

The Pressure and Temperature Dependent Creep Behavior Modeling of an Automotive Instrument Panel Material

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Abstract: The automotive instrument panel is usually constructed with several kinds of polymer materials. Two major roles of the instrument panel are i) holding the instruments, such as velocity meter, tacometer, and control knobs, etc. and ii) protecting driver and passenger from the critical injury from secondary impact in crash. The thermal creep properties of a polymer are the keys for maintaining the shape through the thermal cycles, and the rate-dependencies and energy absorption characteristics are the keys for the crash performance. The creep behavior of a polymer is the main concern of this paper. It is well known that the polymer materials creep under thermal cycles, and the creep responses of the polymers to the tensile and compressive loadings are different. Hyundai MOBIS (MOBIS), Dassault Systèmes Simulia Corp. Great Lakes Region (SGL), and Axel Products, Inc. (Axel Products) performed the creep tests for PPF (filled polypropylene) material. The creep tests were performed for both the tensile and compressive directions in order to capture the pressure dependence of the creep behavior. Each set of tension and compression tests were performed at several different temperature levels. The pressure and temperature dependent creep behavior was modeled with the Drucker-Prager type creep model by using the CREEP user subroutine in Abaqus. The entire tests showed relatively good repeatability and the developed material model with the power law Drucker-Prager type creep model showed good correlation with test data.

Keywords: Instrument Panel, Polymer, Creep, Tensile and Compressive Creep Test, User Subroutine

1. Introduction

It is well known that the polymer materials creep under thermal cycles, and the creep responses of the plastics to the tensile and compressive loadings are different (Ariyama and Kaneko, 1995; Takahara *et al.*, 2001; Kolarik *et al.*, 2002; Sanomura, 2003). The default creep model in Abaqus is suitable for metallic materials (Dassault Systèmes Simulia Corp., 2008). However, these default models in Abaqus cannot capture the tension and compression creep difference, which is very important in the polymer material. Therefore, we need to use the user subroutine 'CREEP' to define the creep model that can exhibit different creep in the tensile and compressive states.

The modeling of the well known pressure and temperature dependent plasticity and creep behaviors of the polymer material was introduced in this paper. The polymer material was tested and calibrated to complete the material modeling for the Abaqus simulation. Three types of tests; (i) thermal expansion, (ii) tension/compression property tests (elasto-plastic), and (iii) tension/compression creep tests, were performed. The thermal expansion test was performed in the temperature range which covers the operational temperature of the instrument panel. The tension and compression property tests were performed at six different temperature levels, and the tension and compression creep tests were at four temperature levels. Both the property and creep tests were done in the iso-thermal conditions. The details of the tests are described in Chapter 2.

The thermal expansion of the polymer material was modeled with the temperature dependent isotropic thermal expansion coefficient. The elastic properties were modeled with the linear elasticity. The field variable dependent plasticity model (`*PLASTIC, DEPENDENCIES=1`) was used to calibrate the plasticity of the material. The creep behavior was modeled with '`*CREEP, LAW=USER`' option by using two kinds of popular creep laws, the time hardening form of the Power law and the Singh-Mitchell law with respect to the equivalent creep stress. The details of the material modeling are described in Chapter 3.

In addition to the material model and the user subroutines, we developed the material parameter calibration process for the ease of material parameter extraction.

2. Test

For the complete material modeling of a polymer, the following tests were performed:

- The thermal expansion tests in the operation temperature range.
- The tension/compression property tests at various temperatures ($T1 \sim T6$).
- The tension/compression creep tests at several temperatures ($TC1 \sim TC4$) and creep stress levels (Stress1, Stress2, Stress3).

The temperature levels for the property tests have a relation $T1 < T2 < T3 < T4 < T5 < T6$. The temperature levels for the creep tests have a relation $TC1 < TC2 < TC3 < TC4$ and the creep stress levels have a relation $Stress1 < Stress2 < Stress3$. The dog-bone (ASTM D 638 Type I, for tension tests) and circular disc specimens shown in Figure 1 were used. Smaller disc shape specimens were used for the thermal expansion tests and the bigger disc shape specimens were used for the compressive tests.

2.1 Thermal expansion tests

The thermal expansion was measured with the test set-up as shown in Figure 2. The temperature was controlled by the pre-programmed heater and a negligibly small force was maintained same through-out the test by the closed loop feedback control.

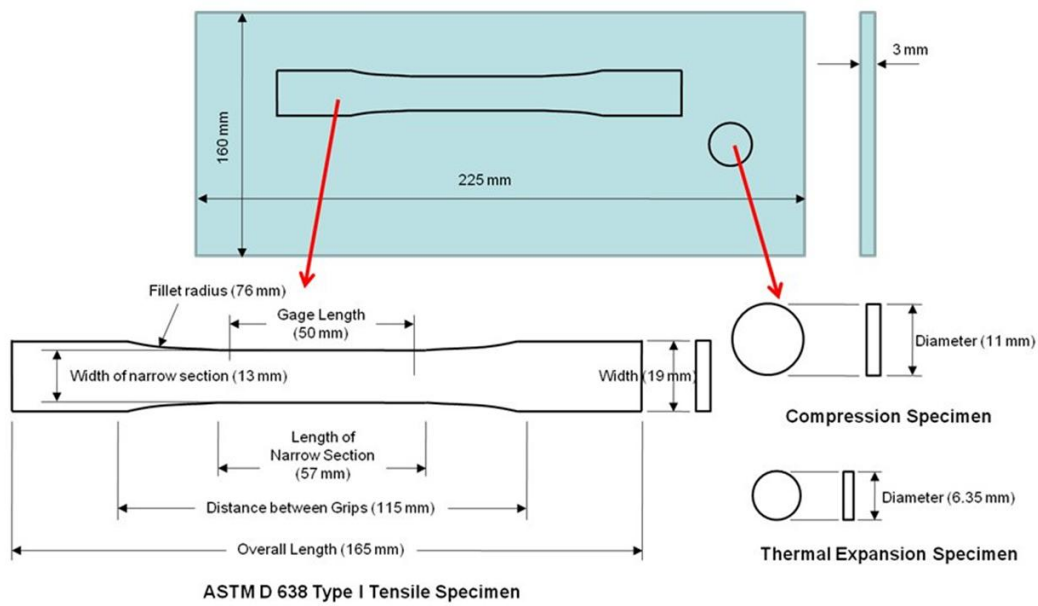


Figure 1. The shape and dimension of test specimens.

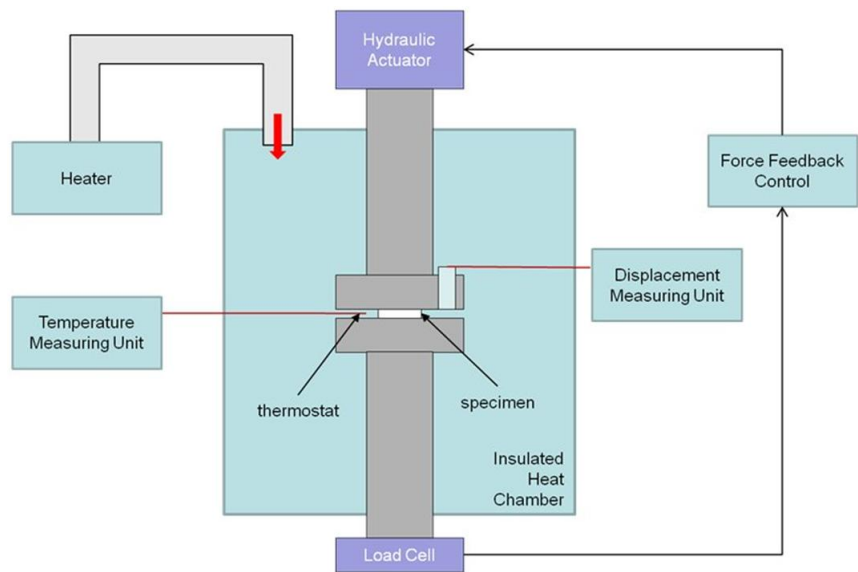


Figure 2. A schematic of the thermal expansion tests.

2.2 Tension and compression property tests

The tensile and compressive properties of a polymer material were measured with test set-up shown in Figure 3 and Figure 4 at 6 different temperatures. The specimen temperature was controlled by the feedback control of a temperature measuring unit and a heater. The data measurements were started after the specified temperature was stabilized.

We measured the tensile (vertical direction in Figure 3) elongation with extensometer (green color) and the lateral (horizontal direction) elongation with yellow colored extensometer. The ratio of these deformations to two different directions gives the in-plane Poisson's ratio.

We gathered the tension and compression measures (nominal stress – nominal strain), then converted to the true stress and strain for the elasto-plastic material model calibration.

Figure 5 compares these two types of stress and strain measures. We can see that the 'true' measure conversion increased the stress values so that the absolute value of compressive yield stress was decreased and the tensile value was increased.

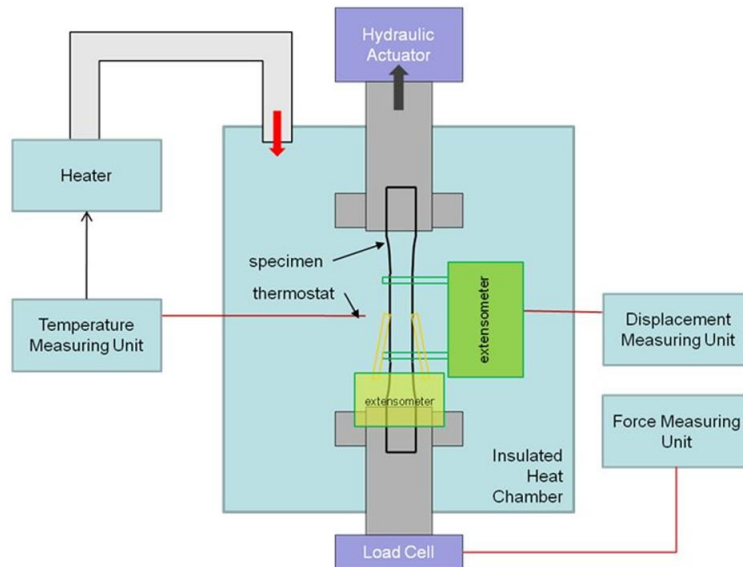


Figure 3. A schematic of the tensile property test set-up.

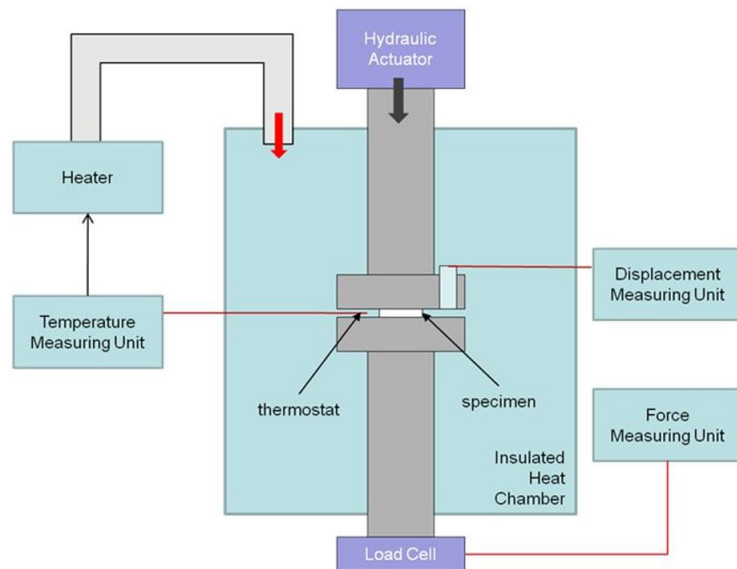


Figure 4. A schematic of the compressive property test set-up.

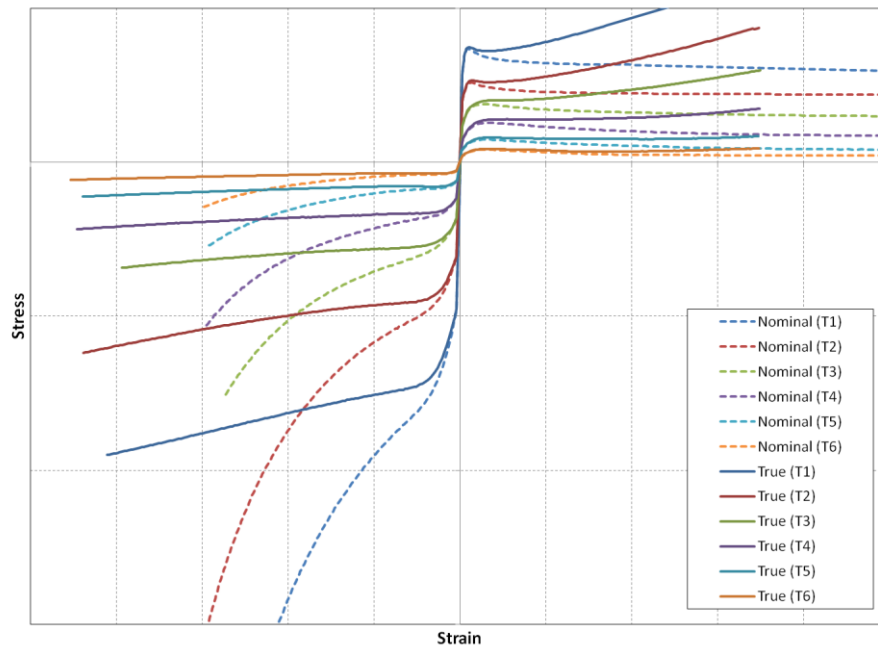


Figure 5. Stress – strain comparison (engineering vs. true measures).

2.3 Tension and compression creep tests

The tension and compression creep tests used the similar test set-ups as the tension/compression property tests (tension creep: Figure 6, compression creep: Figure 7). The difference between the property and the creep test set-ups is the existence of the force feedback control. The force was controlled to maintain the stress during the creep test. This constant stress is the equivalent creep stress, and the stress levels used for the tests were different at each temperature to produce measurable creep displacements.

Figure 8 shows the tension and compression creep test results at temperature TC1. Even though all test data showed good specimen to specimen repeatability and the quality of the test data looked fine for the material calibration, there are inconsistencies between the tension and compression creep test data. The compressive creep (hollow circle) is less than the tensile creep (filled circle) at stress level Stress3. However, the compressive creeps (hollow diamond and square) at the stress levels Stress1 and Stress2 are larger than the corresponding tensile creeps (filled diamond and square). It is well known that the polymer materials behave stronger in the compressive direction than tension (Ariyama *et al.*, 1995; Sanomura, 2003), those are high yield and low creep.

The tensile creep was measured in the in-plane direction (see Figure 1) and the compressive creep was measured in the out-of-plane (thickness) direction of the molded polymer plates. From these observations and facts, we can claim that there may be some problem with the compressive creep test set-up or a certain degree of directional dependencies due to the injection molding.

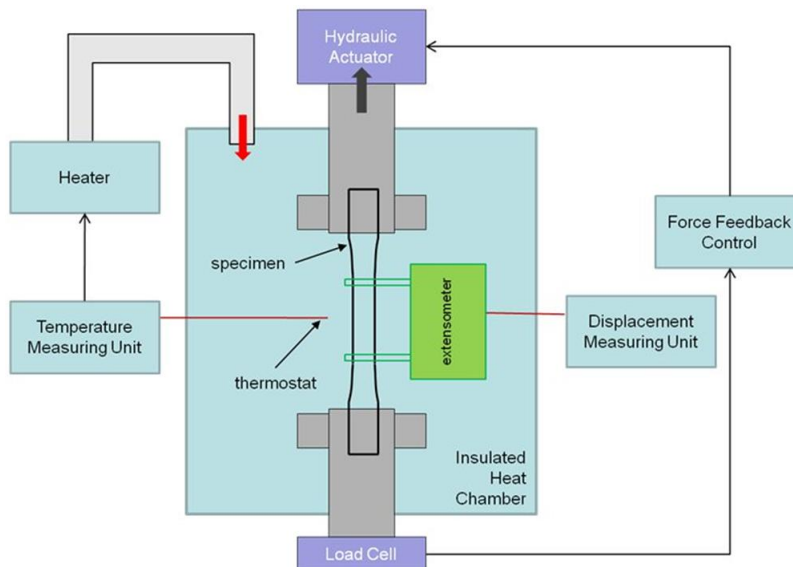


Figure 6. A schematic of the tension creep test set-up.

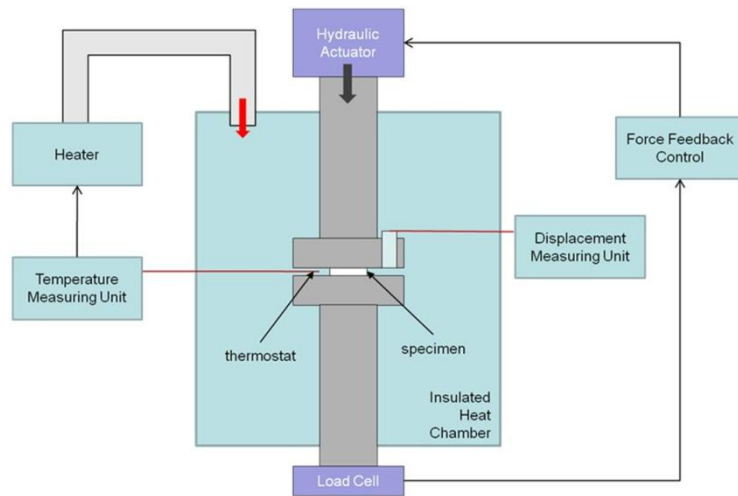


Figure 7. A schematic of the compression creep (out-of-plane direction) test set-up.

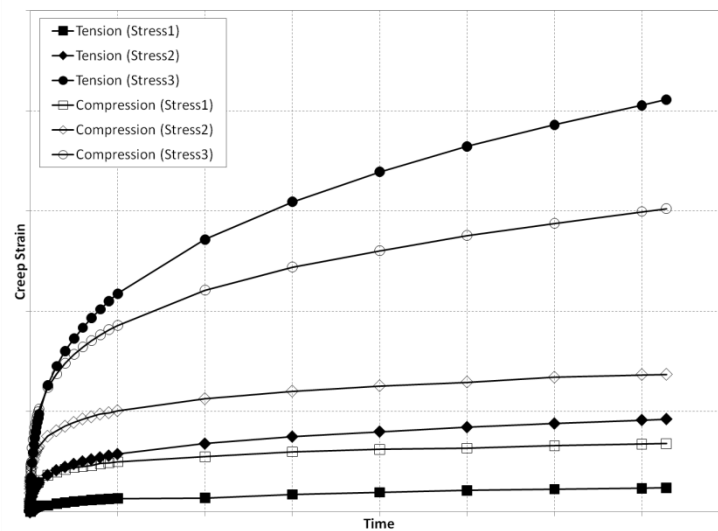


Figure 8. Tension and compression (out-of-plane) creep test data at one temperature TC1.

We measured the in-plane compressive creep with a test set-up shown in Figure 9 to remove any directional dependency issue. Since the fabrication of the compressive specimen through the in-plane direction is almost impossible, we decided to use the dog-bone specimen and modify the compressive creep test apparatus to exclude the buckling issue. Two circular shafts and bearings were used to stabilize the specimen during the compression of a dog-bone shape specimen to the in-plane direction.

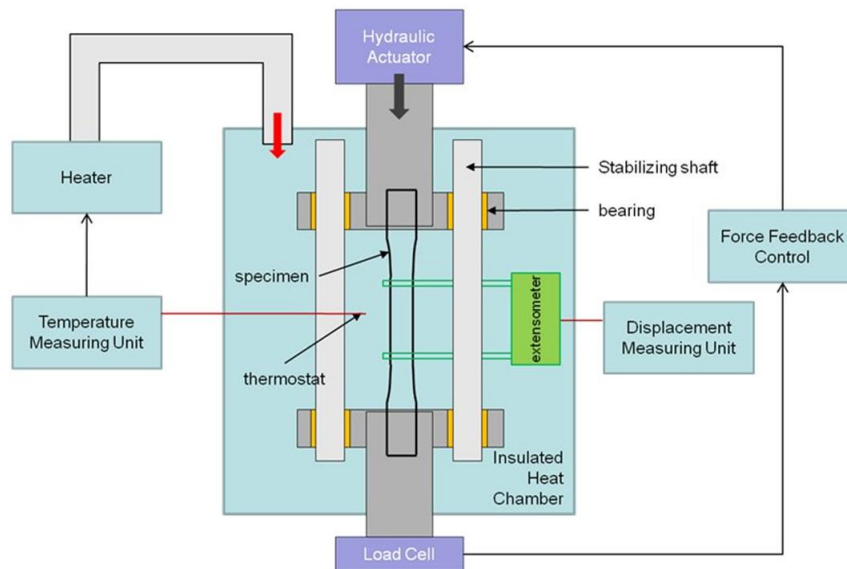


Figure 9. A schematic of the in-plane compressive creep test set-up.

The tensile and in-plane compressive creep test data are shown in Figure 10. We can see that the data shows good consistency. We used these data for the creep material calibration.

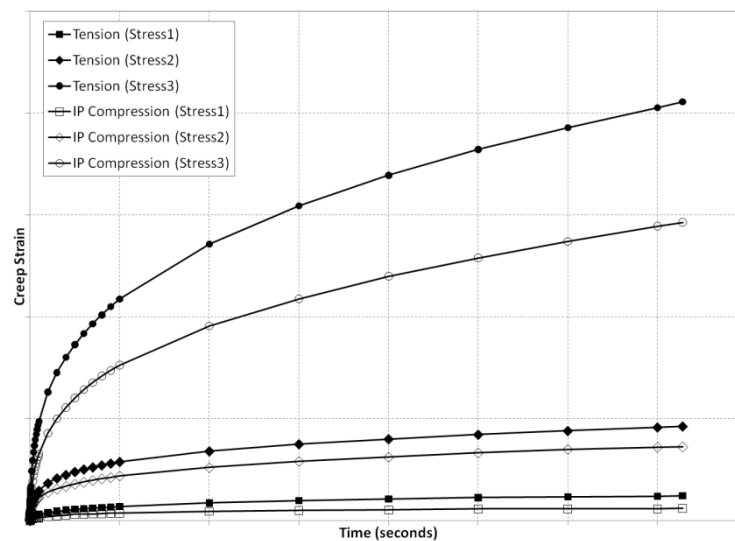


Figure 10. Tension and compression (in-plane) creep test data at temperature T1.

3. Material Model

The complete material model was constructed with:

- The temperature dependent coefficient of thermal expansion
- The temperature dependent elasticity
- The temperature and pressure dependent plasticity
- The temperature and pressure dependent creep

3.1 The coefficient of thermal expansion

The thermal expansion of a polymer material was modeled with the temperature dependent isotropic coefficients of thermal expansion (CTE). The temperature dependent CTEs were calibrated with the thermal expansion test data.

Figure 11 illustrates the definition of CTE used in Abaqus. The slopes of red lines (α_1 and α_2 , not α'_1 and α'_2) are the CTE values Abaqus interprets. So, CTE in Abaqus is the ratio of the thermal expansion with respect to the zero temperature (θ^0).

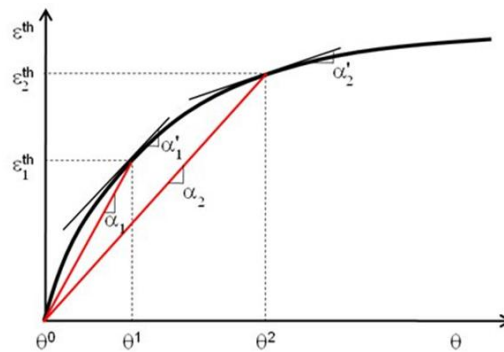


Figure 11. Definition of the coefficients of thermal expansion.

3.2 The elasticity modeling

The temperature dependent elastic moduli of the material model can be calibrated by extracting the initial constant slopes of the tension property test results. The temperature dependent Poisson's ratio values were also retrieved from the tension property test data.

3.3 The plasticity modeling

The plasticity of a target material was modeled with the field variable dependent plasticity in Abaqus. The field variable value (0 for compression and 1 for tension) is determined by the

solution dependent pressure during the Abaqus simulation at each material point. This method exhibits pressure-dependent yield (the material becomes stronger as the pressure increases).

The measured tension and compression property test data (nominal stress and strain) was converted to the true stress and strain data and the absolute values are shown in Figure 12. The absolute values of the compressive stress and strain were shown in the figure for the comparison with the tension data. The compressive yield stress is higher than that of the tensile yield stress at all temperatures except T6, which is the highest. The difference between the tensile and compressive yield stresses is decreasing as temperature increases (from T1 to T6).

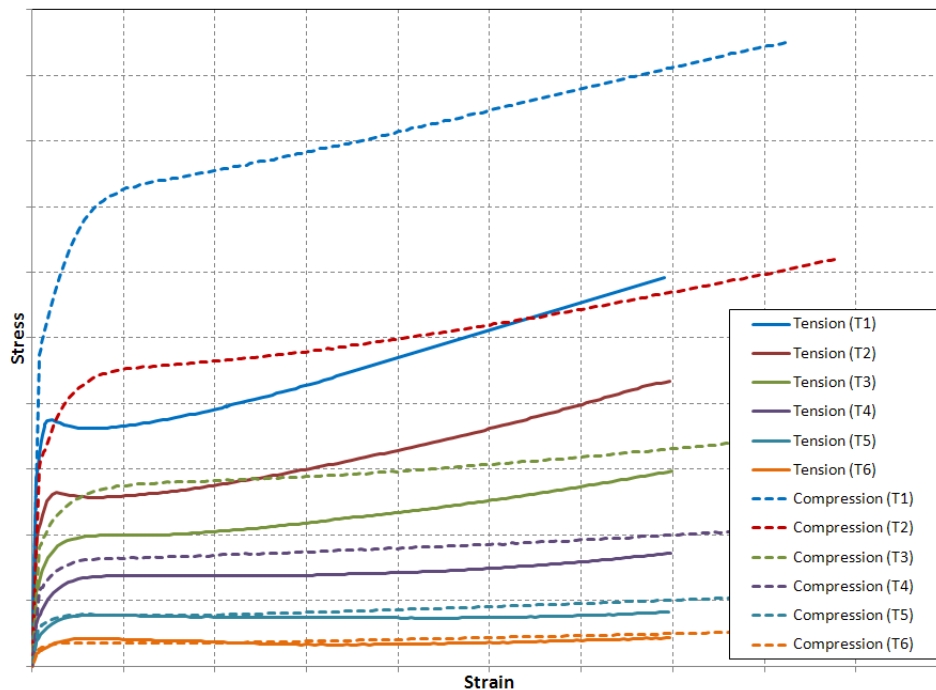


Figure 12. Tension and compression plasticity data.

3.4 The creep modeling

Since the `*Plastic` was used to define the temperature and pressure dependent plasticity of a material, we need to use `*Creep` for the creep material modeling. The default creep model of `*Creep` does not exhibit the pressure dependency so that it is not adequate to model the creep of a polymer material. We used a CREEP user subroutine to model the pressure dependent creep with Drucker-Prager type creep model.

While the default creep model uses a deviatoric stress as a creep stress, Drucker-Prager type creep model uses an equivalent creep stress as:

$$\bar{\sigma}^{cr} = \frac{q - p \tan \beta}{1 - \frac{1}{3} \tan \beta} \quad \text{if creep is defined with the uniaxial compressive stress}$$

$$\bar{\sigma}^{cr} = \frac{q - p \tan \beta}{1 + \frac{1}{3} \tan \beta} \quad \text{if creep is defined with the uniaxial tension stress}$$

where $\bar{\sigma}^{cr}$ is the equivalent creep stress, q is the deviatoric stress, p is the pressure, and β is the friction angle of a material. The equivalent creep stress is calculated in 'CREEP' user subroutine with q and p , which are passed in to the user subroutine as solution dependent variables, and the friction angle, β , of a tested material by fitting the plasticity data (true measures of Figure 5) with the linear or hyperbolic Drucker-Prager plasticity (Dassault Systèmes Simulia Corp., 2008).

There are two widely used creep laws, the power law and Singh-Mitchell law, where the equivalent creep strain rate can be expressed as:

$$\frac{\dot{\epsilon}^{cr}}{\epsilon} = A (\bar{\sigma}^{cr})^n t^m \quad \rightarrow \text{Power law}$$

and

$$\frac{\dot{\epsilon}^{cr}}{\epsilon} = A e^{(\alpha \bar{\sigma}^{cr})} (t_1/t)^m \quad \rightarrow \text{Singh-Mitchell law}$$

where $\frac{\dot{\epsilon}^{cr}}{\epsilon}$ is the equivalent creep strain rate, t is the total time, A , n , and m are material parameters for the Power law, and A , α , t_1 , and m are material parameters for the Singh-Mitchell law. For physically reasonable behavior, there are the following restrictions on the material parameters:

- A and m must be positive and $-1 < m \leq 0$ (Power law)
- A and α must be positive, $0 < m \leq 1$, and t_1 should be small compared to the total time (Singh-Mitchell law)

The parameter n of the Power law is the exponent of the equivalent creep stress, $\bar{\sigma}^{cr}$ (see the equation for the Power law equivalent creep strain rate). So, we can extract the parameter n by curve-fitting the long term creep strains to the equivalent creep stress relation with the power function. Then the parameters A and m were calculated by fitting the test data with the Power law equation. The parameters of Singh-Mitchell law were also extracted in a similar way.

The CREEP user subroutines for both Power and Singh-Mitchell laws were developed with the material parameters. The developed user subroutine calculates the creep strain at each time

increments explicitly with the solution dependent variables, such as the deviatoric stress, pressure, and temperature, and the material parameters, such as the creep coefficients and the friction angle of the material.

3.5 Abaqus usage

The developed material model and extracted parameters were used with Abaqus input as:

```

*MATERIAL, NAME=PLASTIC1
*DENSITY
Material_density
*EXPANSION
CTE1, T1
.....
CTE6, T6
*ELASTIC
Modulus1, Poisson1, T1
.....
Modulus6, Poisson6, T6
*PLASTIC, DEPENDENCIES=1
YieldC1, Plastic_strainC1, T1, 0
.....
YieldC6, Plastic_strianC6, T6, 0
YieldT1, Plastic_strainT1, T1, 1
.....
YieldT6, Plastic_strianT6, T6, 1
*CREEP, LAW=USER

```

→ Temperature dependent CTE

→ Temperature dependent elastic properties

→ Pressure and temperature dependent plasticity
Field variable (0 or 1) is specified by USDFLD

→ User-defined creep calculated by CREEP

The field variable required for the plasticity definition was calculated by USDFLD user subroutine and the creep strain calculation was performed by CREEP user subroutine.

4. Correlation and Application

The validation of the developed material model and extracted parameters was performed by using a one-element model. Figure 13 shows the correlation of the Abaqus simulations (red lines) with developed material model and user subroutines to the test data (black lines) at temperature TC4. The lines with filled markers are for the tensile creep and the lines with hollow markers are for the compressive creep. The labels 'Tens1,' 'Tens2,' and 'Tens3' represent the tensile creep stresses and 'Comp1,' 'Comp2,' and 'Comp3' represent the compressive creep stresses

($|Tens1| = |Tens1|$, $|Tens2| = |Comp2|$, $|Tens3| = |Comp3|$). As shown in the figure, the correlation of the developed model is very good. The Singh-Mitchell model was also tested, but the Power law showed better correlation.

We applied the developed modeling technique to the simple cantilever beam model shown in Figure 14. One end of the beam was fixed and the small force (F) was applied in the reference point of the kinematic coupling (connects the reference point and the small square region). Both shell and solid (4 layers through thickness) elements were used in order to demonstrate the element availability, and the room and high temperatures were used as the temperature conditions.

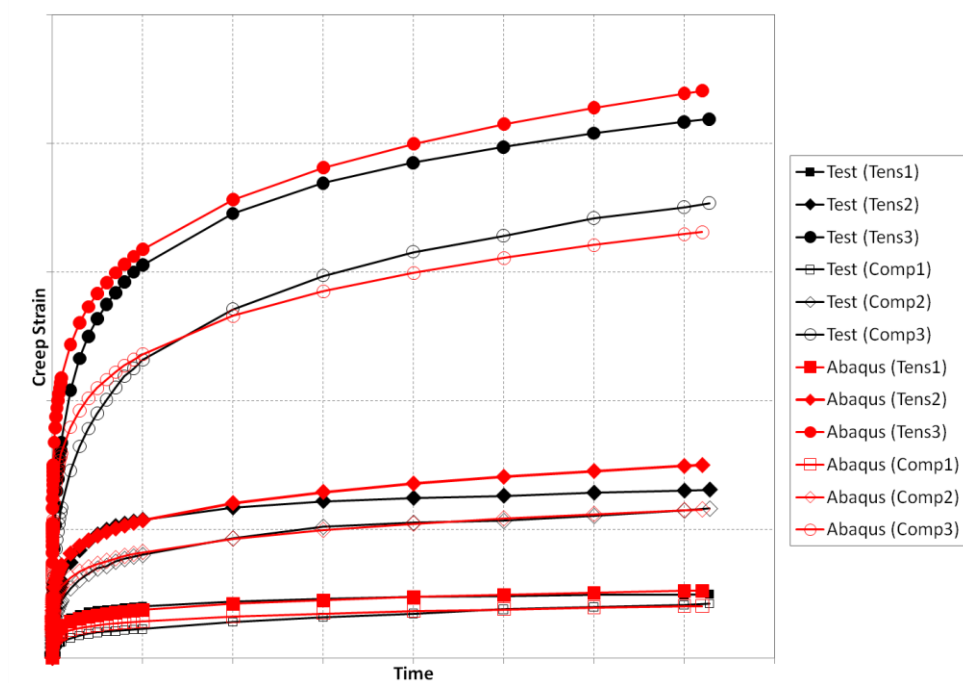


Figure 13. Correlation of the creep model (TC4 temperature).

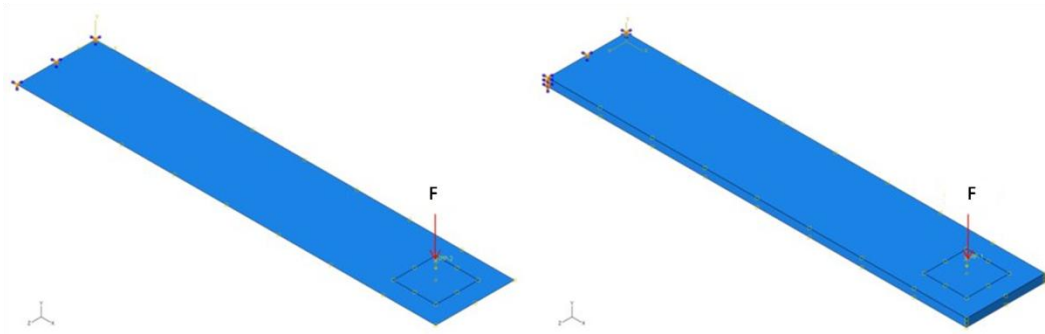


Figure 14. Simple cantilever beam model (shell and solid elements).

The creep analysis results of the simple model are shown in Figure 15. We can see that the shell model predicts more creep than the solid model at both room and high temperatures. So, the shell element is good for modeling plate-like part. The early time creep at high temperature is more rapid than at room temperature, which is physically reasonable.

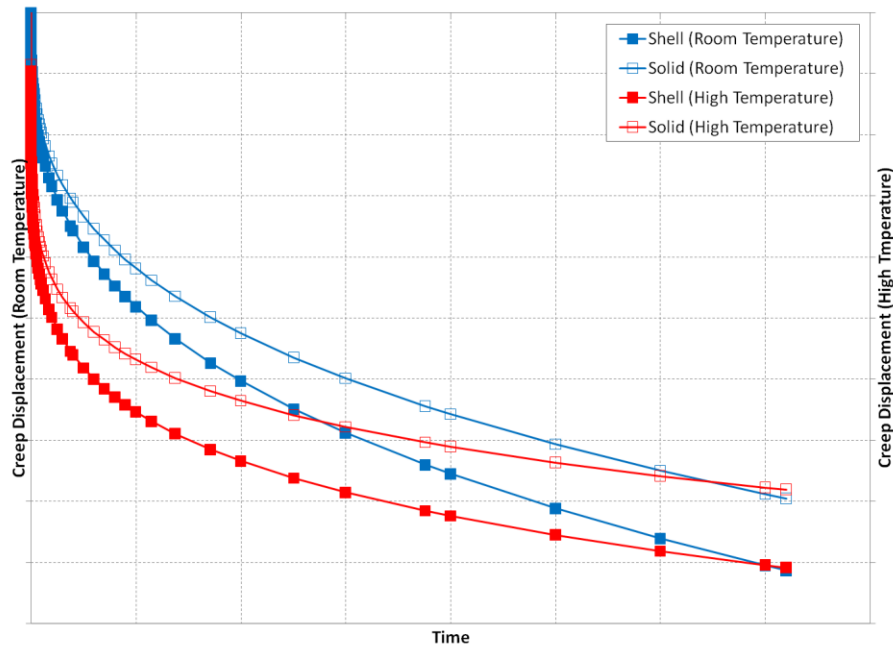


Figure 15. Simple cantilever beam creep analysis results.

5. Conclusions

The polymer material, which is widely used for the instrument panel, was modeled with pressure and temperature dependent plasticity and creep. The main focus was the definition of the pressure and temperature dependent creep behavior. To complete the material definition and modeling, three types of test listed in Chapter 2 were performed and the Abaqus material model was calibrated. The pressure and temperature dependent plasticity with Drucker-Prager type creep model was calibrated, and the related Excel spreadsheets for the material parameter extraction were developed. Both the power law and Singh-Mitchell law creep models were calibrated and coded with the CREEP user subroutine.

Test results showed good repeatability, and the Abaqus material model calibration results showed good correlation. The power law model showed better correlation for a target polymer material than the Singh-Mitchell law.

6. Acknowledgment

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7. References

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