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Noncontact optical measurement of CTOA and CTOD for interface crack in DCB test

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ABSTRACT

The crack-tip opening angle (CTOA) and the crack-tip opening displacement (CTOD) are used as fracture parameters for characterizing the resistance of a material to fracture and predicting the instability of crack propagating fracture process. Digital image correlation method (DIC) was used to measure the displacement fields in a double cantilever beam (DCB) test with an initial interfacial crack. An apparent crack-tip was determined using the *y*-displacement along two parallel lines of the two crack flanks, which in turn enables the CTOA and CTOD to be evaluated. The experimental results revealed that the extension process for interface crack is divided into stable and unstable crack extension phases which changed alternately in the DCB test. The crack growth rate (CGR) varied from one stable phase to another, but was a constant value within each stable phase. The CGR, however, increased gradually over time within the unstable phases. The CTOA and CTOD did not increase synchronously in the loading process: the CTOA begins to increase at the first stable crack growth phase, whereas, the CTOD increased rapidly with the CTOA until entered into the second phase of unstable crack propagation. The above crack propagation behaviour on the bi-material corresponds to the interface crack transition, which is transformed from the tearing crack Mode I gradually into the mixed Mode I/II crack form.

1. Introduction

The critical crack-tip-opening angle (CTOA) and displacement (CTOD) are considered as basic parameters to characterize the ability of resistance-tearing and the prediction of instability during materials fracture process. The CTOA is a fracture criterion to judge the opening extent of two crack flanks at specified distance behind the moving crack-tip. The criteria of linear elastic fracture considers that the CTOA is a constant and is independent of the loading and geometry conditions when the crack length is about 4 times greater than the plate thickness [1,2]. However, the CTOA would be smaller along the thickness direction and can be considered as a function of the crack extension length when a tunnelling effect appears on the fracture specimen [3,4]. For the elastic–plastic fracture mechanics, the energy dissipation rate has been introduced as a driving force for crack extension. The energy dissipation rate is calculated from the CTOD, which is obtained from the CTOA experiment.

There are two basic experimental methods to characterize the crack CTOA value [5]. A typical method is the so-called δ_5 experimental method, which uses a strain gauge to measure the displacement at a position which is 5 mm away from the initial crack-tip. At the beginning of loading δ_5 is an initial local deformation parameter, but with the spread of crack δ_5 becomes a global deformation parameter. The other one is an optical experimental method, namely, the real-time images of crack-tip extension are captured and the crack-tip location is accurately determined at every moment, from which the CTOA results can be obtained. The disadvantage of the optical experimental method is that it is sometimes difficult to determine the crack-tip locations from the captured images. Recently, an "apparent crack-tip" method, which depends only on the shape of crack flanks to determine CTOA and thus reduces the exact requirements to determine the crack-tip position and is helpful to study the cracking case at edge of the crack-tip [6–8].

A method for measuring the CTOA is provided by the guidelines of ASTM E2472 [9]. As shown in Fig. 1(a), nine parallel lines come from nine pairs of points intersecting at two crack flanks in the image when the location of the crack-tip is given. The distance to the crack-tip for the first pair of intersections is $r_1 = 0.5$ mm, and the other pairs of points have an interval of r_n-$r_{n-1} = 0.125$ mm. By measuring the distance δ_n between each pair of intersections, the

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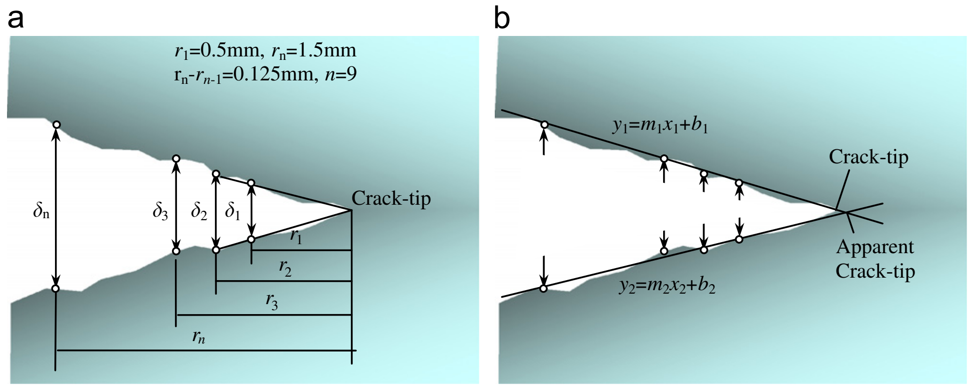

Fig. 1. Illustration of CTOA measurements, (a) ASTM E2427 guidline and (b) fitting line method.

CTOA can be obtained and then an average of the nine CTOAs is regarded as a standard CTOA for this moment.

In many cases, the crack-tip is invisible and it is difficult to determine the true location of the crack-tip from the images, and hence the ASTM E2472 specifications cannot be applied to actual measurement. An improved method is to use the points on the crack flanks to fit linearly [6], as shown in Fig. 1(b), there the intersection of the two fitted line is defined as the apparent crack-tip. Using the nine pairs of points specified in the ASTM E2472 guidelines as the reference points to fit two lines, there is no limit to the fitted straight lines through these reference points. The apparent crack-tip is not the real crack-tip but the location drived by the crack flanks. It also reflects the degree of crack opening. The advantage of using the apparent crack-tip instead of the real crack-tip is the ability to determine the location of the invisible crack-tip.

In this study, an improved optical measurement method is developed to determine the CTOA and CTOD of a bi-material cantilever including an interface crack. Using a digital image correlation method (DIC) to determine the displacement fields near the bi-material interface, the apparent crack-tip position is located from the linear fitting of the vertical displacement field at two parallel reference lines along the interface. The evolution of CTOA and CTOD fracture parameters in the loading process is discussed, and the crack propagation behaviour of the bi-material interface is further explored.

2. Methodology and experimental

2.1. DIC

The DIC method is a powerful optical numerical method to estimate full-field relative displacements from two digital images including the deformational information of the specimen [10,11]. The basic principle of the DIC method is to match the maximum correlation between subsets in the images, which have the undeformed and deformed states of the specimen coated by a random pattern (see Fig. 2). The image correlation is performed by comparing subsets from a reference image with subsets from each of the deformed images.

Consider a situation when a point P located at coordinate (x, y) and its adjacent subset f in the undeformed image change to the point P' at coordinate (x', y') and its adjacent subset g in the deformed image. This subset is used to find the corresponding target subset on the deformed image. DIC is used to search the location P' accurately by maximising the correlation coefficient. The relative in-plane displacement (u, v) at the subset centre satisfies

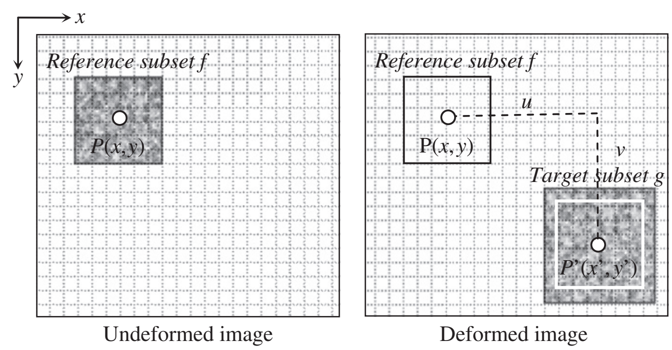

Fig. 2. Illustration of our proposed CTOA measurement in this study.

$$\begin{cases} x' = x + u + \frac{\partial u}{\partial x}dx + \frac{\partial u}{\partial y}dy \\ y' = y + v + \frac{\partial v}{\partial x}dx + \frac{\partial v}{\partial y}dy \end{cases}, \tag{1}$$

where the displacements (u, v) and first derivations $(\partial u/\partial x, \partial u/\partial y, \partial v/\partial x, \partial v/\partial y)$ are evaluated iteratively and determined from the position with the maximum correlation coefficient C, which is defined as

$$C = \frac{\Sigma(f_i(x,y)-f_m)(g_i(x',y')-g_m)}{\sqrt{\Sigma(f_i(x,y)-f_m)^2\,\Sigma(g_i(x',y')-g_m)^2}}, \tag{2}$$

where $f(x, y)$ and $g(x', y')$ are the grey-scale matrices of the subset f at location (x, y) in the undeformed image and the subset g at location (x', y') in the deformed image, respectively. f_m and g_m are the mean value of the elements in the subset f and g.

The classic cross-correlation method has proven to be efficient and robust in conducting a correlation search [11]. After the search of integer pixel with maximum correlation, the successive search can be continued in the subpixel domain from 0.1 pixels to 0.01 pixels. As the accuracy of this method is approximately equal to 0.01 pixels, it provides an accurate detector to study how the crack initiats and propagats [12,13].

2.2. DCB test

Using a bi-material cantilever beam test (DCB) to study the behaviour of interface crack, as shown in Fig. 3, a carbon fibre laminate ($80 \times 26 \times 2$ mm^3) and a piezoelectric ceramic plate ($80 \times 26 \times 6$ mm^3) are binded together. An interface crack is made with a 13 μm thick Teflon film, and the crack length is $a_o = 20$ mm. The distance from the load position to the crack-tip is about 18 mm.