Material modeling of hyperelastic silicone adhesives considering stiffness reduction

Elisabeth Toups1,* , Robert Seewald2, Benjamin Schaaf3, Uwe Reisgen2, Markus Feldmann5, Stefanie Reese1, and Jaan-Willem Simon1

1 Institute of Applied Mechanics, RWTH Aachen University, Mies-van-der-Rohe-Str. 1, D-52074 Aachen
2 Welding and Joining Institute, RWTH Aachen University, Pontstraße 49, D-52062 Aachen
3 Institute of Steel Construction, RWTH Aachen University, Mies-van-der-Rohe-Str. 1, D-52074 Aachen

Predicting the hyperelastic behavior and the stiffness reduction of adhesive is essential for the economical dimensioning of load-bearing bonds in the field of glass façade construction. The typical hyperelastic behavior can be modeled by using one of well-known hyperelastic models. In addition, a new variable for modeling stiffness reduction was defined. A new material model based on the Ogden model for representing hyperelasticity and stiffness reduction was defined.

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1 Introduction

Load bearing bonds become increasingly common in glass-façade structures due to their beneficial characteristics, such as the more continuous load transfer between glass and the supporting elements compared to alternative connections, and the possibility to enable a more transparent design [1]. Current German regulations [2] for dimensioning such load bearing bonds include very high safety factors which could be reduced by a better prediction of the real material behavior [3]. Certainly, a higher material utilization would be possible. For this reason, a suitable material model for representing the behavior of the adhesive is needed.

2 Material modeling

The model is based on the well-known Ogden model, the free energy function of which is defined as a function of the principal stretches and contains the material parameters $\mu_k$ and $\alpha_k$. $J$ is the product of the principal stretches and $\Lambda$ is the Lamé constant.

$$\psi_{Ogden} = \sum_k \mu_k \frac{1}{\alpha_k} (\lambda_1^\alpha_k + \lambda_2^\alpha_k + \lambda_3^\alpha_k - 3) - \ln J + \frac{\Lambda}{4} (J^2 - 1 - 2\ln J)$$

(1)

A new variable $\rho$ is defined for taking into account stiffness reduction. This variable is assumed to be a scalar and works as an internal variable taking values between 0 and 1. Depending on these limits, the followig formulation $\mu_k(\rho)$ is defined, which is used instead of the original parameters $\mu_k$:

$$\mu_k(\rho) = (1 - \rho)^{\rho_k} (\mu_k^0 - \mu_\infty) + \mu_\infty$$

(2)

$$\mu_k^0$$ if $\rho = 0$

$$\mu_k^\infty$$ if $\rho = 1$

In the standard continuum damage mechanics approach, the model response results in failure for the case $D = 1$ ($D$ is the damage variable). On the contrary, in the current formulation $\rho = 1$ does not refer to failure but to a final stress-strain relationship which can be represented by the model. The parameters $\mu_k^\infty$ is needed to describe this last stress-strain curve. In contrast, $\mu_k^0$ (the value of $\mu_k(\rho = 0)$) are artificial parameters, which are needed to describe the stress-strain behavior during the stiffness reduction, and do not reflect any physical properties. The advantage of this embedded variable $\rho$ is, that stiffness reduction is considered specifically in each Ogden term. The consideration of the newly introduced variable leads to an additional term $\psi_\rho$, which is added in the free energy function to control the development of stiffness reduction. For this control part, the following exponential formulation $\psi_\rho = c_1 (\delta + \frac{\exp(-c_2 \delta) - 1}{c_2})$ was chosen, which depends on the variable $\delta$ and also contains the two parameters $c_1$ and $c_2$. In order to derive the state relations of the model, the total Helmholtz free energy of this model is defined as:

$$\psi = \psi_1(\lambda_1, \lambda_2, \lambda_3, \rho) + \psi_\rho(\delta)$$

(3)

Both parts, $\mu_k(\rho)$ and $\psi_\rho(\delta)$, can be chosen freely and independently. Following general thermodynamical considerations, the second law of thermodynamics must be fulfilled and is therefore exploited to derive the state relations of the model. In the

* Corresponding author: e-mail elisabeth.toups@ifam.rwth-aachen.de, phone +49 241 80 25006, fax +49 241 80 25001
considered case, the first Piola-Kirchhoff stress tensor $\mathbf{P}$ can be calculated by $\frac{\partial \psi}{\partial \mathbf{F}}$, where $\mathbf{F}$ is the deformation gradient. The remaining dissipation inequality provides the thermodynamic conjugated forces of the model, which can be computed by $\frac{\partial \psi}{\partial \rho}$ and $\frac{\partial \psi}{\partial \delta}$.

### 3 Fitting procedure and selected results

The model contains in total fifteen parameters. For the fitting procedure, the Lame constant $\Lambda$ can be fitted separately to the experimental data of a compression test at the beginning, while the remaining parameters are initially divided into two groups. The first parameter group comprises the parameters $\mu_\infty^k$ and $\alpha_k$, which describes more or less the general S-shape of the stress-strain curve. The second group contains the parameters from the stiffness reduction ($p_k$), the control term ($c_1$, $c_2$) and the artifical parameters $\mu_0^k$. This group influences the occurrence and progression of stiffness reduction. These two groups can be fitted independently. The first group containing $\mu_\infty^k$, which relates to the last unloading path, can be fitted together with $\alpha_k$ to the last stress-strain curve measured in the experiment. The remaining parameters (group 2) are fitted to the experimental results of the cyclically loaded tests. The fitted parameter set (Tab. 1) results in a very good representation of the uniaxial tension test, shown in Fig. 1, and of a pure shear test, shown in Fig. 2. Both specimens were loaded cyclically under tensile stress and evaluated in the center of the specimen, since a homogeneous material behavior is to be expected there.

![Fig. 1: Model fit to uniaxial tension test](image1)

![Fig. 2: Model fit to pure shear test](image2)

| Parameter               | Value          |
|-------------------------|----------------|
| $\mu_1^\infty$ [MPa]    | 0.250          |
| $\mu_2^\infty$ [MPa]    | 3.91E-07       |
| $\mu_3^\infty$ [MPa]    | -0.195         |
| $\alpha_1$ [-]          | 0.011          |
| $\alpha_2$ [-]          | 21.422         |
| $\alpha_3$ [-]          | -4.398         |
| $\Lambda$ [MPa]         | 1168           |

| Parameter               | Value          |
|-------------------------|----------------|
| $\mu_0^1$ [MPa]         | 33.496         |
| $\mu_0^2$ [MPa]         | 0.118          |
| $\mu_0^3$ [MPa]         | -0.523         |
| $p_1$ [-]               | 4312.2         |
| $p_2$ [-]               | 149.27         |
| $p_3$ [-]               | 1017.6         |
| $c_1$ [MPa]             | 3327.8         |
| $c_2$ [-]               | 43.73          |

Table 1: Material parameters

### 4 Conclusion and outlook

A flexible model for a hyperelastic material with exchangeable parts such as the stiffness reduction function, the elastic formulation, and the control term was presented. The parameters of the model were successfully fitted to uniaxial tensile and pure shear test data. In order to enable the representation of multi-axial stress states, which are expected during the application of adhesives in structural sealant glazing, it is necessary to validate further the model on corresponding samples.

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