ANALYSIS AND DESIGN OF COMPOSITE LAMINATES SUBJECTED TO IMPACT OF FOREIGN OBJECTS

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ABSTRACT

A theoretical and experimental study is developed in this paper, on the dynamic response and damage characterization of composite laminates subject to low–energy impact of foreign objects.

A simple and fast algorithm and a dynamic finite element method are developed to analyze the effects of preload in laminates, the difference between different impact energy states, and the dynamic stress and deformation responses in impacted laminates.

Several detecting techniques are used in experiments to record the information of dynamic response and damage feature of the laminates during impact. Compression After Impact (CAI) tests and compression–dominant fatigue tests are made to investigate the strength and fatigue behavior of impact–damaged laminates.

The paper then discusses and concludes on some critical problems which should be solved in analysis and design of composited structures involving the impact damages.

I INTRODUCTION

Aircraft structures are liable to impact of foreign objects, and composite laminated structures are sensitive to this impact. Low–energy impact of foreign objects may produce internal damage in the laminates, and may result in significant degradation in their properties. The initial research in this field was made by Goldsmith(1), who combined the dynamic analysis of a beam with the law of indentation between the beam and the impactor. As the increasing application of composite laminates to aircraft structures, many researchers pay their attention on impact response, damage characteristics and post–impact effects of composite laminates, and significant achievements are made(2),(3),(4). Even though, many problems remain to be solved. A challenge one among them is how to take the impact damage into account in structural design. This paper presents a comprehensive investigation in the aspect.

II DYNAMIC RESPONSE ANALYSIS OF IMPACTED LAMINATES

1 A Simple and Fast Solution of Dynamic Response of Laminates

Free vibration equations of a laminate are expressed, applying Whitney–Pagano's plate theory(5),(6) concerning the transverse shear effects, as:

$$\begin{aligned}
&D_{11}\psi_{x,xx} + D_{66}\psi_{x,yy} + (D_{12}+D_{66})\psi_{y,xy} - \kappa A_{55}\psi_x \\
&\quad - \kappa A_{55} w_{,x} = I\psi_x \\
&(D_{12}+D_{66})\psi_{x,xy} + D_{66}\psi_{y,xx} + D_{22}\psi_{y,yy} - \kappa A_{44}\psi_y \\
&\quad - \kappa A_{44} w_{,y} = I\psi_y \qquad (1)\\
&\kappa A_{55}\psi_{x,xx} + (\kappa A_{55}+N_x)w_{,xx} + \kappa A_{44}\psi_{y,y} + (\kappa A_{44} \\
&\quad + N_y)w_{,yy} = Pw
\end{aligned}$$

in which w is flexural displacement of the mid–plane, ψ_x and ψ_y are rotation angles of the cross–section, κ is transverse shear coefficient, and

$$(A_{ij},D_{ij}) = \int_{-\frac{h}{2}}^{+\frac{h}{2}} Q_{ij}(1,z^2)dz$$

$$(P,I) = \int_{-\frac{h}{2}}^{+\frac{h}{2}} \rho(1,z^2)dz \qquad (2)$$

in which Q_{ij} is reduced stiffness coefficients, ρ is material density, h is laminate thickness.

For a simply–supported rectangular $a \times b$ laminate, the general solution can be expressed as:

$$\psi_x = A_{mn} \cos\frac{m\pi x}{a} \sin\frac{n\pi y}{b} e^{i\omega t}$$
$$\psi_y = B_{mn} \sin\frac{m\pi x}{a} \cos\frac{n\pi y}{b} e^{i\omega t} \quad (3)$$
$$w = C_{mn} \sin\frac{m\pi x}{a} \sin\frac{n\pi y}{b} e^{i\omega t}$$

which automatically satisfies the boundary conditions:

$$x = 0,a: \; w = \psi_{x,x} = 0; \quad y = 0,b: \; w = \psi_{y,y} = 0$$

Substituting equations (3) into (1), and neglecting the effect of rotation inertia, ie., I = 0, we obtain:

$$[L_{ij}] = \begin{Bmatrix} A_{mn} \\ B_{mn} \\ C_{mn} \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \end{Bmatrix} \quad (4)$$

in which [L] is a 3×3 coefficient matrix containing natural frequency ω_{mn}, which can be determined by letting:

$$| L_{ij} | = 0 \quad (5)$$

The flexural displacement of the laminate is assumed as:

$$w(x,y,t) = \sum_{m=1}^{M} \sum_{n=1}^{N} E_{mn}(t) \sin\frac{m\pi x}{a} \sin\frac{n\pi y}{b} \quad (6)$$

The above equation can be rewritten, substituting the energy expression into Lagrange's dynamic equation, as:

$$w(x,y,t) = A \sum_{m=1}^{M} \sum_{n=1}^{N} B_{mn} \int_0^t F(\tau) \sin\omega_{mn}(t-\tau) d\tau \quad (7)$$

in which F(t) is a point force acting at the central point of the laminate, and

$$A = \frac{4}{Pab}$$
$$B_{mn} = \frac{1}{\omega_{mn}} \sin\frac{m\pi}{2} \sin\frac{n\pi}{2} \sin\frac{m\pi x}{a} \sin\frac{n\pi y}{b}$$

We take F(t) as the impact contact force, and assume it to be linear within a small time interval Δt, then:

$$F(t) = \sum_{i=0,1,2,...} q_i R(t - i\Delta t) \quad (8)$$

and

$$R(t - t_0) = \begin{cases} 0, & 0 \leqslant t \leqslant t_0 \\ (t - t_0)/\Delta t, & t_0 \leqslant t \leqslant t_0 + \Delta t \\ 1, & t > t_0 + \Delta t \end{cases} \quad (9)$$

Substituting the above expressions into (7), yields:

$$w(x,y,t) = A \sum\sum B_{mn} \sum q_i \int_0^{t - i\Delta t} R(\tau) \sin\omega_{mn} (t - i\Delta t - \tau) d\tau$$

or

$$w(x,y,t) = \sum q_i S(t - i\Delta t) \quad (10)$$

and

$$S(t) = A \sum\sum B_{mn} \int_0^t R(\tau) \sin\omega_{mn}(t-\tau) d\tau \quad (11)$$

It can be seen from equations (7) and (11) that S(t) is nothing but the characteristic dynamic response of the laminate under the load R(t), which is pre–determined in (9). So S(t) can be calculated by integrating eq. (11), as:

$$S(x,y,t) = \frac{4}{Pab} \sum\sum \frac{1}{\omega_{mn}^2} \{1 - \frac{1}{\Delta t \omega_{mn}} [\sin\omega_{mn} t - \sin\omega_{mn}(t - \Delta t)]\} \sin\frac{m\pi}{2} \sin\frac{n\pi}{2} \sin\frac{m\pi x}{a} \sin\frac{n\pi y}{b} \quad (12)$$

The unknown quantities q_i indicate the increaments of contact force at every time step $t = i\Delta t$. The other quantities can be expressed by q_i as:

$$F_i = q_0 + q_1 + q_2 + ... + q_{i-1} = F_{i-1} + q_{i-1}$$
$$V_i = V_{i-1} - F_{i-1}\Delta t / m - q_{i-1}\Delta t / 2m$$
$$\chi_i = \chi_{i-1} + V_{i-1}\Delta t - F_{i-1}\Delta t^2 / 2m - q_{i-1}\Delta t^2 / 6m$$
$$w_i = q_0 S_i + q_1 S_{i-1} + q_2 S_{i-2} + ... + q_{i-1} S_1 \quad (13)$$

in which F, V, χ and w indicates impact force, velocity of impactor, displacement of impactor and displacement of laminate, respectively. m is the mass of the impactor.

The relationship between the above quantities can be established through Hertz's indentation law:

$$\alpha_i = \chi_i - w_i$$
$$F_i = \Phi(\alpha)$$

from which we obtain an approaching equation to solve q_i:

$$q_{i-1} = \frac{C_i - \overline{\Phi}(F_{i-1} + q_{i-1})}{S_1 + \Delta t^2 / 6m} \quad (14)$$

in which $C_i = \chi_{i-1} - w_{i-1} + V_{i-1}\Delta t - F_{i-1}\Delta t^2 / 2m$

The method described above is simple and effective, but it is limited in a certain laminate configuration (orthotropic, simply supported and rectangular laminate). It is noted that no matter how S(t) is calculated, equation (10), (13) and (14) are valid. So we develop a finite element method to deal with the varieties of laminates.

2 Dynamic Finite Element Analysis

Concerning the effect of transverse shear deformation, The governing equation of dynamic FEA is[7]:

$$\{P\} = [K]\{u\} + [M]\{u''\} \quad (15)$$

Assuming u″ to be linear within Δt, we have:

$$[H]\{u''\}_{t+\Delta t} = \{P\}_{t+\Delta t} - [K]\{b\}_t \quad (16)$$

where

$$[H] = [M] + \frac{\Delta t^2}{6}[K]$$

$$\{b\}_t = \{u\}_t + \Delta t\{u'\}_t + \frac{\Delta t^2}{3}\{u''\}_t$$

The load vector {P} contains only one non–zero component, R(t), as defined in (9). Solving equation (12), we obtain $\{u''\}_{t+\Delta t}$, and then $\{u'\}_{t+\Delta t}$ and $\{u\}_{t+\Delta t}$. Displacement vector {u} contains transverse shear of laminates, from which the interlaminar shear stresses can be calculated.

The above calculations give the characteristic response S(t), substituting it into expression (10), the real response of laminates subjected to impact force F(t) can be calculated.

III CHARACTERISTIC RESPONSE OF IMPACTED LAMINATES

A typical illustration of dynamic response of a laminate is shown in Figure 1, in which F is impact contact force, V is velocity of impactor, w and χ is displacement of laminate and impactor, respectively. It is seen from the figure that the impact duration is within one micro–second, and the impact history is in nature a multiple–impact. Figure 2 gives a comparison between the calculation and the experiment. It shows a good agreement between them.

1 Effects of Preload on Dynamic Response of Laminates

Calculation[7],[8],[9] shows that the effect of preload is slight on impact force, but is significant on impact duration and laminate deformation. A compressive preload increases the impact duration and the laminate deformation, and a tensile preload decreases them. In this sense, a compressive preload may produce harmful effect on laminates.

2 Effects of Different Impact Energy States

Consider a laminate subjected to impact of two kinds of energy states: large–mass / low–velocity impact(blunt impact) and small–mass / high–velocity impact (sharp impact). Calculation[7],[8],[9] indicates that a sharp impact results in a short impact duration and conversely a blunt impact, while the maximum impact force, maximum displacement and total energy absorption of the laminate changes little.

It is noted that a sharp impact creates a localized deformation in a small area as the impact force reaches maximum, while a blunt impact creates a relatively uniformed deformation all over the laminate. It reveals a similar feature of the interlaminar shear stress with that of deformation, ie., a sharp impact creates a stress concentration in a small area, while a blunt impact creates a uniformed stress distribution.

It is also noted that a similar difference exists between a thin plate and a thick one, ie., a thin plate behaves as it is subjected to a sharp impact, and a thick one as subjected to a blunt impact.

In this sense, it can be deduced that a sharp impact may produce a small area of ″hard″ damage such as fiber breaking or material collapsing, while a blunt impact may result in a large area of ″soft″ damage such as delamination.

Calculation also indicates that the maximum interlaminar shear stress is relatively much higher than the bending stress compared with the corresponding strength. In the calculation, the bending stress is about 3 times greater than the shear stress, while the bending strength is usually 30–50 times greater than the interlaminar shear strength. So the interlaminar shear stress takes a dominant role in the formation and propagation of impact damage, and the impact damage may mainly be delamination. This deduction is only valid for low velocity impact, because the impact wave propagation through the thickness of laminates is neglected.

IV IMPACT EXPERIMENT AND DAMAGE OBSERVATION

Carbon / Epoxy laminate specimens are experimented in accordance with References [10] and [11]. The impact force is recorded by piezoelectric film placed at the impacted point of the specimen. The deformation of the laminate is detected by super–transient strain gages arranged at different points on the specimen. Figure 2 shows the recorded information and calculated result from finite element method (FEM).

The impact damage features are detected through dye–penetrant enhanced X–ray photography from two directions, as well as C–scan and micro photography. Figure 3 shows a damaged section across the impact point through the thickness of the laminate. Figure 4 is a X–ray photograph, showing the overview of impact damage and details at several sequential sections through thickness of the laminate. The pictures show that delamiantion is a major mode of damages, while other types of damages also exist, such as matrix cracking and fiber breaking.

Figure 4 shows that delamination damage distributes as a conical stage through the thickness of laminates, and the interfaces near back surface (away from impacted surface) may suffer more serious damage, and these interfaces are usually between cross–orientated plies[7] (see figure 6).

The observation indicates that an impact of a foreign object produces a serious damage inner a laminate and in the back surface, but it is hardly visible to the naked eye from the front surface (impacted surface)[7].

The observation also shows that a thick laminate suffers more serious delamination than a thin one. Figure 5 gives C–scan pictures showing the damage area in different laminates subject to different energy impact. The tendency that a thicker laminate suffers a greater damage is valid within the thickness range from 2.7mm to 5.8mm.

V COMPRESSION AND FATIGUE TEST AFTER IMPACT

The compressive strength of laminates is very sensitive to impact damage. Tests are conducted to investigate the failure mode, damage propagation and strength reduction of the laminates.

Experiments show that the buckling of delaminated region of laminates(delaminated subdelaminates) and the unstable growth of delamination dominates the failure mode of the laminates, and the strength reduction due to impact damage is significant. Table 1 gives the information of impact energy, impact damage area, compressive strain and compressive strength of specimens. The data indicate that upon an impactenergy from 3.6J to 15J, a serious strength reduction is caused, with the rate from 57% to 77% compared with the undamaged laminates, especially for thick specimens.

Same kind of specimens are tested in compression–compression fatigue, the damage propagation is detected with C–scan. Three stress level are selected in the tests:

1 $\sigma_{max} = 0.5\sigma_c = 60.2$MPa, R = 0.1, f = 10Hz
Specimens are tested up to 1.4×10^5cycles, and then detected with C–scan. No damage growth is observed.

2 $\sigma_{max} = 0.75\sigma_c = 90.3$MPa, R = 0.1, f = 10Hz
Specimens are tested up to 0.5×10^5, $1.0\times 10^5$and 1.4×10^5cycles respectively, and no damage growth is scanned. The tests are repeated with the stress ration R = −1 (that is a compression–tension fatigue), and the results are the same.

3 $\sigma_{max} = 0.9\sigma_c = 121.2$MPa, R = 0.1, f = 10Hz
Specimens are tested only up to 1500 cycles, when the delamination damage propagates through the whole width of the laminates, and the buckling deformation of the delaminated sublaminates are obvious. The specimens break down when tested to about 11500 cycles.

The above information shows that the impact damage does not grow until the fatigue load is applied at a quite high level, which is very close to the static compressive strength of the impact–damaged laminates. In the other words, the impact damage behaves as a ″no–growth damage″ during fatigue.

DISCUSSIONS

The following factors (extracted from calculations and experiments mentioned above) constitute a fundamental knowledge about impact damage and post–impact effects on composite laminates:

1 An impact of foreign objects may produce serious damage inner the laminates, and the major mode of the damage is delamination. But the damage is hardly visible from the front surface.

2 Compression is the critical load case for impact–damaged laminates, and the local buckling of delaminated sublaminates is a dominant mode of failure. The compressive strenght reduction due to impact damage is significant.

3 The impact damage does not grow until the fatigue load is applied at a quite high level, ie., the impact damage behaves as a ″no–growth damage″ during fatigue.

From the above understanding, we may make such comments as following:

1 An effective approach to analyze the impact damage in laminates should involve the wave propagation analysis, to simulate or predict the impact damage; ″delamination fracture mechanics″ should be further developed, due to the major mode of damage is delamination; buckling analysis of laminates containing delamination should be emphasized, for the buckling of delaminated sublaminates is a dominant mode of failure.

2 A careful design of lamiantes may enhance their ability to endure impact of foreign objects, toughened materials and reasonable ply–orientation are two of effective ways.

3 Impact damage is a critical case in Damage Tolerance Design of composite laminates, which dominates the design allowables of the structures. The fact that the impact damage behaves as a ″no–growth″ damage takes an important role in Damage Tolerance Design.

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No.	Impact Energy (J)	Damage Area (cm^2)	Failure Strain ($\mu\varepsilon$)	Failure Stress (σ_c MPa)	σ_c / σ_b
A–00	0	0	6047	$\sigma_b = 398.2$	
A–01	3.60	4.40	2607	171.65	0.431
A–02	3.75	4.12	2410	158.67	0.398
A–03	7.20	6.92	1997	131.50	0.330
A–05	15.0	15.1	1833	120.70	0.303
B–00	0	0	6267	$\sigma_b = 412.6$	
B–01	7.20	17.9	1859	122.40	0.297
B–03	15.0	55.3	1408	92.72	0.225

A: Thin laminate (t = 2.7mm)
B: Thick laminate (t = 5.8mm)

Table 1 Compression Test Data of Impacted Laminates

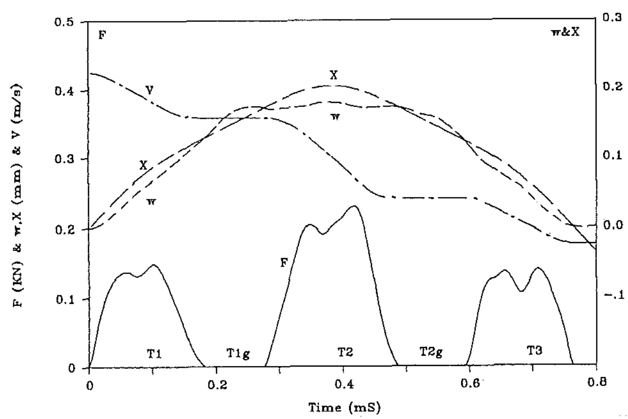

Fig. 1 Typical of Impact History

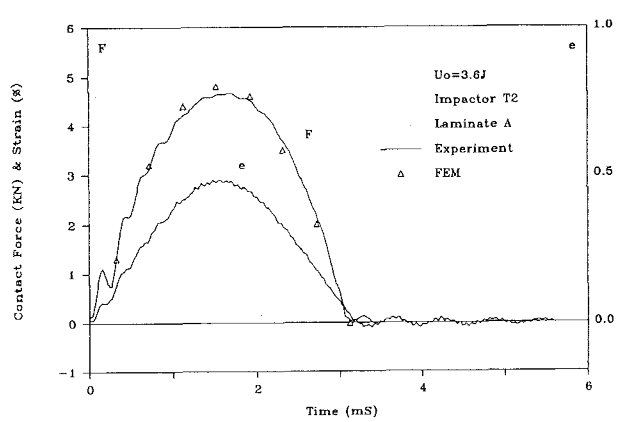

Fig. 2 Comparison of Impact History between Calculation and Experiment

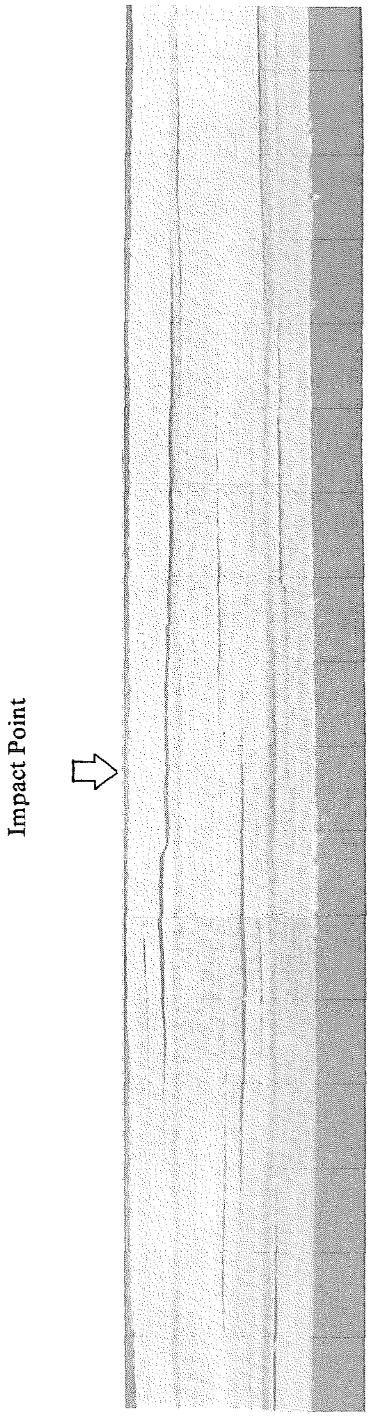

Fig. 3 Sectional View of Impact Damage

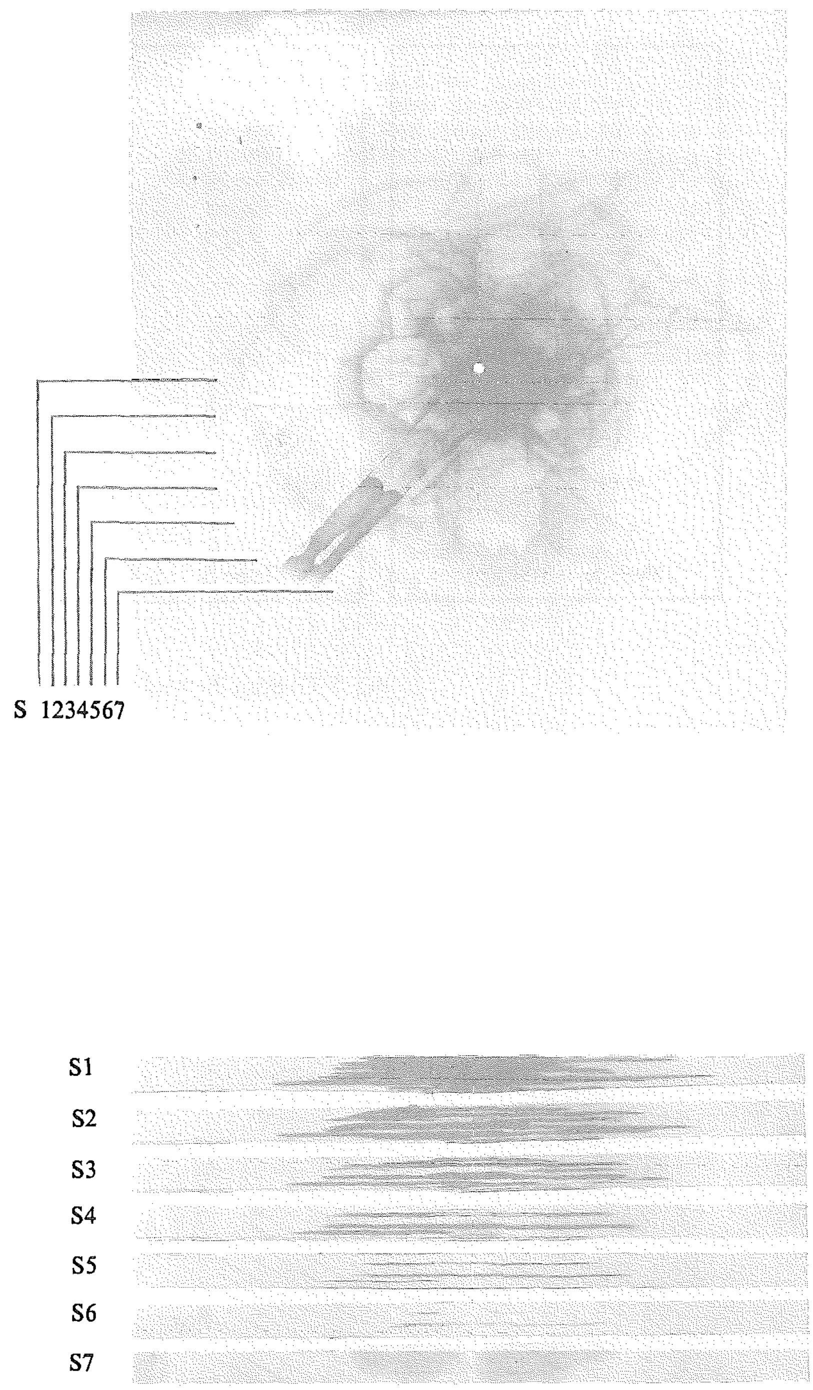

Fig. 4 X–Ray Photograph of Damage Details

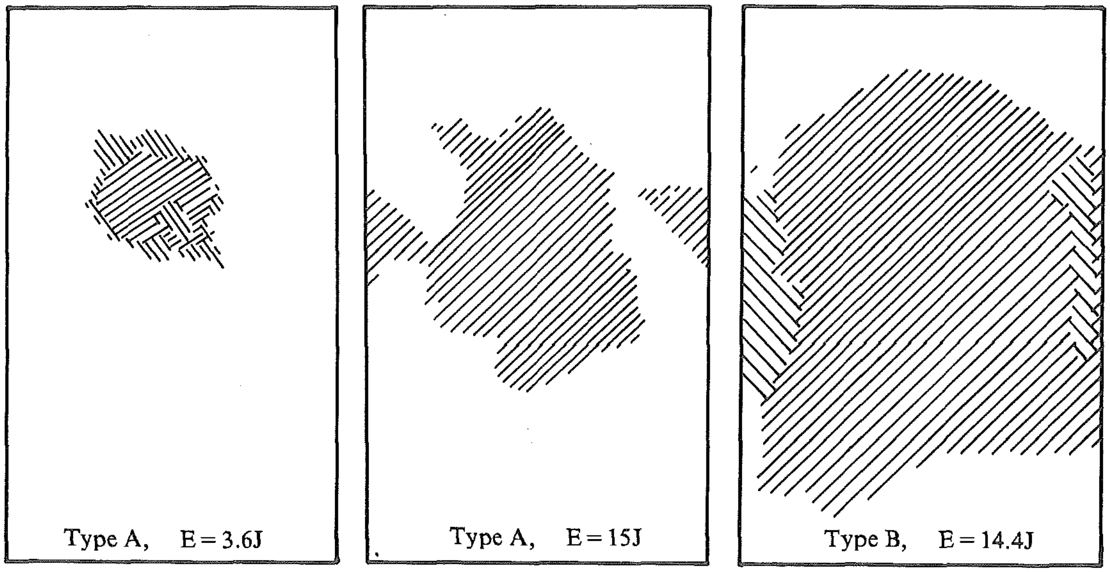

Fig. 5 C–Scan Pictures of Impact Damage

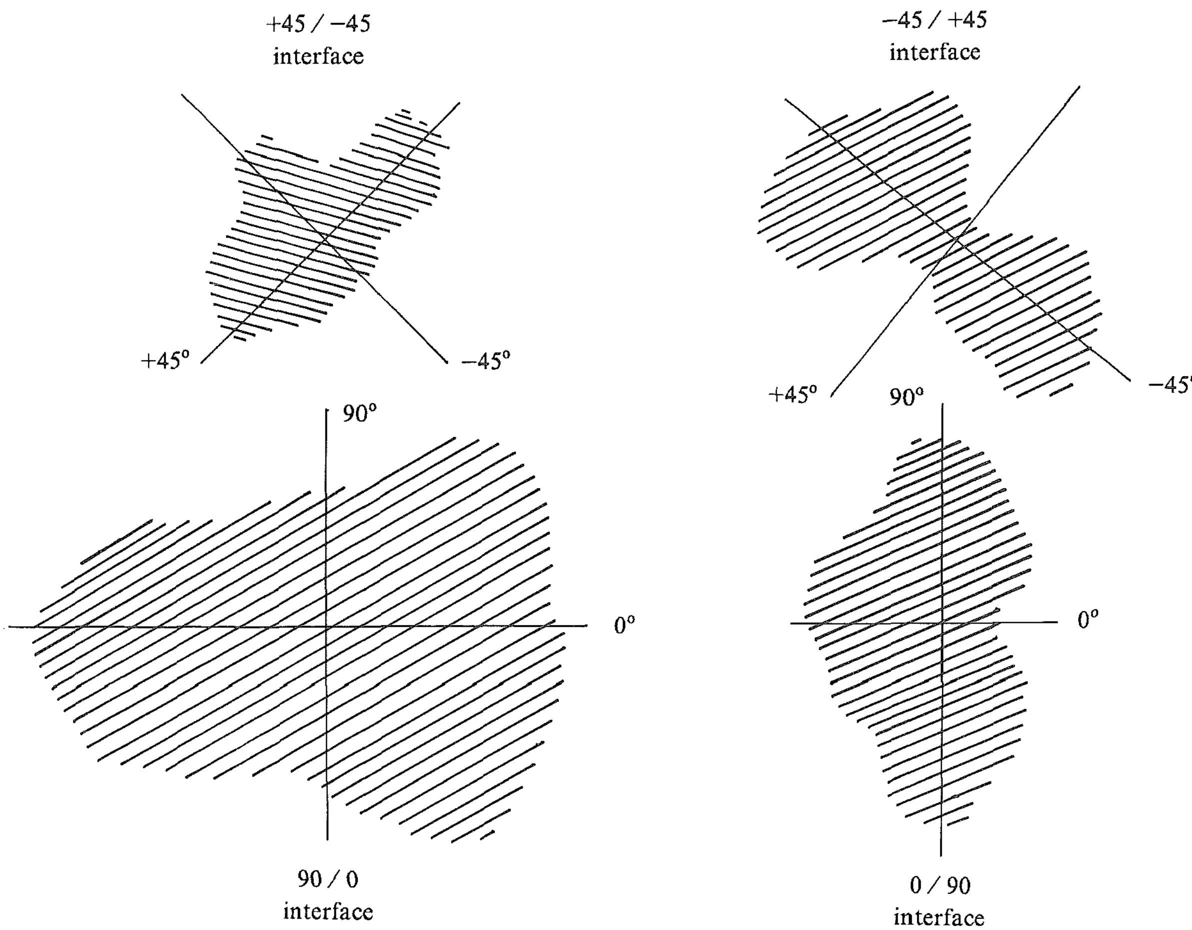

Figure 6 Damages in Interfaces