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DAMAGE IN UNIDIRECTIONAL GRAPHITE/EPOXY LAMINATES CONTAINING A CIRCULAR HOLE

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ABSTRACT

In this paper, a damage mechanics model is described for determining progressive damage processes in unidirectional graphite/epoxy composite plates containing a central hole subjected to off-axis uniaxial tension. The inelastic behavior of these composite materials is attributed to the irreversible thermodynamics processes involving energy dissipation and stiffness variation caused by damage initiation and accumulation. The mechanical response of the composites is investigated by using a nonlinear finite element procedure formulated with a set of damage coupled constitutive equations. Separate damage criteria are derived for fiber failure and for matrix or fiber/matrix interaction failure in unidirectional composites. Validation of the damage model is achieved by comparing the numerical prediction and experimental data obtained from a Moiré interferometry technique. It has been found that failure of the composite material near the hole region takes the form of an extensive damage zone. The macrocrack initiates at the material point near the hole boundary with a high damage value and propagates along the direction of damage zone extension. Preliminary results indicate that the proposed damage model is an effective method of studying progressive failure behavior of unidirectional composite laminates containing a circular hole and can be readily extended to examine the damage response of composite structures.

INTRODUCTION

The application of fiber reinforced composite laminates in secondary and primary engineering structures has increased rapidly in recent years. While composite materials offer many desirable structural properties over conventional materials, they also pose challenging mechanics problems in understanding and prediction of their mechanical performance and failure behavior. Intensive investigation has revealed that these materials exhibit extremely complex damage modes under different loading conditions (Reifsnider, 1982). Typical damage patterns in a composite laminate include matrix cracking, matrix/fiber interface debonding, interply delamination, fiber breakage, etc., which are detected from the early stage of useful life of a composite until its final rupture. The presence and the evolution of these damage mechanisms will affect mechanical properties of the composite plies and subsequently, response of the composite structures. Accordingly, it is important to characterize these defects and their evolution in evaluation of composite durability and structural integrity.

The theory of damage mechanics provides an effective analytical tool to determine progressive failure including the characterization of failure mechanisms and damage propagation in composite laminates. The phenomenon of material progressive degradation is caused by the nucleation and the growth of distributed microscopic cavities and cracks that are commonly known as damage. Recently, Allix et al. (1990), Kamimura (1985), Talreja (1990), and Allen and Lee (1990) presented some damage models for composite laminates. In their models, based on the thermodynamics of irreversible process, damage entities are represented by an appropriate set of averaging vector- or tensor-valued internal state variables and the constitutive relations for elastic composites with distributed damage are formulated. Although their attentions are mainly focused on the prediction of stiffness loss of the laminate for a given damage state, these investigations offer a way to incorporate the micromechanics level damage mechanisms into macromechanics failure analyses.

Usually, there are two practical approaches in the investigation of macroscopic behaviors of damage in fiber-reinforced composite laminates. One approach is to treat the laminate as an entity and a special material, e.g., a particular kind of stacking sequence makes a unique

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material. This type of "direct" approach requires a complete characterization of the failure behavior of each laminate and demands a great deal of expensive and laborious testing. This is because each laminate is considered a particular material. Another approach is to treat each composite ply as a basic element in the overall representation of the mechanical properties of a laminate, i.e., using the properties of the unidirectional layer as a "building block" to predict the performance of the laminate. This approach is chosen for the proposed investigation due to its ability in characterizing the laminate equivalent to a structure rather than an artificial material.

The behavior of fiber reinforced composite laminates with stress concentrations such as cutouts is of practical importance in the design of composite structures because of the resulting significant variations of strength reduction and the damage growth around these stress concentrations in service. This paper is concerned with prediction of the response of unidirectional composite laminates containing a circular hole. The study of unidirectional lamina represents a simpler and perhaps a fundamental investigation which should proceed before an attempt is made to understand damage accumulation in complex laminates. The anisotropic damage model proposed by Chow et al. (1992) and the finite element procedure developed by Chow and Yang (1994) are employed to characterize notched laminate problems. An experimental technique, Moiré interferometry, is chosen to observe the behaviors of unidirectional composite laminates containing a circular hole under off-axis tensile loading. The predicted results are compared with the experimental ones.

ANALYTICAL FORMULATION FOR LAMINA WITH DAMAGE

Physically, the deviation of the elastic response of composite plies can be attributed to the nucleation of new damage entities and the growth of existing damage entities, for instance, damage accumulation due to fiber or matrix cracking, interfacial debonding, or any combination of the above. Various investigators have proposed that such micromechanical phenomena can be described macroscopically with the framework of damage mechanics, thus providing the impetus for the elastic-damaged model presented here.

Based on past experimental observations, damage evolution in a brittle fiber reinforced unidirectional composite lamina under static loading may be described as an elastic-damaged process. The observations reveal that under service loading, a material element is linear elastic without damage and after that, the damage process starts and further develops with increase in load, producing a nonlinear material response. Upon unloading, the lamina will recover elastically and its effective elastic stiffness, ascertained from the initial state of unloading, remains constant and permanent strain is negligible. In addition, damage in the element will not progress unless its previous unloading state is surpassed when reloaded. This phenomenon can be characterized with the aid of the concept of a damage surface. The damage surfaces in stress space can be introduced to distinguish between loading, which is accompanied by degradation of material properties, and elastic unloading or reloading (Dragon and Mroz, 1979; Krajcinovic and Fonsea, 1981; Krajcinovic et al. 1991). As the prevailing attention focuses on the inelastic behavior of composite lamina with damage, the method introduced by Chow et al. (1992) is employed here.

In what follows, a unidirectional composite ply is regarded as a homogeneous orthotropic material with orthogonal directions x_1 and x_2 along the principal axes of planar orthotropy. Restricting the formulation to a plane stress state, a damage surface in stress space, which also represents an initial and subsequent damage surface in stress space, may be written as

$$F(\sigma_i , D) = \sigma_o - K(D) = 0 \tag{1}$$

It is a function of the state of stress σ_i (i=1,2,6, here, the contracted notation is utilized) and the internal damage variable D. K(D) is a state function which changes as D develops. In this equation, σ_o is an equivalent stress defined as

$$\sigma_o = (R_{mn} \sigma_m \sigma_n)^{1/2} \tag{2}$$

the coefficients R_{ij} ($R_{ij} = R_{ji}$ is assumed) depict the influence of each stress component on the material damage state and can be determined from experiments.

For a brittle fiber reinforced composite material at a certain damage state, when the residual deformation is negligible compared with the total reversible deformation, the stress and strain relation can be expressed as

$$\varepsilon_i^r = C_{ij}(D)\sigma_j \quad \text{(D fixed)} \tag{3}$$

The superscript *r* stands for reversible strain. $C_{ij}=C_{ji}$ are the elastic compliance components at the current state and will change their values during the loading process when damage in the material grows.

The total reversible strain increment during a damage process is

$$d\varepsilon_i^r = C_{ij} d\sigma_j + dC_{ij}\sigma_j \tag{4}$$

and can be considered as composed of two portions:

$$d\varepsilon_i^r = d\varepsilon_i^e + d\varepsilon_i^d \tag{5}$$

where superscripts *e* and *d* represent elastic and damaged components, respectively. The elastic strain increment $d\varepsilon_i^e$, may be related to the stress increment $d\sigma_j$ through the generalized Hooke's law

$$d\varepsilon_i^e = C_{ij} d\sigma_j \tag{6}$$

The damaged strain increment is written as

$$d\varepsilon_i^d = dC_{ij}\sigma_j \tag{7}$$

Restricting the analysis to an "associated" damage rule, the damage strain increments under the damage process can also be estimated from the normality rule or flow rule by using the damage function F,

$$d\varepsilon_i^d = d\lambda \frac{\partial F}{\partial \sigma_i} = d\lambda \frac{\partial \sigma_o}{\partial \sigma_i} \tag{8}$$

From Eqs. (5) and (6), one has the elastic constitutive equation

$$d\sigma_i = S_{ij}(D)(d\varepsilon_i^r - d\varepsilon_j^d) \tag{9}$$

where S_{ij} is the current material stiffness and $[S_{ij}]^{-1}=C_{ij}$ if the inverse exists. The equation may be expressed in orthotropic form under plane stress as

$$\left[S_{ij}\right] = \frac{1}{1-\nu_{12}\nu_{21}} \begin{bmatrix} E_{11} & \nu_{12}E_{22} & 0 \\ & E_{22} & 0 \\ \text{Sym.} & & G(1-\nu_{12}\nu_{21}) \end{bmatrix}$$

In this equation, E_{11} and E_{22} are elastic moduli in the principal directions x_1 and x_2, respectively, ν_{12} and ν_{21} are Poisson's ratios, and G is the in-plane shear modulus.

From Eqs. (7), (8) and (9) as well as the condition to satisfy dF=0, the relationship between the elastic-damaged stress increments and the total strain increments can be finally expressed as

$$d\sigma_i = S_{ij}^{ed}\, d\varepsilon_j^r \tag{10}$$

where

$$S_{ij}^{ed} = S_{ij} - \frac{S_{ik} \dfrac{\partial F}{\partial \sigma_k} \dfrac{\partial F}{\partial \sigma_l} S_{lj}}{\dfrac{\partial F}{\partial \sigma_m} S_{mn} \dfrac{\partial F}{\partial \sigma_n} - \dfrac{1}{2} \dfrac{\partial F}{\partial D} \sigma_p \dfrac{\partial F}{\partial \sigma_p}}$$

S_{ij}^{ed} is the elastic-damaged instantaneous tangent modulus matrix. It should be noticed that the values of S_{ij} in this equation are no longer constant. Usually, S_{ij} is a function of stress state and is dependent upon the previous loading histories that involve damage progression.

Here, the energy per unit volume dissipated during a damaging process is selected as the damage variable D. It can be represented by

$$D = \int_0^{\varepsilon_i^r} \sigma_i d\varepsilon_i - \frac{1}{2}\sigma_i \varepsilon_i^r$$

and its increment is expressed as

$$dD = \frac{1}{2}\sigma_i d\varepsilon_i^d \tag{11}$$

It is convenient to define ε_o as

$$\varepsilon_o = \int d\varepsilon_o$$

where $d\varepsilon_o$ is the equivalent damage strain increment related to the energy dissipation increment by

$$dD = \frac{1}{2}\sigma_i d\varepsilon_i^d = \frac{1}{2}\sigma_o d\varepsilon_o \tag{12}$$

C_{ij} only depends on the damage variable D and is not directly dependent on the stress components as observed by Schapery (1990). In addition, any stress increment $\delta\sigma_i$ coinciding with the damage surface will not cause changes in the ε_i^d, or the compliance components C_{ij}. When the σ_o-ε_o relation is chosen as

$$\varepsilon_o = a\sigma_o^b - a\sigma_s^b \tag{13}$$

where *a* and *b* are material constants, σ_s is the equivalent stress at the threshold of damage, the change of compliance in a lamina can be readily derived and expressed as

$$C_{ij}(D) = C_{ij}(0) + \frac{ab}{(b-1)}\left[\left(\frac{2(b+1)}{ab}D + \sigma_s^{b+1}\right)^{\frac{b-1}{b+1}} - \sigma_s^{b-1}\right]R_{ij} \tag{14}$$

where

$$D = \frac{ab}{2(b+1)}\left(\sigma_o^{b+1} - \sigma_s^{b+1}\right) \quad (\text{for } d\sigma_o \geq 0) \tag{15}$$

and $C_{ij}(0)$ denotes the compliance components of the material without damage.

From Eq.(14), it can be seen that the coefficients R_{ij} reflect the anisotropic behavior induced by material damage. During a damaging process, Eq.(14) is employed to predict instantaneous C_{ij} values. For unloading, the coefficients C_{ij} remain constant and are determined from σ_o at the start of unloading. Upon reloading, D as well as C_{ij} , do not change unless σ_o exceeds its previous maximum value. Schapery (1990) has proven that for unloading, $d\sigma_o<0$, the thermodynamic requirement of positive entropy production and the path-independence of unloading work are violated unless D is a constant. Consequently, for arbitrary stress histories, D is always determined by the largest value of σ_o up to the current time. Equations (3), (9), (10), and (14) formulate a general constitutive description for an elastic-damaged composite material element.

The observation that fibers in a composite are much stronger than the matrix phase and the failure of the laminate in the fiber direction is dominated by the ultimate strength of the fibers readily leads to $R_{ij}=0$ (j=1, 2, 6) in (14). Therefore, the following damage criterion can be formulated by the decomposition of failure mechanisms.

For fiber failure due to overload or overstress, the failure criterion is

$$\varepsilon_f^- \leq \varepsilon_1 \leq \varepsilon_f^+ \tag{16}$$

where ε_f^- and ε_f^+ are the compressive and tensile fiber strain failure levels, respectively.

For the matrix and the fiber/matrix interaction failure, the criterion is written as

$$D = D_c \tag{17}$$

D_c is postulated to control the threshold of macrocrack initiation. The physical basis of this postulation is as follows: when a material element is loaded externally, part of the supplied energy is dissipated due to the damage event, which is taken as the damage variable as defined in Eq.(11), and failure occurs as a result of accumulated damage in a highly damaged process zone of the material.

From the above equations, it is clear that the direct effect of the fiber reinforcement and thereby fiber failure can be decoupled from the type of failure that represents the matrix and fiber/matrix interaction including the possible effect of the interface. Typically, the matrix failure and fiber/matrix debonding modes occur in concert to produce a transverse crack parallel to the fiber direction. For resin matrix composites, this mode of failure is generally the first type of damage to be observed. Thus, it is most important in the development of failure and damage models that this mode should be fully understood and characterized. The proposed criterion is developed to provide a minimum number of parameters to be evaluated from simple experiments and at the same time encompass the complicated physical characteristics of the failure process.

To provide a validation analysis of the proposed damage theory, a comparison between experimental measurement and theoretical prediction of response of composite laminates is to be performed. For the present investigation, a unidirectional, rectangular, fiber reinforced composite plate of dimensions L, W containing a circular hole radius R subjected to far-field uniaxial tensile stress p is shown in Fig.1. Under such a loading condition, the composite laminate is in a state of plane stress and only three stress components σ_{xx}, σ_{yy} and σ_{xy} need to be considered. Two coordinate systems, global coordinates x-y and material principal system 1-2 are set at the center of the hole. θ stands for the fiber orientation angle between the loading direction and the maximum principal material axis. Boundary conditions are such that the far ends ($y=\pm L/2$) remain plane and parallel during loading, representing perfect gripping and no rotation of the grips.

NUMERICAL ANALYSIS

To provide analytical solutions to the general damage response of notched composite laminates, numerical algorithms based on the proposed laminate model have been systematically explored within the context of an ordinary displacement finite element method (Chow and Yang, 1994). The procedure for implementing the corresponding finite element equations is similar to the conventional nonlinear analysis. The main difference lies in the stress-strain relations, which currently include a damage variable. Displacements of the composites under loading are assumed to be infinitesimally small so that only material nonlinearity due to damage needs to be introduced. The nonlinearities in the equilibrium equations are handled by the modified Newton-Raphson iteration procedure. Quantities such as, stress, strain, and damage are monitored at each Gaussian integration point of every element.

The stresses at each integration point are formulated in a form of, for example, the damage function in Eq.(1) or the failure criteria in Eqs.(16) and (17), to check for damage initiation or failure onset, respectively. During a damaging process, a radial return algorithm with smaller strain increment is adopted for integration of the elastic-damaged constitutive equations. It is necessary to modify the stiffness matrix in the computation during a progressive damage process. Once the failure condition is fulfilled, fiber and matrix or matrix/fiber interaction modes of failure can be identified. Macrocracks are assumed to emerge in the areas of the failed integration points. After the onset of failure, new constitutive relationships should be established. S_{ij}^{ed} in Eq.(10) at the failed location in an element is replaced by a modified one with zero stiffness components depending upon the failure mode, i.e., at the ruptured integration point the element is unable to carry any more increments of stress in certain directions. For instance, the only non-zero component in Eq.(9) is E_{22} if the failure is fiber-dominated, while E_{11} is non-zero if the failure is matrix-dominated. This procedure is repeated until the failure spreads throughout the laminate. The computation is then terminated and the laminate is considered to have failed. Current investigation is mainly focused on the failure initiation in a notched unidirectional composite laminate.

Theoretical calculations for the problem are obtained with an incremental scheme using a recently developed two-dimensional finite element algorithm due to Chow and Yang (1994). Because of the non-symmetrical nature of the specimen, the whole off-axis unidirectional composite laminate is modeled with 96 in-plane eight-node isoparametric elements consisting of 328 nodes, and the finite element mesh is refined near the hole area as shown in Fig.2. The numerical solution, which allows damage to initiate and accumulate throughout the specimen as a field quantity, can also simulate the variations of the stiffness due to the coupling between damage and elasticity. Linear elastic analysis for the laminate without damage consideration is first conducted to identify the stress and strain concentration points possible for damage emergence. Loading of the notched composite specimen is then applied incrementally to observe the initiation and propagation of damage zones. The failure criterion described in Eqs.(16) and (17) is checked at all times to determine the onset of failure.

EXPERIMENTS

The objectives of the experiments are to find material constants and to validate the damage formulation. The unidirectional composite systems studied here are made of 648 epoxy matrix reinforced by 65 volume percent of T300 graphite fibers. A series of uniaxial tests for standard tensile specimens with different fiber orientations are conducted to analyze two-dimensional response of composite laminate with damage and to determine in-plane related damage variables. The main purpose of these tests is to investigate the anisotropic damage characteristics of unidirectional composite laminates loaded in different directions and to measure the effect of damage on the elastic compliance in Eq.(3), which is used to determine the relevant coefficients in Eqs.(13) and (14). The measured properties of initial undamaged laminate based on the tests of fibers oriented along $\theta=0^\circ$, 22.5°, 45°, 67.5°, and 90° are

$$E_{11} = 1.25\times10^{5}\ \text{MPa},\quad E_{22} = 1.11\times10^{4}\ \text{MPa},$$
$$\nu_{12} = 0.338,\quad G = 3.3\times10^{3}\ \text{MPa}$$

Experimental information on ε_x-σ_x behavior of any two fiber angles has been used to evaluate R_{66} and the function $\varepsilon_o(\sigma_o)$. Results from tests at other fiber angles then serve to check the formulation. The corresponding material coefficients in Eqs.(13) and (14) are

$$a = 0.114\times10^{-4}\ ,\quad b = 1.242,\quad \sigma_s = 9.0\text{MPa},$$
$$R_{11} = R_{12} = R_{16} = R_{26} = 0\ ,\quad R_{22} = 1,\ \text{and}\ R_{66} = 1.9$$

These material coefficients of the composite laminate are to be used as input data for the finite element scheme.

Moiré interferometry (Post, 1987), with its potential for revealing displacement fields with high sensitivity for composite analysis (Asundi, 1990), has been applied to interrogate the deformation and damage in the laminate specimen. For this investigation, a Moiré interferometry setup, shown in Fig.3, has been designed and constructed so as to allow the measurement of both components of in-plane displacement field on the specimen surface (Asundi and Yang, 1993). To examine the details of damage around the edge of a central hole, both video camera and photographic camera are utilized to monitor the localized hole area and the global response of the specimen, respectively. These cameras are also employed to capture the Moiré fringe patterns for subsequent image processing. A computerized image processing system has been developed to quantitatively evaluate the Moiré patterns taken from the experiment. The system software estimates the displacement field of the specimen under a certain load level, using the fast Fourier transform (FFT) technique. The brightness function of a Moiré image pattern is Fourier-transformed, allowing the frequency components of the image containing displacement information to be isolated (Asundi and Yang, 1993). Then, the strain distribution is computed as the derivative of the corresponding displacement.

RESULTS AND DISCUSSIONS

Shown in Fig.4 are the damage zones of the composite specimen with 22.5° fiber orientation. The material point on the hole edge at $\theta=70.07^\circ$ (and 250.07°) first experiences damage as the applied stress reaches the level of 8.14 MPa. Theoretical analysis indicates that the combination of normal and shear stress components at that point leads to a higher equivalent damage stress than those around the hole periphery. The damage value of this point increases with the applied load causing the formation of a damage zone around this point. It can be observed from the figure that the damage zone expands from the hole boundary towards the specimen edge along the composite material principal directions. The damage values of the material element in the fiber direction are higher than those perpendicular to the fibers. This implies that failure of the specimen initiating from the hole edge will be along the fiber direction, i.e., $\theta=22.5^\circ$. Calculation also shows that the failure initiated at $\theta=70.07^\circ$ (and 250.07°) is matrix-dominated.

For the 90° laminate, the material point on the hole edge at $\theta=90^\circ$ (and 270°) is found to suffer damage at the stress level of 3.62 MPa. Tensile stresses near the hole boundary are mainly responsible for the damage initiation. Because of the special loading condition and specimen configuration, symmetric evolution of the damage zone along the fiber direction perpendicular to the applied load is predicted as displayed in Fig.5. It is evident that the failure of the specimen will be along $\theta=90^\circ$ (and 270°), which is the weakest region in the composite, because damage of the material elements lying in that direction continues to accumulate and extend with increasing load. The failure mode initiated at the hole boundary is also matrix-dominated.

Figure 6 shows the Moiré patterns representing the contours of the displacement components U and V along the x and y directions, respectively, for the 90 degree specimen. The load level for Fig.6(a) and (b), the whole-field v- and u-displacement components, respectively, is 440N. Figures 6(c) and (d) are the whole-field fringe patterns corresponding to y and x directions for the load of 792N, respectively. Under the same load, Fig.6(e) and (f) are the localized V and U Moiré fringes, respectively, recorded by video camera VC in Fig.3, zoomed in the vicinity of the hole. Generally, from these pictures, it can be seen that as the load increases, there is an increase in strain concentration near the hole. The fringe pattern elsewhere remains uniform. This is mainly due to very large strain near the hole. At a higher load, the fringe patterns become increasingly dense. However, the fringe contrast is still excellent, a credit to the Moiré interferometric method. Also along the principal material direction of the specimens, i.e., 90 degrees to the y-axis, a noticeable band where the fringe pattern, and hence the deformation, is different from the rest of the specimen, can be observed. These bands can be used as an indicator of increased damage of the composite as compared to other regions. It can be concluded that when the damage zone around the hole develops, it remains narrow, is constrained to the immediate vicinity of the hole, and tends to propagate perpendicular to the loading direction. Application of higher load leads to higher overall damage of the composite specimen. Abrupt change in the Moiré fringe pattern near the edge of the hole, which represents a macrocrack emergence, is evident in Figs.6(c) and (e). The failure of the specimen started at the hole edge and separated the specimen. Its mode is matrix-dominated. This confirms the calculated results obtained from the finite element analysis.

It should be pointed out that all the fringe patterns shown include their respective reference patterns which are some initial fringes, partly due to the imperfections in the optics and partly due to the small clamping load that was applied to the specimen. This pattern was subtracted from the subsequent patterns to obtain deformation from the external load alone. Quantitative evaluation of the Moiré patterns taken from the experiment is performed by employing image processing software. For simplicity, only one strain component distribution, ε_{yy}, along the x-axis is evaluated. A similar procedure can be applied to obtain other strain components. In Figs.7 and 8, the predicted and measured results of the strain component, ε_{yy}, along the x-axis are compared for the 45° and 90° specimens under the loads 968N and 440N, respectively. Under the same external load, predictions from conventional linear elastic theory with the original undamaged material stiffness are also included. It can be observed from Figs.7 and 8 that the damage theory produces higher strain values and provides more accurate prediction than that based on the linear elasticity theory. The discrepancy becomes more significant near the edge of the hole. The strain concentration effect is, as expected, enhanced due to damage. The difference in strain magnitude between linear elasticity and nonlinear damage theory becomes more pronounced with further damage as the applied load increases.

SUMMARY

The purpose of this investigation is to gain better knowledge and understanding of the parameters affecting progressive damage in unidirectional graphite fiber/epoxy laminates. To achieve this, both analytical and experimental techniques are necessary. An analytical constitutive equation model has been developed to analyze the behavior of a unidirectional composite laminate containing a central circular hole under off-axis tension. The in-plane mechanical performance of a composite laminate is predicted by using a nonlinear two-dimensional finite element procedure. Based on the analysis, a composite failure criterion is derived to identify different failure modes. Results given from the tests and analyses reveal fundamental behaviors of damage development. The damage mechanism involves material stiffness deterioration and redistribution of stress and strain, which determine the subsequent development of damage and the load capacity of the laminates. Moiré interferometry, a high sensitivity whole-field experimental technique, with a computerized image processing system has been applied to determine and interrogate the two-dimensional deformation field in the composites with the aim of verifying the theoretical predictions. It can be concluded that macrocracking is expected to initiate at the material point with a high damage value and its propagation would be along the direction of damage zone extension. The strain distributions from the predictions are in good agreement with those from the experiments. This indicates that the current approach can provide a convenient and effective tool for examining stress states, failure modes, and damage propagation patterns and allow accurate monitoring of damage initiation and progressive failure in composites. It should also be emphasized that the current investigation is a preliminary one. To study the progressive failure behavior, for example, crack propagation in laminated composite structures subjected to complex service loading conditions, the proposed anisotropic damage model can be readily generalized and extended to three-dimensional analysis.

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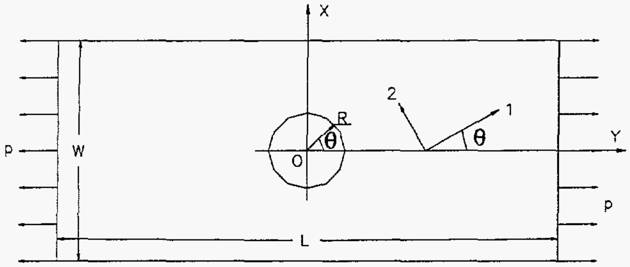


Fig.1 Unidirectional laminate with a hole subjected to tension

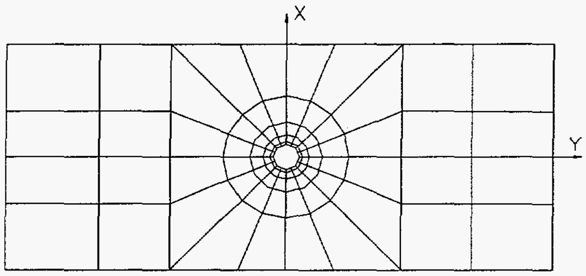


Fig.2 Finite element modelling for the laminate with a hole

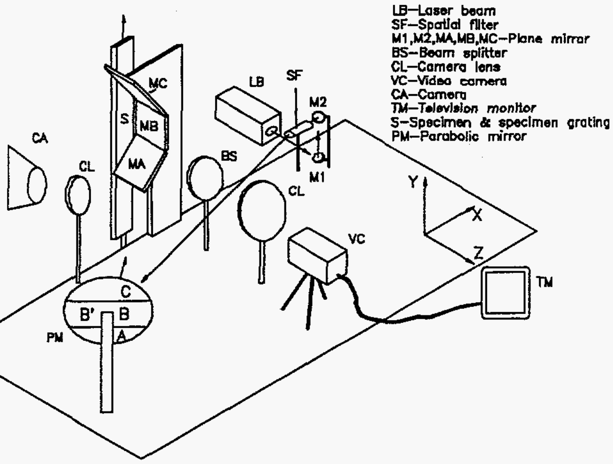


Fig.3 Optical arrangement for Moiré interferometry

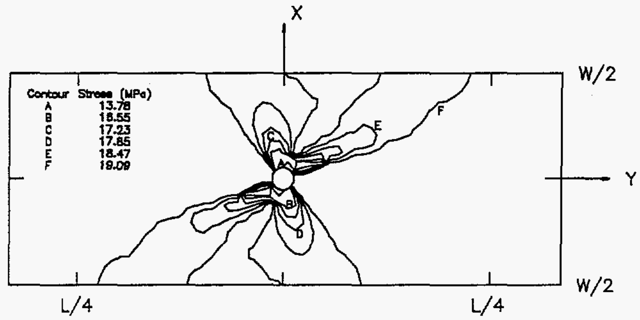


Fig.4 Damage zones for laminate with θ=22.5°

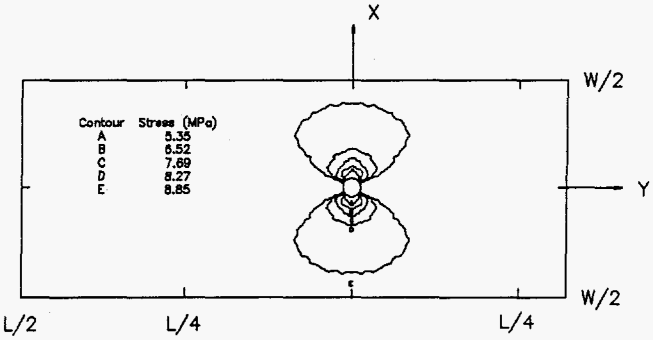
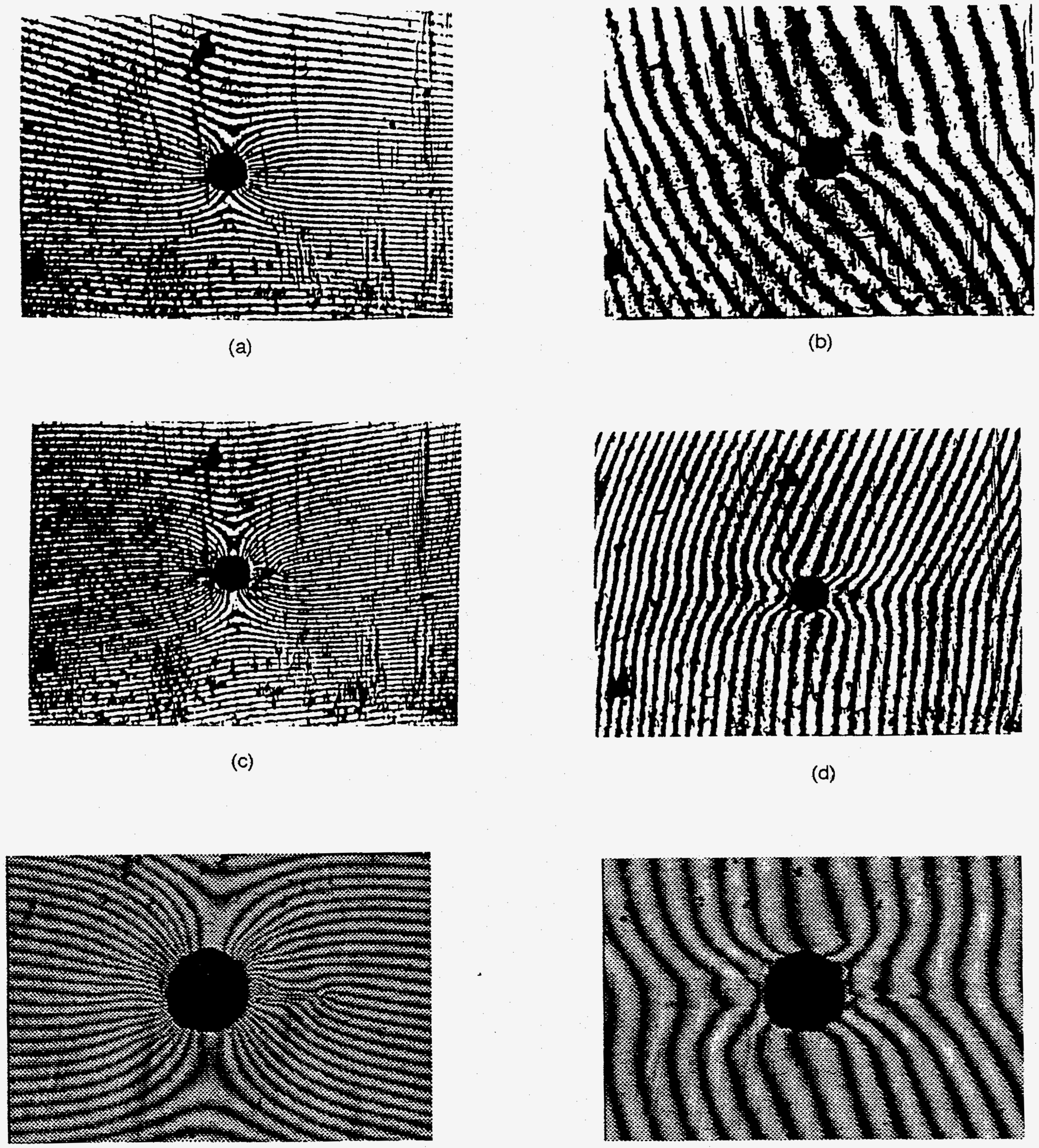


Fig.5 Damage zones for laminate with θ=90°



(a) (b)

(c) (d)

(e) (f)

Fig.6 Fringe patterns for 90° specimen

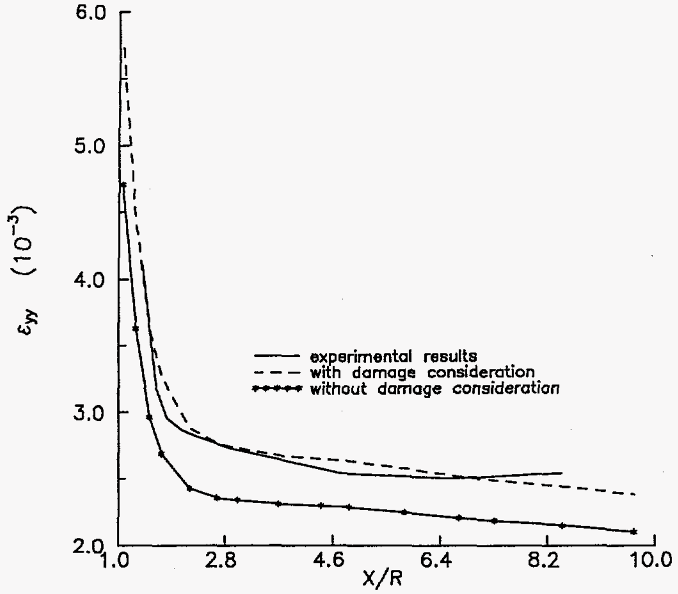


Fig.7 Strain ε_{yy} distribution along x-axis for 45° specimen

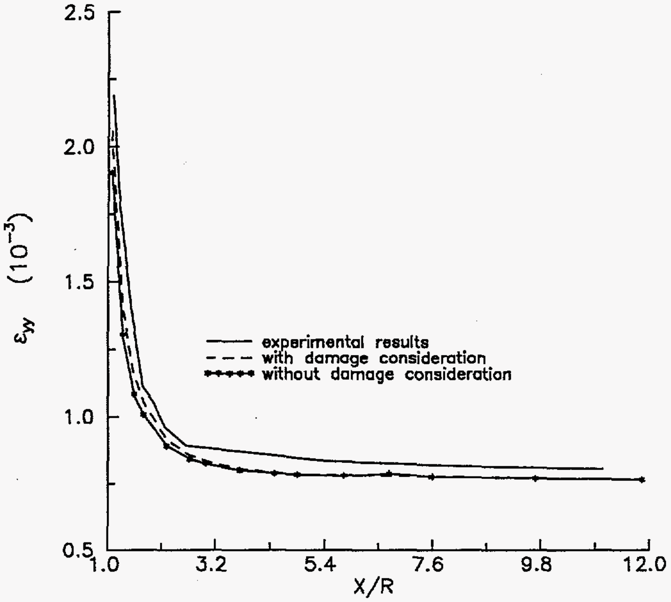


Fig.8 Strain ε_{yy} distribution along x-axis for 90° specimen