dominated structures material model which was included in Abaqus 6.12. This is because parallel network nonlinear viscoelastic model ("*VISCOELASTIC, NONLINEAR; the General Maxwell model) is not supported for shells.

Another material, the two-layer visco-elasto-plastic (Kelvin-like material) model is available by combining the keywords *VISCOUS, *PLASTIC, *ELASTIC. The model is suitable for simulation where the nonlinear (creep) deformations are able to relax to initial position (before loading). For viscous section we can use a Power Law definition of the subroutine CREEP (same as in our Maxwell model). In our simulation, the nonlinear deformation dominates the residual deformation (for weakly filed PP, temperatures about 80°C and higher stresses), so we can't use this material model.

The last possibility is viscoelastic material is available by keyword *ELASTIC, *VISCOELASTIC – the material works only for small deformation and supposes a linear scaling response with stress – linear model of creep. So we can't use the material model as we see strong stress dependency.

Advantages of using Maxwell model:

- Easy defined model – three parameters for each temperature
- Easy convergence

- Is implemented directly to Abaqus / Standard

Disadvantages:

- Not possible to fit material coefficients for wide range of stresses (was possible overcome the disadvantage by using Modified Power Law
- Behavior of primary creep (short time scales) not possible effectively control and there is danger that it isn't accurate enough.
- The Maxwell model doesn't assure that the model will behave correctly after unloading and for cyclic loading.

2.1 Creep equations

2.1.1 Power law

The Power Law equation for creep is defined by Eq. 1, where A, n, and m are constants, $\bar{\varepsilon}^{cr}$ je is the equivalent (uniaxial) deviatoric creep strain rate, σ is the equivalent deviatoric stress (Mises), and t is time

$$\bar{\varepsilon}^{cr} = \frac{A\bar{\sigma}^{n}t^{m+1}}{m+1} \quad (1)$$

$$\dot{\bar{\varepsilon}}^{cr} = A\bar{\sigma}^{n}t^{m} \quad (2)$$

2.1.2 Modified Power law

We propose an extension of the Power Law equation – the origin equations (1) and (2) are converted to (3) and (4). We use the following substitution: $A\bar{\sigma}^{n} = A(\bar{\sigma}^{n1} + B\bar{\sigma}^{n2} + C\bar{\sigma}^{n3})$, where A, B, C, n1, n2, and n3 are constants.

$$\bar{\varepsilon}^{cr} = \frac{A(\bar{\sigma}^{n1}+B\bar{\sigma}^{n2}+C\bar{\sigma}^{n3})t^{m+1}}{m+1} \quad (3)$$

$$\dot{\bar{\varepsilon}}^{cr} = A(\bar{\sigma}^{n1} + B\bar{\sigma}^{n2} + C\bar{\sigma}^{n3})t^{m} \quad (4)$$

For the strain hardening calculation of creep we have to define creep strain rate as a function of creep strain – we have to eliminate time from Eq. 4. We can express time from Eq. 3 to Eq. 5.

$$t = \left[\frac{(m+1)\bar{\varepsilon}^{cr}}{A(\bar{\sigma}^{n1}+B\bar{\sigma}^{n2}+C\bar{\sigma}^{n3})}\right]^{1/(m+1)} \quad (5)$$

After substituting t (Eq. 5) into Eq. 4 we get the equation for creep strain rate as a function of creep strain.

Subroutine CREEP request define by user equivalent (uniaxial) deviatoric creep strain increment $\Delta\varepsilon = \dot{\bar{\varepsilon}}^{cr}\Delta t$. After expressing we get Eq. 6.

$$\Delta\bar{\varepsilon}^{cr} = A(\bar{\sigma}^{n1} + B\bar{\sigma}^{n2} + C\bar{\sigma}^{n3})\left[\frac{(m+1)\bar{\varepsilon}^{cr}}{A(\bar{\sigma}^{n1}+B\bar{\sigma}^{n2}+C\bar{\sigma}^{n3})}\right]^{m/(m+1)} \Delta t \quad (6)$$

For implicit solution of creep (to able calculate long time loadings) we have to define partial derivation of equivalent (uniaxial) deviatoric creep strain increment by equivalent deviatoric stress (Eq. 7.).

$$\frac{\partial \Delta \bar{\varepsilon}^{cr}}{\partial \Delta \bar{\sigma}} = \frac{A\left(n1 \cdot \bar{\sigma}^{n1} + B \cdot n2 \cdot \bar{\sigma}^{n2} + C \cdot n3 \cdot \bar{\sigma}^{n3}\right)\left[\frac{(m+1)\bar{\varepsilon}^{cr}}{A\left(\bar{\sigma}^{n1} + B\bar{\sigma}^{n2} + C\bar{\sigma}^{n3}\right)}\right]^{m/(m+1)} \Delta t}{\bar{\sigma}(m+1)} \quad (7)$$

Partial derivation of equivalent (uniaxial) deviatoric creep strain increment by equivalent (uniaxial) deviatoric creep strain is express in Eq. (8.).

$$\frac{\partial \Delta \bar{\varepsilon}^{cr}}{\partial \bar{\varepsilon}^{cr}} = \frac{A \cdot m\left(\bar{\sigma}^{n1} + B\bar{\sigma}^{n2} + C\bar{\sigma}^{n3}\right)\left[\frac{(m+1)\bar{\varepsilon}^{cr}}{A\left(\bar{\sigma}^{n1} + B\bar{\sigma}^{n2} + C\bar{\sigma}^{n3}\right)}\right]^{m/(m+1)} \Delta t}{\bar{\varepsilon}^{cr} \cdot (m+1)} \quad (8)$$

The equation 6 – 8 was set to Abaqus subroutine CREEP. For temperatures below zero, the creep is negligible and only the plasticity is taken account.

For each user-defined temperature T_i constants were defined n_j kde j=1, 2, 3. For n_j, a logarithmic interpolation was used (Eq. 10); a linear interpolation was used between ranges of temperatures for A, B, C (Eq. 11 - 13).

$$\mathrm{Tratio}_i = \frac{T_i - T}{T_{i+1} - T_i} \quad (9)$$

$$n_j = n_{ij} + \mathrm{Tratio}_i \cdot (n_{ji+1} + n_{ji}) \quad (10)$$

$$A = \exp\left[\mathrm{LOG}(A_i) + \mathrm{Tratio}_i \cdot \left(\mathrm{LOG}(A_{i+1}) - \mathrm{LOG}(A_i)\right)\right] \quad (11)$$

$$B = \exp\left[\mathrm{LOG}(A_i B_i) + \mathrm{Tratio}_i \cdot \left(\mathrm{LOG}(A_{i+1} B_{i+1}) - \mathrm{LOG}(A_i B_i)\right)\right] / A \quad (12)$$

$$C = \exp\left[\mathrm{LOG}(A_i C_i) + \mathrm{Tratio}_i \cdot \left(\mathrm{LOG}(A_{i+1} C_{i+1}) - \mathrm{LOG}(A_i C_i)\right)\right] / A \quad (13)$$

Where index i – are values related to the temperature T_i,and index j is related to name of constants.

2.2 Creep measurement and constants of equations

To be able to fit seven materials constant, we have to prepare a suitable measurement of complex measurements on testing samples for a wide range temperatures and pressures.

Measurement was prepared for samples by EN ISO 527-2: type A1. Measurements were carried out with a Toyoseiki Creep Tester Cat. No. 259.

The load was realized by direct load, the temperature was maintained in a temperature chamber device with an accuracy of ± 1 °C. The actual measurements were performed at temperatures 23 °C, 60 °C and 80 °C.

Measurements were carried out at constant nominal stress levels (Table 1.) and maximum time was 140 h. Deformation was recorded with sampling period (1 s, 60 s, 600 s and 3600 s) depends at strain rate. The deformation was converted to graph creep strain – time for each temperature and stress. Setup of temperatures and stresses was in Table 2.

Table 2. Setup of creep measurement

Temperature [°C]	Set of nominal stress levels [MPa]		
23	0,5	3	6
60	0,5	2	4
80	0,5	1,5	2

2.3 Constants of creep equations

Constants for materials were fitted by a script in Octave program, where used the optimization function SAMIN (simulation of annealing). This robust optimization algorithm ensures a quick and reliable way for getting coefficients for material models. The obtained coefficients were checked by Abaqus solver through asimulation of the measurement test itself (Figure 5.).

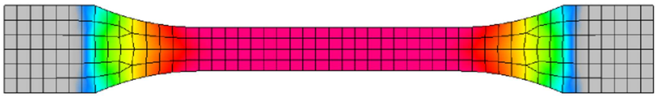


Figure 5. Mesh of sample for simulation of creep.

2.4 Comparison of Modified Power Law versus Power Law

To improve the original Power Law model of creep we used subroutine CREEP for Abaqus/Standard. We expanded the Power Law stress dependency – we added some terms, which improve fitting material model by results of measurement.

Figure 6Figure 6 shows dramatic improvements in correlation between measurement and simulation. The original Power Law isn't able to describe stress dependency for a wide range of temperatures – the behavior is only consistent with test for high temperatures and stresses.

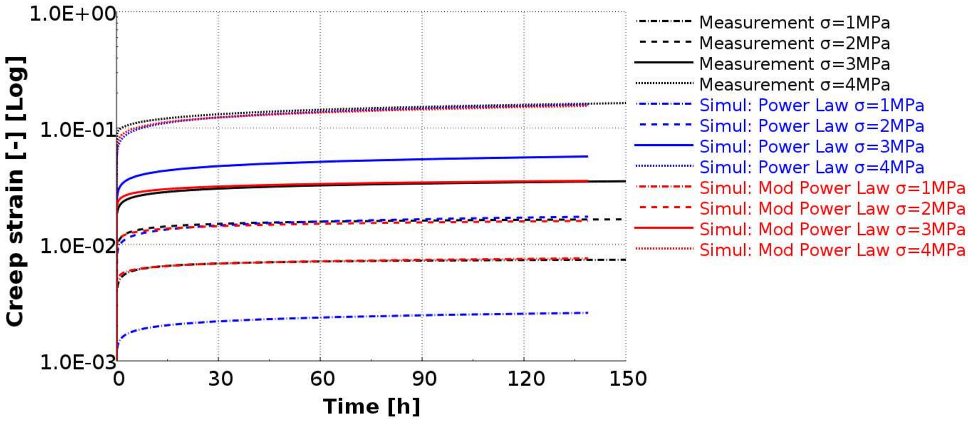


Figure 6. Curve creep strain – time for measurement, Power law model and Modified Power load.

In Table 3. we see comparison of differences between measurement and simulation of the uniaxial tension test.

Table 3. Correlation between Mod./Power law and measurement

Stress [MPa]	**Error - Power Law** [%]	**Error - Mod. Power Law** [%]
1	-65.0	3.0
2	5.7	-2.8
3	64.4	1.4
4	-1.8	-4.2

3. Method of simulation – model preparation

The accuracy of the simulation is not only defined by the accuracy of material model. Other significant influences to the accuracy of the model are the connections between parts and contacts between parts. The most common instances are:

- snaps
- rivets
- bolts – screw and nut

3.1 Snaps - Model of connections

The snaps are the most frequently used entities for connecting two plastic parts – an example of the snap is shown below (Figure 7.). It is not possible to prepare a detailed model for each snap, because there are lots of snaps in the model and there are limits of elements length. So we use a substitution of the detailed mesh – three CONNECTOR elements for each snap. This way how we can describe the kinematics of behavior of a snap – we define three translation gaps including three rotation gaps. The solution is a compromise between accuracy, solver time and time for preparing the model. The gaps, which are defined by connectors, are measured from CAD with accuracy 0.1 mm, thus eliminating inaccuracy of the mesh. When we model the snap as a rigid constraint, we aren't able to get accurate results as with the model as a snap connection

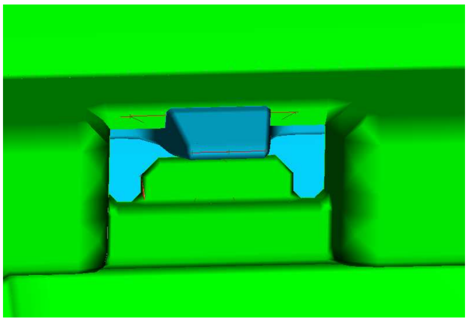


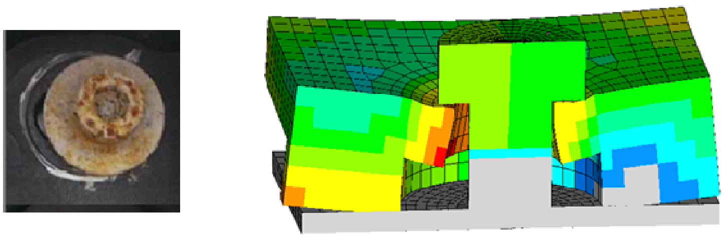
Figure 7. CAD of snap.

3.2 Rivet Snaps - Model of connections

To model a rivet we use one element CONNECTOR with one free axial rotation; it is possible also include gaps in two transactions directions.

3.3 Bolt - Model of connections

At first view, it seems to reliable to model bolt connections as rigid constraints. But results of physical test shows that plastic parts below the steel bold are quite soft. For some cases the plastic parts slip below the head screw (Figure 8.).



a) b)

Figure 8. Deformation of plastic parts below head of screw a, test b, simulation.

In the case of temperature cyclic loading, the initial screw pretension can be around 1500 N (~ 1.5 Nm) and may fall during cyclic loading to approximately 290 N – Figure 9. The surfaces below the head are locally deformed at higher temperature. This leads to rapid falling axial forces and possibilities of sliding connections parts – Figure 8.

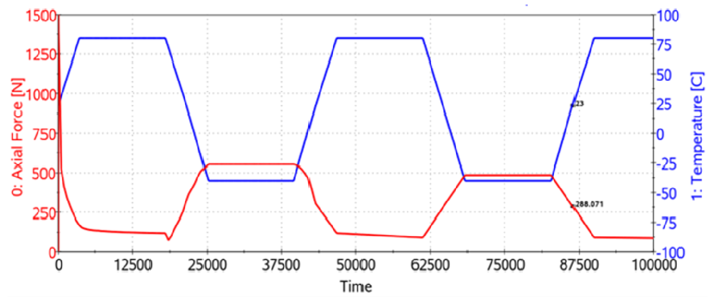


Figure 9. Axial screw force at temperature cycling.

For a more accurate model we need to mesh the area in contact with the bolt with solid elements – this is difficult from a work-flow point of view for preparing the model. The second disadvantage of the accurate bolt model is that we haven't accuracy values of friction (and associated dependencies). A third disadvantage is the added risk of slow convergence of the solver.
We are testing a simplification of the bolt model – body of screw is meshed by element BEAM, and heads by rigid elements; origin SHELL elements are slightly modified to improved behavior.

4. Methodic of simulation – results evaluation

4.1 Residual deformation

The main value of results is evaluated – residual displacement – the displacement after test at room temperature. The second value which should be evaluated is the change of gaps between parts. The evaluation of this is not easy. We prepared a special script to the postprocessor META, which automatically generates these figures – define dependency of change gap between two parts after test on edge length (for example Figure 10.).

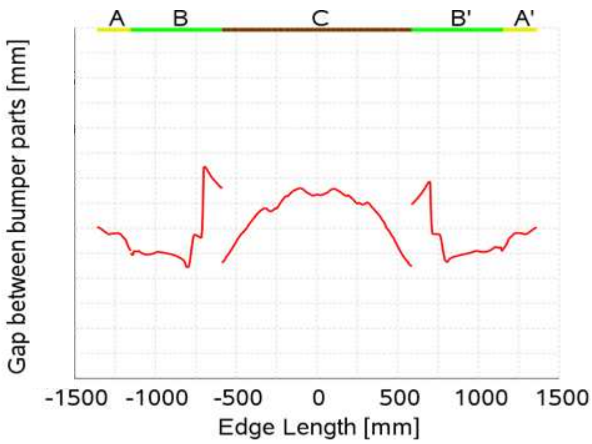


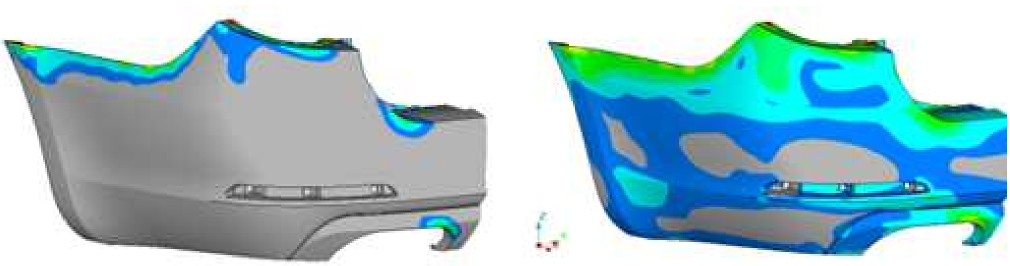
Figure 10. Change of gaps between parts after test.

The process of preparing of measure change of gaps between parts after test is following:

- The way of defining of the value of change of gaps is following – the gap before test minus the gap after test.
- We define two opposite sets of nodes which define the path of gaps and first node of path.
- For each node which defines a measured edge, we define a unified coordinate system which determines the local orientation of gaps – a normal and two tangent directions. For our purposes it is most important to measure the gaps in the normal.
- We calculate the change of gaps between the parts after test. This is done by calculating the differences of vectors length between corresponding nodes at the beginning and at the end of the simulation. We obtain the vector change of gaps which we decompose to the local coordinate system of the node. For visualization we use the normal direction of the coordinate system.

4.2 Creep strain – influence of model improvements (Modified Power Law)

In Figure 11 we see the difference due to different choices of the material model. With the Modified Power model we can get quite different (and more accurate) results. The creep strain has influence on the residual displacement.



a) Power Law material model a) Modified Power Law material

Figure 11. Creep strain - bumper after 24 h at 40°C.

5. Conclusion

This paper describes some important aspects of temperature mechanical simulation of the plastic parts. The choice of material model is very important – we described the Modified Power Law creep model which dramatically improves accuracy of fitting results to sample measurements and ultimately improves the accuracy of the simulation.

We also discuss another critical topic of simulation – modeling of connections. This has strong influence on the accuracy of results. There still remain some areas for further improvements, particularly in the simulation of pretension bolt connections.

6. References

1. http://www.me.umn.edu/labs/composites/Projects/Polymer%20Heat%20Exchanger/Creep%20description.pdf