RESEARCH ARTICLE

Prediction of Long-Term Behavior for Dynamically Loaded TPU

Robert Eberlein[1,*], **Lucian Pasieka**[2]

[1]Institute of Mechanical Systems, Zurich University of Applied Sciences, Winterthur, Switzerland
[2]Eugen Seitz AG, Wetzikon, Switzerland

*Corresponding author: E-mail: ebei@zhaw.ch

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Thermoplastic polyurethanes (TPU) are often subject to highly dynamic loading conditions in engineering applications. Due to their robust mechanical properties, TPU materials form an excellent fit for dynamically loaded system components in many cases. However, for dynamically loaded TPU the long-term material behavior is of special interest, since TPU shows distinct creep, as generally observed in polymers. This article illustrates a rather simple but efficient and consistent method for predicting the long-term material behavior of a selected TPU grade under uniaxial dynamic loading conditions. The research arises from practical challenges of design engineers. These are often confronted with lifetime quantification issues of critical components, e.g. in a mechanical damping element under cyclic loading conditions, for which a permissible deformation may not be exceeded. In those cases the transient stress-strain behavior of the material is of special interest. As will be shown an important prerequisite for the derivation of a reliable material model is the acquisition of relevant creep data for the respective TPU material. In a second step, the creep data is extrapolated in time by employing a suitable method resulting in a time-dependent stress relaxation modulus function. Parallel Maxwell models expressed by Prony parameters yield the rheological properties of this function. Due to their derivation, these Prony parameters represent quasi-static material response. Nevertheless, by employing a novel dynamic-static loading analogy the Prony parameters form the basis for TPU lifetime prediction under uniaxial dynamic loading conditions. By comparing numerical FE results for a damper with experimental results from an endurance test, the proposed modeling concept demonstrates its validity.

Introduction

For polymer components, also including TPU, long-term material assessments are important for predicting product lifetime. Today qualified FE analyses are widely used to perform those assessments. In order to retrieve realistic results from the numerical investigations, it is necessary to provide suitable material models, which allow reliable statements on the long-term behavior in a polymer material. If subjected to dynamic or cyclic loading conditions, the lifetime prediction becomes even more demanding compared with purely static loading patterns. A first assessment of TPU materials under highly dynamic loading conditions was given in [**8**]. There the strain rate dependency of TPU materials was addressed and validated by means of two different modeling strategies. Based on the findings lifetime assessments of TPU components are a next logical step.

Starting point of the current research was developing a TPU damper component and predicting its dynamic creep deformation over a time span of minimum two years. Doing that the major scientific/technical challenge is the development of a suitable TPU material model accounting for the accumulated time dependent creep deformations of the damper under cyclic loading conditions. Creep in general describes a process where molecular chains of a (polymer) material stretch over time under constant loading conditions. It is therefore a quasi-static deformation process. For a recent account on microstructural changes of viscoelastic polymers, the interested reader may refer to [**12**]. The most important result of a creep test is the quantification of the time dependent elongation of a creep test specimen. A damper under cyclic loading conditions also faces creep deformations. The transfer of quasi-static creep test results into the dynamic (cyclic) creep response of a TPU damper forms a major subject of this paper. Only proper determination of dynamic creep response allows an accurate lifetime prediction of the discussed TPU damper system.

As an alternative, one could think about elaborate endurance tests for lifetime prediction. For cost reasons, however, this is not a realistic option in the product development process. Nowadays, it is simply too expensive to test various design iterations of e.g. TPU dampers under realistic operating loading conditions in the full time domain. The same already holds for pure material creep tests. Therefore, the aforementioned TPU material model must refer to experimental material data that can only cover a limited time span of the actual product lifetime. Consequently, one important subject of this paper is the extrapolation of experimental material data (quasi-static creep curves) to the expected lifetime of the damper. This correlates with the characterization of the long-term creep performance of polymers. There exist recent publications for a variety of thermoplastic materials exactly on this topic (refer to [**1**], [**9**] and [**10**]).

On top of that a suitable method is discussed how to utilize the measured creep curves for a damper under cyclic loading conditions. Because of that, the innovation content of the current article aims at the development of a material model accurately accounting for creep strains (called "creep material model" throughout this paper) that allows predicting the lifetime specific creep deformations of a TPU damper under uniaxial dynamic (cyclic) loading conditions. Finally, cross-validation demonstrates the validity of the proposed method. That means a separate validation test for the TPU damper proves the accuracy of the proposed creep material model that originates from quasi-static creep tests. By doing that, FE analyses employ the creep material model and account for the damper geometry as well as boundary conditions used in the validation test.

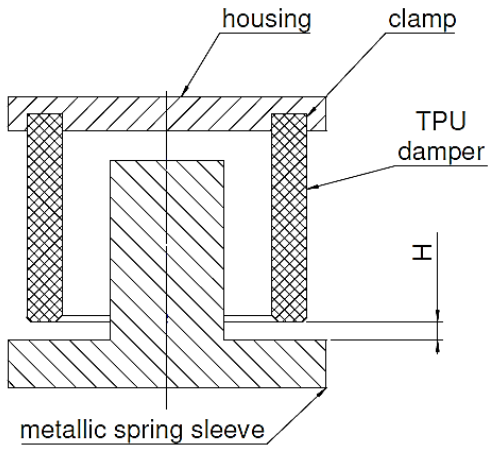
The creep material model itself only considers changes in the mechanical properties that occur within the permissible operating limits of the selected TPU material. In case of additional damaging effects, such as exceeding temperatures or media causing material damage, the proposed model is not valid. In those cases, dedicated experimental material tests need to address the influence of the damaging effects. Henceforth, the material model presented in this article is restricted to the admissible changes in the mechanical properties of TPU without irreversible damage.

Experimental

For the prediction of the TPU damper lifetime, the effectiveness of the creep material model is assessed via the cross-validation principle (test used for validation is different to these used for material model calibration, i.e. TPU material creep tests here). To achieve so, a dedicated test-bench is used to measure "implicitly" the creep behavior of the TPU under test (**Fig. 1**). In parallel, this test-bench system is modelled based on FE simulations that employ the aforementioned creep material model. Via comparing the simulated to the experimentally obtained counterparts, the validity of the proposed creep material model is demonstrated. As shown in the subsequent section, the minimum admissible distance x in between sleeve and housing sets the base for lifetime prediction of the TPU damper.

To execute a cyclic loading test on the test-bench, the TPU under test is firmly clamped at the housing with minor prestress in radial direction (**Fig. 1**). The metallic spring sleeve, while lying on its "starting position" [**Fig. 1 (a)**], is getting ejected towards the TPU under test by an activator force minus the force of an elastic spring which eventually pulls the sleeve back to its initial position after deactivation of the activator (also compare with **Fig. 5**). When the piston establishes contact with the TPU, there is a remaining gap between sleeve and housing. This gap shrinks over time due to the creep behavior of the TPU. On the other hand, the damping behavior of TPU is required to prevent metallic sleeve and housing parts from direct contact and eventually metal fatigue. Therefore, the minimum admissible distance x [**Fig. 1 (b)**] is a crucial value to safeguard lifetime of the underlying dynamically loaded damper system. Reaching the threshold value x over time means reaching the maximum lifetime of the TPU damper and the underlying system application.

a) Starting position



b) Contact position

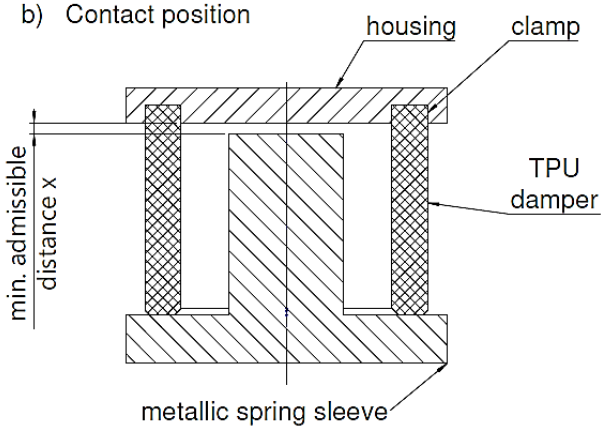


Fig. 1. Cross-sectional view of the test-bench for creep validation of the TPU under test: (a) Starting position: the metallic spring sleeve is about to be ejected towards the TPU damper; (b) Contact position: the lightweight metallic piston contacts the TPU under test; during contact the minimum admissible distance x in between sleeve and housing must be respected over time.

The sleeve, while moving: **Fig. 1 (a)** → **Fig. 1 (b)**, is monitored by a Polytec laser vibrometer. Due to this, the displacement and velocity of the sleeve (**Fig. 1**) are both measurable and readily available as acquired signals (both sampled at 100 kHz). The measured displacement of the sleeve during contact is an "implicit" expression of the TPU creep deformation behavior. Therefore, the comparison of the measured displacement with the FE-based simulated counterpart provides an independent high-level criterion to assess the ability of the underlying creep material model to capture the creep propagation of the TPU material over time and thus enables lifetime prediction of the TPU damper.

As mentioned before, the calibration of the TPU creep material model refers to quasi-static creep curves obtained from standard specimen (ISO 37 type 2). In order to account for dynamic loading conditions, the determination of an averaged stress state in the relevant component (i.e. the TPU damper) is crucial. The subsequent section shows the underlying procedure for calculating the averaged stress state. After calculating the averaged stress state, the creep test specimen is subject to a permanent force loading derived from this stress state. In particular, the force results by assuming a uniaxial homogeneous stress state in the creep test specimen.

All creep measurements were performed on a Coesfeld Tear and Fatigue Analyzer (TFA) at ZHAW. Besides quasi-static creep tests, the TFA allows to run dynamic fatigue, i.e. crack propagation measurements on elastomer-like polymers like TPU. It contains ten measuring stations in parallel with separate load cells. For creep tests, force controlled stepper-motors with a maximum load capacity of 500N are used. By using a control unit, the force on the specimen is held constant. The resulting strain is calculated by visual measurements of the clamp distances. This is done by a CCD video camera system mounted onto a motor driven sled outside the test-chamber (**Fig. 2**). The camera moves in lateral direction from sample to sample, each of which is mounted in front of a light screen.

Fig. 2. Creep test setup in TFA including CCD video camera system for measuring creep strains.

The TPU specimen were cut from die-casted plates according to ISO 37 type 2. After mounting the samples, the force per specimen was increased to 27 N and held constant for one week, resulting in a constant stress of approximately 3.5 MPa. The force of 27 N results from the so called equivalent static creep force that is introduced in the subsequent section. It ensures proper material loading during creep according to the TPU damper application. Measurements were taken at different temperatures between room temperature and +80°C. Three samples per temperature were tested and averaged. The time for each measurement was set to zero as soon as a force of 26.9N was reached during intial loading.

Results and discussion

This section presents a validated concept for lifetime prediction of a TPU damper system. For doing this, an accurate creep material model is a major prerequisite. As already explained above the time extrapolation of the measured creep curves is essential.

Time extrapolation of creep curves

The expected lifetime of the TPU damper system is minimum two years. In contrast to that, the measured creep curves cover a time span of approximately one week (effectively 166h) only as shown in **Fig. 3**. The chart depicts averaged creep strains over time for 30°C 40°C and 80°C, respectively. From this data, a time dependent stress relaxation modulus per temperature results by:

$$E(t) = \frac{\sigma(t)}{\varepsilon(t)} = \frac{\sigma = const.}{\varepsilon(t)}$$

The stress per specimen is nearly constant over time, since the reported strain values in **Fig. 3** remain rather small and therefore the cross-sectional areas per specimen remain unchanged. For time extrapolation of creep data only strains in the time range >100h are used. The reason for that is also visible in **Fig. 3**.

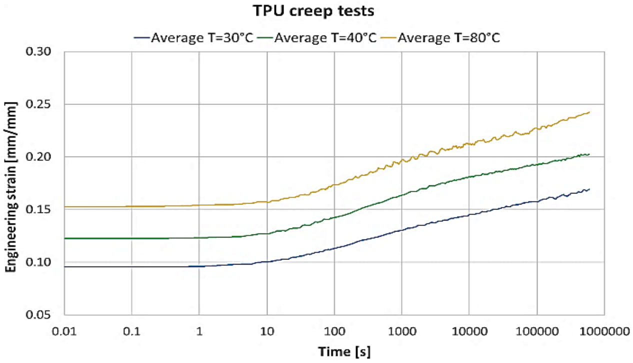


Fig. 3. Quasi-static creep curves for selected TPU.

The creep curves deviate significantly from a linear strain – log (time) relation for time points <100h. Based on that observation and as already reported in [7], only time points from the range >100h are under consideration for extrapolation according to:

$$\varepsilon(t) = a \cdot \log(t) + b$$
$$(3.6 \cdot 10^5 s \ < \ t \ < \ 5.94 \cdot 10^5 s)$$

This equation eventually yields the extrapolated curve for the stress relaxation modulus as depicted in **Fig. 4**. The function $E(t)$ results from the measured and extrapolated creep data at 60°C. A temperature of 60°C is equivalent to the operating temperature of the discussed TPU damper under cyclic loading conditions. In **Fig. 4** the extrapolation of the stress relaxation modulus function is shown up to about 31 years.

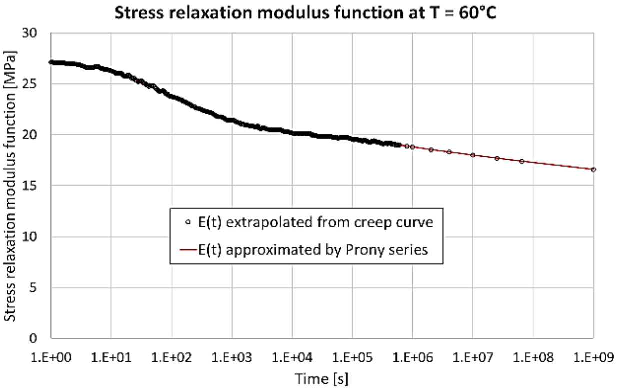


Fig. 4. Time **e**xtrapolated stress relaxation modulus function.

Physically, according to e.g. [**4**] parallel Maxwell models describe the stress relaxation modulus in the following form:

$$E(t) = E_0 \left[1 - \sum_{i=1}^{N} e_i \left\{ 1 - e^{-\frac{t}{\tau_i}} \right\} \right]$$

The underlying theoretical framework has been applied for years and the interested reader is referred to standard literature on the subject [**5, 6, 11**]. The previous equation defines the stress relaxation modulus function or alternatively, the Prony series relaxation modulus function. The Prony series parameters are given by e_i and τ_i, respectively. They can be numerically determined, e.g. through the software ViscoData (refer to [**3**] for a recent account on optimal discrete-time Prony series fitting). **Fig. 4** also depicts the approximation of the extrapolated stress relaxation modulus function $E(t)$ by 20 Prony series terms. The instantaneous modulus E_0 results from the equation $E_0 = \lim_{t \to 0} E(t)$. In the current case that means $E_0 = 27.2\ MPa$ (compare with **Fig. 4**).

Dynamic-static loading analogy

The previously discussed creep curves and extrapolated stress relaxation modulus functions represent quasi-static material response of TPU. The prediction of the long-term behavior of the TPU damper depends on cyclic loading patterns, though. **Fig. 5** illustrates the periodic loading function.

Distance H indicates the clearance in between metallic spring sleeve and TPU damper, compare with Fig. 1 (a). It is obvious that distance H increases with time due to accumulating creep deformations in the TPU damper. Distance D describes the damper deformation after impact. That means that H + D eventually determine the remaining gap in between metallic spring sleeve and housing. At any time, this gap must be larger than the minimum admissible distance x reported in Fig. 1 (b).

It is important to note that distance D remains unchanged over time. In fact, the loading pattern for the metallic spring sleeve reported in **Fig. 5** looks very similar at arbitrary loading times, except for a gradual increase of value H. That also means that the impact time t_{imp} does not depend on the amount of dynamic loading cycles, either. A simple reason for that are rather small creep deformations within the TPU damper, which keeps the impact velocity of the sleeve literally constant over time.

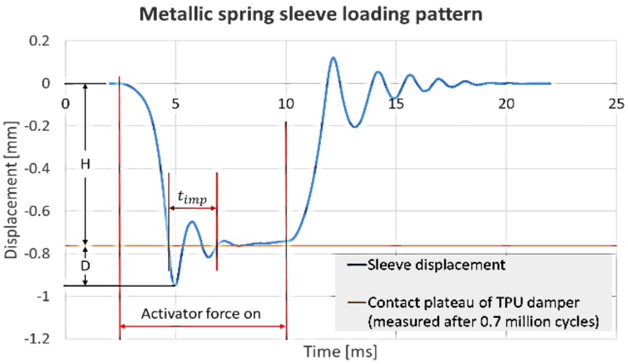


Fig. 5. Recurrent displacement pattern for metallic spring sleeve (period: 120ms).

A FE impact simulation (i.e. AC type simulation as discussed in [**8**]) of the TPU damper system yields the time dependent stress distribution in the sleeve-damper interface. Due to small strains, only stress components normal to the damper contact surface are considered. The normal stresses are averaged across the surface, multiplied by the cross-sectional area of the damper and are finally integrated in the time interval t_{imp} (see **Fig. 5**). This yields the linear momentum subjected to the TPU damper during impact.

The basic assumption of the dynamic-static loading analogy is that the linear momentum caused by impact loading is equally contained in a statically loaded TPU damper expressed by the creep material model presented above. The balance law of linear momentum states that in a rigid body the force acting on a body is equal to the time-derivative of its linear momentum (see [**4**] and [**14**] for further reference). During impact, various forces act simultaneously on the sleeve. Nevertheless, the dynamic contact forces are significantly larger than any other forces during impact (i.e. activator and elastic spring force moving the sleeve), which are therefore neglected. The rigid body assumption is also valid, because the metallic spring sleeve is orders of magnitude stiffer than the TPU damper. For this reason, a representative constant force acting on the TPU damper during creep (called "equivalent static creep force" throughout this paper) results from the linear momentum of the sleeve during impact divided by the constant time interval t_{imp}.

Lifetime prediction TPU damper

Applying the aforementioned dynamic-static loading analogy to a FE model of the TPU damper system yields a constant load acting via the sleeve on the damper. The creep deformation of the TPU damper in the time domain follows from the **e**xtrapolated stress relaxation modulus function $E(t)$ as basis for Prony parameters describing the creep material model. For the time independent response of the TPU damper, simple linear elastic material parameters are sufficient due to small strains. The elastic stiffness is given by the instantaneous Young's modulus $E_0 = 27.2\ MPa$ and the Poisson ratio is set to $\nu = 0.4$.

Fig. 6 represents the corresponding FE simulation results at 60°C. The solid blue line indicates the increase of the initial clearance H over time, i.e. creep deformation of the damper ΔH(t), whereas the dashed blue line depicts the sum of distances ΔH(t) + D. This line indicates the threshold value given by the minimum admissible distance x [**Fig. 1 (b)**] and defines the lifetime of the TPU damper system (projected lifetime).

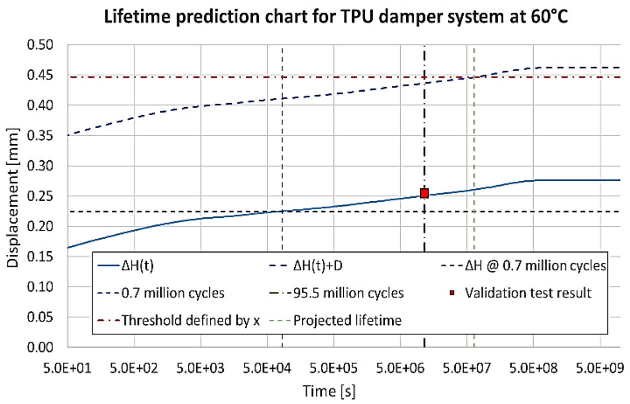


Fig. 6. Lifetime prediction chart for dynamically loaded TPU damper system.

In fact, the recurrent deformation pattern for the metallic spring sleeve shown in Fig. 5 results after 0.7 million loading cycles. As mentioned before the data from **Fig. 5** determines the equivalent static creep force acting on the sleeve. **Fig. 6** reports another measurement for ΔH after 95.5 million loading cycles (equivalent to $1.15 \cdot 10^7 s$ on the time axis). The measured value for ΔH and the quasi-static FE simulation correlate very well at this time point. In addition, the FE simulation quantifies the lifetime of the TPU damper system to $6.46 \cdot 10^7 s$ (two years) which corresponds to approximately 538 million loading cycles. The validation test was finished recently. The experimentally confirmed lifetime of the TPU damper system was about 520 million loading cycles, which is a very close match to the theoretical forecast. Indeed, the numerical error is just about 3.5%. That is a very good result for lifetime prediction of polymers.

Conclusion

The current paper demonstrates a simple but efficient scheme for lifetime prediction of TPU systems under uniaxial dynamic loading conditions. Lifetime predictions of FE simulations are in very good agreement with experimental findings. As described throughout the paper, the presented concept for the prediction of long-term behavior of TPU materials contains some limitations. It is only valid for applications with (a) rather small deformations combined with (b) uniaxial loading directions in compression. The concept would not work for arbitrary 3D loading patterns and large deformations. In those cases, the relevant contact interface for the dynamic-static loading analogy could change its spatial orientation during loading. That would be contradictory to some major assumptions made throughout this paper. On the other hand, varying impact velocities are within the scope of the presented concept. Then the impact time t_{imp} and consequently the resulting equivalent static creep force become time dependent. Therefore, a predefined time dependent impact velocity will directly yield a time dependent equivalent static creep force.

For many industrial applications, the presented concept is highly efficient due to its simplicity. The idea of extrapolating rather cheap material creep tests in time for lifetime prediction is quite innovative in combination with the presented dynamic-static loading analogy. This helps reducing product development costs significantly and boosts competitiveness by tremendously reducing time to market for many dynamically loaded products. The numerical results for the selected TPU damper system predict the findings of a validation test very favorably. That fact clearly proves the validity of the proposed concept. In addition, the concept is applicable to other polymers in exactly the same way as long as the underlying technical applications respect its limitations.

In future, various extensions or modifications of the presented concept for lifetime prediction of TPU components are under consideration. One example is creep failure time prediction for applications dominated by tensile loads (compare with [**2**] and [**13**] for recent accounts on the subject). In those cases, the aforementioned TFA forms a basis for quantifying crack propagation in damaged TPU materials under cyclic loading conditions and consequently the lifetime prediction in damaged TPU components.

Alternatively, there is an optimization potential for the damping behavior of the presented TPU damper system. Currently the sleeve reenters the damper during impact for a second time. This behavior can be smoothened in such a way that the impact time is increased, which at the same time will reduce the equivalent static creep force as presented throughout this paper. This measure can further increase the system lifetime and it is currently under investigation at the involved industrial partner.

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Author's contributions

Conceived the plan: RE, LP; Performed the expeirments: LP; Data analysis: RE, LP; Wrote the paper: RE, LP. Authors have no competing financial interests.

Keywords

TPU, creep, relaxation, lifetime prediction, system validation, FE simulation.

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