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Abstract. We report on an analytical model for damage description in adhesive butt joints. In the model, the thin adhesive layer is replaced by a damaging bonding interface. The mechanical behavior of the interface is described by a nonlinear and rate-dependent imperfect contact law. The law takes into account both stress and displacement jumps, and it can describe both soft and hard adhesive layers. Unlike classic cohesive zone models, phenomenological in nature, the proposed contact law explicitly accounts for material and damage properties of the adhesive layer. A first comparison with literature data of adhesive butt joints loaded in torsion indicates that the model can successfully reproduce their experimental stress-strain response.

Introduction

Adhesive bonding is an assembly technique used in the manufacture and repair of a variety of products in aeronautical, automotive, civil and biomedical engineering [1, 2, 3, 4, 5]. Adhesive bonding provides many advantages over mechanical assembly: the possibility of joining dissimilar materials, a minimal increase in weight of assembly, protection from corrosion, a better stress distribution [6, 7]. The disadvantages are an increased sensitivity to surfaces preparation compared to mechanical fastening, the perishability of adhesive materials and their susceptibility to service temperature, humidity and other environmental conditions [8, 9].

A reliable strength prediction for adhesive joints is complicated by the multifactorial and multiscale nature of the phenomena occurring during damage. For example, the typical tensile stress-strain response of structural polymeric adhesives presents an initial linear elastic behavior, followed by softening and rupture. At the microscopic scale, microcracks generated during surface preparation before bonding are seen to propagate during the softening phase, causing debonding and subsequent failure [10].

Besides the complex damage behavior of adhesives, the thinness of adhesive layers introduces further modeling complications (*i.e.* small mesh size, mesh-dependency, large number of degrees of freedom, high computational time). Thus, interface models are often preferred to continuum bulk descriptions. Cohesive zone models represent a classic modeling strategy. These models are based on a traction-separation law across the cohesive surface, taking different possible shapes, *i.e.* bilateral, trapezoidal, polynomial, etc., cf. [7, 12, 13, 14, 15, 16, 17] and the references therein. This approach, however, presents a drawback: the model parameters describing damage/failure behavior of the adhesive are phenomenological and not based on their physical properties (like material properties, geometry, defects distribution, *etc.*).

A viable modeling alternative is a traction-separation law combining together an imperfect interface approach, continuum damage mechanics and asymptotic homogenization [24, 26]. Imperfect interface laws, describing the behavior of *hard* adhesive layers (*i.e.* as stiff as adherents) in which both stress and displacement jumps occur, have already proven to effectively describe the micromechanical properties of elastic adhesives, such as anisotropy and second order elasticity effects [18, 19, 20], micro-cracking and roughness [23], multiphysics behavior [21, 22]. Recently, the authors provided a

new hard imperfect interface model accounting for micro-cracking damage [24] via an evolution law embedding Kachanov's micro-cracking damaging model [25], thus directly related to the mechanical properties of the adhesive. The imperfect (hard) interface model cited above has been recently applied to adhesive layers in glued butt joints undergoing combined tensile-torsion loads [26]. Tube-to-tube butt joints configurations were shown to simulate standard characterization tests for structural adhesives [27]. Here, we extend the stress analysis of butt joints under torsion loads by implementing the micro-cracking damaging model proposed by Welemane and Goidescu [11]. The paper is organized as follows: after presenting the Welemane and Goidescu micro-cracking damaging model, we give a sketch of the model for the tube-to-tube joint proposed in [26] and its numerical implementation. After a comparison of modeling results with the experimental data by [27], we highlight conclusions and perspectives of future work.

Micro-Cracking Damaging Adhesive Model

In [11], the damage state of the adhesive material is described by a scalar microcrack density distribution ρ, measure of the extent of crack-like defects in the plane of the adhesive. A thermodynamic potential takes into account the damage contribution to energy due to microcracks opening, and damage growth is assumed to be progressive and rate independent, with an evolution law expressed within a standard thermodynamic framework. The equivalent elastic moduli of the damaged material can be obtained by the expression of the free elastic energy for an orthotropic matrix with a particular microcracks distribution. For an orthotropic matrix embedding a family of parallel microcracks distributed in the $(1,2)-$plane of the adhesive, the effective planar shear modulus, $\bar{G}(\rho)$, is:

$$\bar{G}(\rho) = G_{12}^0\,(1 - C_g\,\rho), \tag{1}$$

with G_{12}^0 the shear modulus of the matrix in the plane of the adhesive and C_g a (constant) material parameter depending on the elasticity parameters of the matrix. In the approach proposed in the present paper, the parameter C_g has to be identified, the average porous microstructure of the adhesive being not known *a priori.*

Proposed Model for Damage Prediction in Torsion Tests

The tube-to-tube specimen is composed of two identical cylindrical adherents joined together. The lower basis of the specimen is fixed and the upper one is subjected to a torque T. Under the simplifying hypotheses of small strains, isotropic linear elastic material behavior, and assuming that the adhesive layer can be replaced by an interface law of imperfect contact, in [26] it is shown that the shear stress-shear strain response of adhesive can be given as

$$\tau = G\,\bar{G}(\rho)/(G - \bar{G}(\rho))\gamma, \tag{2}$$

with G the (in-plane) shear modulus of the adherent material and $\bar{G}(\rho)$ the (damaging) modulus of the adhesive (see Eq. (1)). The damage parameter ρ evolves via a kinetic equation related to the imperfect contact behavior of the adhesive and to the chosen microcracking model, cf. [26]. The kinetic equation has the form

$$\begin{cases} \eta\,\dot{\rho} = \{\omega + \mathcal{T}(\rho,T)\}_+\,, \\ \rho(0) = \rho_0, \end{cases} \tag{3}$$

with η a (positive) damage viscosity related to the velocity of damage evolution, ω a (negative) damage energy threshold, analogous to the energy of adhesion of polymers [28], and ρ_0 the initial damage value. $\mathcal{T}$ is a function of damage ρ and applied torque T, and it depends also on the damaging parameter C_g and on the geometrical and material parameters of the composite, as follows:

$$\mathcal{T}(\rho,T) = C_g\,D^2\,T^2\,\varepsilon\,(4\,G_{12}^0\,(\nu+1)(C_g\,\rho-1) + E)^2/(4\,E^2\,G_{12}^0\,I_0^2\,(C_g\,\rho-1)^2) \tag{4}$$

where D is the outer diameter of the cylindrical adherents, I_0 is the inertial polar moment of the cross-sectional area, ε is the (small) thickness of the adhesive, and E and ν are the elastic modulus and Poisson's coefficient of the adherent material, respectively.

Comparison of Numerical Results with Experimental Data by Murakami et al.

We validate the model by comparison with some experimental data obtained by Murakami et al. in torsion tests of adhesive butt joints [27]. Note that in [26] these same experimental data were used to validate a damage model based on the micro-cracking homogenization model of Kachanov [25], which is different from the micro-cracking homogenization model of Welemane and Goidescu [11] considered in the present paper.

Murakami and coworkers tested two S45C carbonsteel cylinders joined by an epoxy adhesive (XA7416, 3M Japan Ltd., Tokyo, Japan). The geometrical parameters of the joint specimen are the following: outer diameter $D = 26.0$ mm; inner diameter $d = 20.0$ mm; adhesive thickness $\varepsilon = 0.3$ mm. The mechanical properties of the joint materials are as follows: adhesive Young's modulus $E_0 = 4.53$ GPa; adhesive Poisson's ratio $\nu_0 = 0.36$; adherents' Young's modulus $E = 200$ GPa; adherents' Poisson's ratio $\nu = 0.30$. With these data, an (undamaged) initial shear modulus G_{12}^0 of 1.67 GPa can be calculated.

In the torsion tests, two different stress-rates were applied: 6.67×10^{-2} MPa/s for the so-called quasi-static (QS) condition and 1.00×10^3 MPa/s for the so-called high-rate (HR) condition. In the present paper, numerical simulations are stopped at failure, *i.e.* when the stress reaches the shear limit strength, which was experimentally evaluated to be 53.2 MPa in the QS case and 70.0 MPa in the HR case, cf. [27].

In the present numerical analysis, the viscosity η and the energy threshold ω have been taken to be equal to the values identified in [26] starting from the same experimental data: $\eta = 2296.70$ Ns/m, $\omega = -679.34$ N/m for the QS case; $\eta = 0.90$ Ns/m, $\omega = -1135.64$ N/m for the HR case. The reason of this choice is due to the fact that the viscosity and the damage initiation should not depend on the particular micro-cracking homogenization scheme (Welemane-Goidescu or Kachanov) adopted in the numerical model.

The remaining parameters, that is the material parameter C_g and the initial damage value ρ_0, which are linked to the particular choice of the micro-cracking homogenization model (Welemane-Goidescu in the present paper) have been identified by fitting the experimental data by [27] with the model proposed in the previous section. The results are the following: $C_g = 0.47$ and $\rho_0 = 1.43$ in the QS case; $C_g = 0.49$ and $\rho_0 = 1.24$ in the HR case. These data have been obtained i) by assuming the same initial linear stress-strain behavior of the responses calculated using Kachanov's scheme, and ii) by assuming, as for Kachanov's scheme, that the damage initiates after the stress thresold of 50.25 MPa for QS conditions, and 64.97 MPa for HR conditions.

Solid lines in Fig. 1 are the experimental shear stress– strain response of the adhesive layer tested by Murakami and coworkers under torsional loading in QS (grey) and HR (black) conditions. The curves were obtained by extracting the data from Figure 10 in [27] by using the free online software WebPlotDigitizer [29]. Fig.1 shows also the numerical simulations of the shear stress-strain responses calculated by using the model proposed by the authors in [26] (dashed lines) and the model proposed in the present paper (dash-dotted lines). We recall that the two models differ for the adopted micro-cracking homogenization approach, which is Kachanov's scheme in [26] and Welemane-Goidescu scheme in the present paper.

Fig.1 allows to compare the numerical simulations obtained using the two different homogenization schemes with the experimental responses obtained in [27]. First, we note that both experimental curves (solid lines) exhibit a softening behavior not reproducible by the numerical simulations, which are in a force (torque, precisely) control mode. Next, the numerical simulations are able to reproduce the ductile stress-strain responses of the structural adhesive tested in torsion by Murakami and coworkers. After a linear stress-stress response, corresponding to an elastic linear behavior of the adhesive material, damage initiates (at 50.25 MPa for QS conditions, and 64.97 MPa for HR conditions) and ductile behavior occurs resulting in an increase of deformation at almost constant stress. In fact, the numerical simulations obtained with Kachanov micro-cracking homogenization scheme (dashed

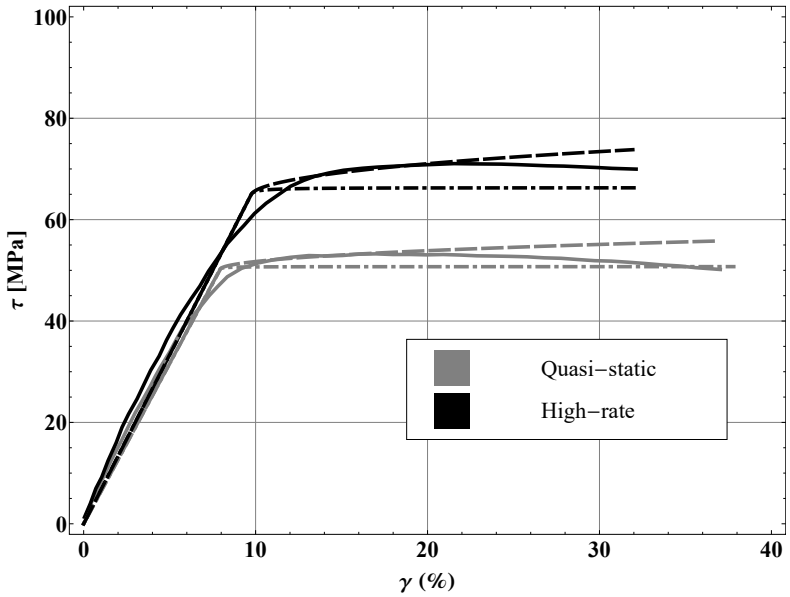

Fig. 1: Torsion stress–strain curves of the adhesive layer obtained by the proposed model for quasi-static (gray lines) and high-rate (black lines) loading. Solid lines correspond to experimental data collected by Murakami et al. [27]. Dashed lines are numerical simulations obtained in [26] using the micro-cracking homogenization scheme by Kachanov [25]. Dash-dotted lines are numerical simulations obtained in the present paper using the micro-cracking homogenization scheme by Welemane and Goidescu [11].

lines) show a slight strain hardening, while those obtained with Welemane-Goidescu micro-cracking homogenization scheme show a quasi perfect plastic behavior. This different behavior between the two homogenization schemes has already been highlighted in [24, Fig. 14], and it is believed to be intrinsic of the force-controlled structural responses of the two interface models obtained by incorporating the two different homogenization schemes into a hard interface model. For a full description of the resulting interface models, we refer the reader to [24].

Summary

In the present paper, we have extended a damage model for adhesive butt joints in torsion based on an imperfect interface approach merging continuum damage mechanics and asymptotic homogenization [26]. The extension consisted in assuming, as homogenization scheme, the micro-cracking approach proposed by Welemane and Goidescu [11], as opposed to Kachanov's homogenization scheme adopted in [26]. Numerical simulations were obtained and compared with the experimental shear stress-strain response of adhesive butt joints obtained by Murakami et al. in [27]. Both models based on the two different homogenization schemes are able to successfully reproduce the ductile behavior observed in Murakami's experiments and commonly observed in experimental studies (see also [30]).

As in [26], there are many limitations to the model proposed in the present paper. First, it neglects stress concentrations occurring in the adhesive layer, which may lead to brittle failure. However, this failure mechanism is more typical for joints with thick bondlines, cf. [31], while thin adhesive layers have been considered in the present paper.

Next, the model assumes thickness uniformity for the adhesive, an occurrence rarely satisfied in real applications. Nonetheless, it would be possible to generalize the analytical model by taking into account a smooth roughness of the interface modeling the adhesive, as proposed in [23]. Finally, more general adhesive material behaviors, like viscoplasticity and viscoelasticity typical of structural adhesives, could be incorporated. We postpone these aspects to future work.

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