Received: 21 June 2020 | Accepted: 12 November 2020

DOI: 10.1002/pamm.202000092

Damage modelling for the lifetime prediction of structural adhesive joints subjected to hygro-thermo-mechanical long-term loading

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A damage model is presented for the lifetime prediction of structural adhesive joints under hygro-thermo-mechanical loading. The damage approach is applied through a cohesive zone model together with the concept of effective stress. It consists of a temperature-dependent creep and hygro damage evolution due to mechanical loading and chemical aging, caused by the local water concentration. The creep damage part considers multiaxiality of the loading by an equivalent stress. The model parameters are identified by means of rupture times from creep tests under different mechanical loadings, temperatures and humidity conditions. The model and the identified parameters are verified by means of FE-simulations until rupture of an adhesive joint.

1 Damage model for cohesive zone

The thin structural adhesive joint is idealised as a cohesive zone. Its local traction vector consists of the tangential (t_t), binormal (t_b) and normal (t_n) component and is computed through the effective stress concept according to equation (1).

$$\mathbf{t} = \begin{bmatrix} t_\mathrm{t} & t_\mathrm{b} & t_\mathrm{n} \end{bmatrix}^\mathsf{T} = (1 - D_\mathrm{ca})\tilde{\mathbf{t}} \tag{1}$$

The vector of the effective traction $\tilde{\mathbf{t}}$ is determined by a constitutive equation. However, it does not depend on damage D_ca, which evolves due to the following nonlinear first order ordinary differential equation over time t, proposed in [1] to predict the lifetime of structural adhesive joints under hygro-thermo-mechanical loading.

$$\frac{\mathrm{d}D_\mathrm{ca}}{\mathrm{d}t} = \dot{D}_\mathrm{ca} = \dot{D}_\mathrm{c} + \dot{D}_\mathrm{a} \ , \ D_\mathrm{ca} \in [0, 1] \tag{2}$$

$$\dot{D}_\mathrm{c} = \frac{1}{c_0}\left(\frac{\sigma_\mathrm{eqc}}{\sigma_\mathrm{ref}(1 - D_\mathrm{ca})}\right)^n \exp\left(p_\mathrm{c}\left(\frac{1}{T_\mathrm{refc}} - \frac{1}{T}\right)\right) \ , \ \sigma_\mathrm{eqc} = \sqrt{\left\langle b_\mathrm{1c}\left\langle t_\mathrm{n}\right\rangle^2 + b_\mathrm{2c} t_\mathrm{n} + t_\mathrm{t}^2 + t_\mathrm{b}^2\right\rangle} \ , \ c_0 = 1 \ \mathrm{s} \tag{3}$$

$$\dot{D}_\mathrm{a} = B_\mathrm{a}(1 - D_\mathrm{ca})\left(\frac{c}{c_{\infty,\mathrm{ref}}}\right)^l \exp\left(p_\mathrm{a}\left(\frac{1}{T_\mathrm{refa}} - \frac{1}{T}\right)\right) \tag{4}$$

The creep damage evolution $\dot{D}_\mathrm{c}$ depends on the equivalent stress σ_eqc, which takes into account the multiaxiality of the mechanical loading. The hygro damage evolution $\dot{D}_\mathrm{a}$ depends on the water concentration c and models aging. The reference concentration $c_{\infty,\mathrm{ref}}$ and the constant c_0 are introduced for dimensionless arguments. The parameters n, σ_ref, B_a, l, p_a, p_c, b_1c, b_2c, T_refc and T_refa are identified by means of rupture times from creep tests.

2 Damage parameter identification and model verification

The damage model parameters are identified in order to match the rupture times from FE-simulations and creep rupture tests with constant mechanical load levels, temperatures ϑ and humidity conditions, represented by the relative humidity in percentage φ of the surrounding wet air. Therefore, the FE-model in Fig. 1(b) is applied, which depicts the FE-mesh for the bluntly jointed steel tube specimen in Fig. 1(a). The FE-model is an idealisation of the test setup and represents a radial section of 1/32 of the circumference of the specimen. The steel substrates are assumed to be elastic with typical elasticity constants for steel. They are much stiffer than the structural adhesive, which is why they are idealised as thin layers and rigid bodies at top and bottom of the adhesive layer, represented by cohesive elements with the proposed damage model. The constant temperature T for each creep test is prescribed at each node of the FE-mesh. Thus, the FE-simulation is treated as a hygromechanical two-field-problem with prescribed temperature. Mechanical loading is applied through the torsional moment M and the tensile force F. The relative humidity φ yields the concentration c_∞, representing the boundary condition for the simulation of the water diffusion. Three levels of relative humidity are used for the parameter identification: $\varphi = 10$, $\varphi = 50$ and $\varphi = 90$, implying the concentrations $c_\infty = 2.8 \cdot 10^{-6}\ \mathrm{g/mm^3}$, $c_\infty = 1.8 \cdot 10^{-5}\ \mathrm{g/mm^3}$, and $c_\infty = 3.6 \cdot 10^{-5}\ \mathrm{g/mm^3}$,

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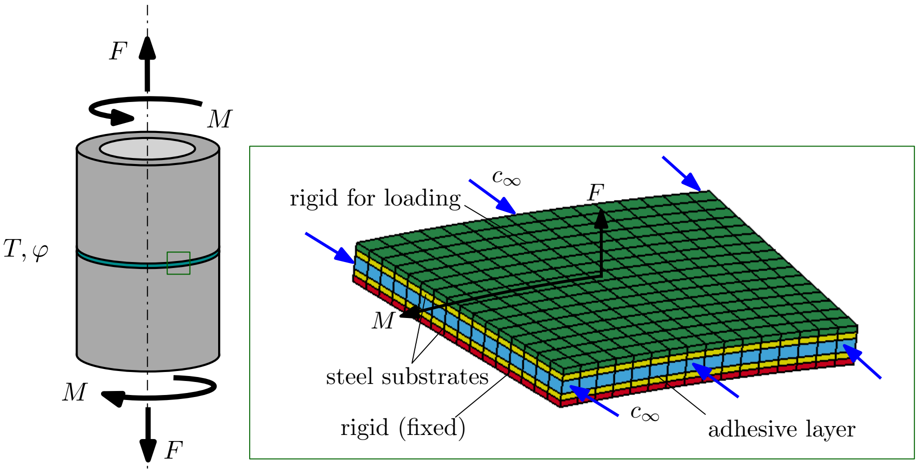
see [1]. Diffusion is computed according to the FICK model, for which a temperature-dependent diffusion coefficient D is applied, which takes the values of $D = 3.68 \cdot 10^{-7}$ mm^2/s, $D = 2.35 \cdot 10^{-6}$ mm^2/s and $D = 1.3 \cdot 10^{-5}$ mm^2/s for the temperatures $T = 296.15$ K, $T = 323.15$ K and $T = 353.15$ K, applied for the identification, see [1].

The parameter identification is performed with the optimisation tool LS-OPT together with the FE-solver LS-DYNA. The results are shown in Table 1. The identification procedure consists of the following steps: First, the parameters σ_{ref}, B_{a}, n, and l are determined with vanishing tensile force $F = 0$ at the temperature $T = T_{\text{refc}} = T_{\text{refa}} = 323.15$ K, whereby the levels of relative humidity and shear stress in Fig. 2(a) are applied. The shear stress results from the torsional moment M. The model predictions for the rupture times in Fig. 2(a) match very well with the test data, which verifies the identification. In the second step, the parameters p_{c} and p_{a} are identified at the temperatures $T = 296.15$ K and $T = 353.15$ K with the vanishing tensile force $F = 0$ and the mechanical load levels in Fig. 2(b). The simulation results match well with the test data again. The remaining parameters $b_{1\text{c}}$ and $b_{2\text{c}}$ are identified with the nonzero tensile force $F \neq 0$ and the vanishing torsional moment $M = 0$, which together imply $b_{2\text{c}} = 0$, see [1]. The tensile force results in the load levels of the normal stress in Fig. 2(c), where the shown simulation results coincide well with the test data for the relative humidity of $\varphi = 50$. For the case with $\varphi = 90$, only the creep rupture time for the lowest load level is predicted well, while the rupture times of the other load levels are overestimated. Further investigations of the combined loading with shear and tension may improve the predictions for the case with relative humidity of $\varphi = 90$ in Fig. 2(c).



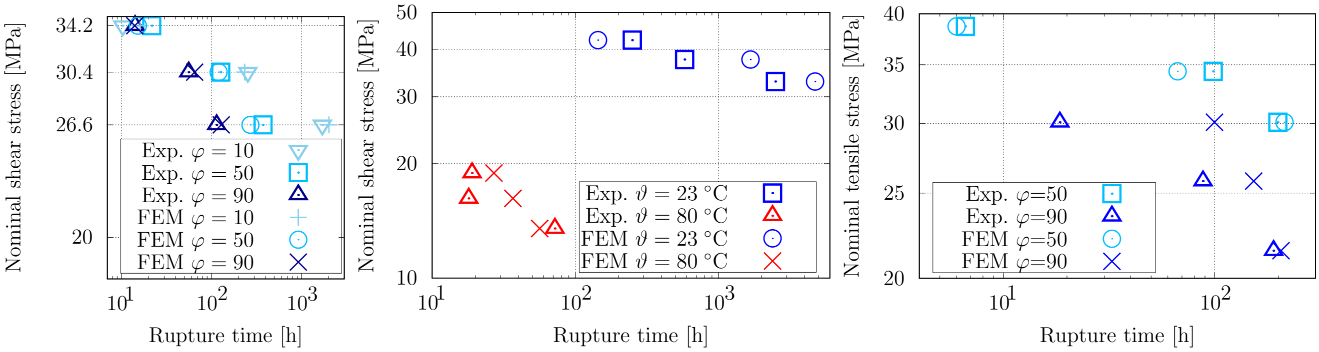
(a) Sketch of creep rupture test setup

(b) FE-model for the simulations of creep rupture tests: radial section (1/32 of the circumference) of the specimen with loading due to concentration boundary c_∞, torsional moment M and tensile force F

Fig. 1: Creep rupture test and FE-model for parameter identification

Table 1: Summary of the parameter identification of the damage model ($c_{\infty,\text{ref}} = 4 \cdot 10^{-5}$ g/mm^3, $T_{\text{refc}} = T_{\text{refa}} = 323.15$ K)

n [–]	σ_{ref} [MPa]	B_{a} [–]	l [–]	p_{c} [K]	p_{a} [K]	$b_{1\text{c}}$ [–]	$b_{2\text{c}}$ [MPa]
22.89	60.19	$6.611 \cdot 10^{-6}$	2.285	25120	13320	0.7666	0



(a) $M \neq 0$, $F = 0$, $\vartheta = 50°$ C **(b)** $M \neq 0$, $F = 0$, $\varphi = 50$ **(c)** $M = 0$, $F \neq 0$, $\vartheta = 50°$ C

Fig. 2: Verification of the identified parameters in Table 1: comparison of results from FE-simulations (FEM) and creep rupture tests (Exp.) from [2] in double-logarithmic scale

Acknowledgements Open access funding enabled and organized by Projekt DEAL.

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