Engineering Fracture Mechanics 133 (2015) 112–137

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Rate dependent behavior of crash-optimized adhesives – Experimental characterization, model development, and simulation

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ARTICLE INFO

Article history:
Received 5 December 2013
Received in revised form 9 October 2014
Accepted 15 November 2014
Available online 20 November 2014

Keywords:
Adhesive joints
Cohesive zone modeling
Strain rate effects

ABSTRACT

The mechanical properties of crash-optimized adhesive BETAMATE 1496V are characterized over a wide range of strain rates. The information gathered from the mechanical tests are used for developing a fully rate-dependent constitutive law for cohesive interface elements considering both, the strain rate dependency of the initiation stress and the strain rate dependency of the fracture toughness. The model is calibrated and verified against experimental data for tapered double cantilever beam (TDCB) and tapered end notched flexure (TENF) tests. Finally, the model is validated against quasi-static and dynamic experimental results on an adhesively bonded T-joint. The numerical predictions show good correlation with the experimental results.

1. Introduction

In recent years, structural adhesives have become more important in the automotive industry due to the possibility of vehicle weight reduction and the associated reduction of fuel consumption and CO_2 emissions. At the same time, the crash worthiness must be maintained and considered in the design process. Consequently, there is a requirement to simulate the mechanical response of structural adhesives subjected to crash loading accurately. A good understanding of the mechanical response of structural adhesives is required in order to develop numerical models with predictive capabilities. A state-of-the-art technique for modeling damage and failure in structures with well-defined fracture planes, such as laminated composites or adhesively bonded structures is the application of cohesive zone models. Cohesive zone models are particularly interesting due to their intrinsic ability to model damage initiation and subsequent propagation in a single, coherent analysis which cannot be achieved with numerical methods requiring the presence of a pre-crack such as the Virtual Crack Extension Technique [1] or the Virtual Crack Closure Technique (VCCT) [2]. In addition to the well-established cohesive interface formulations (see recent review by Wisnom [3]) for describing quasi-static loading, there have recently been efforts for modeling the fatigue (see recent review by Pascoe et al. [4]) and crash response (see for example Marzi et al. [5], Samudrala et al. [6] or May et al. [7]). The promising results presented by Marzi et al. [5] and May et al. [7] indicate the need for taking into

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http://dx.doi.org/10.1016/j.engfracmech.2014.11.006
0013-7944/

Nomenclature

Latin characters

C_I	constant
C_{II}	constant
D	damage
E	Young's modulus
G_{IC}	mode I fracture toughness
$G_{IC,ref}$	quasi-static mode I fracture toughness
$G_{IC,inf}$	upper bound of the mode I fracture toughness
G_{IIC}	mode II fracture toughness
$G_{IIC,ref}$	quasi-static mode II fracture toughness
G_{diss}	total energy dissipated
K_I	stiffness of the adhesive layer
K_{II}	shear stiffness of the adhesive layer
l_{cz}	cohesive zone length
m_I	constant
m_{II}	constant
M	constant
T	specimen thickness
t_a	thickness of the adhesive layer

Greek characters

β	mode-mixity
Γ_{II}	pseudo-plasticity parameter
δ_I	mode I displacement
δ_{II}	mode II displacement
δ_m	mixed-mode displacement
δ_I^0	displacement at initiation, pure mode I
δ_I^f	displacement at failure, pure mode I
δ_{II}^0	displacement at initiation, pure mode II
δ_{II}^f	displacement at failure, pure mode II
δ_{II}^{pl}	displacement at the end of the plastic plateau, pure mode II
δ_m^0	mixed-mode displacement at initiation
δ_m^f	mixed-mode displacement at final failure
δ_m^{pl}	mixed-mode displacement at the end of the plastic plateau
$\dot{\varepsilon}$	strain rate
$\dot{\varepsilon}_I$	strain rate in peel-direction
$\dot{\varepsilon}_{II}$	shear rate
$\dot{\varepsilon}_{I,ref}$	reference strain rate in peel-direction defining quasi-static loading
$\dot{\varepsilon}_{II,ref}$	reference shear rate defining quasi-static loading
η	constant
ν	Poissons' ratio
σ_I	mode I stress
σ_{II}	mode II stress
σ_I^0	stress at initiation, pure mode I
σ_{II}^0	stress at initiation, pure mode II
$\sigma_{I,ref}^0$	mode I initiation stress at quasi-static loading
$\sigma_{II,ref}^0$	mode II initiation stress at quasi-static loading

account potentially rate dependent properties. Previous experimental work on structural adhesives has shown that both, the strength [8–11] and the fracture toughness [5,11–13] are sensitive to high strain rate loading. In the first part of this paper an extensive experimental programme for characterization of rate dependent material properties of the crash-optimized structural adhesive BETAMATE 1496V is presented. Using the information obtained from the experimental work (rate dependent properties, shape of the cohesive law), a cohesive zone model is developed and implemented into the commercial FE package ABAQUS/Explicit. The model is an extension to the formulation previously presented by May et al. [7]. In the original formulation given in [7], rate dependent material properties such as the initiation stress and fracture toughness are assumed to be constant once damage initiation has occurred. However, in real life, the strain rate is usually not constant. This paper