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Fracture of notched samples in epoxy resin: Experiments and cohesive model

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ABSTRACT

The prediction of failure loads in notched samples has been one of the most motivating fracture mechanics issues for a long time. Most efforts have been focused on the application of theoretical models with much less care in the experiments themselves.

In this work the fracture of notched samples in epoxy resin is addressed from experimental and theoretical approaches. A set of fracture experiments has been carried out with a wide range of notch tip radii. Special care has been taken to ensure the accuracy of the notch geometry. Experiments have been compared with numerical predictions using the cohesive zone model and local fracture criteria based on the Theory of Critical Distances.

1. Introduction

Brittle fracture is promoted by the presence of stress concentration, which is inevitable in engineering components as a consequence of geometric features such as holes, corners and grooves. Loading modes can also produce stress gradients including torsion or bending [1].

A notch is an easy way to introduce stress concentration in laboratory specimens, firstly, due to simplicity and, secondly, because the mode of testing is basically unaltered in comparison with un-notched specimens. The conditions created inside the material by the introduction of a notch are intermediate between cracks and plain specimens. Fracture Mechanics or the simple use of stress concentration factor may not be enough to describe the failure of a notched specimen. Predicting failure under stress concentration effects is not so straightforward and, then, failure criteria considering these effects are needed [1,2].

1.1. Stress fields around notches

The main characteristics of a notch are the depth, a, the tip radius, ρ, the notch angle, α, and the notch shape. The most influential factors are, in practice, a and ρ, provided that α is limited to small values ($\alpha < 90°$).

Stress fields near the tip of sharp V-notches can be characterized in mode I loading by the generalized stress intensity factor, K^V, when dealing with linear elastic materials.

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Nomenclature

a	notch depth
A	α dependent function
B	α dependent function
d_c	critical distance (mean stress and maximum stress criteria)
D	geometrical dimension of the specimen
f_{ij}	function of the polar angle θ
f_t	tensile strength
G_C	cohesive fracture energy
K_{IC}	fracture toughness
K_t	stress concentration factor
K^U	stress intensity factor of a U-notch
K^{U*}	non-dimensional stress intensity factor of a U-notch
K^V	stress intensity factor of a sharp V-notch
$K^{V,\rho}$	stress intensity factor of a blunted V-notch
l_{ch}	characteristic length
PC	polycarbonate
PMMA	poly(methyl methacrylate)
r	radial coordinate of a polar coordinate system
R^*	non-dimensional tip radius
T	temperature
w	crack opening displacement
w_c	critical crack opening displacement
α	notch angle
$\dot{\varepsilon}$	strain rate
θ	angular coordinate of a polar coordinate system
λ	non-dimensional parameter that characterizes the strength of singularity
μ	α dependent function
ρ	tip radius
σ_c	critical stress (mean stress and maximum stress criteria)
σ_{ij}	stress around a notch
σ_N	nominal stress
σ_t	cohesive strength
σ_{TIP}	maximum principal stress at the notch tip
σ_θ	circumferential stress at the notch tip

$$\sigma_{ij}(r,\theta) = \frac{K^V}{\sqrt{2\pi} r^{1-\lambda}} f_{ij}(\theta,\lambda) \tag{1}$$

where (r,θ) represent the polar coordinate system with origin indicated in Fig. 1, λ is a function of α and f_{ij} a function of the polar angle θ, and also of the notch angle, α, [3,4]. The parameter λ characterizes the strength of the singularity, ranging from 0.5 when α is zero to 1.0 when 2α is 180°. The generalized stress intensity factor, K^V, can be written in terms of the nominal stress, σ_N, α, a geometrical dimension of the specimen, D, and the notch depth, a, according to the following expression:

$$K^V = \sigma_N D^{1-\lambda} f(\alpha, a/D) \tag{2}$$

At the limit, when α approaches to zero and λ to 0.5 the last equation reduces to the standard stress intensity factor of Fracture Mechanics for cracks.

Stresses around blunted V-notches can be similarly stated. Filippi et al. [5] derived approximate expressions that can be used for stresses along the x-axis, for mode I and near the notch root (Fig. 1):

$$\sigma_\theta(r,0) = \frac{K^{V,\rho}}{\sqrt{2\pi} r^{1-\lambda}} + \frac{K^{V,\rho}}{\sqrt{2\pi} r^{1-\lambda}} \left(\frac{r_0}{r}\right)^{\lambda-\mu} \frac{B(\alpha)}{1+A(\alpha)} \tag{3}$$

where A, B, λ and μ are functions of α, being $\lambda > \mu$, and r_0 is shown in Fig. 1. The first term of the last expression has the same r dependence as those for sharp V-notches and in the cases when it is dominant, the result is similar to that of Eq. (1). In the paper of Filippi et al. [5] a detailed discussion is included about the significance of every term in Eqs. (2) and (3). In the Eq. (3), the generalized stress intensity factor for blunted V-notches in the case of linear elastic behaviour can be written in terms of the circumferential stress at the notch tip:

$$K^{V,\rho} = \sqrt{2\pi}\sigma_\theta(r_0,0) r_0^{1-\lambda} f(\alpha) \tag{4}$$