Analytical model for static and cyclic creep behaviour of PSAs

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Abstract

The increasing interest in the use of adhesives in the development of lighter and optimized structures raises design concerns on the durability of these materials, thus the importance of studying creep behaviour in adhesives. Pressure sensitive adhesives (PSAs) present some advantages over other adhesives as simplicity of handling and assembly of bonded joints without the need for curing processes since PSAs form bonds with the application of pressure for a short period of time. A unified phenomenological creep model, initially considered for polymer-bonded composite materials, was applied to PSAs to model creep behaviour. This model captures the three creep phases and can predict creep curves based on the temperature and applied stress [1]. Experimental data is used for determining the model parameters and validate the model.

Experimental details

Joint details

The specimens' geometry is presented in Figure 1. The material for the substrates was poly(methyl methacrylate) or acrylic, and the PSA used was a thin acrylic adhesive, having a Young's modulus of 0.45 MPa, a Poisson's ratio of 0.499, and a failure load of 78.22 ± 6.75 N determined from quasi-static tests at 1 mm/min in single lap joints (SLJ).

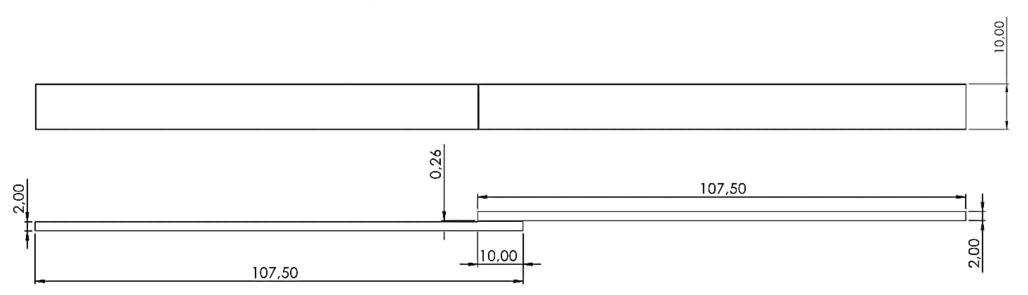


Figure 1 – Specimens' geometry, in mm.

Testing setup

For static creep tests, a simple rig presented in Figure 2 was used with a LVDT measuring the displacement at the joint. For cyclic creep tests, a servo hydraulic machine was used with a trapezoidal waveform defined for a frequency of 0.04 Hz. To collect the data, a camera was used to collect two photos per cycle, one when the joint is unloaded and another when the joint is loaded (Figure 2 right). The photos were then processed using digital image correlation (DIC).

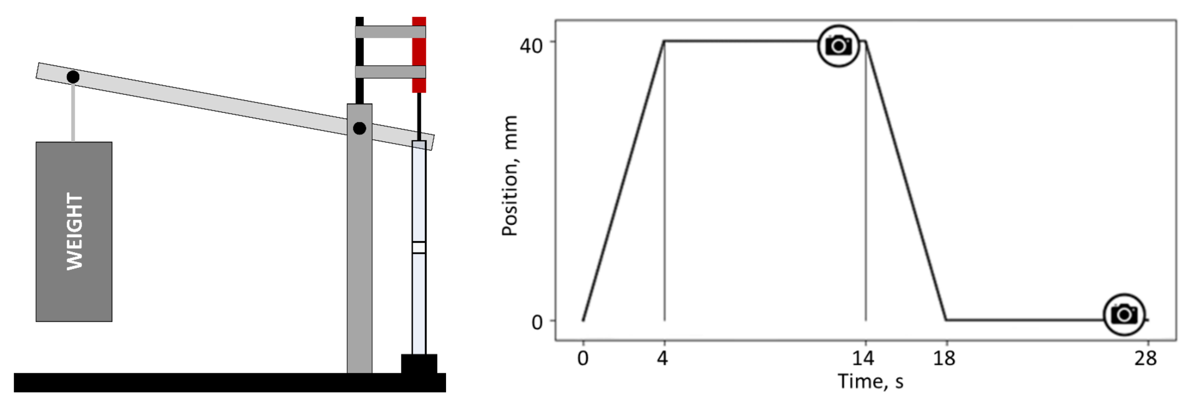


Figure 2 –Scheme of static creep testing rig (left) and waveform defined for cyclic creep (right).

Creep strain rate model

Equation 1 represents the log-transformed creep strain rate, where t_{in}, t_{rup} are the initial and rupture times, and a, b, c are the model parameters. The creep strain can be determined by integrating Equation 1, resulting in Equation 2 where ε_0 is the instantaneous elastic strain [1].

$$ln\left(\frac{d\varepsilon}{dt}(t)\right) = \frac{a}{(t - t_{ini})^b \cdot (t_{rup} - t)^c} \quad (1)$$

$$\varepsilon(t) = \int_{t_{ini}}^{t} \dot{\varepsilon}(\tau)d\tau + \varepsilon_0 \quad (2)$$

The prediction of the creep curve considers the applied stress and temperature as inputs, and it's given by Equation 3, supported by the relations in Equations 4 and 5 [1].

$$\dot{\varepsilon}(t) = \frac{d\varepsilon}{dt}(t) = exp\left[\frac{a(T,\sigma)}{(t - t_{ini})^{b(T,\sigma)} \cdot (t_{rup}(T,\sigma) - t)^{c(T,\sigma)}}\right] \quad (3)$$

$$\begin{cases} a(\sigma,T) = \alpha_1 \cdot T + \alpha_2 \cdot \sigma + \alpha_3 \\ b(\sigma,T) = \beta_1 \cdot T + \beta_2 \cdot \sigma + \beta_3 \\ c(\sigma,T) = \gamma_1 \cdot T + \gamma_2 \cdot \sigma + \gamma_3 \end{cases} \quad (4)$$

$$t_{rup}(\sigma,T) = exp\left[\frac{1}{m}\left(\frac{ln\,\sigma - p_0}{p_1} \cdot \frac{1000}{T + 273.15} - C\right)\right] \quad (5)$$

Where C, m, p_0, p_1 and $\alpha_i, \beta_i, \gamma_i$ $(i = 1,2,3)$ are fitting coefficients, LMP is the Larson-Miller parameter, T is the temperature in Celsius, and σ is the applied stress. For cyclic creep, the points of maximum amplitude are selected for the model as these are the critical strains values over time. Figure 3 shows a cyclic creep curve and the points of maximum amplitude.

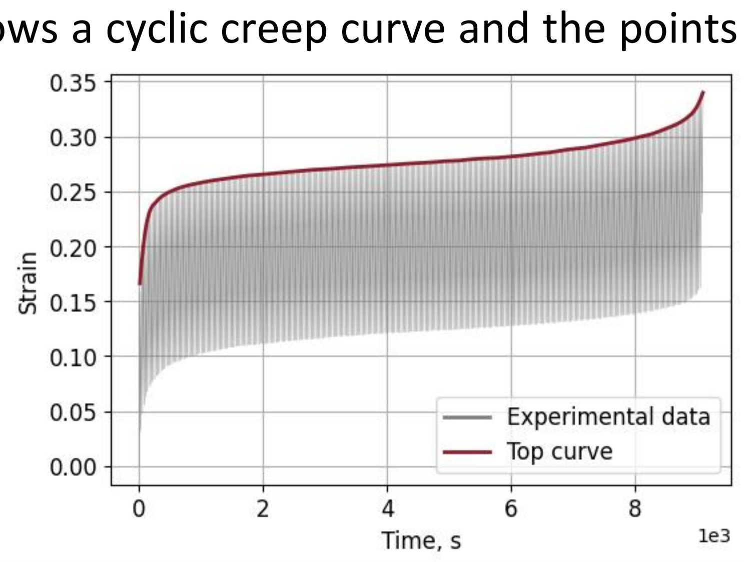


Figure 3 – Cyclic creep curve and points of maximum strain amplitude.

Results

Experimental results

The data fed to the analytical model considered various temperatures between 23 °C and 50 °C, and applied loads between 30 % and 80 % of the failure load for quasi-static tests. The curve fitting using Equation 1 shows very good results, observed in Figure 4. The prediction of the rupture time appears to be good as well, presented in Figure 4.

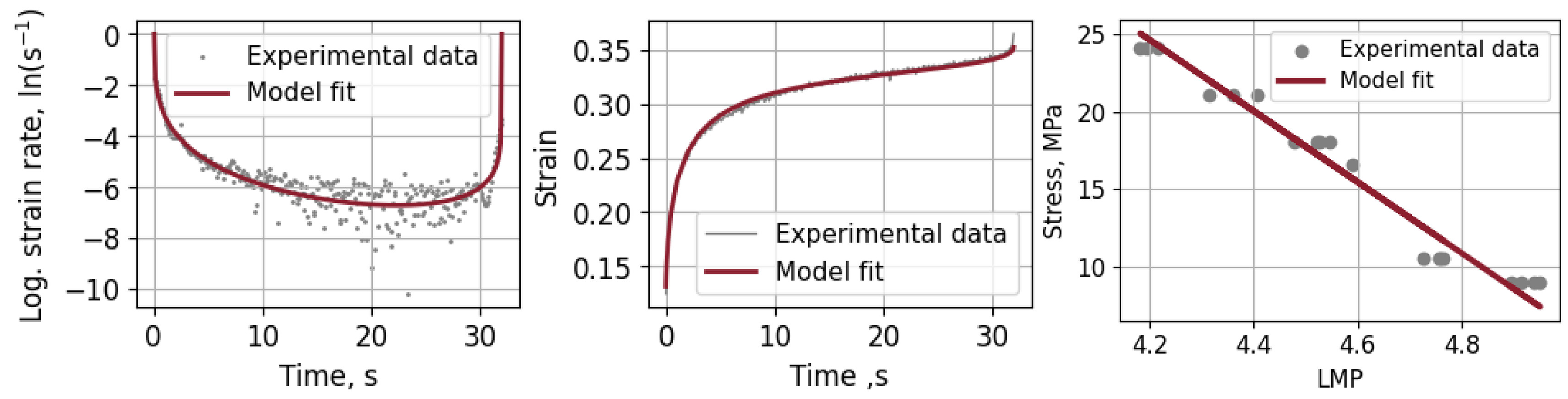


Figure 4 – Curve fitting of log-transformed strain rate (left), creep strain (center), and correlation of applied stress and LMP for prediction of rupture time (right).

Then, the prediction of the model parameters a, b, c as a function of temperature and applied stress are shown in Figure 5, where it can be seen that parameter b fits well also, however parameters a and c do not, due to the variability in the shape of the tertiary creep phase with introduces considerable dispersion in parameter c which consequently affects parameter a that tries to counterbalance the dispersion in c.

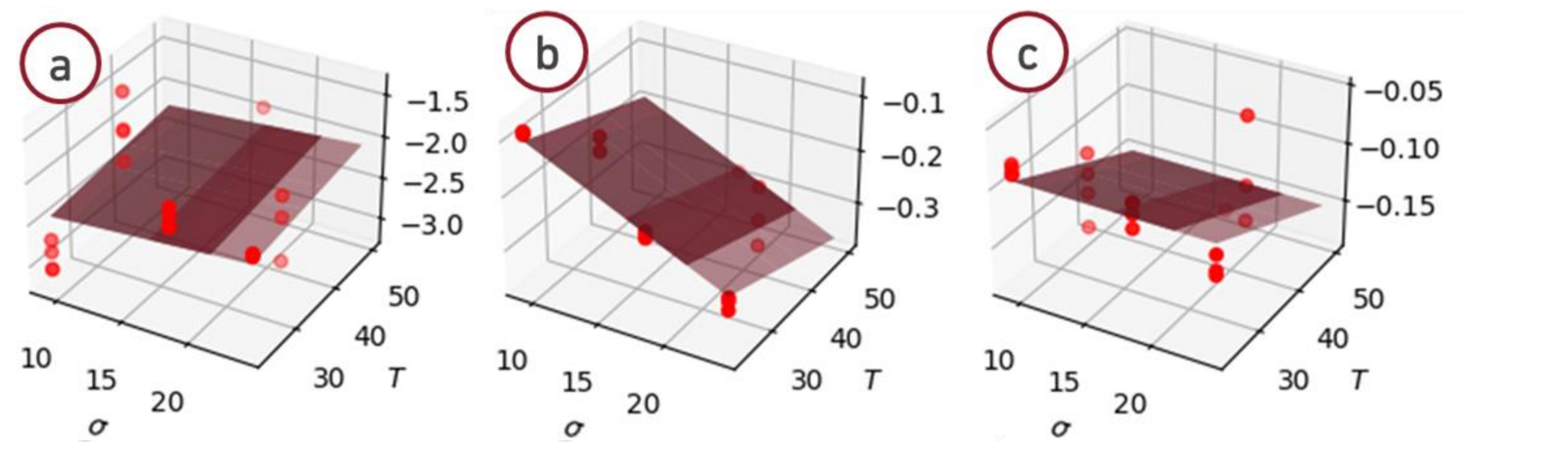
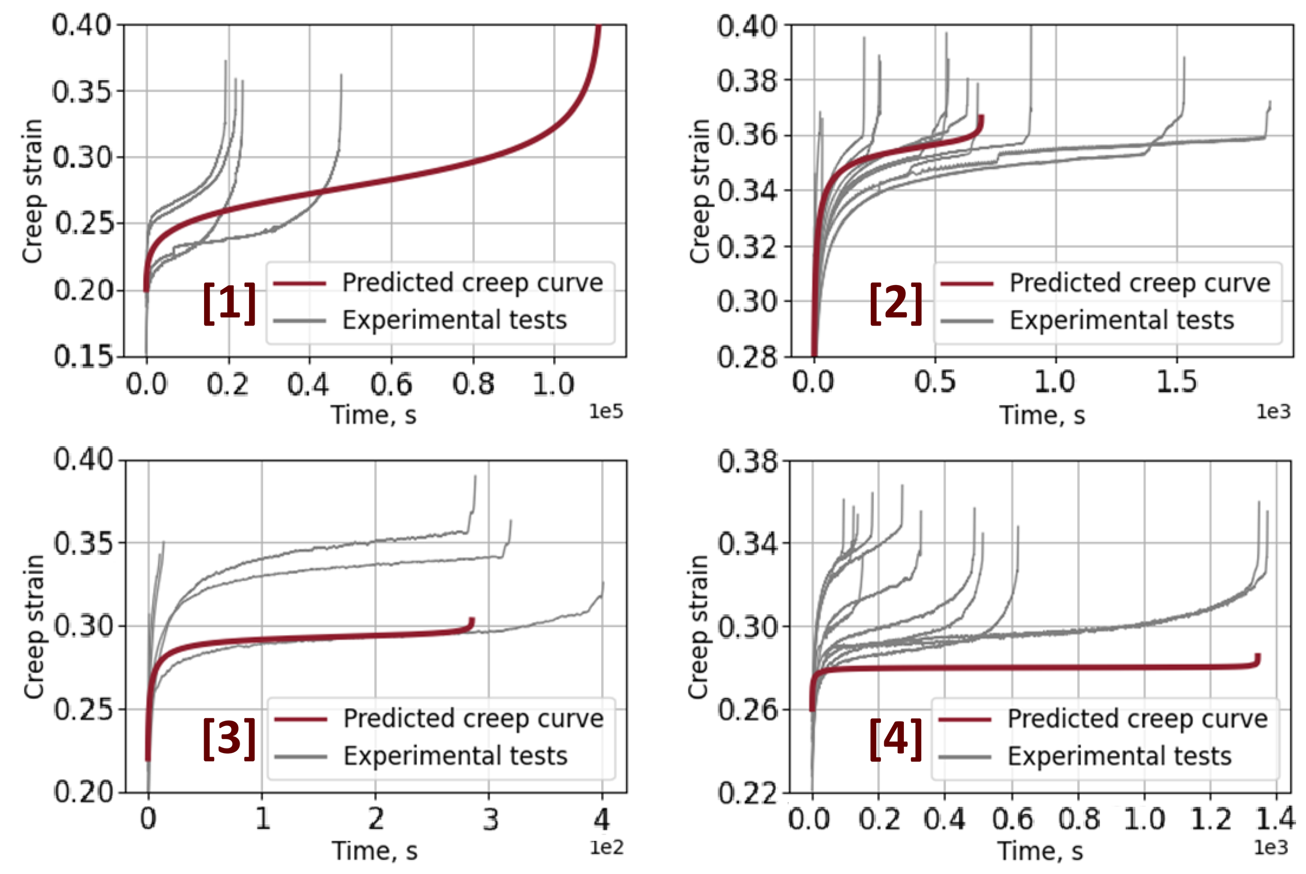


Figure 5 – Correlation of model parameters a, b, c.

To validate the model, four conditions were considered at different temperatures and applied loads, and the curves are shown in Figure 6. The dispersion of parameters a, c affects considerably the prediction for more extreme conditions as 20 % of failure load, and at 40 °C. However, for the other two conditions the prediction is good for the failure strain and time.



[1] Load = 20 %
Temp = 23 °C

[2] Load = 50 %
Temp = 23 °C

[3] Load = 45 %
Temp = 35 °C

[4] Load = 30 %
Temp = 40 °C

Figure 6 – Comparison of analytical predictions and experimental data for four testing conditions.

Conclusions

The model can predict the full curve considering the three creep phases, as well as the failure time. However, the dispersion observed in the experimental data, which is common with PSAs, affect the accuracy of the predictions, especially near the limit of applied stress and temperature. Therefore, a careful approach of selecting creep curves should be considered in order to reduce the dispersion and improve the accuracy of the analytical predictions.

References

[1] X. Duan, H. Yuan, W. Tang, J. He, and X. Guan, "A Phenomenological Primary–Secondary–Tertiary Creep Model for Polymer-Bonded Composite Materials," Polymers, vol. 13, no. 14, p. 2353, 2021. [Online]. Available: https://www.mdpi.com/2073-4360/13/14/2353.

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