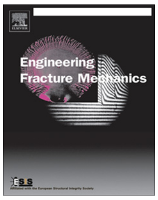
Engineering Fracture Mechanics 158 (2016) 1–12

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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



Micro-mechanics based pressure dependent failure model for highly cross-linked epoxy resins

J. Chevalier [a,*], X.P. Morelle [a], C. Bailly [b], P.P. Camanho [c], T. Pardoen [a], F. Lani [a]

[a] Institute of Mechanics, Materials and Civil Engineering (IMMC), Université catholique de Louvain, Place Sainte-Barbe, n2, L05.02.02, 1348 Louvain-la-Neuve, Belgium
[b] Institute of Condensed Matter and Nanosciences (IMCN), Université catholique de Louvain, Place L. Pasteur, n1, L04.01.01, 1348 Louvain-la-Neuve, Belgium
[c] aDEMec, Faculdade de Engenharia, Universidade do Porto, Rua Dr. Roberto Frias, s/n, 4200-465 Porto, Portugal

ARTICLE INFO

Article history:
Received 6 October 2015
Received in revised form 15 February 2016
Accepted 18 February 2016
Available online 3 March 2016

Keywords:
Failure criterion
Maximum principal stress
Pressure dependence
Finite element method
Unreinforced resin

ABSTRACT

A new fracture criterion for semi brittle epoxy materials is developed, expressed in terms of the attainment of a local critical value of the maximum principal stress at the tip of small internal defects. The criterion is assessed on the highly cross-linked structural epoxy resin RTM6 used as matrix in fiber reinforced composites. Based on finite element simulations of unit cells, the local stress field at the tip of ellipsoidal defects is related to the macroscopic loading. The overall fracture stress levels measured on uniaxial tension and compression specimens are used to identify the two parameters of the failure criterion which involves the characteristic aspect ratio of the microdefects and the critical maximum principal tensile stress. An upper bound to the size of the microdefect is determined based on fracture mechanics arguments. The fracture criterion accurately predicts the fracture for a wide range of stress triaxialities from overall compression conditions to tensile with additional hydrostatic component related to different notched configurations.

1. Introduction

The proper modeling and prediction of the mechanical response of fiber reinforced polymers (FRP) used in high-performance structural applications require an accurate and physically sound description of the deformation and failure behavior of the matrix. On the one hand, in many occasions, the composite is considered linear elastic and a variety of failure criteria are used to predict the load carrying capability of components. Advanced criteria [1,2] already include well identified matrix-dominated failure modes, incorporating some (limited) non-linearity in the behavior of the latter [2], based on rough estimations of the stress and strain partitioning between the matrix and the fibers. As in several instances the resin is the locus of first damage [3,4], the assessment of these engineering criteria against detailed micromechanical models of plies and even laminates requires properly identified and accurate constitutive models and failure criteria for the resin itself, in order to predict the failure locus. The failure locus is an image of the dependence of the deformation and failure of the composite on the stress/strain level and stress triaxiality in the constituents of the plies. On the other hand, in certain shear-dominated conditions, the resin dictates even more the response of the component as its ductility plays a more prominent role. A typical example is the bias-loading of biaxial laminates where significant non-linear deformation can be achieved before the occurence of delamination [5]. Beside a good geometrical description of the meso and

---

* Corresponding author.
E-mail address: jeremy.chevalier@uclouvain.be (J. Chevalier).

http://dx.doi.org/10.1016/j.engfracmech.2016.02.039
0013-7944/© 2016 Elsevier Ltd. All rights reserved.

Nomenclature

FE	Finite Element
RVE	representative volume element
MPS	maximum principal stress
CTOD, δ	crack tip opening displacement
$\sigma^{\mathrm{local}}_{\mathrm{princ,\,max}}$	maximum principal stress reached in the vicinity of the small internal microstructural defects
A_r	aspect ratio of the spheroidal defects
σ^{∞}_{ij}	stress tensor at RVE scale
σ_c	local critical principal stress at which failure is initiated
$\bar{\varepsilon}^p$	equivalent plastic strain
σ_y	yield strength
ΔMPS	$\mathrm{MPS}_{tension}-\mathrm{MPS}_{compression}$
ε_f	equivalent fracture strain
G_{Ic}	mode I critical energy release rate
δ_c	critical CTOD

micro-architectures, the modeling of this configuration obviously requires a very good knowledge of the deformation and failure behavior of the resin (as well as of the interfaces). Note that the non-linear behavior of the resin is expected to be of increasing influence as the strain-rate decreases, e.g. such as in creep, and as the temperature increases [6].

In this work, as a major ingredient to subsequent multi-scale analyses, the failure of the aerospace grade structural epoxy resin RTM6 is investigated based on a micromechanical approach, considering the non-linear deformation behavior identified by Morelle et al. [7] as input data.

At first sight, the mechanical behavior of the RTM6 epoxy resin is in line with the generally reported behavior of cross-linked thermoset polymers. It exhibits much larger ductility under compression than under tension in which fracture occurs after a few percents of elongation. However, when considering the mechanical behavior of the RTM6 resin, two main issues arise. First, crazing is not observed. Crazing is known to lead to a brittle failure mechanism, initiated by the fracture of the remaining polymer fibrils within the crazes. The occurrence of crazes within epoxy resins has been reported only very few times and only in moderately cross-linked resins [8,9]. To the authors' knowledge, the appearance of crazes has never been proved in highly cross-linked glassy polymers under tensile loadings, in the presence or not of stress concentrators such as notches or cracks [7,10–12]. Therefore, the highly cross-linked network should prevent RTM6 from crazing, even under positive triaxialities, hence disabling the usual origin for explaining a brittle failure mechanism in glassy polymers. Second, brittle fracture is observed in compression tests albeit at very large deformation above 50%, which can neither be explained by the appearance of crazes nor by the sole propagation of shear bands through the material. This aspect will be addressed in details in this paper. As crazing involves the appearance of micro-voids, the negative triaxiality induced in compression test clearly inhibits such a mechanism, while it is the main mechanism triggered under positive triaxialities [11]. Shear bands were not observed in uniaxial compression tests of RTM6 [7]. However, it is now admitted that shear-yielding can be a true intrinsic diffuse phenomenon, where softening is the result of the initiation, growth and coalescence of micro-shearing zones [13,14]. Nevertheless, despite a significant ductility in compression, Morelle et al. [7] show that no plasticity-related progressive damage could be indirectly (through reduction of the modulus, or a non-saturation of back-stress upon unloading) or directly observed (e.g. particular features on fracture surfaces), and, as a consequence, failure could not be related to shear-induced plasticity or damage.

Some earlier studies in the literature have already been dedicated to the characterization of the visco-plasticity, creep, thermo-mechanical response and/or failure behavior of the RTM6 [7,15,16], as well as of other epoxy systems [12,17–20], including moderately cross-linked resins.

In [7] Morelle et al. identified a series of empirical pressure or triaxiality-dependent macroscopic failure criteria, in-line with the works of Asp et al. [12] and Fiedler et al. [21]. The proposed criteria tacitly assume that micro-cavitation is responsible for failure and have shown a satisfactory predictive capability; however, the link with the micromechanics of cavitation was not made. Besides, several failure criteria for brittle and quasi-brittle solids have been identified beyond the particular case of glassy polymers. Most of them are based on the macroscopic properties of the material, such as the fracture toughness and the tensile strength [22], or on a characteristic length, which, often, does not possess a clear physical basis [23–26]. While these criteria have been shown to successfully predict the failure of many brittle materials, they are not able to unify the cases of brittle failure in both positive and negative triaxialities, and they are mainly motivated by the failure prediction in the presence of a macro-scale stress concentrator. An exception is the criterion developed by Leguillon [22] which was extended by Zhang and Li [27,28] to un-notched specimens. None of these criteria provide a satisfying approach to explain the brittle failure both in compression and in tension of RTM6. The brittle and quasi-brittle fracture of materials under compression has been extensively studied by Wang and Shrive [29–31], mainly considering concrete and rocks. Their approach consists in considering that brittle fracture in compression is caused by surface separation involving a mode I cracking mechanism. They explained the appearance of this mode I cracking by the nucleation of cracks at the tip of