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Comparison and evaluation of two types of cohesive zone models for the finite element analysis of fracture propagation in industrial bonded structures

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ABSTRACT

This paper evaluates and compares two material constitutive models for the finite element analysis of structural adhesively bonded joints in large industrial bonded structures. The first model is a classical bi-linear traction–separation model whereas the second model is a more advanced pressure-dependent elasto-plastic-damage model. On one hand, both models predict different global force–displacement responses when simulating small lab experiments where the adhesive layer is confined between thick metal substrates, such as a Thick Adherend Shear Test. On the other hand, these differences become negligible when simulating the deformation and fracture behaviour of adhesive bonds in industrial benchmarks. These differences are extensively discussed and interpreted carefully and a special attention is paid to the compromise between computational accuracy, computational efficiency and modelling simplicity, which are key requirement to the transfer of such material constitutive models to the industry.

1. Introduction

Adhesive bonding is currently considered by the industry as an innovative structural joining solution. In the specific case of the automotive industry, adhesive bonding is a major actor in the current race to light-weight and to the reduction of fossils fuel emissions since it makes possible to join lighter materials such as aluminium and composites with more traditional materials such as steel, where other conventional joining techniques such as spot-welding would be inefficient.

A limitation to the use of adhesive bonding still lies in the lack of reliable material constitutive models that can accurately and efficiently predict the mechanical behaviour of bonded structures in Finite Element (FE) analysis. Validation procedures in the design's cycle of a car require stringent procedures, such as crash-tests, where some parts of the structures and part connections, among which adhesive layers, are submitted to damage and fracture. Consequently, there is a need for constitutive models that can efficiently predict damage and fracture propagation in adhesive layers.

In order to fill this gap, the last decade has seen the development of constitutive models that can predict the non-linear elasto-plastic behaviour of structural epoxy adhesives under complex multi-axial loading. Such models have been implemented and validated, for instance in [1,2]. The main originality of such constitutive models lies in the definition of a yield surface and of a plastic potential that depends not only on the second deviatoric-stress invariants (like in the usual J2

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Nomenclature

u	traction opening displacement in mode I
w	shear opening displacement in mode II
K_I	stiffness parameter in mode I
K_{II}	stiffness parameter in mode II
σ_0	critical peak stress for fracture initiation in mode I
τ_0	critical peak stress for fracture initiation in mode II
G_{Ic}	critical fracture energy in mode I
G_{IIc}	critical fracture energy in mode II
G_c	critical fracture energy in mixed mode
ξ	parameter controlling the influence of mixed mode loading
σ	current normal stress in the adhesive
τ_1, τ_2	shear stress components parallel to the bonded surface in the adhesive
s_{init}	stress criterion for damage initiation
$\bar{u}^{pl}$	plastic displacement
$d\bar{u}^{pl}$	effective plastic displacement
du_n^{pl}, du_t^{pl}	normal and tangential components of the effective plastic displacement
$d\varepsilon_n$	normal strain components active in the adhesive
$d\varepsilon_{t1}$, $d\varepsilon_{t2}$	in-plane tangential strain components active in the adhesive
L_c	element characteristic length
D	damage variable linked to the effective stress
D_n, D_t	normal and tangential part of D
$\bar{\sigma}$	effective stress tensor
u_n^{plf}, u_t^{plf}	ultimate normal and tangential plastic displacements
Λ_n	parameter influencing the evolution of D_n
Λ_t	parameter influencing the evolution of D_t
a	crack length
l, L	total length of the DCB specimen
h	thickness of the DCB substrate
F	force applied to separate the arms of the DCB
θ	rotation of the loading point
J	J integral
W	strain energy density
S	area circumscribing the crack tip
T	traction force acting on the area S
B	width of the specimen
t	adhesive thickness
E	Young's modulus
w_0	shear deformation at the start of the adhesive layer
k	initial stiffness of the adhesive layer
Δt	stable time step
ρ	material density
l_{pz}^i	length of the fracture process zone in mode i, $i = (1,2,3)$
t_0^i	interface strength
M	parameter ranging from 0.21 to 1.0
M_t	torsional moment
$SDEG$	parameter representing the degradation of the adhesive layer
X	global displacement in the longitudinal direction

plasticity commonly used to describe plasticity in metals), but also on the first stress invariant, i.e., on the hydrostatic pressure. Such constitutive models have the ability to describe the dissymmetric and non-linear behaviour of a structural adhesive submitted to complex load-paths, mixing both traction and shear loading.

Recently, the constitutive model developed in [1] has been further developed to predict fracture initiation and propagation in the adhesive layer [3]. It now contains all the features to predict accurately the complex elasto-plastic-damage behaviour of the adhesive. However, the counterpart to such a detailed model can be the time spent to identify the relevant material parameters as well as the computation time required to obtain an accurate solution. Consequently, modelling and computation time efficiency are aspects to consider carefully before the whole constitutive model can be transferred to the industry.