FRACTURE ANALYSIS BY CAUSTIC METHOD OF LAMINATED FIBER RE-INFORCED PLASTICS

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The fracture behaviour of different composite material systems and laminate configurations was investigated by the optical method of caustics.

Both high-performance laminates, such as long fibers reinforced plastics (GFRP), and short (chopped) glass fibers reinforced thermoset resins were experimentally studied. The basic damage mechanisms and fracture initiation and growth were analyzed in cracked laminates and an attempt to determine the energy release rate as a function of the applied load and cracked geometry was made.

The actual and potential capabilities of the caustics method for studing such composite materials were singled out.

INTRODUCTION

Composite materials, considered as reinforced plastics, is a comprehensive term which describe a broad range of material systems. Design engineers and manufacturers are now using both short and long fiber reinforced plastics in almost all general engineering fields.

For high-performance structural applications the engineers require a good confidence in design procedure and material properties. The experience on the behaviour of composite materials is still far from being exhaustive and even if significant progress have been made in the characterization of defects, in the mechanics of orthotropic materials and more generally in the fracture characterization of composite structures [1], [2], [3], the understanding of the microstructural damage mechanisms and the damage growth up to the complete failure is not satisfactory.

Currently the Fracture Mechanics approach, with some proper modifications, is widely used for modeling the fracture processes. However, the utility of the models based on such theory is restricted due to the intrinsic nature of composites which leads to non-unique but several

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concurrent damage phenomena with synergic effects. Much experimental and theoretical work was carried out both from the microscopic and macroscopic point of view [4], [5], [6].

In this paper the fracture behaviour of different simmetric laminate configurations, namely $(0)_n$, $(0/90)_n$, and material systems (chopped glass fibers/polyester resins, woven glass fibers/polyester resins, unidirectional glass fibers/epoxy resins) have been investigated by the optical method of caustics.

A phenomenological analysis has been carried out in order to point out, for the different material systems and laminates, the damage mechanisms and macroscopic growth of crack-like defects.

The energy release rate has been experimentally and numerically evaluated in order to characterize the damage process and the stability domain of the initial defects.

CAUSTIC METHOD FOR COMPOSITE MATERIAL PLATES: GOVERNING EQUATIONS AND BASIC THEORY

The fracture behaviour of composite structure can be effectively characterized by evaluating the energy release rate related to the damage processes such as the increase of the overall crack length, delamination around the crack tip, crack branching and kinking etc. The caustics methods is a usefull experimental method to evaluate such energy parameter. Under the hypothesis of homogeneous and orthotropic or isotropic bodies, depending on the particular configuration of composite materials at hand, it's possible to determine the Stress Intensity Factor, K, which is related to the energy release rate, G, by the relations proposed by Sih, Paris and Irwin [3].

Following the formulation proposed by Theocaris, [7] for orthotropic plates, the caustic curve is expressed by the relations:

$$\begin{cases} W_x = -2 z_0 t \,\mathrm{Re}\left[\delta_1 \dfrac{d\phi_1(z_1)}{dz_1} + \delta_2 \dfrac{d\phi_2(z_2)}{dz_2}\right] \\ W_y = -2 z_0 t \,\mathrm{Re}\left[\delta_1\, s_2 \dfrac{d\phi_1(z_1)}{dz_1} + \delta_2\, s_2 \dfrac{d\phi_2(z_2)}{dz_2}\right] \end{cases} \qquad \delta_i = a_{31} s_i^2 - a_{36} s_i + a_{32} \quad i = 1, 2 \tag{1}$$

where s_i are related to the roots of an equation of the 4th order depending on the orthotropic material properties. The expressions of the analytic functions $\phi_1(z_1)$ and $\phi_2(z_2)$ can be found in [7].

It can be found, [8], that the initial curve of caustic is given by the equation:

$$
\begin{aligned}
& r^{5} - r^{5/2} \cdot 3[K_{II}(1-\beta_2^2)\gamma_2^{-5/2}\cos(\tfrac{5}{2}\theta_2) - K_I(1-\beta_1^2)\gamma_1^{-5/2}\cos(\tfrac{5}{2}\theta_1)] - \\
& +9[K_{II}^2\beta_2^2\gamma_2^{-5} + K_I^2\beta_1^2\gamma_1^{-5} - K_I K_{II}(\gamma_1\gamma_2)^{-5/2}\{(\beta_1^2+\beta_2^2)\cos(\tfrac{5}{2}\theta_1)\cos(\tfrac{5}{2}\theta_2) + \\
& +2\beta_1\beta_2\sin(\tfrac{5}{2}\theta_1)\sin(\tfrac{5}{2}\theta_2)\}] = 0
\end{aligned}
\tag{2}
$$

which can be resolved for the variable r (radius of the initial curve) by introducing the substitution $x = r^{5/2}$.

To obtain a direct relation between $K_{I,II}$ and the caustic diameter, the point corresponding to $\theta = 90°$, having as coordinates $W_x = 0$; $W_y = (W_y)^{max}$, has to be considered and the radius of the initial curve must be substituted in the following relation:

$$
W_y = \lambda_m [r \sin\theta + r^{-3/2}\{K_2\beta_2 \sin(\tfrac{3}{2}\theta_2 + \omega_2) - K_1\beta_1\sin(\tfrac{3}{2}\theta_1 + \omega_1)\}] \tag{3}
$$

The applicable relation for the S.I.F. calculation is (in the case of pure mode I of fracture, $K_{II} = 0$):

$$
K_I = \frac{(D_t)^{5/2}}{2\lambda_m^{5/2}[A^{2/5}\sin\theta + A^{-3/5}\{C_1\beta_1\beta_2\sin(\tfrac{3}{2}\theta_2) - C_2\beta_1\beta_2\sin(\tfrac{3}{2}\theta_1)\}]^{5/2}} \tag{4}
$$

Some digressions on the capabilities and restrictions of the caustic method are in order.

The caustic method is able to provide informations, both quantitative and qualitative, regarding the near tip stress-strain fields. However, because of the 3D character of the elastic fields in the neighborhood of the crack location area some local 3D effects are not taken into account in the theory of the caustic method which is based on a plane stress field assumption [9]. From the experimental observations, it results that the caustic diameter is subjected to sudden variations when the fibers close to the crack tip are failed. Moreover, if some damage has occurred around the crack tip, like delaminations or plasticization, the caustic image is directly affected by such a damage. Of course, the governing equations of the method have to be changed in such a way that these non-linear phenomena are taken into account.

MATERIAL SYSTEMS, TEST PROCEDURES AND RESULTS

Three basically different groups of material systems were studied and they differ both for the type of resin or for the type of fibers reinforcement. The three groups of materials are:

a) short fibers-polyester resin
b) long fibers-polyester resin
c) long fibers-epoxy resin.

The first group of composite materials contain in-plane randomly oriented chopped fibers, namely the chopped-strand mat, and the laminates were made by hand lay-up technique. To obtain a reflective surface, the first and the last two layers were made by using a surface chopped-strand mat.

As regard the fracture behaviour of such a material, it can be observed that due to the random in-plane distribution of the fibers, the fracture mechanisms strongly depends on the orientation of the near-tip reinforcing fibers. However, fibers fracture, pull-out of bundles and matrix cracking are the basic fracture mechanisms. The second group of composite materials were made by woven glass fibers and polyester resin manufactured by hand lay-up technique. Two different laminates were studied: (0°/90°) and (surface mat/0°/90°). The second type of laminates were studied in order to evaluate, from the point of view of fracture behaviour, the effects of the inter-ply surface chopped strand mat which provide a better inter-ply mechanical bonding. The third group of composite materials were made by unidirectional preimpregnated with epoxy resin and cured in autoclave. For this third group of materials, two basic laminate configurations were studied: $(0°)_{12}$ and $(0°/90°)_6$. Particular attention were given to the surface finishing and to obtain a mirror-like surface a special release agent and a mold with mirror-like surfaces were used. The experimental tests were made by loading the cracked specimens with a uniform remote tension. All the specimens are 150 mm long and 80 mm wide, with a lateral crack initiated by a saw cut. The initial cracks have been propagated by applying a cycling load with small amplitude, in order to obtain a fatigue crack with small radius of the crack tip. After the crack lengths have reached sufficient values, the caustic images were aquired at different load values, with a constant crack length, and at different crack length for the same load values. As regards the short fiber specimens, the crack propagation is not uniform and the crack path is not rectilinear. However the overall crack propagation can be considered self-similar. The fracture mechanisms have been investigated by analyzing the fracture surfaces. Fibers pull-out of the longitudinally oriented bundles and matrix cracking have been observed in all the specimens. For the S.I.F. and G calculations, the equation for isotropic material has been used and Fig. 1 shows the comparison between the experimental, numerical (Finite Element Method) and analytical results for the value of G.

It can be observed that the higher is the load the higher is the difference between the numerical and experimental results. This can be ascribed to a non-linear behaviour of the material above a certain load level. For the woven specimen, the caustic method has provided very interesting informations about the crack propagation. For instance it is clearly visible the occurrence of fiber failure before the crack growth. The caustic curve is almost circular because of the same degree of orthotropy in the longitudinal and transverse directions. Fig. 2, shows the variations of the G as a function of the load intensity for a cross-ply laminate (0°/90°), and for three different crack length. In Fig. 3 the effect of the laminate configuration, for the same crack length, on the G is shown. It is found that the higher is the content of the longitudinal fibers (orthogonal to the crack axis) the lower is the energy release rate. Fig. 4 shows the variation of G in function of the load intensity for different values of the ratio of the elastic modulus. The effect of the ratio E_1/E_2 is clearly shown and it can be concluded that the degree of orthotropy is a significant parameter which can significantly affect the toughness of the material.

The fracture mechanisms in the woven and laminated specimens are very similar. Delamination around the crack tip occur in both type of specimens even if in the laminated one this damage phenomenon is more pronounced.

Fig. 5 (a) and (b) show two experimentally obtained caustic from a laminated plate and from a woven glass fiber plate. The grid in the shadow image represents the fibers of the material and it is interesting to observe how they behave near the crack tip. Fig. 6 shows a caustic image obtained after the crack have been propagated and a brancing phenomenon has occurred.

SYMBOLS USED

$$C_{1,2} = \frac{z_0\, t\, \delta_{1,2}}{2\sqrt{2\pi}\, \lambda_m(\beta_1 - \beta_2)}$$

$$D = C_2\,\beta_1(1-\beta_2^2)\,\gamma_2^{-5/2}\cos\left(\frac{5}{2}\theta_2\right) - C_1\,\beta_1(1-\beta_1^2)\,\gamma_1^{-5/2}\cos\left(\frac{5}{2}\theta_1\right)$$

$$F_1 = \beta_1^2\,\beta_2^2\,C_2^2\,\gamma_2^{-5}$$

$$F_2 = \beta_1^2\,\beta_2^2\,C_1^2\,\gamma_1^{-5}$$

$$F_3 = \beta_1\,\beta_2\,C_1\,C_2(\gamma_1\,\gamma_2)^{-5/2}\left[(\beta_1^2+\beta_2^2)\cos\left(\frac{5}{2}\theta_1\right)\cos\left(\frac{5}{2}\theta_2\right)+\right.$$

$$\left.+2\,\beta_1\,\beta_2\sin\left(\frac{5}{2}\theta_1\right)\sin\left(\frac{5}{2}\theta_2\right)\right]$$

$$A = 3D \pm [9\,D^2 + 36\,(F_1 + F_2 - F_3)^{1/2}]^{2/5}$$

$$K_{1,2} = K_I\,C_{1,2}\,\beta_{2,1}$$

$\beta_{1,2}$ = roots of the equation: $\beta^4 - (\frac{E_1}{G} - 2\nu_{12})\beta^2 + \frac{E_1}{E_2} = 0$

$\omega_{1,2} = tg^{-1}\frac{K_{II}}{\beta_{2,1}K_I}$; $\lambda_m = \frac{z_0 \pm z_i}{z_i}$

z_0 = screen-specimen distance

z_i = focus-specimen distance

a_{ij} = elastic constants of the material

D_t = transverse diameter of the caustic

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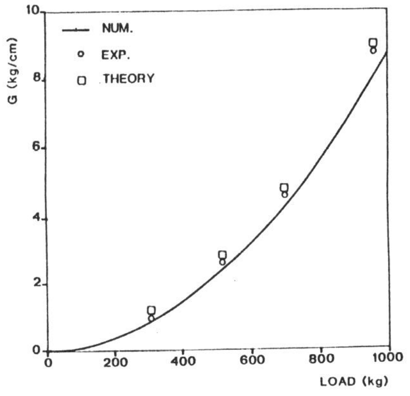


Figure 1 Short fiber: comparison between experimental, numerical and analytical results

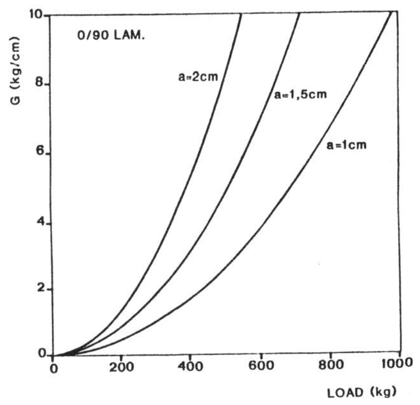


Figure 2 Long fiber: energy release rate variation as a function of the applied load and of the crack length

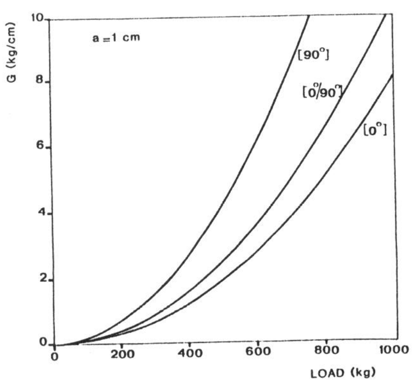


Figure 3 Effects of the laminate configuration on the energy release rate

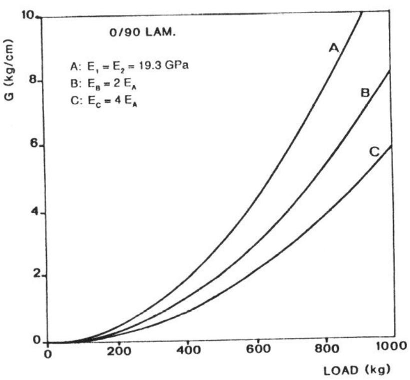
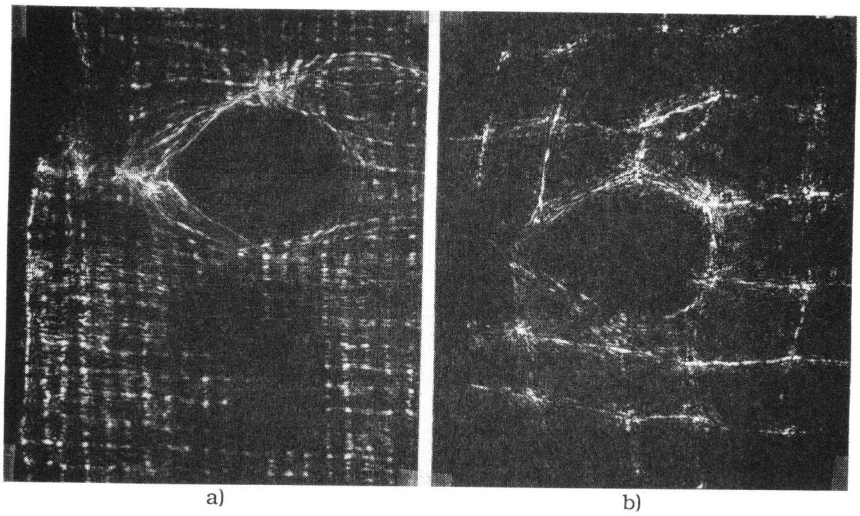


Figure 4 Variation of the energy release rate in function of the applied load and elasticity modulus



a) b)

Figure 5 Experimentally obtained caustics:
a) from (0/90) laminated plate
b) from cracked woven fibers specimen

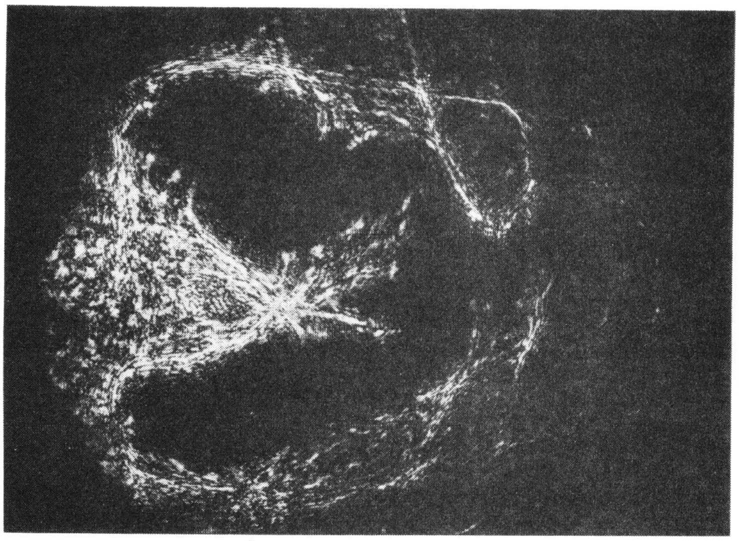


Figure 6 Caustic image observed from a woven fibers specimen with branched crack