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Technical Note

Fracture toughness of woven textile composites

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ABSTRACT

Single edge notched tensile specimens (SENT) are used to measure the fracture toughness of a woven textile composite. Both, the finite element method and available stress intensity factor (SIF) solutions to the SENT are used to calculate the SIF. Linear elastic fracture mechanics, the size effect law and cohesive zone model are used to determine the critical energy release rate. In this note, the importance of using an accurate SIF solution and a proper method to determine the fracture toughness are demonstrated.

1. Introduction

Fracture mechanics has been widely used in metal and composite structural analysis. The application of linear elastic fracture mechanics (LEFM) in residual strength prediction requires the measurement of the material resistance and elastic solution to the fracture mechanics parameters, for example, SIF and energy release rates. Various test specimens are designed and used to obtain the fracture properties of different composite materials, ranging from continuous fiber reinforced composites to textile composites. The solutions to the stress and displacement fields for various cracked configurations of isotropic plates have been provided in handbooks [1]. However, there are only relatively few cases of solutions to cracked composite laminated plates, modeled as equivalent orthotropic materials [2]. This is due to the fact that the SIFs for cracks in orthotropic materials are not only a function of the crack geometries and boundary conditions, but are also related to the material properties [2–4]. Closed form solutions to the commonly used fracture test specimens were given by Bao et al. [3,4]. For purposes of expediency, the SIF solution to an isotropic cracked specimen was sometimes used for analyzing cracks in orthotropic materials [5]. It was shown [2–4] that the correction factors (finite size) for SIF of a cracked specimen made of isotropic and orthotropic material may be quite different. In this paper, it is shown that if Bao et al.'s closed form solution to a center crack in an orthotropic material plate is not appropriately used, it can lead to a non-negligible error when interpreting its application to test results. This aspect is addressed in this paper by studying the single edge notched tensile (SENT) specimen for obtaining fracture toughness.

LEFM is restricted to those cases where the damage zone size in the vicinity of a crack tip is much smaller than the crack length. An invalid fracture resistance will be obtained without checking this constraint of LEFM. Therefore, a valid fracture resistance should be based on the correct SIF solution that also meets the small damage zone size constraint. In this note, results from SENT specimens are used to address the importance of the correct SIF solution and the validation of LEFM to determine the correct fracture toughness.

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2. SENT specimen

Two different sizes of SENT specimens were designed and tested by the present authors [6]. The notch in the SENT specimens was made by first cutting it with a 2 mm thickness blade, then a 0.26 mm thickness saw was used to sharpen the notch to make it closer to an ideal crack. The small sharpened crack is about 1.0 mm. The geometry and size of the specimens are given in Fig. 1 and Table 1. For each type of SENT, three specimens were tested. The specimen was made of carbon fiber twill weave textile composite. Displacement control loading was used for this test.

2.1. Bao et al.'s SIF solution

A closed form expression for the SIF solution to a single edge crack in an orthotropic material under uniform tensile stress was given by Bao et al. [3,4]. It has been widely used in the calculation of SIF or equivalently energy release rate. The SIF was given as [3,4]:

$$K_I = \sigma\sqrt{\pi a}Y(\rho)F(a/w) \tag{1a}$$

$$Y(\rho) = [1 + 0.1(\rho - 1) - 0.016(\rho - 1)^2 + 0.002(\rho - 1)^3] \cdot \left(\frac{1+\rho}{2}\right)^{-1/4} \tag{1b}$$

$$F(a/w) = \sqrt{\frac{2w}{\pi a}\tan\frac{\pi a}{2w}} \cdot \frac{0.752 + 2.02\frac{a}{w} + 0.37\left(1 - \sin\frac{\pi a}{2w}\right)^3}{\cos\frac{\pi a}{2w}} \tag{1c}$$

$$\rho = \frac{\sqrt{E_{xx} \cdot E_{yy}}}{2G_{xy}} - \sqrt{\nu_{xy} \cdot \nu_{yx}} \tag{1d}$$

$$\lambda = \frac{E_{yy}}{E_{xx}} \tag{1e}$$

where a and w are the crack length and the width of the specimen, respectively. The orthotropic mechanical properties of the textile composite are $E_{xx} = E_{yy} = 60.5$ GPa, $\nu_{xy} = 0.056$, $G_{xy} = 4.07$ GPa, given in [6].

The accuracy of (1b) was stated to be within 2% for $0 \leqslant \rho \leqslant 4$ and any λ. However, in the present case, ρ is 7.4, which means the accuracy of (1b) may be not guaranteed. In addition, Eq. (1) was obtained from SENT subjected to uniform tensile pressure at the left and right edges as shown in Fig. 1. In a laboratory test, the boundary condition is close to that of uniform displacement. Due to these two reasons, Eq. (1) may be not accurate for the present SENT. As a result, the finite element method (FEM) was used to calculate the SIF by first calculating the energy release rate.

2.2. Finite element solution to SIF

There are many ways to calculate G for a Mode I crack using FEM. The Virtual Crack Closure Technique (VCCT) and J-integral implemented in the commercial FE code ABAQUS are used to obtain the energy release rate. The finite element model for the large SENT tested is shown in Fig. 2. Only one half of the specimen is modeled. The global size of the finite element model is 50 mm × 75 mm. Very fine mesh is used to model the crack tip. The finest element size is 0.0195 mm × 0.0195 mm. The element size is gradually transferred into large element to reduce the computational demand. Plane stress elements, CPS4, are used in the calculation. Both the remote uniform displacement and tensile pressure boundary conditions are used to study the effect of boundary conditions on the SIF. The remote uniform boundary condition is shown in Fig. 2b, where the top edge is applied uniform pressure, the node at the right bottom corner is constrained to move. As show in Fig. 1, a significantly long region of the specimen is gripped by the hydraulic test machine. Therefore, specimen rotation is prevented at the clamped edge, despite the fact that the SENT specimen has propensity to rotate at the edges due to the asymmetry. The clamped location in the real specimen is modeled by uniform displacement boundary conditions. That is $u_x = 0$, $u_y = \delta$ are applied at the clamped edge as shown in Fig. 2c.

The outputs from the simulation are the nodal displacements, nodal reaction forces and the J-integral. Using the nodal force and displacement component in the y-direction at the crack tip and behind the crack tip, the energy release rate

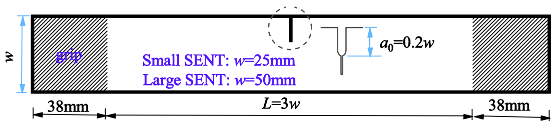

Fig. 1. Geometry and dimension of the SENT specimens.