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Progressive damage modeling of adhesively bonded lap joints

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ABSTRACT

A continuum damage model for simulating damage propagation of bonded joints is presented, introducing a linear softening damage process for the adhesive agent. Material models simulating anisotropic non-linear elastic behavior and distributed damage accumulation were used for the composite adherends as well. The proposed modeling procedure was applied to a series of lap joints accounting for adhesion either by means of secondary bonding or co-bonding. Stress analysis was performed using plane strain elements of a commercial finite element code allowing implementation of user defined constitutive equations. Numerical results for the different overlap lengths under investigation were in good agreement with experimental data in terms of joint strength and overall structural behavior.

1. Introduction

The increasing size of structures built exclusively from lightweight composite materials, such as wind turbine rotor blades, has raised the need for more advanced design tools to optimize the joints between the various components. Moreover, the fact that maintenance and repair of such structures is becoming a major issue, due to the high replacement cost, increases the demand of more efficient joint design techniques.

Numerous studies on the analysis of bonded joints with composite adherends, using the Finite Element method, have been published, see the recent reviews [1,2]. These studies can be categorized by their approach for predicting the strength of the adhesive joints. The continuum mechanics approach, that assumes perfect bonding between the adhesive and the adherends, suffers from the bimaterial singularities inherent in a bonded joint and as a result maximum stress and strain for such a model will vary greatly with mesh refinement. The fracture mechanics approach addresses the singularity issue but still there are limitations such as the difficulty of the finite element modeling procedure to calculate the stress state at the crack tip and the need for measuring the fracture properties of the materials. Finally, there is the Cohesive Zone Modeling (CZM) approach which simulates the macroscopic damage along a predefined crack path by specification of a traction-separation response between initially coincident nodes on either side of the path. The great advantage of the cohesive models is their ability to simulate onset and non-self-similar growth of adhesive damage. However, except from the downside of predefining the damage path in CZMs, fracture characterization experiments must be performed to specify the cohesive law parameters.

In the present work a modeling procedure for simulating adhesive joint behavior is presented. Degradation models, simulating damage propagation, without predefining the failure path, are introduced for both composite adherends and polymeric adhesives. Material nonlinearity of the adherends is also implemented, while the presented softening procedure accounts for energy dissipation during debonding. A series of secondary bonded and co-bonded lap joints, of varying overlap length, were analyzed by means of the Finite Elements method to verify the predictive capabilities of the proposed model. The mesh refinement issue is addressed by correlating element size with the softening law parameters so that the FE results are independent from the mesh density. Validation of the FE modeling procedure was performed by comparing predictions with experimental results and numerical predictions using the CZM approach.

2. Material nonlinearity and progressive damage model

2.1. Composite nonlinear behavior

Mechanical properties of both, the glass fiber composite adherends and adhesive paste, used for coupon manufacturing, were determined experimentally in a comprehensive material characterization campaign. The epoxy resin system used was HUNTSMAN Araldite® LY 3505 / Hardener Aradur® 3405 and laminate unidirectional reinforcement was AHLSTROM E-glass fibers of an areal weight equal to 700 g/m^2. Slight material non-linearity was found parallel to the fibers, whereas a more pronounced one was measured transverse to the fibers, different in tension and compression.

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As expected, a highly non-linear behavior under in-plane shear was observed as well.

To account for material non-linearity, incremental stress–strain relations were implemented, retaining the validity of the generalized Hooke law for each individual interval as described in [3,4]:

$$d\sigma_1 = \frac{E_{1t}}{1-(E_{2t}/E_{1t})\nu_{12}^2}d\varepsilon_1 + \frac{\nu_{12}E_{2t}}{1-(E_{2t}/E_{1t})\nu_{12}^2}d\varepsilon_2$$
$$d\sigma_2 = \frac{\nu_{12}E_{2t}}{1-(E_{2t}/E_{1t})\nu_{12}^2}d\varepsilon_1 + \frac{E_{2t}}{1-(E_{2t}/E_{1t})\nu_{12}^2}d\varepsilon_2$$
$$d\sigma_6 = G_{12t}d\varepsilon_6 \tag{1}$$

The tangential elastic moduli in the principal coordinate system of the orthotropic material, E_{1t} (parallel to the fiber), E_{2t} (transversely), G_{12t} (in-plane shear) were derived as follows by adopting the nonlinear constitutive model introduced by Richard and Blacklock [5]:

$$\sigma_i = \frac{E_{o_i}\varepsilon_i}{\left[1+\left(E_{o_i}\varepsilon_i/\sigma_{o_i}\right)^{n_i}\right]^{(1/n_i)}}, \quad i=1,2,6 \tag{2}$$

By differentiating Eq. (2) one has:

$$E_{it} = \frac{d\sigma_i}{d\varepsilon_i} = E_{o_i}\left[1-\left(\frac{\sigma_i}{\sigma_{o_i}}\right)^{n_i}\right]^{((1/n_i)+1)} \quad i=1,2,$$
$$G_{12t} = \frac{d\sigma_6}{d\varepsilon_6} = G_{o_{12}}\left[1-\left(\frac{\sigma_6}{\sigma_{o_6}}\right)^{n_6}\right]^{((1/n_6)+1)} \tag{3}$$

A summary of the numerical values for all constants in elasticity expressions can be found in Table 1; they were derived through non-linear regression on the experimental data. Mean values for tensile and compressive strength properties in the fiber direction (X_T, X_c), transversely to the fibers (Y_T, Y_c) and in shear (S) for the composite tested are given in Table 2. The relatively low elastic properties of the adherend are due to the wet hand-layup manufacturing technique, characteristic of the in-situ patching procedure of the industrial partner; typically this results in a fiber weight fraction of ca. 51%. Mean values were deduced from 5 tests for each specimen type while engineering elastic constants were derived as suggested by relevant standards.

2.2. Polymer matrix and adhesive resin properties

The epoxy resin, used as adhesive for the secondary bonded specimens, is HUNTSMAN XD 4734 with XD 4741-S hardener cured at 80 °C for 1 h. The response of both the, previously described, polymer matrix of the adherends and adhesive resin was found to be slightly non-linear especially under shear stressing. In this work the epoxy resins are assumed to have linear behavior until failure since the experimental stress–strain curve deviates from linearity close to coupon failure. Properties of the two resins are listed in Table 3.

Table 1
Elasticity constants for the non-linear model, Eq. (3), of UD Glass/Epoxy composite.

	$\nu_{12}=0.26$		
	E_{o_i}[MPa]	σ_{o_i}[MPa]	n_i
E_{1t}	26,870.00	9,016.00	1.00
$E_{2t}^{(T)}$	9,478.00	49.00	3.04
$E_{2t}^{(C)}$	10,473.00	178.00	2.54
G_{12t}	2,760.00	44.00	1.87

Table 2
Failure stresses for the Composite material (in MPa).

X_T	X_C	Y_T	Y_C	S
558.60	411.12	40.00	128.14	38.42

2.3. Progressive damage model

2.3.1. Composite adherends

Besides non-linear mechanical response, progressive damage mechanics were also implemented in the FE modeling procedure. To account for the composite adherends progressive failure, the Puck criterion [6] with the associated property degradation strategy is used. Details of the failure mode dependent stiffness degradation were described in [3] and are summarized for completeness in Table 4. According to Puck theory, there are 5 ply damage modes, two associated with either tensile or compressive fiber failure (FF) and three describing matrix cracking or inter-fiber failure (IFF); IFFA, -B, -C resulting mainly from a combination of transverse to the fiber normal stress and in-plane shear.

Index (k) in the above relations refers to an arbitrary load step after failure has been detected. The degradation factor, $\eta \le 1$, multiplying the engineering elastic constants to account for damage growth in the ply is given by [6]:

$$\eta^{(k-1)} = \frac{1-\eta_r}{1+c\left(f_{E(IFF)}^{(k-1)}-1\right)^{\xi}} + \eta_r \tag{4}$$

where $f_{E(IFF)}$ is the failure effort as calculated by Puck's matrix failure criterion while $c=5$, $\xi=3$ and $\eta_r = 1\times10^{-6}$ are the values of the parameters of Eq. (4).

2.3.2. Polymer resin

To account for the adhesive paste progressive damage (microcracking), since a brittle isotropic adhesive material is assumed, the paraboloid failure surface criterion by Stassi D' Alia [7], adapted for generalized plane strain, is implemented:

$$(\sigma_x-\sigma_y)^2+(\sigma_y-\sigma_z)^2+(\sigma_z-\sigma_x)^2+6\tau_{xy}^2+2\sigma_u(R-1)(\sigma_x+\sigma_y+\sigma_z)-2R\sigma_u^2 \le 0 \tag{5}$$

where σ_u represents the adhesive tensile strength and R, expressing the strength differential effect, is the ratio of compressive to tensile failure stress. Here R is calculated in terms of the measured values

Table 3
Engineering elastic constants and failure stresses for the polymer systems.

	E [GPa]	G [GPa]	σ_u [MPa]	τ_u [MPa]
Araldite LY3505/Aradur 3405	3.98	1.48	56.94	51.64
XD 4734/XD 4741-S	4.01	1.39	35.29	39.94

Table 4
Progressive stiffness degradation model for the composite adherends.

Failure mode	
FF(T) or FF(C)	$E_1^{(k)}=10^{-10}\times E_1$ $E_2^{(k)}=10^{-10}\times E_2$ $G_{12}^{(k)}=10^{-10}\times G_{12}$
IFF(A)	$E_2^{(k)}=\eta^{(k-1)}\times E_2$ $G_{12}^{(k)}=\eta^{(k-1)}\times G_{12}$
IFF(B)	$G_{12}^{(k)}=\eta^{(k-1)}\times G_{12}$
IFF(C)	$E_2^{(k)}=10^{-10}\times E_2$ $G_{12}^{(k)}=10^{-10}\times G_{12}$