Micromechanical modeling of time-dependent failure in transversely loaded composites
Govaert, L.E.; Smit, R.J.M.; Peijs, A.A.J.M.

Published in:
10th International conference on deformation, yield and fracture of polymers, Cambridge, UK, April 7-10, 1997

Published: 01/01/1997

Document Version
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the author's version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Citation for published version (APA):

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.
MICROMECHANICAL MODELLING OF TIME-DEPENDENT FAILURE IN TRANSVERSELY LOADED COMPOSITES

L.E. Govaert*, R.J.M. Smit† and T. Peijs†

In this study the time-dependent fracture behaviour of transversely loaded E-glass/epoxy laminates is investigated using a 3-D micromechanical finite element approach in combination with a constitutive equation, that is able to capture the yield behaviour of the epoxy matrix. It is shown that this approach, in combination with a strain criterion for matrix failure, can be used successfully for the prediction of the rate dependent tensile strength and the creep lifetime of transversely loaded E-glass/epoxy composites.

Introduction

Models for the prediction of strength of composite materials are generally directed to short-term failure using laminate analysis based on classical mechanics, coupled with a common failure theory such as maximum stress or maximum strain concepts. Since almost all engineering components are subjected to load and environmental histories which differ strongly over the service time of the component, it is clear that there is a need for the development of new approaches for the prediction of failure of composites which enable us to include time-variable circumstances. In case of matrix dominated failure-modes, such as transverse and shear failure, it seems therefore obvious to investigate the time- and stress-dependent failure of the polymer matrix.

With recent developments in three-dimensional constitutive modelling of large strain plasticity in amorphous polymers [1-3], the numerical simulation of the behaviour of the polymer matrix under complex loading conditions is well within reach. In this research this technique was employed, in combination with micromechanics, to evaluate short-term and long-term transverse failure of unidirectional glass/epoxy laminates.

Experimental

A rather brittle epoxy system of Ciba Geigy (Araldite LY556/HY917/DY070) was used as matrix system in this study. This epoxy system is based on diglycidyl ether of bisphenol-A with an anhydride curing agent. E-glass fibres (Silenka 0.84-M28) were used as reinforcement material.

* Centre for Polymers and Composites, Eindhoven University of Technology
In order to characterize the yielding behaviour of the matrix five different (multi-axial) tests were performed on the pure matrix material at strain rates varying over several decades, viz. uniaxial extension, uniaxial compression, planar extension, planar compression and simple shear tests. The testing of the unidirectional composites consisted of transverse three-point bending experiments at different strain rates. The composites were also tested under (constant load) creep conditions in three-point bending.

Characterization of matrix material

In this research, a three-dimensional yield expression, usually referred to as pressure modified Eyring flow, is employed to describe the multi-axial yield behaviour of the epoxy matrix. This approach was initially proposed by Ward and Duckett [4] and expresses the stress state and deformation rate at the yield point in terms of the octahedral shear stress \( \sigma_{oct} \) and the octahedral shear rate \( \dot{\gamma}_{oct} \), respectively:

\[
\dot{\gamma}_{oct} = \gamma_s \sinh \left( \frac{\sigma_{oct} - \gamma_s}{k T} \right) \exp \left( \frac{-P \Omega}{k T} \right)
\]

where \( T \) is the absolute temperature, \( k \) is Boltzmann's constant, \( \Omega \) is the shear activation volume, \( P \) is the hydrostatic pressure, \( \gamma_s \) is the pressure activation volume and \( \gamma_s \) is, in isothermal conditions, a material constant. The results of the uniaxial extension, planar extension, uniaxial compression, planar compression and simple shear test are presented in Fig. 1, where the octahedral shear stress is plotted versus the octahedral shear rate for all loading geometries. All experiments were performed at room temperature (295 Kelvin). The drawn lines are predicted by Eq. 1, using: \( \gamma_s = 1.5 \times 10^{-21} \text{ s}^{-1}, \) \( \Omega = 0.441 \text{ nm}^3 \) and \( \sigma = 3.5 \text{ nm}^3 \), showing clearly that all experiments are in good agreement with this modified Eyring equation.

Micromechanical analysis of composite materials

To account for the complex stress and strain situation in a composite, micromechanical simulations are performed with the Finite Element Method (FEM). The micromechanical simulations are based on a hexagonal fibre array, from which the finite element mesh, representing a fibre volume fraction of 50\% is shown in Fig. 2. To facilitate finite element analysis a three-dimensional constitutive model is required. In this study the compressible Leonov model was used, which is described in detail elsewhere [3]. In this model the matrix material is regarded as a linear elastic, compressible solid up to the yield point, with a modulus of 3200 MPa and a Poisson's ratio of 0.37. The yield behaviour of the material is described as a generalised Newtonian fluid with a flow characteristic according to the data presented in Fig. 1. The strain hardening behaviour was also modelled as a Gaussian, rubber elastic spring. The rubber modulus was estimated at 31.5 MPa, as determined experimentally with dynamic mechanical thermal analysis.

Since there is no limit to the deformation in the constitutive model an additional failure criterion is needed. In this study a limiting value of 15\% for the octahedral shear strain was chosen. This value
was estimated from a numerical simulation of a tensile experiment at a global strain rate of $10^{-4}$ s$^{-1}$ by evaluating the local strain state in the composite at an externally applied stress equal to the experimentally observed tensile strength. For the prediction of failure at other strain rates or under the influence of a statically applied stress (creep), a micromechanical simulation of the desired test was performed up to a global state of deformation where the local maximum of the octahedral shear strain equals the critical value of 15%.

Validation

The results of maximum stress versus strain rate of the composites in three-point bending are presented in Fig. 3. The error bars are the standard deviation of the experimental outcome. The predicted strain rate dependence of the transverse strength is represented by the solid line and shows that the experimental results are well described by the strain criterion. Similar to the constant strain rate tests, the numerical predictions for creep failure were compared with experimental results. Again the local strain criterion is used to predict the creep time to failure for the different applied engineering stresses. The results of the experiments and the numerical simulations are shown in Fig. 4. It can be seen that the micromechanical model in combination with this failure criterion is able to describe time to fracture of the transversely loaded E-glass/epoxy composites.

Conclusions

In this study it is demonstrated that the modified Eyring equation can be satisfactory used for the description of the yield behaviour of the epoxy system under multi-axial loading conditions. The various multi-axial experiments also showed that the epoxy system clearly exhibits a pressure dependent yield behaviour. By introducing these parameters into the compressible Leonov model, numerical (FEM) simulations of the mechanical behaviour of the epoxy system could be performed. Micromechanical simulations of rate dependent transverse strength of unidirectional composites, showed the validity of a failure criterion based on a maximum local strain. Moreover, this failure criterion could be used for the prediction of creep time to failure.

References