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Simulation of Low-velocity Impact Damage in Layered Composites using a Cohesive-based Finite Element Technique

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ABSTRACT

The mechanism of damage initiation and growth in layered composites subjected to low- velocity impact is simulated using a cohesive-based finite element technique. The numerical technique used comprises cohesive elements sandwiched between the regular finite elements. The basic structure of the formulation is presented, followed by the results of the simulation. The success of this numerical technique is dependent on the cohesive model used. The cohesive model is a thermodynamically-based phenomenological model, describing the damage ahead of a crack tip. Details of the rate-independent cohesive model used in this study are also presented.

Keywords: Low-velocity impact, cohesive-based finite element technique, composites, composite laminates, simulation, impact-induced delamination, transverse matrix cracks, traction-separation relation, critical matrix cracks

1. INTRODUCTION

The composite laminates are used in modern aircraft to reduce the weight, which may be exposed to low-velocity impact by foreign objects. A typical example is that of a structure subjected to the impact of a dropped tool or the collision of runway debris. Unlike metals, the polymeric matrix composites deform plastically and absorb the kinetic energy of the impactor. The energy absorption mechanism of these materials creates large fracture area, especially at the weaker interfaces between the composite layers, in a process referred to as impact-induced delamination. The post-impact properties of these structures can be determined by accurate prediction of the mechanism of impact-induced damage. The lack of a precise modelling tool has led the aircraft industry to impose high safety factors when dynamic loading of laminated composite structures is involved.

The basic failure mechanism in a layered composite is depicted schematically in the Fig. 1, and involves various steps. The initial failure mechanism occurs at relatively low-energy levels and involves a series of small transverse matrix cracks oriented towards the impact point. As the energy increases, these cracks extend until they reach the interface of a neighbouring ply with a different fibre orientation. At this point, the matrix cracks can no longer propagate in their original direction and are deflected onto the ply interface, thereby starting the delamination process. The matrix crack, which actually initiates the delamination, is usually referred to as the critical matrix crack [Fig. 1(a)]. The delamination continues towards the point of impact on the top interface and away from the point of impact on the bottom one [Fig. 1(b)]. As the delamination grows further, additional transverse matrix cracks tend to appear

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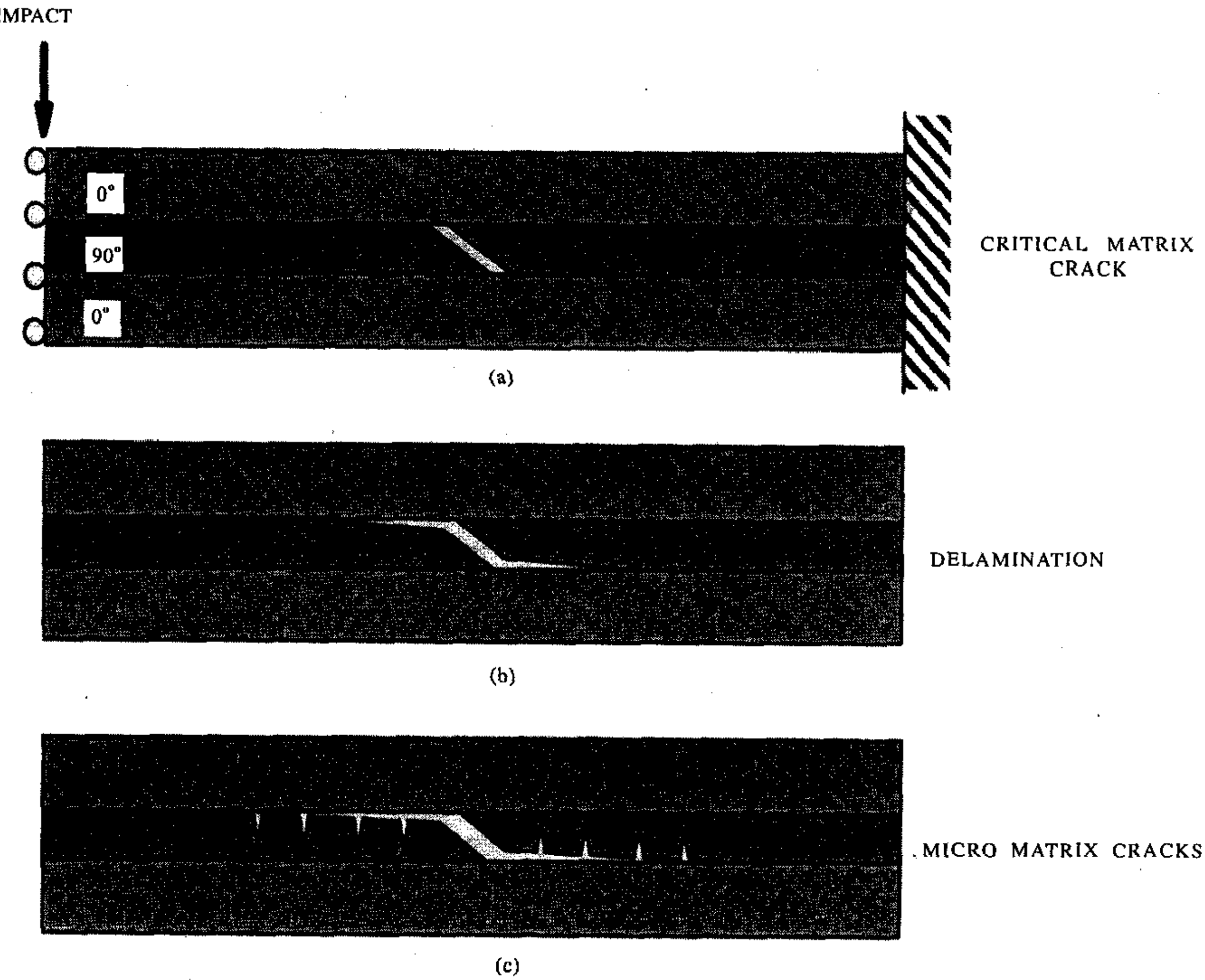

Figure 1. Failure mechanism in a layered composite

[Fig. 1(c)]. The extent of delamination damage depends on a wide range of factors, such as the spatial distribution, amplitude and duration of the loading stress waves, the delamination strength of the interlayer, the number and orientation of the plies, etc. The present study describes the combined cohesive and regular finite element technique suited to simulate spontaneous crack propagation, followed by the results of the 2-D simulation of the impact-induced damage in layered composites.

2. COHESIVE FAILURE

The theory of cohesive failure modelling goes back to the pioneering work of Dugdale[1] and Barrenblatt[2]. This fracture mechanics approach, which models the damage as occurring over a strip-like cohesive zone located immediately ahead of the crack tip, provides some structure to the failure process taking place in the vicinity of the crack tip, and at the same time, addresses the issue of the crack tip singularity.

The concept of cohesive failure is the foundation of the cohesive/volumetric finite element technique used in this study. To allow for the spontaneous initiation and propagation of fracture surfaces, a series of cohesive failure surfaces are introduced within a conventional finite element mesh. These cohesive elements act like nonlinear springs, linking regular volumetric finite elements at interfaces where failure process is possible. These springs resist the opening in accordance to a prescribed traction-separation relation. Eventually, as the opening increases, the tractions tend to zero, simulating the creation of a new traction-free surface (crack face). In the general case, the traction-separation law must account for the arbitrary orientation of the cohesive elements and the possible resulting mode-mixity of the applied tractions. In other words, it must relate the following traction vector (T):

$$T = [T_n, T_t]^T$$

defined by its normal and tangential components, to the displacement jump vector (Δ):

$$\Delta = [\Delta_n, \Delta_t]^T$$

as shown in the Fig. 2. The implementation specifics of a generic cohesive/volume finite element is similar to that provided by Xu and Needleman[3]. To maximise the number of potential cohesive failure sites, triangular volumetric elements are typically used in 2-D and tetrahedral volumetric elements in 3-D.

Within the framework of the cohesive/volumetric finite element technique, the two most noteworthy relations available in the literature are the linear law developed by Camacho and Ortiz[4] (extrinsic) and the exponential-based law used by Xu and Needleman[3] (intrinsic). These two cohesive laws differ not only by their mathematical expressions, but also by their implementation within the cohesive/volumetric finite element technique, especially wrt the damage-initiation process (Kubair and Geubelle[5], and Kubair[6], *et al.*).

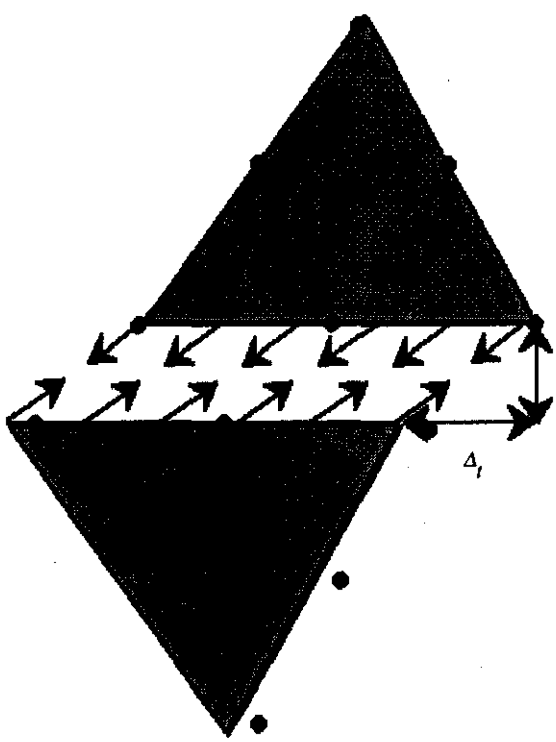

Figure 2. Illustrating the concept of the cohesive/volumetric finite element technique.

In the present study, the intrinsic approach has been used, but with a traction-separation law that is different from the potential-based formulation of Xu and Needleman[3]. The coupled (modes 1 and 2) intrinsic cohesive law used in this work is:

$$S = 1 - \sqrt{\left(\Delta_n^2 + \Delta_t^2\right)} \tag{1}$$

The strength parameter (S) is originally assigned an initial value ($S_{initial}$) close to unity and vanishes when the cohesive failure is completed. The absence of healing of the fracture surfaces is enforced by restricting to be monotonically decreasing and by storing, at each integration point defined on the cohesive elements, its minimum value (S_{min}) as an internal variable is:

$$S = \min\left[S_{\min}, \max\left(0, 1 - \sqrt{\Delta_n^2 + \Delta_t^2}\right)\right] \tag{2}$$

The traction-separation law takes the form:

$$\begin{aligned} T_n &= \sigma_{\max} \frac{S}{1-S} \Delta_n \\ T_t &= \tau_{\max} \frac{S}{1-S} \Delta_t \end{aligned} \tag{3}$$

The cohesive law is plotted in the Fig. 3, for the (a) pure tension and (b) pure shear with the strength parameter initial value set to 0.9.

3. 2-D SIMULATIONS OF IMPACT-INDUCED DELAMINATION

3.1. Problem Description & Finite Element Discretisation

It was chosen to simulate 2-D composite impact experiments performed by Choi[7], *et al.*, in which

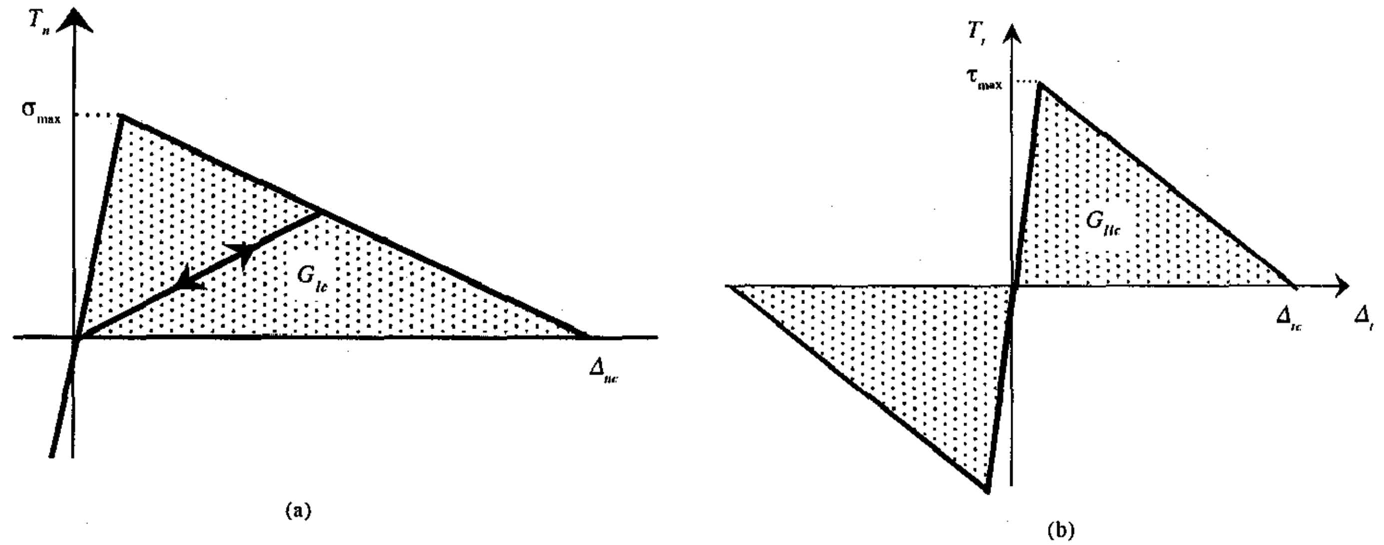

Figure 3. Cohesive law for (a) pure tension and (b) pure shear

a laminated composite beam with the two opposite sides clamped and the other two sides free was impacted with a cylindrical nose impactor along a line located between the two clamped ends. The specific plate to be modelled hereafter was a 10 cm long $[0_6/90_4/0_6]$ laminate of T300/976 graphite/epoxy with a thickness of 2.3 mm. Since the impact was centred, the problem is symmetric about the impact point, and only half of the domain needs to be modelled. The other end of the domain is fixed, representing the clamped edge of the plate (Fig. 4). The mechanical properties for the graphite/epoxy laminate are:

E_1= 156.0 Gpa, ν_{12}= 0.228, ν_{23}= 0.4, and ρ = 1540 kg.m^{-3}.

Uniformly distributed six-node linear strain triangles (LSTs) were used to discretise each of the three layers. Due to the loading conditions, the anticipated failure was entirely within the transverse ply and along the interfaces between the plies with different fibre orientations. Therefore, six-node intrinsic cohesive elements were introduced between the LST only at these locations, leaving the top and bottom layers discretised only with volumetric elements. Since the failure process of the interlaminar interfaces and inside the transverse plies are expected to have

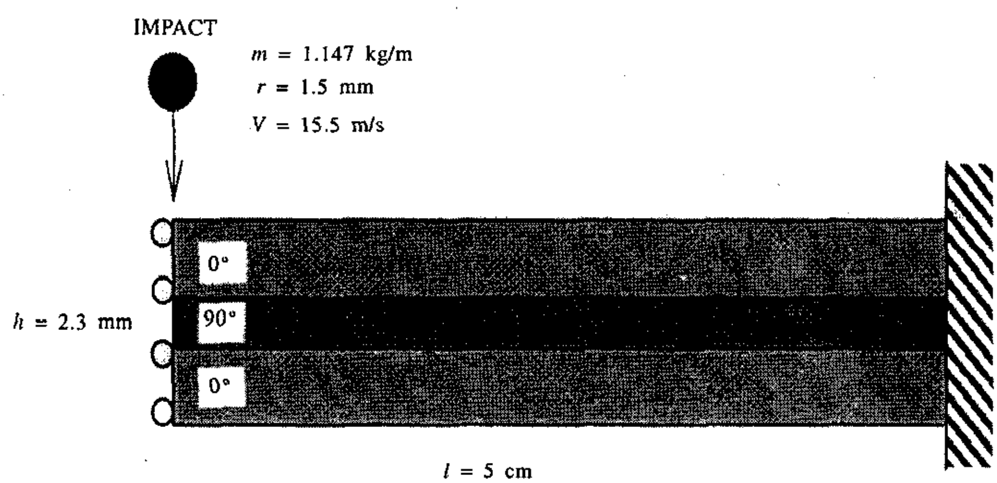

Figure 4. Geometry of the impact problem

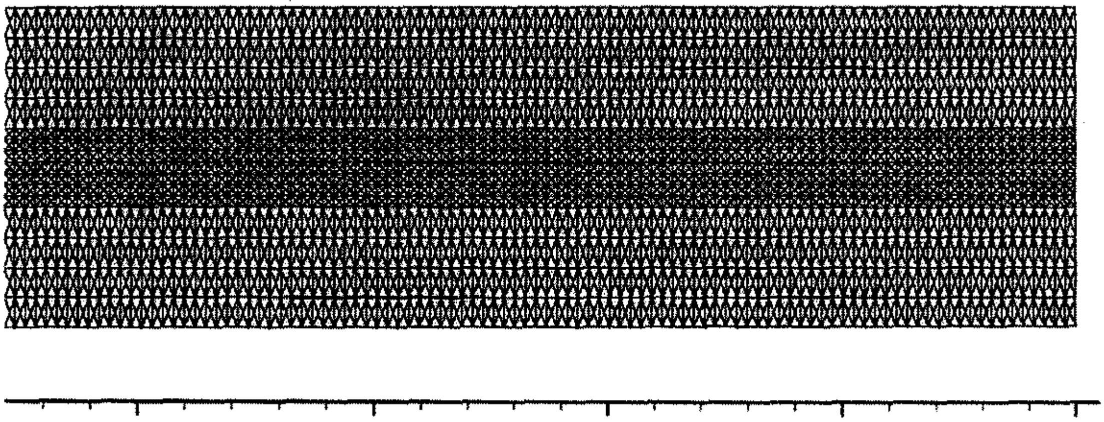

Figure 5. Details of the finite element discretisation

different characteristics, different constitutive properties were used for the corresponding cohesive elements. The fracture toughness values used in this study are:

$$G_{Ic}^{int}=88\ J.m^{-2},\ G_{IIc}^{int}=315\ J.m^{-2},$$

$$G_{Ic}^{ply}=147\ J.m^{-2} \text{ and } G_{IIc}^{int}=526\ J.m^{-2}$$

where int corresponds to the interface between the zero degree and cross plies. The material parameters σ_{max} and τ_{max} introduced in Eqn (3) were assumed to be equal, both for the ply and the interface, and were set to be $\sigma_{max}=0.78$ GPa and $\tau_{max}=2.34$ GPa.

The element size in the fracture zone must be chosen at least two or three times smaller than the size of the cohesive zone to ensure convergence of the cohesive/volumetric finite element technique. Based on the static values of the mechanical properties and energy release rates found in the literature for graphite/epoxy, the size of the cohesive zone for mode 1 fracture in the transverse ply is approx. 180 μm to 650 μm along the interface of the two plies. Since the transverse ply dimensions are 5 cm by 575 μm, at least seven triangular elements must be used through the thickness of the centre layer and about 550 elements along the length. Since these do not contain cohesive elements, the two zero degree plies are discretised more coarsely with only four elements through the thickness. The resulting mesh is composed of quads, each divided into four LST is composed of 130526 nodes and 33180 LST and 23772 cohesive elements (Fig. 5).

To ensure the stability of the cohesive/volumetric finite element technique and to accurately capture the cohesive failure process associated with the matrix cracking and the delamination, a very small time step $\Delta t = h/30C_d$ was chosen, where h represents the longer side of the triangular elements within the transverse ply and C_d (=14.7 km s^{-1}) denotes the dilatational wave speed, ie, the fastest wave speed in the composite material.

3.2 Delamination Damage Simulations

The evolution of the energy components for a typical delamination simulation is presented in the Fig. 6. After approx. 0.35 ms, a substantial drop in the plate strain energy takes place, together with a sudden increase in the fracture energy. Details of the delamination damage in the initiation regions 418 μs after impact are presented in the Fig. 7. One can note the presence of multiple matrix cracks in the 90 ° ply, both during the initiation phase and the delamination phase. One can also note how the critical matrix cracks are oriented towards the applied impact load. The cohesive/volumetric finite element simulation is also able to capture the directionality of the delamination cracks, which propagate towards the point of impact along the upper interface, and away from it, along the lower interface, as observed

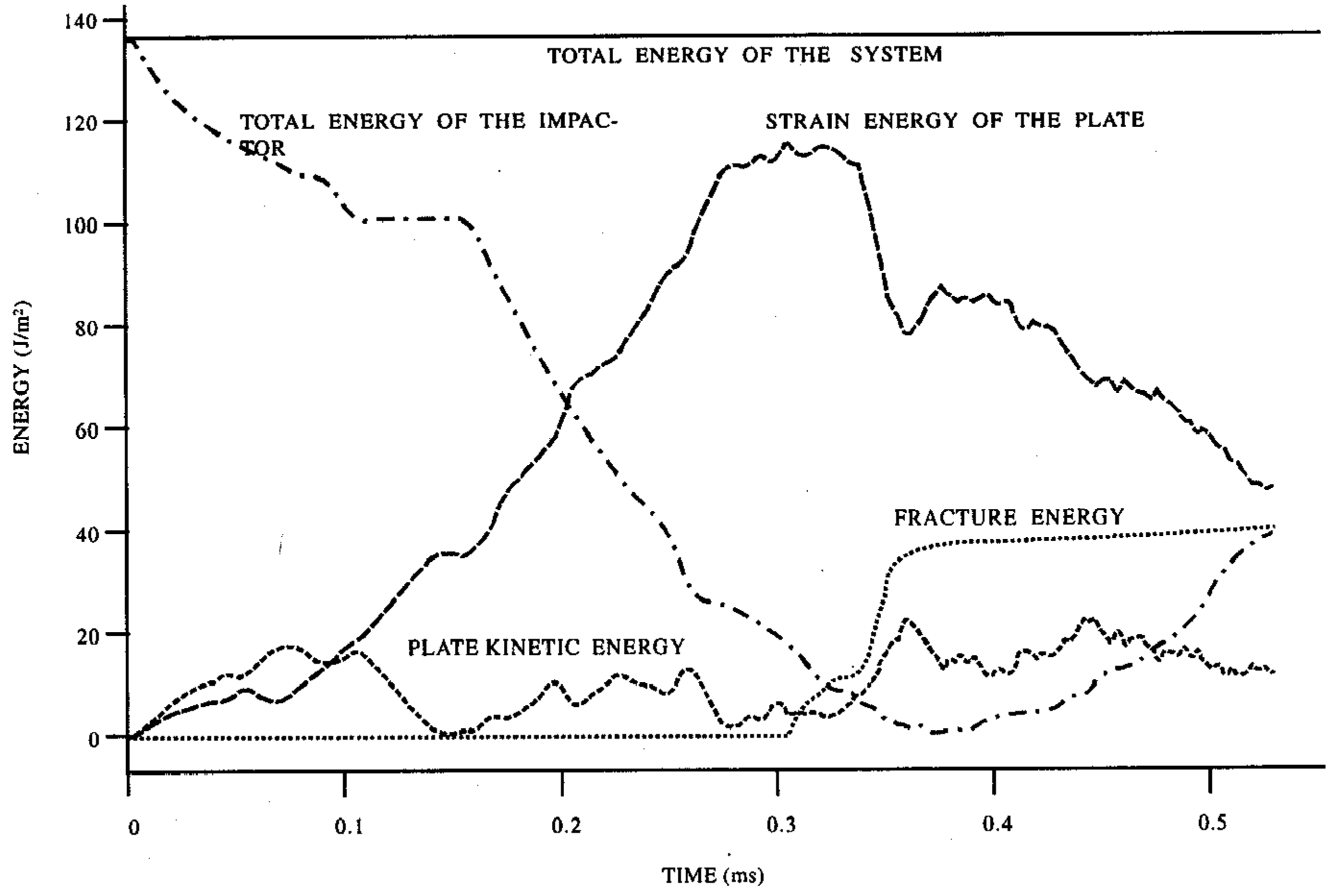

Figure 6. Evolution of energy of the impacted plate

experimentally by Choi[7], *et al.* Investigations of the stress concentration in the vicinity of the delamination fronts indicate that crack propagation takes place under transient mixed-mode conditions, with the shear stress component sometimes exceeding the normal traction stress acting along the interface.

From the results presented so far, one can see that the cohesive/volumetric finite element technique is a useful tool in simulating spontaneous crack initiation and propagation, and the results are in qualitative agreement with the experimental values observed by Choi[7], *et al.* However, various potentially important components have not yet been incorporated in the cohesive/volumetric finite element modelling of the delamination damage process. For example, the structural damping of the composite plate, which could absorb some of the impact energy, is not taken into account. Also, the absence of the composite plate in the simulation is the frictional contact that might take place between the newly created fracture surfaces, especially under shear-dominated situations. Finally, the discreteness of the finite element mesh limits the creation of micro matrix cracks to a finite number of initiations sites. In other words, each cohesive element within the ply can be considered as a being representative of the multiple micro cracks, which could appear in a region corresponding to the adjacent volumetric elements. The inclusion of these terms constitutes the focus of further developments in this technique.

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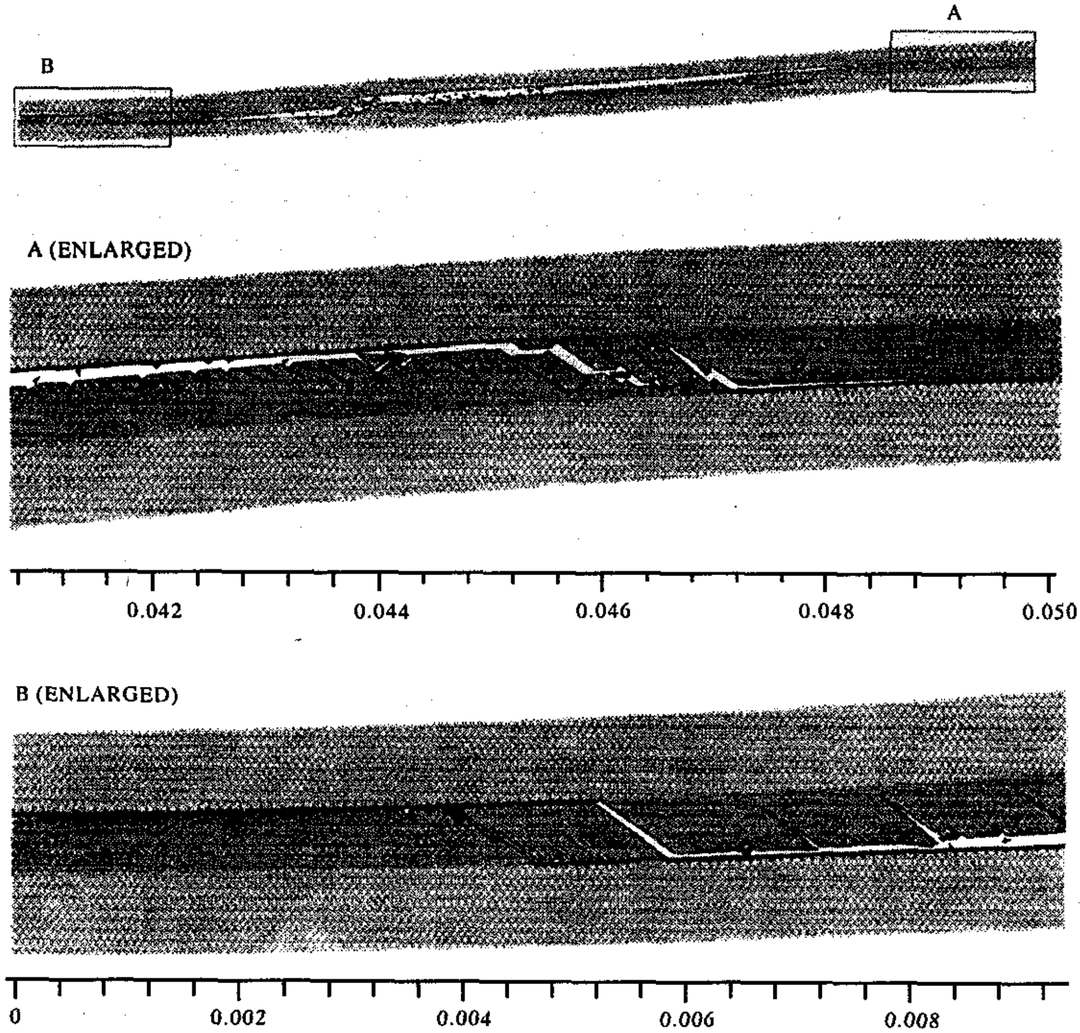

Figure 7. Details of the damage after 418 μs

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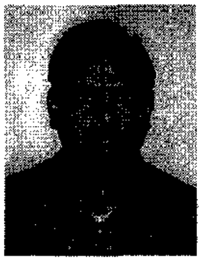

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