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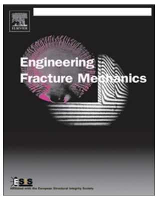

Microscale simulation of adhesive and cohesive failure in rough interfaces

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ABSTRACT

Multi-material lightweight designs, e.g. the combination of aluminum with fiber-reinforced composites, are a key feature for the development of innovative and resource-efficient products. The connection properties of such bi-material interfaces are influenced by the geometric structure on different length scales. In this article a modeling strategy is presented to study the failure behavior of rough interfaces within a computational homogenization scheme. We study different local phenomena and their effects on the overall interface characteristics, e.g. the surface roughness and different local failure types as cohesive failure of the bulk material and adhesive failure of the local interface. Since there is a large separation in the length scales of the surface roughness, which is in the micrometer range, and conventional structural components, we employ a numerical homogenization approach to extract effective traction-separation laws to derive effective interface parameters. Adhesive interface failure is modeled by cohesive elements based on a traction-separation law and cohesive failure of the bulk material is described by an elastic-plastic model with progressive damage evolution.

1. Introduction

The application of fiber reinforced plastics (FRP) in multi-material lightweight structures requires innovative joining concepts to combine the advantages of FRP with conventional lightweight materials as aluminum. Such hybrids are e.g. essential to realize appropriate load transfer elements in automotive or aircraft applications [1,2]. Different from technologies like bolted or riveted joints, which generally induce damage in the composite material, approaches that create the connection during the forming process itself instead of a subsequent joining step are promising solutions. Despite the intrinsic joining process, component failure often initializes in the bonding zone as shown in Fig. 1, since the adhesive strength of polymer-metal interfaces is often much lower than the cohesive strength of the connected materials [3,4]. The adhesion between two materials can be influenced by different mechanisms. These include chemical/physical-chemical mechanisms (hydrogen and van der Waals forces), electrostatic mechanisms (difference in electrical charge) and mechanical mechanisms (interlocking) [5]. This paper focuses on the latter mechanism by analyzing structured interfaces that create a mechanical interlock. For instance in Fig. 1, the design of a macroscopic waviness or an increased microscopic interface roughness due to a certain pre-treatment of the aluminum surface may improve the mechanical properties of the joint.

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Nomenclature

A	vertical expansion of idealized interface profile
b	width of microscale domain
C	autocorrelation function
D_{CDM}	scalar damage variable of continuum damage model
D_{CZM}	scalar damage variable of cohesive zone model
E	Youngs's modulus
f	yield condition of plasticity model
G_{c}	critical energy release rate
$G_{\mathrm{c}}^{\mathrm{eff}}$	effective critical energy
G_I	energy release rate in mode $I = \mathrm{I}, \mathrm{II}$
$G_{\mathrm{c}I}$	critical energy release rate in mode $I = \mathrm{I}, \mathrm{II}$
h	height of microscale domain
$h(x)$	interface height profile
k_I	stiffness of cohesive zone model in $I = \mathrm{n}$ normal and $I = \mathrm{s}$ shear direction
L	effective critical energy
L	length of measured height profile
l_{ACF}	correlation length
$(\cdot)^{\mathrm{M}}$	values related to the macroscale
$(\cdot)^{\mathrm{m}}$	values related to the microscale
$\mathbf{n}$	unit normal vector on domain boundary
$\mathbf{n}_{\mathrm{c}}$	unit normal vector on cohesive interface
R_{a}	arithmetic average of height profile
$\mathbf{s}_{\mathrm{c}}$	unit tangential vector on cohesive interface
$\mathbf{t}$	traction vector on domain boundary
$\mathbf{t}_{\mathrm{c}}$	cohesive traction vector on interface
$\bar{\mathbf{t}}$	prescribed traction vector on domain boundary
t_I^0	strength of cohesive zone model in $I = \mathrm{n}$ normal and $I = \mathrm{s}$ shear direction
$t_{\mathrm{c}}^{\mathrm{eff}}$	effective strength
$t_{\mathrm{c},i}^{\mathrm{M}}$	the i-th discrete effective traction value
$\overline{u}^{\mathrm{pl}}$	equivalent plastic displacement
$\bar{\mathbf{u}}$	prescribed displacement vector on domain boundary
$[\![u]\!]_{\mathrm{c},i}^{\mathrm{M}}$	the i-th discrete separation value
$[\![\mathbf{u}]\!]$	separation vector on interface
$\mathbf{u}$	displacement vector
$\tilde{\mathbf{u}}^{\mathrm{m}}$	displacement fluctuation vector on microscale
$\delta\overline{W_{\mathrm{c}}^{\mathrm{m}}}$	volume average of virtual work of microdomain
$\delta w_{\mathrm{c}}^{\mathrm{M}}$	virtual work at point on $\Gamma_{\mathrm{c}}^{\mathrm{M}}$
$\mathbf{x}$	position vector
δ_{m}^0	mixed mode separation at damage initiation
$\delta_{\mathrm{m}}^{\mathrm{f}}$	mixed mode separation at failure
δ_{m}	mixed mode separation
$\boldsymbol{\varepsilon}$	strain tensor
$\boldsymbol{\varepsilon}^{\mathrm{el}}$	elastic part of strain tensor
$\boldsymbol{\varepsilon}^{\mathrm{pl}}$	plastic part of strain tensor
$\overline{\varepsilon}^{\mathrm{pl},0}$	equivalent plastic strain at damage initiation
$\overline{\varepsilon}^{\mathrm{pl,f}}$	equivalent plastic strain at failure
$\overline{\varepsilon}^{\mathrm{pl}}$	equivalent plastic strain
Γ	cohesive interface
γ	horizontal expansion of modified triangular profile
$\partial\Omega_{\bar{\mathrm{t}}}$	Neumann boundary
$\partial\Omega_{\bar{\mathrm{u}}}$	Dirichlet boundary
κ	scalar multiplier in plastic evolution equation
λ	horizontal expansion of idealized interface profile
ν	Poisson's ratio
Ω	domain
Ω_+	domain of material phase +
Ω_-	domain of material phase −
$\boldsymbol{\sigma}$	Cauchy stress tensor

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