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Delamination, Durability and Damage Tolerance of Laminated Composite Materials

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DELAMINATION, DURABILITY AND DAMAGE TOLERANCE

Durability and damage tolerance may have different connotations to people from different industries and with different backgrounds. In this paper, damage tolerance always refers to a safety of flight issue where the structure must be able to sustain design limit loads in the presence of damage and return to base safely. Durability, on the other hand, is an economic issue where the structure must be able to survive a certain life under load before the initiation of observable damage. Delamination is typically the observable damage mechanism that is of concern for durability, and the growth and accumulation of delaminations through the laminate thickness is often the sequence of events that leads to failure and the loss of structural integrity.

FOCUS

DAMAGE TOLERANCE - SAFETY OF FLIGHT

DURABILITY - ECONOMY OF OPERATION

DELAMINATION - DAMAGE/FAILURE MODE

PROGRESSIVE FAILURE MODELS

Progressive failure analyses are typically based on either continuum damage models or discrete damage models. In the former, damage is treated implicitly through its influence on material parameters. The simplest and earliest example is the ply discount method used to reduce in-plane stiffness properties of a laminate to reflect the presence of damage. Recently, more sophisticated models have emerged where the complete tensoral representation of stiffness properties in a critical volume element are modified to reflect damage growth. In the discrete damage models, however, the size, shape, and orientation of damage is modeled explicitly resulting in models with internal stress free boundaries. In this paper, only examples of the discrete damage approach involving progressive delamination will be discussed.

APPROACHES TO PROGRESSIVE FAILURE ANALYSIS FOR COMPOSITE STRUCTURES

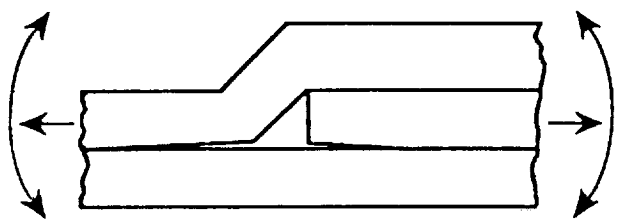
1. Continuum Damage Models - Damage treated implicitly through its influence on material parameters. Properties of critical volume elements are modified to reflect damage growth.

2. Discrete Damage Models - Damage modeled explicitly as to size, shape, orientation, creating new internal boundary conditions.

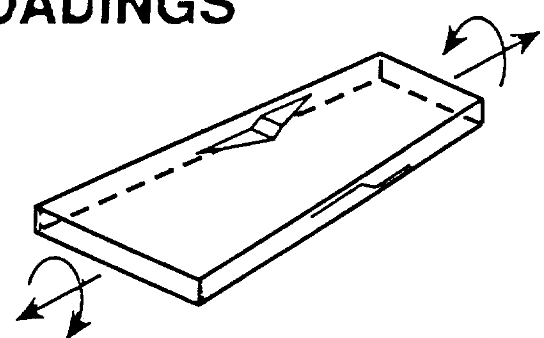
DELAMINATION SOURCES

Delaminations may arise in composite materials and structures anywhere a local discontinuity creates out-of-plane stresses. This may occur at a straight fee edge, an open hole boundary, at a terminated ply, and anywhere in the structure where a matrix ply crack forms. Furthermore, delaminations may occur due to unique configurations and loadings, such as a curved beam in bending or a flat laminate subjected to low velocity impact. Several unique configurations and loadings have been studied to determine the source of delamination and predict the structural durability of components with these features. Some of these include: (1) tapered symmetric laminates, with internal ply drops, subjected to tension and bending loads to simulate the in-board region of composite rotor hubs, (2) laminates subjected to tension and torsion loads to simulate the out-board region of composite rotor hubs, (3) curved laminates subjected to bending loads to simulate curved frames, stiffener caps, and other generic structural components, and (4) flat laminates subjected to low velocity impact.

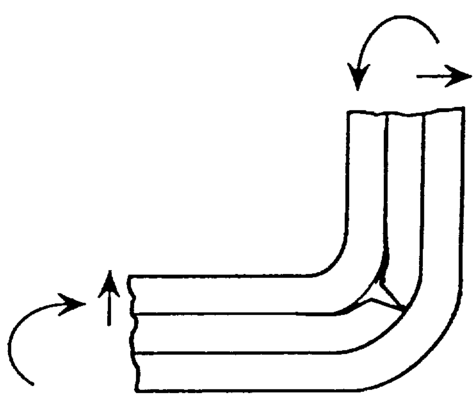
DELAMINATION IN LAMINATES UNDER COMPLEX LOADINGS



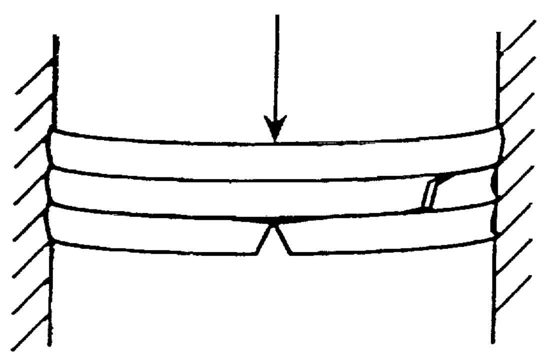
Delamination in tapered laminates



Delamination under tension/torsion loads



Delamination in curved members

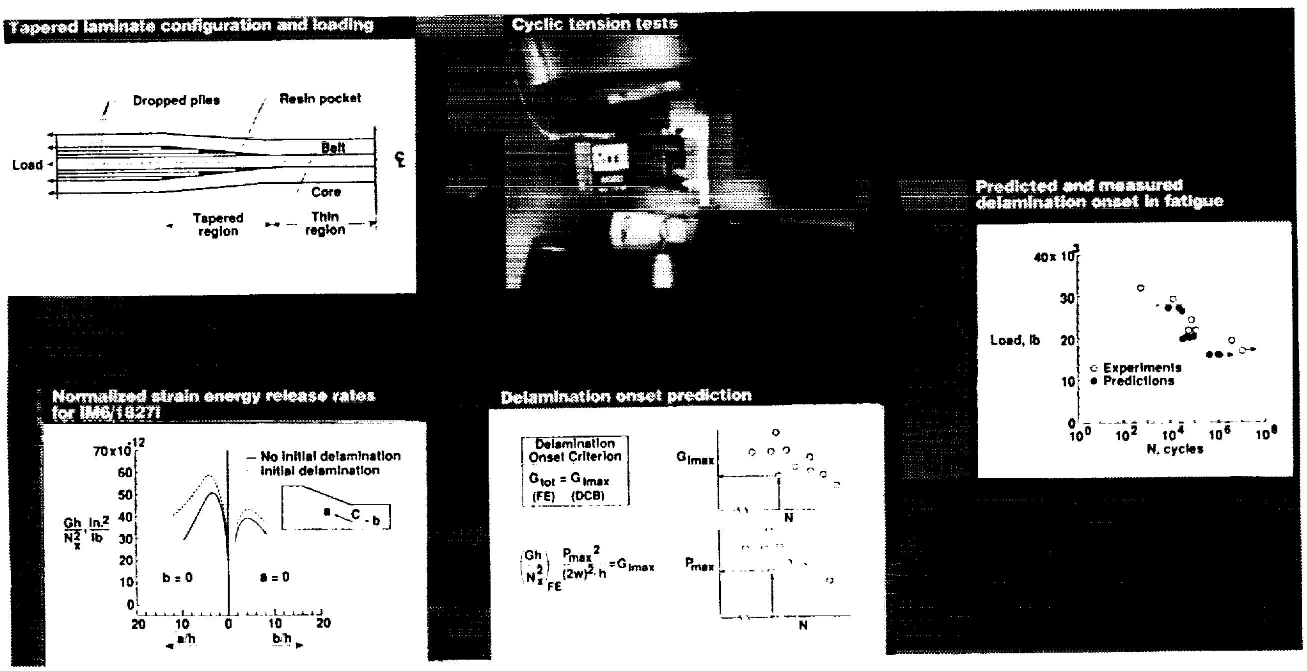


Delamination from matrix cracks in bending

TAPERED LAMINATES

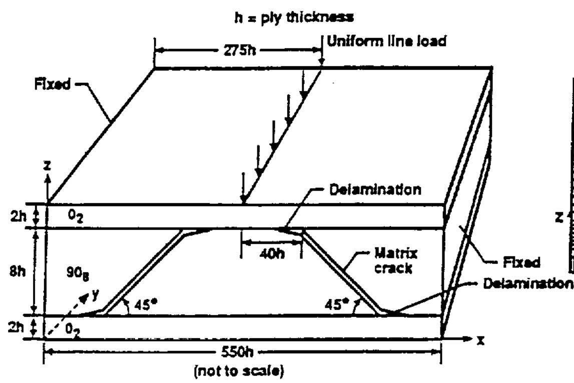
Stress analyses of symmetric tapered laminates subjected to tension loads indicated that interlaminar stress singularities were present at points of material and geometric discontinuities such as ply drop locations and the juncture between the flat and tapered region of the laminate. The virtual crack closure technique was used in a finite element analysis to calculate the strain energy release rate, G, for delamination growth from this juncture point. The maximum G values in these distributions were compared to delamination onset fatigue data generated using double cantilever beam specimens, and plotted as G versus the number of cycles to delamination onset, N, to predict the S-N curves for delamination onset in tapered laminates subjected to tension-tension fatigue. This technique worked well for tapered laminates with a variety of layups and materials.

Delamination Onset Prediction in Tapered Laminates

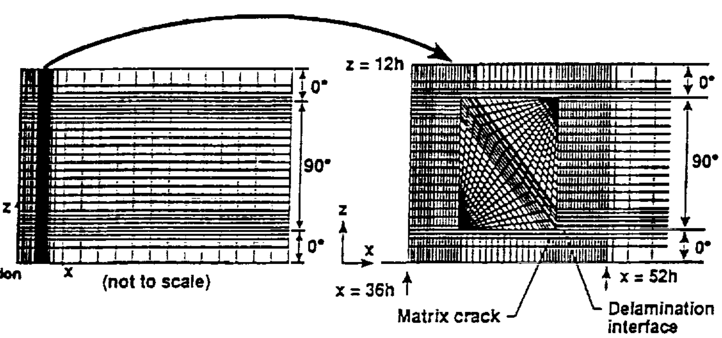


Laminates subjected to low-velocity impacts form a spiral staircase damage pattern consisting of delaminations that form between plies with matrix ply cracks. These matrix ply cracks are created by the high transverse shear stresses generated during the impact. The delaminations, however, may form and grow due to a combination of interlaminar tension and shear stresses. To illustrate this point, a two-dimensional representation of a typical impact damage mechanism was modeled using a finite element analysis. A central line loading was applied to a clamped cross-ply laminate with matrix cracks oriented at 45 degrees through the thickness and located between the central line load and the clamped boundaries. The presence of the internal stress free boundaries due to the matrix cracks yielded tensile interlaminar normal stresses at the matrix crack tips in the 0/90 interfaces in addition to the interlaminar shear stresses that would intuitively be present. The virtual crack closure technique was used in the finite element analysis to calculate the strain energy release rate, G, components for delamination growth from the tip of the matrix cracks. Both an opening mode I and a shear mode II component were always present, with the relative magnitude of the two modes depending on the material modeled (glass or graphite epoxy) and the proximity of the matrix crack tip to the load application point.

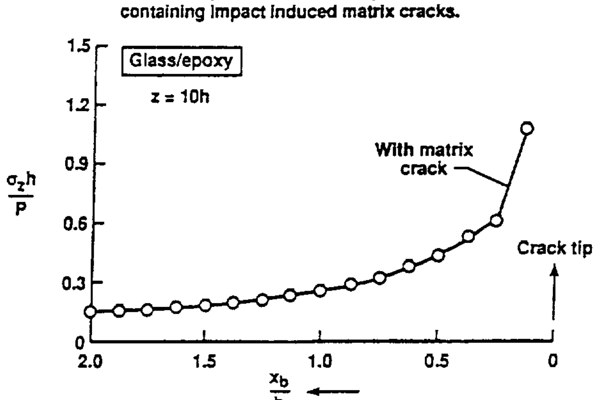
ANALYSIS OF DELAMINATION IN CROSS PLY LAMINATES INITIATING FROM IMPACT INDUCED MATRIX CRACKING



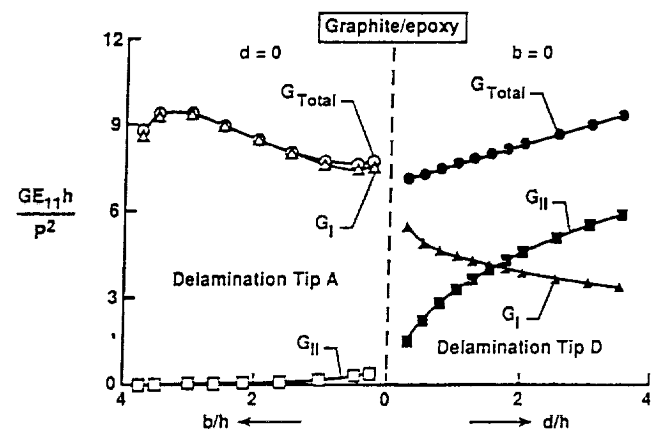
(a). Configuration and loading of a laminate containing impact induced matrix cracks.



(b). Two dimensional finite element mesh of laminate.



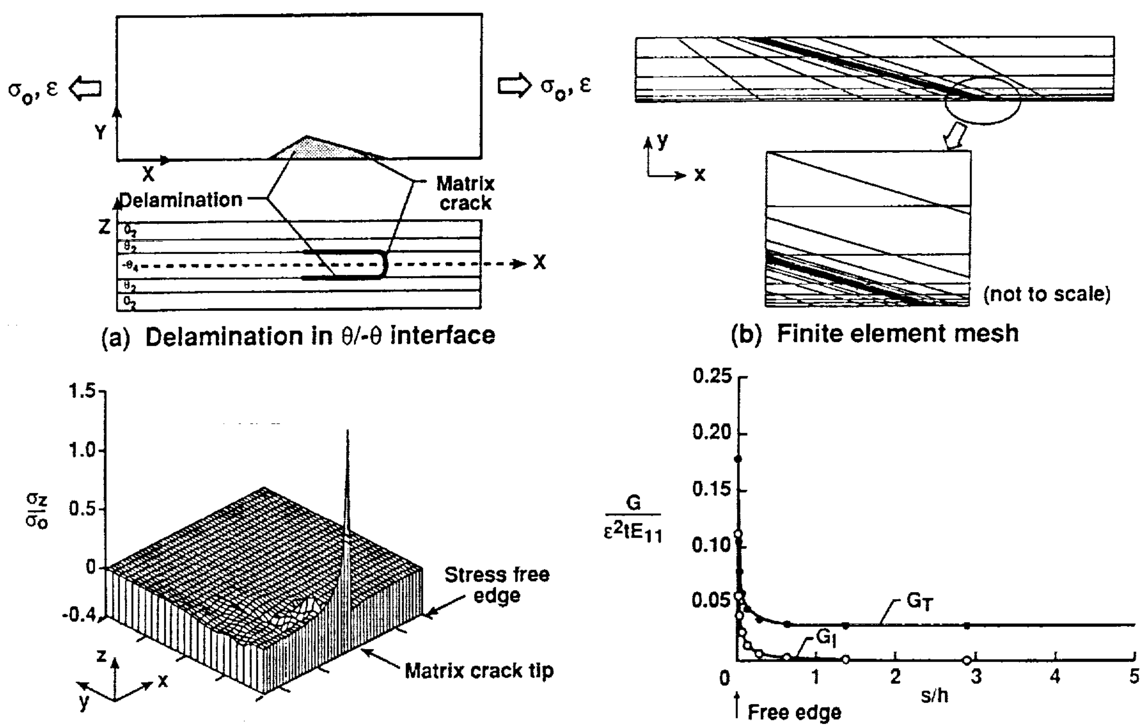
(c). Interlaminar normal stress with a 45° matrix crack.



(d). Variation of G due to delamination growth on either side of the matrix crack.

In laminates with plies oriented at an arbitrary angle to the load axis, the in-plane stresses near free edges may vary in such a way that matrix cracks form due to the tensile stress normal to the fiber direction in addition to the shear stresses along the fiber direction. This situation arises in $(0/\theta/-\theta)_s$ laminates (where θ=15 to 30 degrees) subjected to tension loads. These laminates have often been used to characterize interlaminar shear strength because of the high interlaminar shear stresses in the $\theta/-\theta$ interfaces. However, the presence of matrix cracks is typically ignored in the analyses used to determine the interlaminar shear strength of these laminates. A three-dimensional finite element analysis was performed on a $(0/15/-15)_s$ laminate with a matrix crack simulated along the -15 degree direction in the central -15 degree ply. The presence of the internal stress free boundaries due to the matrix crack yielded interlaminar normal stresses that approached a very high, and apparently singular, value where the matrix crack intersected the free edge. Hence, the local delaminations were mixed-mode delaminations that included a significant opening mode I component.

ANALYSIS OF MATRIX CRACKING AND LOCAL DELAMINATION IN $(0/\theta/-\theta)_S$ GRAPHITE EPOXY LAMINATE



(a) Delamination in $\theta/-\theta$ interface

(b) Finite element mesh

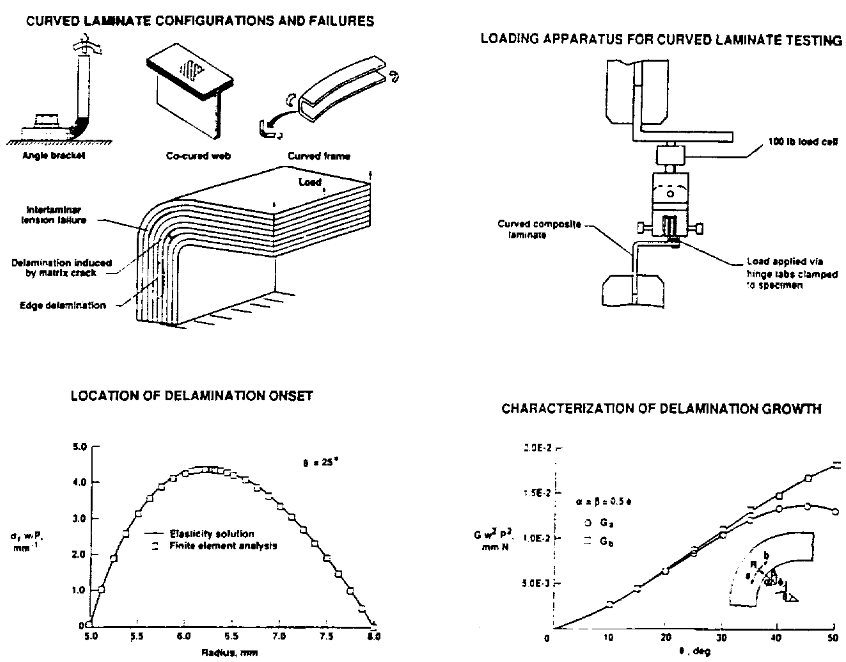
(c) Normalized σ_z due to $-\theta$ ply crack

(d) Normalized G along delamination front

CURVED LAMINATES

Curved composite laminates subjected to bending loads often delaminate due to the interlaminar normal stresses created in the curved portion of the beam. If the laminate has off-axis angle plies, however, the membrane stresses may cause matrix cracks to form prior to delamination. In these cases, post-mortem inspection reveals that each delamination is associated with a matrix crack. The onset of the delaminations may be influenced by the presence of these matrix cracks. The virtual crack closure technique was used in the finite element analysis to calculate the strain energy release rate, G, components for delamination growth from the tip of the matrix cracks. A significant mode I component always dominated the response. The strain energy release rate increased monotonically with delamination length, indicating that delamination onset would result in unstable delamination growth. The point of inflection in the G versus a plot was compared to delamination onset fatigue data generated using double cantilever beam specimens, and plotted as G versus the number of cycles to delamination onset, N, to predict the S-N curves for delamination onset in curved laminates subjected to bending fatigue loads. This technique worked well for a variety of layups.

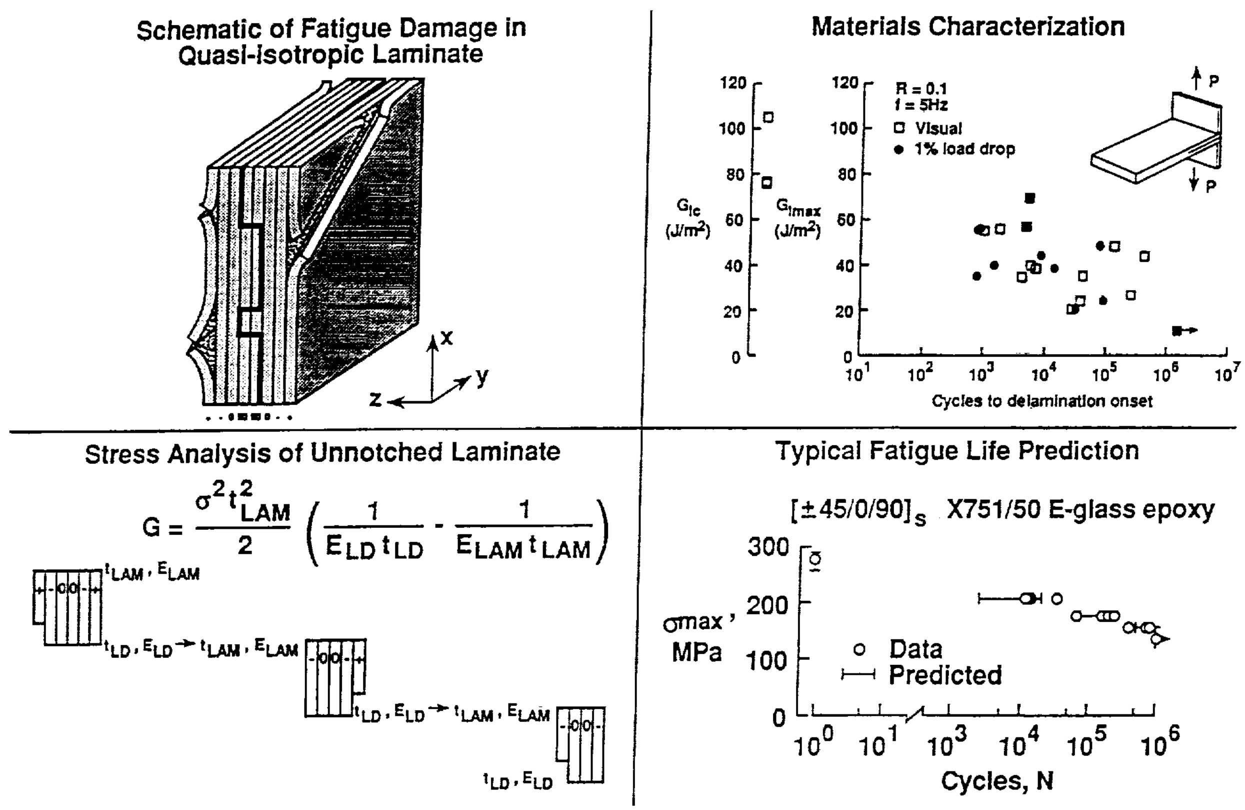
DELAMINATION IN CURVED COMPOSITE LAMINATES



TENSION FATIGUE LIFE PREDICTION

Composite laminates subjected to tension-tension cyclic loading undergo a variety of damage scenarios prior to fatigue failure. Matrix cracks form in the off-axis angle plies and create local delaminations. These local delaminations yield strain concentrations in the primary load bearing zero degree plies. When enough local delaminations have formed through the thickness of the laminate at a particular location, the strain concentrations may be high enough to fail the zero degree plies and cause a fatigue rupture of the laminate. A model was developed to account for this fatigue failure mechanism. The strain energy release rates, G, associated with local delaminations were calculated and used to model a progression of damage starting at the top surface and working toward the laminate center. These G values were compared to delamination onset data generated from free edge delamination tests to predict the accumulation of delamination through the laminated thickness. S-N curves for a variety of layups and material combinations were predicted accurately.

DELAMINATION-BASED LIFE PREDICTION METHODOLOGY



Status: Methodology must be extended to notched laminates and must include loadings typical of a built-up structure

DAMAGE THRESHOLD/FAIL SAFETY METHODOLOGY

A damaged threshold/fail safety methodology was proposed for addressing composite damage tolerance. In this procedure, matrix cracks are assumed to be present in the off-axis angle plies. Delamination onset from these matrix cracks and any other material or geometric discontinuities in the structure are predicted using fracture mechanics. Delamination growth is assessed by using either delamination growth laws along with delamination resistance curves, measuring stiffness loss, or by assuming catastrophic growth at delamination onset. The latter technique is the simplest and most conservative, and may be the only practical technique for structural components. Once a delamination is assumed to be present, however, it may not result in failure of the component even if it has grown catastrophically throughout a particular interface. An assessment of the presence of delamination on the load carrying capability of the laminate must be performed to determine the fail safety of the component. If the component is demonstrated to retain load carrying capability, the procedure must be repeated for the next source of delamination through the laminate thickness until the composite can no longer sustain the applied load.

APPROACH FOR COMPOSITES

1. Assume matrix cracks exist in off-axis plies
2. Predict delamination onset using strain energy release rate
3. Account for delamination growth
   a. Predict using growth laws and resistance curves
   b. Measure stiffness loss
   c. Assume onset corresponds to catastrophic growth
4. Assess fail safety of damaged composite
5. Repeat steps to account for accumulation of delaminations through the thickness

CONCLUSIONS

I. STRAIN ENERGY RELEASE RATE IS A USEFUL GENERIC PARAMETER FOR CHARACTERIZING, ANALYZING, AND PREDICTING DELAMINATION

II. DAMAGE THRESHOLD / FAIL SAFETY METHODOLOGY PROVIDES A GENERIC FRAMEWORK FOR ASSESSING THE DURABILITY AND DAMAGE TOLERANCE OF LAMINATED COMPOSITES