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Experimental determination of the micro-scale strength and stress-strain relation of an epoxy resin

Sanita Zike *, Bent F. Sørensen, Lars P. Mikkelsen

Composites and Materials Mechanics Section, Department of Wind Energy, Technical University of Denmark, Risø Campus, 4000 Roskilde, Denmark

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ABSTRACT

An approach is developed for determining the stress-strain law and a failure stress appropriate for micro-mechanical models of polymer materials. Double cantilever beam test specimens, made of an epoxy polymer with notches having finite root radius, were subjected to pure bending moments in an environmental scanning electron microscope. The recorded images were used to measure strains around the notch with a 2D digital image correlation method. The strain in front of the notch was found to reach 20% before the failure initiation, which significantly exceeds the failure strain measured at the macro-scale (5–6%). The hardening exponent of a power law hardening material was obtained by the use of the J-integral, estimating the strain energy density around the notch. The hardening exponent was found to be within the range of 5–6 and the corresponding micro-scale failure stress was in the range of 220–300 MPa. Furthermore, the experimentally measured strains around the notch edge were compared with the strain field of the HRR-field. In addition, our experimental study shows that the strain fields between the notches with different notch root radii are comparable, if all length parameters are normalized with the width of deformed notch.

1. Introduction

Polymer/fibre composite materials are often used in structural load carrying components. For instance, in the wind energy industry, polymer/fibre composites are used in rotor blades, due to their high stiffness, low density, and good fatigue performance [1,2]. The fibres are usually designed to carry the main load of the composite structure. Some of the microscopic processes, however, are greatly dependent on the matrix behaviour, e.g. loading transverse to the fibres. At the micro-scale, the failure of the matrix initiates from a flaw in the matrix or at a fibre/matrix interface leading to the fibre-matrix debonding and fibre cracking. These micro-scale events result in a macro-scale failure, e.g. delamination between plies, reducing performance of the composite structure [3]. For this reason, micro-mechanical models are often used to study the effect of micro-scale material properties and microscopic defects on the microscopic damage evolution.

In this paper, we aim to determine the matrix material properties (the stress-strain law and the failure stress) to be used in micro-mechanical models for the simulation of progressive damage evolution in composite materials. First, in order to characterize micro-mechanical behaviour of matrix, its properties have to be determined at the relevant length scale. The macroscopic stress-strain law and tensile strength of a material is not sufficient for use in micro-mechanical modelling. Consider a simple uniaxial tensile testing of a material, shown in Fig. 1a, that fails by brittle fracture, i.e. from pre-existing flaws. At the macro-scale, we consider the material as well as stress and strain fields to be uniform, i.e. the same at any point within the gauge section. Model wise, the macroscopic failure stress would be determined simply as the force at failure, F_u, divided by the cross-section area, A, i.e. the average failure stress $\tilde{\sigma}_u = F_u/A$. Likewise, the macroscopic failure strain $\tilde{\varepsilon}_u$ will be determined from the macroscopic deformation, e.g. the elongation ΔL measured by an extensometer with a certain initial gauge length, L_o, $\tilde{\varepsilon}_u = \Delta L/L_o$. A strain gauge will also give the strain averaged over its gauge length. These strength values are appropriate for modelling structures at the macro-scale.

On the micro-scale, however, the situation is very different. Here we will consider the material as heterogeneous, such as a composite consisting of discrete fibres in a matrix material that contains micro-scale defects (Fig. 1b). The stress and strain fields will be non-uniform, depending on micro-scale features. Failure will initiate from a pre-existing flaw. A pre-existing flaw, e.g. a pore (e.g. an air bubble) in a polymer material, will create a local stress concentration and multi-axial stress state at the vicinity of the pore (Fig. 1b) and a plastic zone can form around the fracture process zone (Fig. 1c), represented by a non-linear stress strain law. A fracture process zone will form when the stress at a pore reaches the micro-scale strength, denoted as σ_n. The fracture process zone will develop into a micro-crack that will eventually grow into a macro-crack that will propagate across the entire cross-section of the specimen leading to macro-scale failure. At the instance when the fracture process zone begins to form, and the micro-scale stress at the pore is equal to $\sigma = \sigma_n$, the associated strain is

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* Corresponding author.
E-mail address: sanita.zike@gmail.com (S. Zike).

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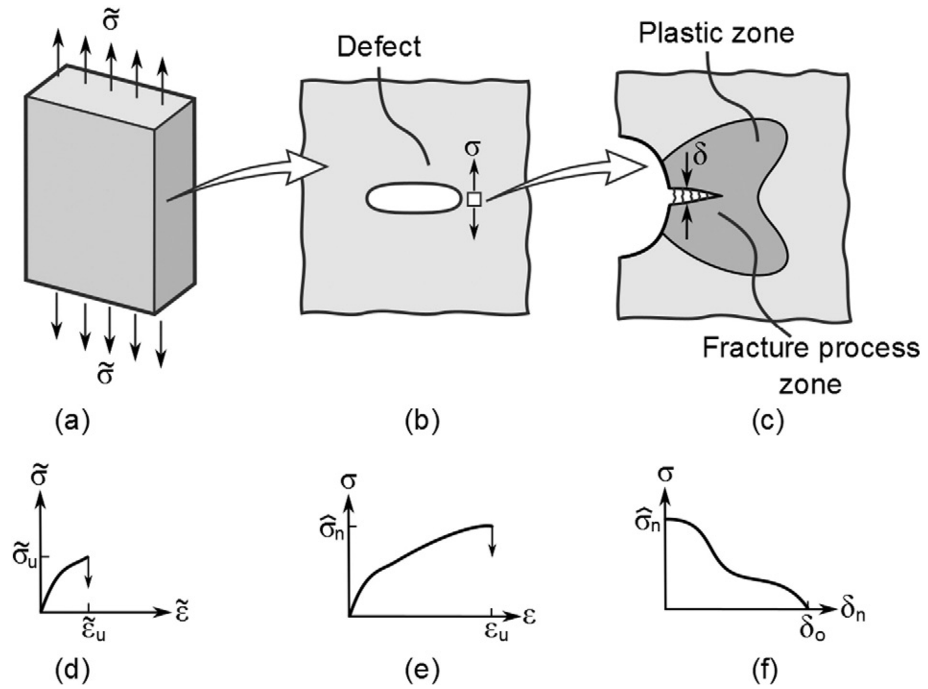

Fig. 1. Schematics of failure at macro-scale (a) and micro-scale with defects (b) and plasticity at the fracture process zone. Macro-scale stress-strain law (d), micro-scale stress-strain law (e), micro-scale traction-separation (cohesive) law (f).

equal to the micro-scale failure strain, ε_u (Fig. 1d). Once a fracture process zone has formed, its mechanical behaviour can be represented by a cohesive law (traction-separation law) as shown in Fig. 1f, i.e. $\sigma_n = \sigma_n(\delta_n)$, where δ_n is the normal opening displacement of the formed crack faces within the fracture process zone. The micro-scale strength, σ_n, and the associated failure strain, ε_u, will be higher (Fig. 1e) than the associated macroscopic properties (Fig. 1d), $\sigma_n > \tilde{\sigma}_u$ and $\varepsilon_u > \tilde{\varepsilon}_u$ An example of a determination of a complete micro-scale cohesive law, obtained by a J-integral approach based on the measurement of the end-opening, δ_n^*, of a sharp pre-crack by high-resolution images obtained by ESEM experiments is given by Goutianos et al. [4].

In case we wish to make a micro-mechanical model of the experiment described above, it is obvious that we cannot use $\tilde{\sigma}_u$ as a local stress criterion for failure at the micro-scale. We need to know the local micro-scale strength σ_n, and we must know the micro-scale stress-strain law in the entire strain range, $0 < \varepsilon < \varepsilon_u$. It is thus the micro-scale failure strength and failure strain that should be used in micro-mechanical models. Therefore, in the present study, we aim to develop an approach to determine the micro-scale stress-strain law in the strain range beyond that obtainable from a traditional macroscopic tensile test, $\tilde{\varepsilon}_u < \varepsilon < \varepsilon_u$, and determine the micro-scale strength σ_n.

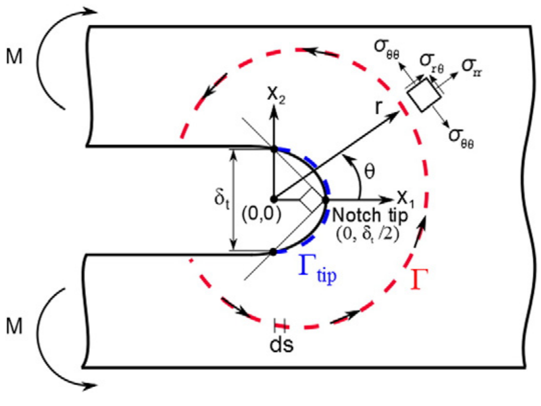

Fig. 2. Contours used for the J-integral determination.

In order to obtain the micro-mechanical properties of a polymer material, specimens with a finite notch root radii were made to mimic the stress state around a void. The specimens were subjected to double cantilever beam (DCB) tests in a vacuum chamber of an environmental scanning electron microscope (ESEM). From the images captured in the ESEM, the micro-scale strains around deformed notches were measured with the 2D digital image correlation (DIC) method using the commercial software ARAMIS [5]. The strain fields between the notches with initially different root radii were compared normalizing all length parameters with the width of deformed notch in accordance to McMeeking's numerical study [6].

2. Theory

2.1. Strain field at the notch

In order to characterize mechanical behaviour of a non-linear elastic polymer around the notches with finite root radii, the theory of non-

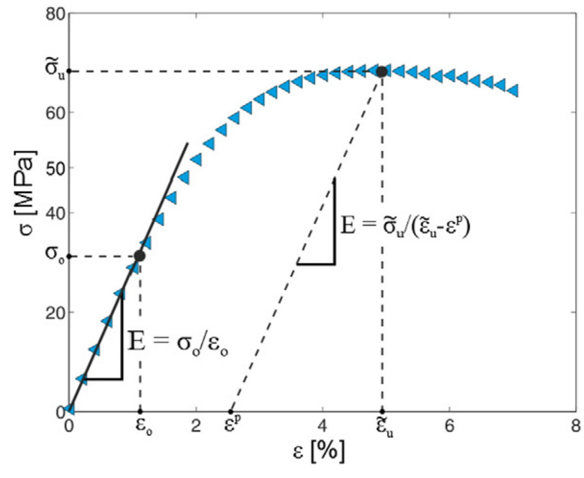

Fig. 3. The averaged macroscopic stress-strain curve in tension of the epoxy resin.