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Finite Element Modelling of Bi-Material Interface for Crack Growth Evaluation: Technical Note

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ABSTRACT:

Finite element (FE) method is commonly used to study cracks in structures. In this paper, J-integral method is applied over FE model of a cracked body to determine stress intensity factor (SIF) in the domain of linear elastic fracture mechanics (LEFM). This paper formulates the J-integral methodology for 2D FE model using a coarse mesh with less degrees of freedom. Two cases , a finite plate with edge cracks and a normal crack growth in fiber metal laminated plate, are demonstrated. Numerical implementation and mesh refinement issues to maintain path independent J-integral values are explored.

KEYWORDS:

Fiber metal laminate; Finite element analysis; Crack growth; Stress intensity factor; J-integral; Fracture mechanics

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1. Introduction

A technique was developed using conventional finite element (FE) analysis to determine stress intensity factors (SIFs) for normal cracks under mode-I loading. This technique involves the calculation of crack-tip stresses using singular finite elements. FE method (FEM) and boundary element method (BEM) are the most widely used techniques for evaluating SIF (K1) [1]. The most important region in modelling the fracture region is the region around the crack. While the domain is meshed, crack tip elements with nodal singularity are used [2]. Displacement correlation was employed to determine SIFs. A 2D structural analysis was performed with ANSYS to extract in an automatic fashion the value of the SIF for various cracks. Design of composite structures in many important industrial applications requires good understanding of the fracture behaviour near the bi-material interfaces. For example, it has become a widespread practice to strengthen reinforced or pressurised concrete structures with externally bonded Fiber-Reinforced Plastic (FRP) plates [3].

The SIFs of a crack between two dissimilar materials are important parameters for evaluating delamination strength. Delamination failure can significantly affect the fatigue and damage tolerance behaviours of fiber metal laminates (FML) [4]. In order to prevent the failure in bi-materials, energy approaches and contour-integral approaches have the excellent feature of providing an accurate energy release rate or SIF even in the case of a coarse FE mesh. Moreover, contour-integrals including the J-integral are potentially important as nonlinear fracture mechanics parameters. The contour-integral approaches are applied to SIF analyses of two-dimensional crack problems [5]. The J-integral is applied to a crack in a bi-material to an interface crack between two dissimilar materials. The proposed method gives accurate SIFs not only for a crack in a homogeneous material but also for an interface crack between dissimilar materials [6].

Structural design concepts traditionally use strength of material approach for designing a component. This approach does not anticipate the elevated stress levels due to the existence of cracks. The presence of such stresses can lead to catastrophic failure of the structure. Fracture mechanics accounts for the cracks or flaws in a structure. The fracture mechanics approach to the design of structures includes flaw size as one important variable, and fracture toughness replaces strength of material as a relevant material parameter [7].

4. J-integral analysis methodology

Fracture analysis is typically carried out either using the energy criterion or the SIF criterion. When the energy criterion is used, the energy release rate characterizes the fracture toughness. When the SIF criterion is used, the critical value of the amplitude of the stress and deformation fields characterizes the fracture toughness. Under certain circumstances, the two criteria are equivalent [8]. SIFs and energy release rates are limited to Linear Elastic Fracture Mechanics (LEFM). The J-Integral is applicable to both linear elastic and nonlinear elastic-plastic materials. A major achievement in the theoretical foundation of LEFM was the introduction of the SIF K (the demand) as a parameter for the intensity of stresses close to the crack tip and related to the energy release rate [9]. SIF is a measure of the change in stress within the vicinity of the crack tip. Therefore, it is important to know the crack direction and when the crack stops propagating. The SIF is compared with the critical SIF K_{IC} (the capacity) to determine whether or not the crack will propagate. Dimensional analysis can be used to show that the SIF for mode-I fracture K_I, has the following form:

$$K_I = g\sigma \pi a \quad (1)$$

where, σ = nominal far field stress, 2a = crack length, g is a non-dimensional function depending on the size and geometry of the crack & structural component and the type of loading. For normal cracks, its value ranges between 1 and 2. If K_I is the same for two cracked bodies, the same stress field will exist at their crack tips. Thus, K_I can be used as a similitude parameter to compare the response of the same material at the crack tip and also to compare the degree to which materials are influenced by the stress fields [10].

The J-integral was presented by Rice for two-dimensional (2D) domains containing cracks. Consider a 2D linear body of linear or nonlinear elastic material free of body forces and subjected to a 2D deformation field (plane strain, plane stress) so that all stresses σ_{ij} depend only on two Cartesian coordinates (x, y). Supposedly if the body contains an edge crack as shown in Fig. 1, the strain-energy density W is defined as,

$$w = w(x, y) = w(\varepsilon) = \int_0^{\varepsilon} \sigma ij\, \partial \varepsilon ij$$

Where $\varepsilon = (\varepsilon_{ij})$ is the infinitesimal strain tensor. Now, the J-integral is defined as,

$$J = \int w dy - \int \left(T_X \frac{\partial u}{\partial x} + T_Y \frac{\partial u}{\partial y}\right) ds \quad (1)$$

Where w = Strain energy density, u = Displacement along Y and T_X and T_Y are as follows:

$$T_X = \sigma_x n_x + \sigma_{xy} n_y \qquad T_Y = \sigma_y n_y + \sigma_{xy} n_x \quad (2)$$

Rice [4] proved the path independent concepts and found that for small-scale yielding the stress energy release rate G is equal to the J-integral. Therefore, the SIF can be evaluated as follows:

$$J = G \quad (3)$$

$$J = \frac{k^2}{E} \text{ Plain stress} \quad (4)$$

$$J = \frac{k^2}{E}(1 - \nu^2) \text{ Plain strain} \quad (5)$$

The crack tip and integral counter is shown in Fig. 1.

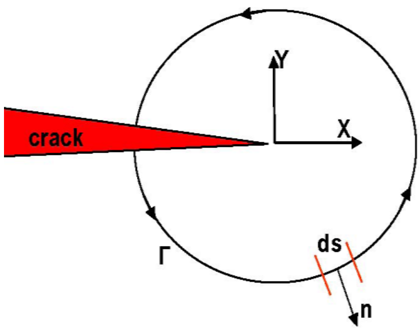

Fig. 1: Crack tip and integral counter

The steps required to calculate J-integral for a 2-D model are described below:

1. Read in the desired set of results, store the volume and strain energy per element, and calculate the strain energy density per element.
2. Define a path for the line integral.
3. Map the strain energy density, which was stored in the element table in step 1, onto the path, integrate it with respect to global Y. This gives us the first term of Eqn. (1).
4. Map the component stresses σ_x, σ_y, and σ_{xy} onto the path, define the Path unit normal vector, and calculate T_X and T_Y using Eqn. (2).
5. Shift the path a small distance in the positive and negative X directions to calculate the derivatives of the displacement vector (du/dx and du/dy) using PCALC as per the following code:

```
*GET, DX, PATH,, LAST, S r + &/2
DX=DX/100
PCALC, ADD, XG, XG,,,, -DX/2
PDEF, UX1, U, X
PDEF, W1, U, Y
PCALC, ADD, XG, XG,,,, DX
PDEF, UX2, U, X
PDEF, W2, U, Y
PCALC, ADD, XG, XG,,,, -DX/2
C=1/DX
PCALC, ADD, C1, VX2, UX1, C,-C
PCALC, ADD, C2,W2, UY1, C,-C
```

6. Calculate J-integral using Eqn. (1).

3. FE modelling:

To illustrate the J-integral approach, the FE modeling of two simple examples, finite plate with double edge crack as shown in Fig. 2 and a bi-metal FML plate as shown in Fig. 3, are only presented. The bi-material of FML consists of 3 layers (0.4mm) of aluminium, 2 layers (0.3mm) of fiber and 4 layers (0.05mm) of resin leading to a total thickness of 2mm with length of 100mm and 50mm width. The geometry parameters are tabulated in Table 1. For the plate with edge crack FE model, solid 8 noded PLANE 82 element, available in ANSYS 11.0 software, is used with plane strain option. Because of symmetry, one-quarter model is considered. The FE mesh of double edge crack is shown in Fig. 4.

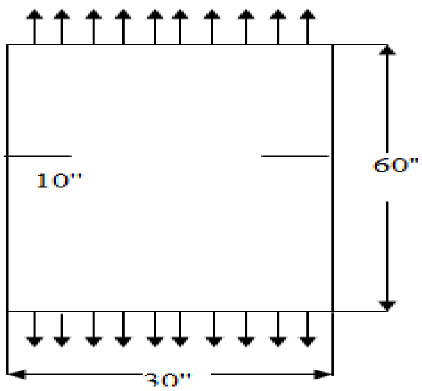

Fig. 2: Finite plate with double edge crack

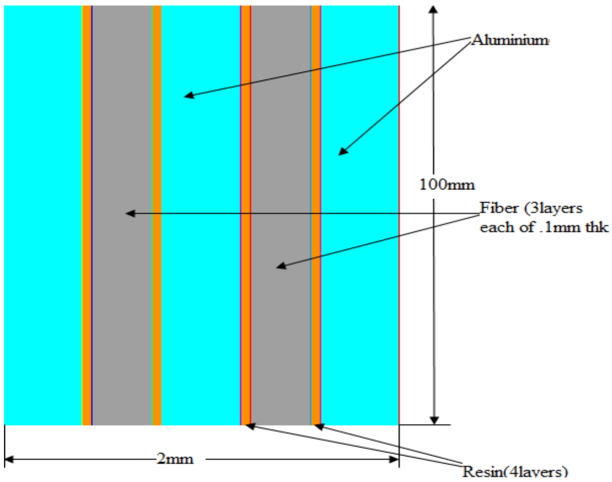

Fig. 3: Schematic view of FML

Table 1: Material properties and thickness

Material	Young's modulus	% elongation	Poisson's ratio	Thickness
Aluminium	72 GPa	18	0.3	0.4mm
Fiber	71 GPa	4.8	0.3	0.3mm
Resin	3.5 GPa	4	0.3	0.05mm

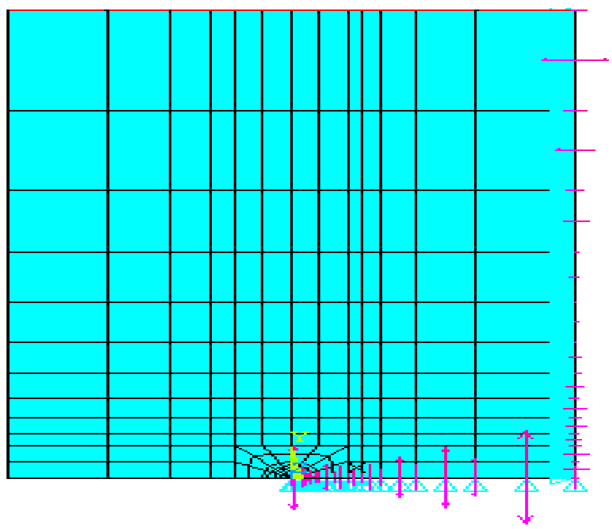

Fig. 4: FE mesh of double edge crack

5. Conclusion

In order to analyse the fracture behaviour of cracked structures, it is necessary to know the SIFs. FE modelling based methodology has been established to obtain the J-integrals from which the SIF can be found. This paper only presented a part of ongoing research. The FE models to demonstrate the application of proposed methodology were presented in this technical note to demonstrate the ongoing research. Full validation and verification along with the predicted SIFs will be presented elsewhere.

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