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An inverse analysis of cohesive zone model parameter values for ductile crack growth simulations

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ABSTRACT

An inverse analysis using a modified Levenberg–Marquardt method is carried out to identify cohesive zone model parameter values for use in 3D finite element simulations of stable tearing crack growth events in Arcan specimens made of 2024-T3 aluminum alloy. The triangular cohesive law is employed in the simulations. The set of cohesive parameter values is determined in the inverse analysis by minimizing the difference between simulation predictions of key points on the load–crack extension curve with experimental measurements. From three different initial values, similar cohesive parameter value sets are reached. Using these sets of values, the predicted load–crack extension curves and the variation of a generalized crack tip opening displacement (CTOD) with crack extension for mixed-mode loading cases are compared with experimental measurements, which provide a validation of the cohesive parameter values and of the finite element simulation predictions.

1. Introduction

Numerical simulations of stable tearing crack growth events play an important role in assessing the structural integrity and residual strength of critical engineering structures such as aircraft. For many fracture events, the cohesive zone model (CZM) concept [1–3] has found wide applications in numerical simulations (e.g. [4,5]). CZM represents the behavior of the fracture process zone and describes the relationship between cohesive tractions and separations across the cohesive crack surfaces. Due to its strong physics basis and ease in numerical implementation, the CZM approach has been utilized for a wide range of material systems (e.g. [6–12]).

In order to apply the CZM approach in numerical simulations, the values of CZM parameters must be properly specified to define the cohesive traction and separation relationship. However, these parameters are often not readily measurable experimentally. There are yet no well-established universal rules for determining CZM parameter values. In practice, the cohesive parameter values are usually assumed or found by trial and error through matching simulation predictions with certain experimental measurements. To make this matching procedure automatic, the use of a numerical inverse analysis method is preferred.

Inverse analysis methods arise from the need to estimate unknown parameters or conditions in a physical system by matching certain system responses with measured or specified conditions. These methods are now widely employed in many fields of engineering and sciences, such as for heat conduction problems [13], medical and biological problems [14], acoustic problems [15], and in modeling explosive events [16], just to name a few. In general, an inverse analysis method is composed of two parts: (a) a forward analysis and (b) an optimization procedure. In the forward analysis, the unknown parameters are assigned initial values or given updated values from the optimization procedure and then the system response is predicted. In the optimization procedure, the predicted system response is compared with the measured response to produce updated parameter values for the forward analysis in order to minimize the difference between the predicted and measured system responses. The forward analysis and optimization procedure are iterated until the difference between the predicted and measured system responses is below a certain error tolerance.

In the optimization procedure, various methods (e.g. [17]) have been proposed for different kinds of problems, including, for example, Golden Section methods, Gauss–Newton methods, extended Kalman filters, genetic algorithms, neural networks. Among these techniques, the Levenberg–Marquardt (LM) method is one of the efficient inverse operators for solving engineering problems. This method was first proposed by Levenberg [18] and Marquardt [19] for least-squares estimation of nonlinear parameters. It is effective for dealing with

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ill-posed problems and small residual problems. In engineering practice, the unknown parameters or conditions should vary within reasonable physical boundaries, instead of a full range of mathematically possible values as in pure mathematical models, otherwise the inverse procedure will not be practical. To this end, the Levenberg–Marquardt method has been modified using weighted penalty functions, so that the parameters will be optimized under specified constraints (e.g. [20]). With this modification, the LM method is called the modified LM method.

There have been few studies in the literature that focus on the identification of cohesive zone model parameter values using inverse analysis. The available studies have been limited to the modeling of fracture in brittle or quasi-brittle materials. Bolzon et al. [21] used the Kalman filter method to solve parameter identification problems in a Mode I cohesive crack model, on the basis of experimental data generated by wedge-splitting tests on concrete specimens. Gain et al. [22] proposed a hybrid technique to extract cohesive fracture properties of a quasi-brittle material (PMMA) using inverse analysis and surface deformation measurement data.

The current investigation will study the viability of inverse analysis technique in estimating cohesive zone model parameter values for ductile materials in stable tearing crack growth tests by using Mode I crack growth measurement data, and will apply the estimated CZM parameter values to simulate both Mode I and mixed-mode I/II stable tearing crack growth tests. After exploring the applicability of a number of inverse analysis methods, the current study finds that the modified LM method, along with experimental measurements of the load vs. crack extension curve of test specimens, can be used to determine CZM parameter values for stable tearing crack growth tests [23] in Arcan specimens made of 2024-T3 aluminum alloy. The details of the current study are presented in subsequent sections.

2. Problem description

2.1. Arcan test

To study the viability of inverse analysis in estimating cohesive parameter values for simulating stable tearing crack growth events in ductile materials, the current study utilizes the Arcan test data [23]. The Arcan fixture and specimen are designed to facilitate stable tearing crack growth tests under mixed-mode I/II loading conditions ranging from pure mode I to pure mode II [23]. The Arcan fixture, shown in Fig. 1a, is made of a 15-5PH stainless steel and has a thickness of 19.05 mm. The test specimen, shown in Fig. 1b, is made of 2024-T3 aluminum alloy and has a thickness of 2.29 mm. A single-edge fatigue pre-crack with a length of 6.35 mm is introduced on one side of the specimen along the middle line of the specimen.

The stainless steel fixture has a Young's modulus of 207 GPa, a Poisson's ratio of 0.3, and an initial yield stress of 1724 MPa; the aluminum alloy has a Young's modulus of 71.7 GPa, a Poisson's ratio of 0.3, and an initial yield stress of 345 MPa. Both the steel and the aluminum alloy exhibit a strain-hardening behavior, which will be represented by their true stress–true strain curves.

The Arcan specimen is loaded in displacement control by a pair of pins in the grips of the fixture at a pair of grip holes on the opposite sides of a radial line, as shown in Fig. 1a, in which the reaction load is denoted by P. Different mixed-mode loading conditions are obtained by changing the pair of loading holes with an angle of Φ from the Mode I loading direction (which is along the center line).

2.2. Triangular cohesive law and CZM parameters

In the literature, various cohesive laws have been developed, among which the triangular, exponential and trapezoidal cohesive laws are most commonly used. Some studies showed different shapes of cohesive laws behave differently in CZM simulations (e.g. [24,25]), although the shape of cohesive law is conventionally considered as a subsidiary. However, there is no clear conclusion to show the effect of different cohesive laws on ductile crack simulations. As such, the triangular cohesive law, which is commonly used in the literature and available in ABAQUS, is employed in the current study. As shown in Fig. 2, when the cohesive crack surfaces separate, the cohesive traction will first increase to a maximum and then decrease gradually. The triangular cohesive law represents the traction–separation relationship using a bilinear (triangle) shape. Fig. 2 shows the triangular cohesive law with key points O, A, B and C. At point O, the material is not loaded and there is no separation. Along the line OA, the material is loaded but no material damage is done so unloading is completely reversible. The slope K (the initial cohesive stiffness) is usually chosen to be large so that its effect on the overall structural compliance is small. At point A (with separation δ_0) the cohesive traction reaches the maximum allowable value (the cohesive strength) denoted by T_{max}, beyond which material damage occurs and the cohesive stiffness is reduced to K_δ at a point B with a separation of δ. When the allowable traction falls down to zero at point C, the separation is equal to δ_{sep} and complete material separation occurs.

The cohesive energy, Π, which is the area of the triangle, is related to the other two CZM parameters through the area relation.

$$\Pi = T_{max}\delta_{sep}/2 \quad (1)$$

Any two of these three parameters in Eq. (1) (e.g. T_{max} and δ_{sep}) can be chosen as the two input parameters for the triangular cohesive law. Besides the two parameters T_{max} and δ_{sep}, another parameter must be defined to fully describe the shape of the

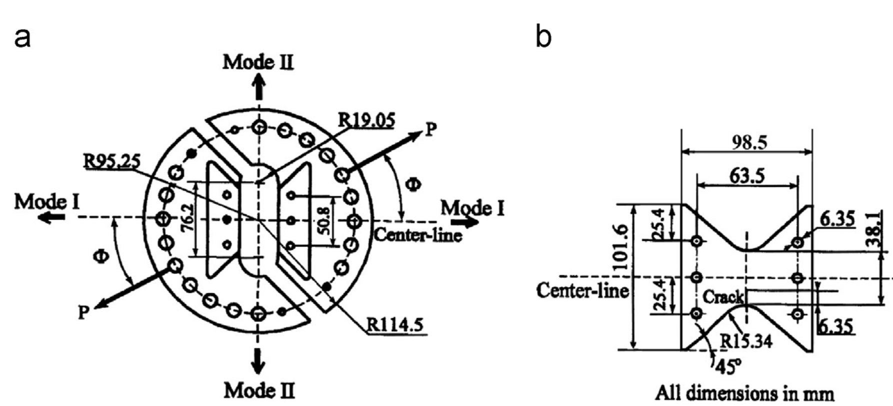

Fig. 1. In-plane dimensions of (a) the Arcan test fixture and (b) the Arcan test specimen [23].