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Damage analysis in composite laminates by using an interface element

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Abstract—A numerical analysis is performed to study an impact damage accumulation problem in composite laminates. A special three-dimensional interface element is developed based on the cohesive model. The element enables the mesh independent configurations of a crack to be calculated and can treat contact problems of the delaminated area. The energy stored in the element per unit area is defined as a function of continuous relative displacements of the delaminated surface. The energy stored before the perfect separation of the interface is equal to the interlaminar fracture toughness. The softening cohesive relations between the tractions and the relative displacements are given by differentiating the energy function with respect to the relative displacements. The maximum value of traction may coincide with interfacial bonding strength. The element is incorporated in a commercially available finite element code. Crack propagation problems under pure Mode I and Mode II loading conditions for three-dimensional models are calculated to show the validity of the present element. The convergence of solution with mesh refinement is examined. The analytical solutions converge smoothly and agree well with the theoretical ones. The present method may be a good tool to simulate the damage accumulation problem of CFRP laminates.

Keywords: Composite laminates; cohesive model; interface element; delamination; finite element analysis.

1. INTRODUCTION

Composite laminates are used in many engineering applications, such as aerospace structures. However, structures made of composite laminates are susceptible to impact damage [1, 2]. The impact-induced damage consists of delamination, matrix cracking, fiber failure, and so on. This damage is difficult to detect from outside the structures, and may cause severe reduction of compressive strength

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(Compression After Impact: CAI) [3]. Design loads of the structures are often limited by the degraded compressive performance. Therefore, the mechanism of damage accumulation due to impact must be well understood in order to utilize the composite laminated structures to their full advantage.

In order to study the mechanism of damage accumulation in composite laminates, many numerical methods have been proposed. The virtual crack closure technique has been successfully used to study the stability of the delamination in composite laminates delamination propagation [4–6]. However, the results show only the stability of the preexisting cracks. It is necessary to discuss crack initiation and propagation to explain the significance of the impact damage with respect to the impact energy. In order to simulate the initiation of delamination and propagation appropriately, a numerical method that can take both interfacial strength and interlaminar fracture toughness into account will be required.

To overcome the problem of delamination propagation, many researchers have studied and numerically simulated the process of delamination in composite laminates based on the damage mechanics, e.g. see Refs [7–13]. Progressive delamination is modeled by introducing the interface element, which has a non-linear softening relationship between traction and relative displacement. The area under the softening curve is equal to critical energy release rate, G_c. The softening relationship is defined as a non-linear material model for an interface element. However, since the non-linear softening material model is very sophisticated, the method is reported to be very sensitive to mesh size [14].

On the other hand, Needleman [15, 16] developed a cohesive interface model to simulate dynamic crack growth in isotropic elastic solids. The formulation is based on the cohesive zone type model. The mechanical response of the interface is specified in terms of both a critical interfacial bonding strength and a critical fracture energy. Since the cohesive zone model is attractive, advanced cohesive models are developed and proposed to simulate crack-like damage in composite materials [17–20].

In the present paper, a three-dimensional interface element based on the cohesive model is proposed to analyze the propagation of the delamination in composite laminates. The element enables calculation of the mesh independent configurations of crack and can treat the contact problem of the delaminated area. The energy stored in the element until failure is defined as a simple function of continuous relative displacements of delaminated surface and equal to the interlaminar fracture toughness. The softening cohesive relations between tractions and relative displacements are given by differentiating the energy function with respect to relative displacements.

2. INTERFACE ELEMENT

Figure 1 shows an interface element proposed to simulate the delamination propagation. The 16-node element is placed to between the 20-node brick elements where

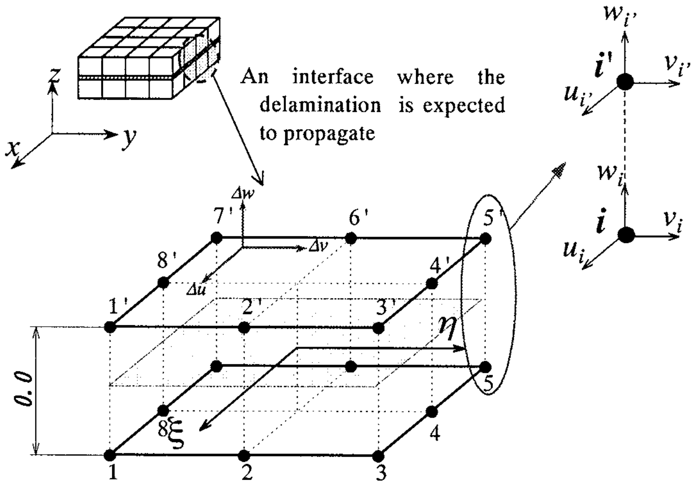

Figure 1. Concept of interface element.

delaminations are expected to propagate. The element has no thickness before deformation. Node i in the lower surface and node i' in the upper surface have the same coordinate in the model. In Fig. 1, *x, y, z* and ξ, η are the global and local coordinate system, respectively. The continuous relative displacements in in-plane $(\Delta u, \Delta v)$ and out-of plane (Δw) directions are defined as

$$\begin{aligned}
&\Delta u = \sum_{i=1}^{8} \phi_i(\xi, \eta)\Delta u_i, \quad \Delta v = \sum_{i=1}^{8} \phi_i(\xi, \eta)\Delta v_i, \quad \Delta w = \sum_{i=1}^{8} \phi_i(\xi, \eta)\Delta w_i, \\
&\Delta u_i = u_{i'} - u_i, \quad \Delta v_i = v_{i'} - v_i, \quad \Delta w_i = w_{i'} - w_i,
\end{aligned} \tag{1}$$

where $\phi_i(\xi, \eta)$ is a shape function, and u_i, v_i, w_i and $u_{i'}, v_{i'}, w_{i'}$ indicate nodal displacement components at nodes i and i', respectively.

The energy stored in the element per unit area is defined as a function of relative displacement.

$$\begin{aligned}
&\Phi = G_t\{1 - \exp(-\varphi)\} + f(\Delta w), \\
&\varphi = \alpha \Delta w^2 + \beta(\Delta u^2 + \Delta v^2),
\end{aligned} \tag{2}$$

where

$$f(\Delta w) = \begin{cases} \dfrac{1}{2} k_c \Delta w^2 & (\Delta w < 0) \\ 0 & (\Delta w > 0), \end{cases}$$

and where G_t is a critical total energy release rate, and α and β are the coefficients that are determined to express the relationship between relative displacement and traction. The second term $f(\Delta w)$ is introduced to consider the contact problem. When the relative displacement Δw goes to negative on the interface, a very large reaction force occurs to prevent the interface from overlapping. The tractions in

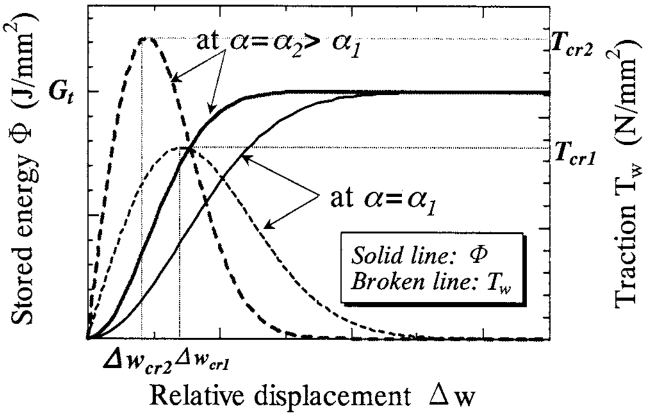

Figure 2. Relationship between potential energy and traction.

each directions are derived by differentiating Φ with respect to displacement as

$$T_u = \frac{\partial \Phi}{\partial \Delta u}, \quad T_v = \frac{\partial \Phi}{\partial \Delta v}, \quad T_w = \frac{\partial \Phi}{\partial \Delta w}. \tag{3}$$

The stored energy and traction are plotted against a relative displacement Δw in Fig. 2. With increase in the relative displacement Δw, the traction across the interface T_w reaches a maximum value T_{wcr} when Δw is a critical value Δw_{cr}, then decreases and eventually reduces to nearly zero. The value of T_{wcr} is equal to interfacial debonding strength, Δw_{cr} is decided by coefficients α and β. If the α sets a larger value, the value of Δw_{cr} is small, and the initial gradient of traction is large. This interface element is incorporated into the finite element code ABAQUS 5.8 using the USER SUBROUTINE command.

3. NUMERICAL RESULTS

To demonstrate the validity of the present interface element, crack propagation in a double cantilever beam and an end notched flexure specimens are simulated.

3.1. Numerical simulation of double cantilever beam problem

The finite element mesh and loading condition is illustrated in Fig. 3. The dimensions of the specimen are 150 mm × 25 mm × 4 mm. The length of an initial crack is 30 mm. Elastic properties of the beam are $E_L = 142$ GPa, $E_T = 10.8$ GPa, $G_{LT} = 5.49$ GPa, $G_{TT} = 3.72$ GPa and $\nu_{LT} = 0.3$, $\nu_{TT} = 0.45$. The value of critical total energy release rate G_t is 400 (J/m^2). The present analysis is performed by a displacement control.

The applied load is plotted against crack opening displacement in Fig. 4. When the critical relative displacements Δu_{cr}, Δv_{cr}, Δw_{cr} are set large, the stiffness of the beam reduces by some amount even at the very early stage of loading,

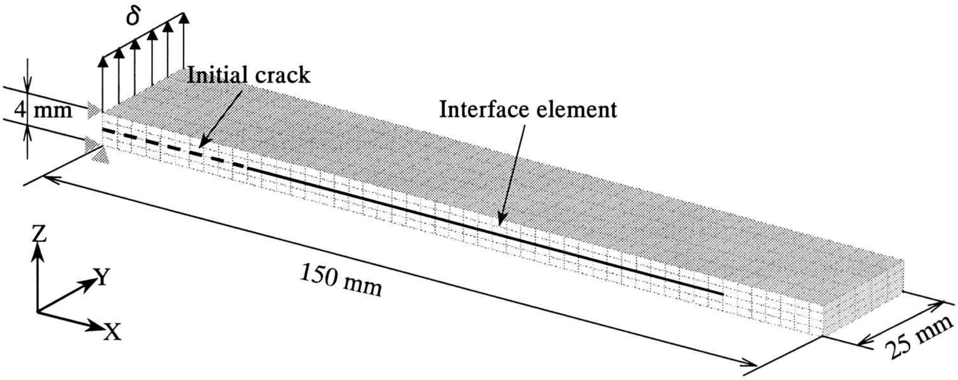

Figure 3. Specimen and finite element modeling.

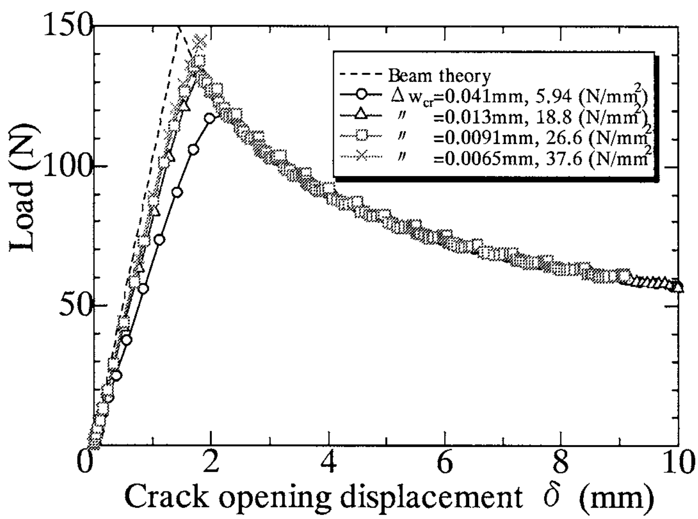

Figure 4. Relationship between load and crack opening displacement for DCB specimen.

because the deformation of the interface element becomes relatively large compared to that of the beam itself. The area of the process zone depends on the critical relative displacement. In the propagation stage, results agree well with theoretical ones based on a beam theory (broken lines [10]). The influence of the mesh refinement is shown in Fig. 5. When 50 elements are used along the length, the propagation process depends on the position of crack tip in an element and the load–displacement curve oscillates significantly. The problem is greatly improved when 100 elements are used along the length. The distributions of the normal stress σ_z at three crack opening stages are shown in Fig. 6.

The figures show the concentration of the stresses around the crack tip area, which moves with propagation of delamination. Stress in the newly delaminated surface is nearly zero. The process zone, that is, high stress area, shows a curved boundary

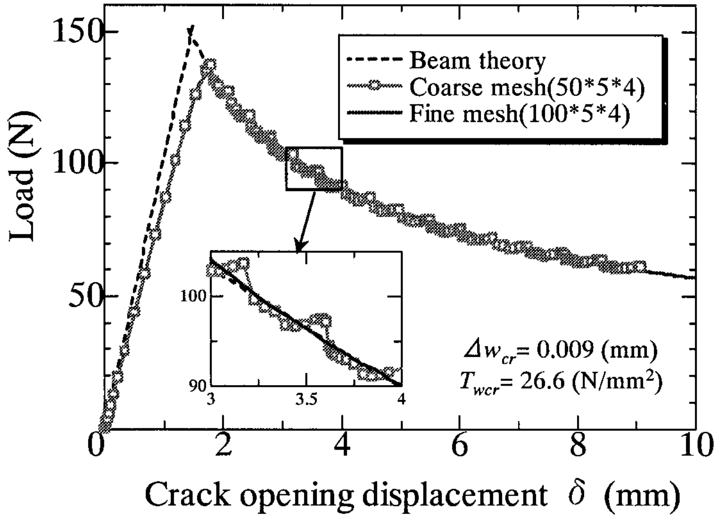

Figure 5. Influence of mesh refinement.

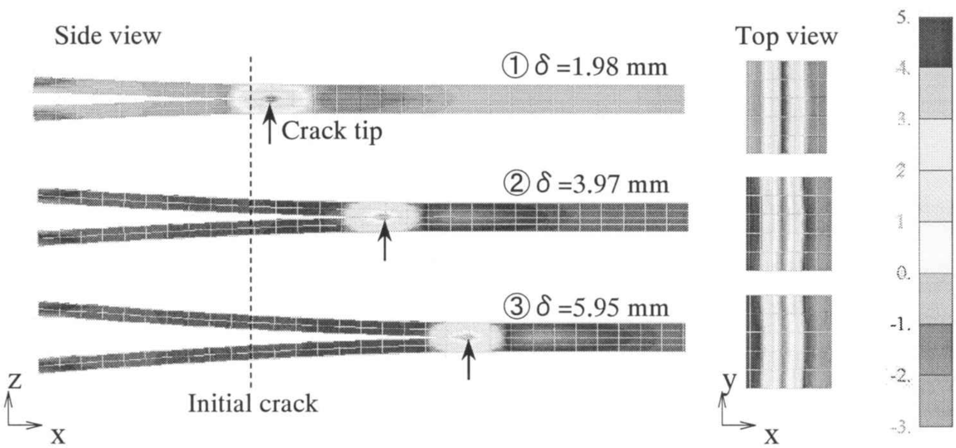

Figure 6. Distribution of the normal stress σ_z.

because of the anticlastic bending effect. The element enables the mesh independent configurations of crack tip area to be calculated.

3.2. Numerical simulation of end notched flexure problem

Let us consider an end notched flexure problem as a pure mode II situation (Fig. 7). Material properties of the beam are same as DCB specimens. The length of an initial crack is 27 mm. A contact problem at the initial crack area is considered using a nonlinear spring element between the double nodes. The element has high stiffness in the compressive direction and no resistance in the tensile direction. Interface

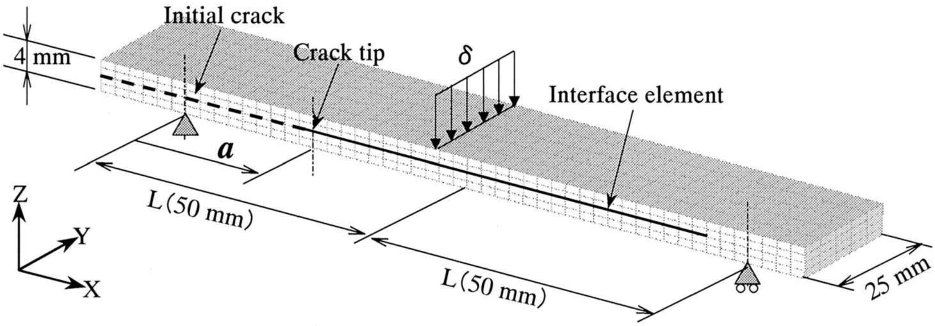

Figure 7. Specimen and finite element modeling.

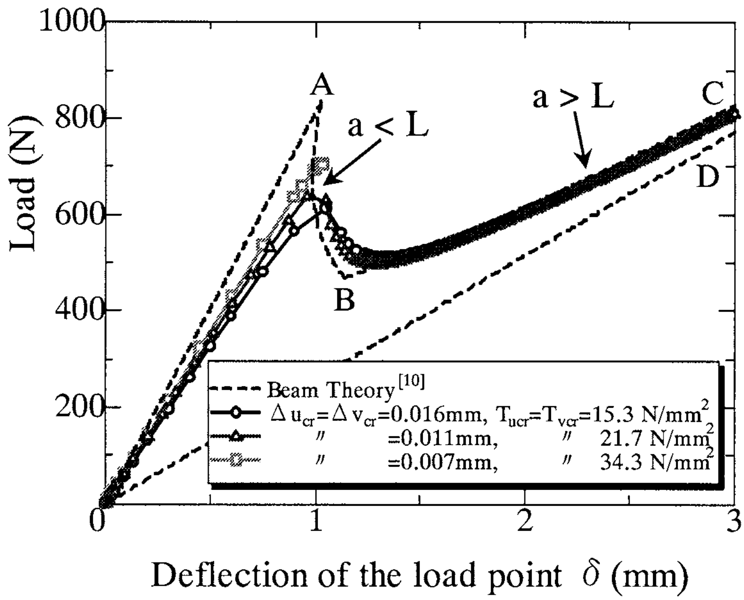

Figure 8. Relationships between center deflection and applied load for ENF specimen.

elements with contact properties were placed at the interface where delamination is expected to propagate.

Figure 8 shows load–deflection relationships for ENF specimens. Broken lines are closed form solutions based on beam theory [10]. The curve OA is obtained from the load–deflection relationship of the beam with crack of an initial length. Along the curve AB, the crack propagates from initial length to the center of the beam ($a < L$), where the energy release rate satisfies the condition $G_{II} = G_c$. Also, along the curve BC, crack advances from center point to the other support ($a > L$), where $G_{II} = G_c$. The line OD is the load–displacement curve of the completely split beam. When the load reaches a critical value, the load decreases abruptly accompanying unstable crack propagation. In the propagation stage (A→B, B→C),

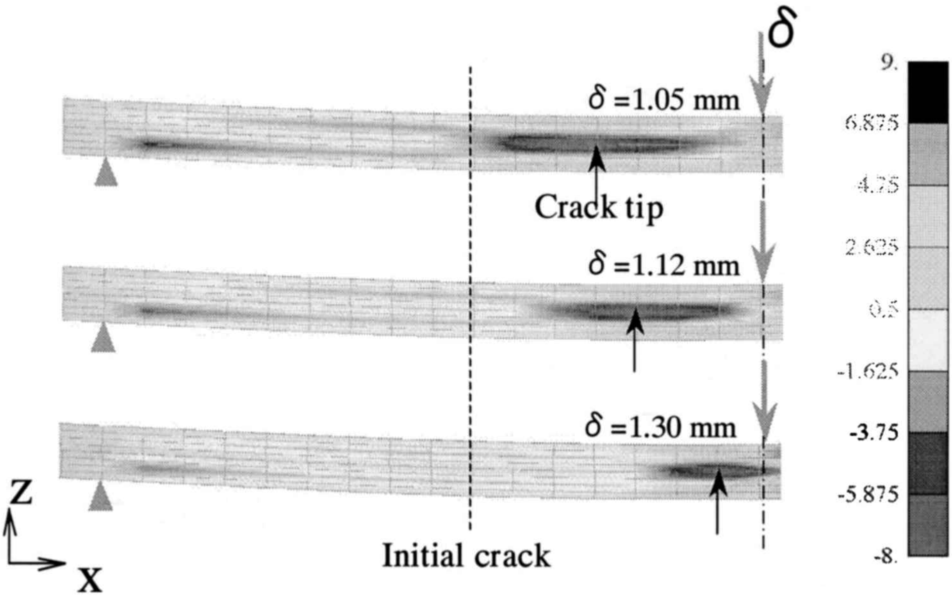

Figure 9. Distribution of the shear stress τ_{zx}.

results agree well with the theoretical ones. The shear stress τ_{zx} in the $x-z$-plane is shown in Fig. 9. Broken line indicates the initial crack location. The interface elements can successfully treat a contact problem at the delaminated area. The crack tip area moves with propagation of delamination, and shear stress on the completely separated surface is nearly zero.

4. SUMMARY

We propose an efficient interface element for crack-like damage propagation in a three-dimensional problem. The energy stored until the perfect separation of the interface is equal to the interlaminar fracture toughness. The softening cohesive relations between the tractions and the relative displacements are given by differentiating the energy function with respect to the relative displacements. The convergence of the solution is smooth when the mesh size is small enough compared to the process zone. Good agreement with the theoretical results is obtained for a crack propagation problem for both DCB and ENF specimens. The element enables the mesh independent configurations of the crack tip area to be calculated and can treat the contact problem of the delaminated area. The present method will be applied to the damage accumulation problem of CFRP laminates. In order to define the damage accumulation problem, the unloading process must be incorporated.

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