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Design of functionally graded joints using a polyurethane-based adhesive with varying amounts of acrylate

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ABSTRACT

Adhesives with graded properties along the bondline are being developed to increase the strength of adhesively bonded joints. Efforts to do this in the past have resulted in mixed results. Two adhesive parameters need to be considered: the geometry of the gradation and the material properties of the adhesive at different gradation levels. In order to consider both of these aspects, a computational model was created to aid in not only the design of adhesive gradations but also judge whether a specific adhesive gradation method will be able to result in strength increases. In this study, the model was introduced and compared with published results. A new adhesive gradation system was created by using a polyurethane-based adhesive with varying amounts of acrylate, and a numerical analysis was performed to determine the potential advantages of the adhesive gradation.

1. Introduction

Adhesively bonded joints have been receiving increased attention with the rise of fiber reinforced composite materials. Adhesively bonded joints generally allow a more gradual transfer of shear load from one adherend to another than bolted or riveted joints and do not require holes, which may interrupt fiber paths. However, peel stress concentrations in the corners of joints often causes a bulk of the adhesive to remain underutilized and can even result in premature failure.

Many methods have been proposed to distribute stress more evenly in joints. Most involve altering the geometry of the joint [1], including tapering the adherend [2], increasing the thickness of the adhesive at the end [3], fillets [4], rounded adherend corners [5], novel joint geometries [6], and joint insertions [7]. More recently, grading the adhesive properties along the length of the joint has become a popular focus of researchers towards relieving stress concentrations and increasing joint strength. Bi-adhesive joints were the first to be widely studied, with most theoretical findings showing positive results and experimental studies showing mixed results, with many important design guidelines identified [8–15]. More recently, continuously graded adhesively bonded joints have been studied theoretically [16–22], with very few experimental studies [23–25].

One of the broad lessons to be learned from these studies is that grading the adhesive does not universally result in performance increases. However, it is probably safe to say that grading the adhesive universally results in increased complication, cost, and/or time. Therefore, it seems necessary that the development of functionally graded adhesives be tightly coupled with design models if it is to ever find industrial application. Although linear elastic models can provide valuable insights in the pre-yielding stress distribution and even stress allowables for adhesive joints, models which include in some way the nonlinear nature of most adhesives is necessary. Therefore, design models which consider material nonlinearities coupled with experimental development of adhesion gradation systems are needed to realize beneficial functionally graded adhesive joints.

The current study uses a design model previously developed [26], which is a combination of a structural model of cylindrical plates on an elastic foundation and a finite element approach. The model requires one element through the thickness of the joint, and a co-rotational formulation includes geometric nonlinearities [27] while adaptive shape functions and an internal adaptive mesh include the effects of material nonlinearities and crack growth [28]. A formulation is presented here which includes a modified Von-Mises plasticity formulation [29] in the framework of a thin adhesive layer constrained by two stiff adherends, along with the interpolation strategy between data curves for the continuously graded adhesive. A few numerical examples are shown to provide insights in considering nonlinearities for graded adhesive systems, and the model is compared with experimental data in the literature [24].

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Finally, a novel adhesive system, which can be graded by changing acrylate content or cure temperature is presented. The difference between the conventional adhesive systems and the adhesive system used in this study is the application of only one formulation that is able to generate graded properties along the bondline for stress peak reduction due to the curing temperature. The adhesive system is based on a polyurethane adhesive in combination with a hydroxyl-terminated acrylate, which is responsible for the adjustable mechanical properties. Due to the hydroxyl-termination, the acrylate is permanently integrated into the polyurethane network after the first global curing process at moderate temperatures. The next locally acting curing step at higher temperatures, the acrylate polymerization proceeds, resulting in an increase in the network density and consequently an increasing stiffness.

The material properties of the acrylate content grading are used to model a single lap joint configuration and, with a linear gradation, the design process is demonstrated.

2. Method

2.1. Computational model

2.1.1. Joint Element model

The bonded joint element model was used as the basis for the analysis. This model uses the linear elastic solution of a structural model to determine the exact shape functions for two overlapping adhesively bonded adherends [26]. Using this method, the overlap section can be represented by a single element for a linear elastic analysis. Furthermore, geometric nonlinearity has been considered by using a co-rotational formulation to capture large rotations [27]. Material nonlinearities were also included, with an increase in the number of elements needed for a converged solution. Finally, to enable a coarse mesh even when using nonlinear materials and considering progressive failure, an adaptive mesh along with adaptive shape functions were derived and applied [28]. The maximum number of joint elements used during this study was six, with a mesh convergence study conducted for each example. All simulations were run on an inhouse finite element software.

2.1.2. Adhesive plasticity

The highly nonlinear nature of most adhesives requires the use of some sort of nonlinear material model for the adhesive. Previous versions of the bonded joint element model used a nonlinear elastic model with the shear and normal modes decoupled, which was intended to be used with characterization tests such as double cantilever beam (DCB) and end notch flexure (ENF) tests. However, the most common method for characterizing adhesives has remained a simple tensile test on a pure adhesive specimen. Therefore, a plasticity model was introduced along with a method to use tensile test data to characterize a thin adhesive layer.

At a material point, we assume that the total strain, $\boldsymbol{\varepsilon}$,can be broken up into a plastic and elastic portion

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^p + \boldsymbol{\varepsilon}^{el} \tag{1}$$

where $\boldsymbol{\varepsilon}^p$ is the plastic strain, $\boldsymbol{\varepsilon}^{el}$ is the elastic strain, and all strains are in the vector form as

$$\boldsymbol{\varepsilon} = [\varepsilon_z \quad \gamma_{xz}]^T. \tag{2}$$

The stress can be calculated based on the elastic strain as

$$\boldsymbol{\sigma} = \boldsymbol{D}\boldsymbol{\varepsilon}^{el} \tag{3}$$

where

$$\boldsymbol{\sigma} = [\sigma_z \quad \tau_{xz}]^T. \tag{4}$$

Assuming that the adhesive is much softer than the adherends, the adhesive strain parallel to the adherends can be considered negligible compared to the peel and shear stress components, or $\varepsilon_x = \varepsilon_y$=0. Assuming this, the stiffness matrix can be written as

$$\boldsymbol{D} = \begin{bmatrix} C_1E_a & 0 \\ 0 & G_a \end{bmatrix} \tag{5}$$

where E_a and G_a are the elastic Young's modulus and shear modulus and

$$C_1 = \frac{1-\nu_a}{(1-2\nu_a)(1+\nu_a)} \tag{6}$$

and ν_a is the Poisson's ratio of the adhesive. A modified Von Mises plasticity theory has been introduced by Gali et al. [29] where the yield behavior is dependent on both deviatoric and hydrostatic stress which causes a difference between uniaxial tension and compression. An effective stress, s_{eff}, is defined as

$$s_{eff} = C_s\sqrt{J_{\sigma 2}} + C_v I_{\sigma 1} \tag{7}$$

where $J_{\sigma 2}$ is the second invariant of the deviatoric stress tensor, $I_{\sigma 1}$ is the first invariant of the stress tensor, and

$$C_s = \frac{\sqrt{3}(S+1)}{2\lambda},\ C_v = \frac{S-1}{2\lambda}, \text{ and } S = \frac{\sigma_c}{\sigma_t} \tag{8}$$

where σ_c and σ_t are the compressive and tension yield stresses. Similarly, an effective strain, e_{eff}, is described by

$$e_{eff} = \frac{C_s}{\nu+1}\sqrt{J_{\varepsilon 2}} + \frac{C_v}{1-2\nu}I_{\varepsilon 1} \tag{9}$$

where $J_{\varepsilon 2}$ is the second invariant of the deviatoric strain tensor and $I_{\varepsilon 1}$ is the first invariant of the strain tensor. Considering the assumptions about the x and y strain components, the effective stress becomes

$$s_{eff} = \frac{C_s}{\sqrt{3}}(\sigma_z^2(C_1-1)^2 + \tau_{xz}^2)^{1/2} + C_v\sigma_z(2C_1+1) \tag{10}$$

and the effective strain is

$$e_{eff} = \frac{C_s}{\nu+1}\left(\frac{1}{3}\varepsilon_z^2 + \frac{1}{4}\tau_{xz}^2\right)^{1/2} + \frac{C_v}{1-2\nu}\varepsilon_z. \tag{11}$$

A tensile test was used to characterize the adhesive, so the tensile stress and strain had to be tied to the effective stress and strain. The effective stress yield stress from a tensile test, $\overline{Y}_{eff}$, can be written as

$$\overline{Y}_{eff} = \left(\frac{C_s}{\sqrt{3}} + C_v\right)\overline{Y}(\bar{\varepsilon}_t, \bar{\varepsilon}^p) \tag{12}$$

where $\overline{Y}(\bar{\varepsilon}_t, \bar{\varepsilon}^p)$ is a function of the tensile strain at initial yield, $\bar{\varepsilon}_t$, and the accumulated plastic strain, $\bar{\varepsilon}^p$. A bar over a value indicates a value from the tensile stress-strain curve or a value which has been converted into that space. Finally, the effective accumulated plastic strain, $\bar{\varepsilon}^p_{eff}$, can be found by the equation

$$\bar{\varepsilon}^p_{eff} = \left(\frac{C_s}{\sqrt{3}} + C_v\right)\bar{\varepsilon}^p. \tag{13}$$

The yield function, f, is defined as

$$f = s_{eff} - \overline{Y}_{eff}. \tag{14}$$

If $f \leq 0$, then the stress calculated was correct. When the initial stress was not correct, an iterative predictor/corrector method was utilized to find the plastic strain which satisfies the yield function. For iteration $n+1$, the flow rule was defined as

$$\boldsymbol{\varepsilon}^p_{n+1} = \boldsymbol{\varepsilon}^p_n + \boldsymbol{n}d\lambda. \tag{15}$$

where

$$\boldsymbol{n} = \frac{\boldsymbol{\sigma}'}{|\boldsymbol{\sigma}'|}, \tag{16}$$

λ is a plastic multiplier, and $\boldsymbol{\sigma}'$ is a vector of the stress, with the shear