Equation Chapter 1 Section 1 The Numerical Research of Influence of Residual Stress on Interface Damage

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Abstract. The crack growth was simulated by mixed-mode cohesive interface model. Based on the principle of equivalence of thermal and mechanics, the effects of residual stress on crack growth and interface damage evolution are researched by finite element model. The results demonstrate that residual compressive stress is more likely to cause material interface crack growth and damage. The material interface is more likely to fail when there is residual compressive stress in the material. The residual compressive stress is more likely to cause the interface crack growth when the crack growth length caused by certain residual compressive stress value is seen an important influence parameter.

Introduction

Residual stresses are unavoidable in welding, coating and other components in practical engineering applications. The Residual stress even exceeds the yield strength of its bulk material. The interface position is very easy to damage, and finally causes the failure due to interface crack growth. The research of influence of residual stress on interface damage is of great importance.

In last several decades, the cohesive interface model has undergone the great improvements and developments in describing the materials fracture process benefiting by the development of the finite element methods [1]. With the continuous improvement of computer performance and the maturity of finite element method, the finite element method is combined with the cohesive model to simulate crack growth of materials by more and more researcher [2, 3].

At present, there are few researches on the evolution of interfacial damage evolution process. In the present investigation, based on the principle of equivalence of thermal and mechanics, the effects of residual stress on crack growth and interface damage evolution are researched by finite element model combined with the mixed-mode cohesive model.

The Mixed-mode Cohesive Interface Model

In the present investigation, a mixed-mode cohesive interface model developed by Turon et al. [4] will be used to describe the damage evolution of interface.

Figure 1 shows the scheme of the mixed-mode cohesive interface model within the space of both traction and separation displacements, and shows the relationship between the mixed-mode cohesive model with the pure normal separation cohesive model as well as with the pure shear separation cohesive model. Referring to Figure 1, the both triangle $O - T_1 - \delta_{1}^i$ and $O - T_3 - \delta_{3}^i$ (O is coordinate origin) are the bilinear responses in pure normal and pure shear modes, respectively. Any point located on the $O - \delta_{1}^i - \delta_{3}^i$ plane will correspond to a mixed-mode interface separation process. Subscripts ‘1’ and ‘s’ are used to represent the pure separation mode and pure shear mode, respectively. The critical relative displacements corresponding to the initiation of damage are...
identified with the superscript ‘0’. The limit relative displacements corresponding to failure state are identified with the superscript ‘f’.

\[
\begin{align*}
T_m & = \text{Total reaction–separation response} \\
S & = \text{SC} \\
\end{align*}
\]

\[
\begin{align*}
G & = \text{G} \\
S & = \text{SC} \\
\end{align*}
\]

\[
\begin{align*}
\delta_m & = \text{δm} \\
\delta_s & = \text{δs} \\
\end{align*}
\]

\[
\begin{align*}
T & = \text{T1} \\
S & = \text{SC} \\
\end{align*}
\]

\[
\begin{align*}
\sigma & = \text{σ} \\
\tau & = \text{τ} \\
\end{align*}
\]

Figure 1. Illustration of mixed-mode cohesive interface model (a) and bilinear T–S response (b).

The damage is assumed to be initiate when the following quadratic relation is satisfied \(^5\):

\[
\left(\frac{\langle \sigma \rangle}{T_1}\right)^2 + \left(\frac{\tau}{T_S}\right)^2 = 1
\]

where \(\sigma\) and \(\tau\) are the normal and shear stresses on the interface, respectively. \(T_1\) and \(T_S\) are the limit separation and shear tractions, respectively.

The mixed-mode fracture criterion is described as follows \(^5\):

\[
\frac{G_1 + G_S}{G_{SC}} = 1
\]

where \(G_1\) and \(G_S\) are the current fracture energies for the normal and shear cases, respectively, \(G_{IC}\) and \(G_{SC}\) are the fracture energies for pure separation mode and pure shear mode, respectively. \(G_C = G_1 + G_S\) is the total current fracture energy for mixed-mode case when above condition is satisfied.

**Characterization of Interface Damage**

In order to characterize the grain boundary damage evolution, it is convenient to define a damage variable \(D\). Its definition can be described as a ratio of “nominal dissipation energy” to “nominal total energy”. Referring to Figure 2, assuming that the cohesive state is currently at the Point B, the nominal total energy can be expressed as the triangular area OCE (area \(S\)) without considering the damage, and the nominal dissipation energy can be calculated as the triangular area OBE (area \(S_1\)), so that the damage variable \(D\) is equal to an area ratio \(S_1/S\). One can easily derive out the \(D\)-expression as follows:

![Figure 2. Damage definition based on the cohesive interface model.](image)
where $\delta_m^0$ and $\delta_m^\ell$ are the critical relative displacement corresponding to the peak stress point and the limit relative displacement, respectively.

**Finite Element Model**

Finite element method (FEM) is used in numerical simulations for interface damage evolution. The 2D finite element model and finite element mesh are shown in Figure 3. The mixed-mode cohesive interface model was used to describe the damage evolution of interface. The plain strain element (CPE4) was adopted in material 1 and 2 which constitutive relation is elastic. The cohesive element COH2D4 was adopted in interface. The under surface of substrate is fixed.

![Figure 3. 2D finite element model and finite element mesh.](image)

In order to simulate the effects of residual tensile and compressive stress, the positive and negative temperature fields are applied to the whole model respectively.

In order to study the damage evolution of the interface at different positions, six typical positions P1 to P6 were selected as shown in Figure 4. According to the symmetry of the model, only the left half can be studied. P1 is located at the far end, and P6 is in the middle.

![Figure 4. Illustration of six typical damage position.](image)

**Results and Discussions**

**The Effects of Residual Stress on Interface Crack Propagation**

The propagation of the interface crack is given in Figure 5 at different residual compressive stress state. With the increase of the residual compressive stress, the interface cracks gradually expand until the final failure.
The Effects of Residual Stress on Interface Damage Evolution

Figure 6 gives comparison of the effects of residual tensile stress and residual compressive stress on the damage evolution of P1-P6. In order to clearly observe and compare the effects of residual tensile stress and residual compressive stress on the damage evolution of P1-P6, the mirror mapping of time axis on damage evolution curve of P1-P6 under residual compressive stress was conducted. Figure 6 (b) is the amplification of Figure 6 (a).

Figure 6 demonstrates that residual compressive stress is more likely to cause material interface crack growth and damage. The material interface is more likely to fail when there is residual compressive stress in the material. Evans[6] pointed out that the high compressive stress in the interface is the important reason for the formation of interface defects, the crack propagation and the failure of interface. The results in Figure 6 give a more explicit explanation.

Conclusions

The crack growth was simulated by mixed-mode cohesive interface model. Based on the principle of equivalence of thermal and mechanics, the effects of residual compressive and tensile stress on crack growth and interface damage evolution are studied. The results demonstrate that residual compressive stress is more likely to cause material interface crack growth and damage. The material interface is more likely to fail when there is residual compressive stress in the material. In a words, residual compressive stress is more likely to cause the interface crack growth when the crack growth length caused by certain residual compressive stress value is seen an important influence parameter.
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