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COMPUTATIONAL SIMULATION OF STRUCTURAL FRACTURE IN FIBER COMPOSITES

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SUMMARY

A methodology has been developed for the computational simulation of structural fracture in fiber composites. This methodology consists of step-by-step procedures for mixed mode fracture in generic components and of an integrated computer code CODSTRAN (Composite Durability Structural Analysis). The generic types of composite structural fracture include: (1) single and combined mode fracture in beams, (2) laminate free-edge delamination fracture, and (3) laminate center flaw progressive fracture. Structural fracture is identified by rapid changes in one or all of the following: (1) displacements, (2) frequencies, (3) the buckling loads, or (4) the strain energy release rate. These rapid changes are herein assumed to denote imminent structural fracture. Based on these rapid changes, parameters are identified which can be used as guidelines for (1) structural fracture, (2) inspection intervals, and (3) retirement for cause.

INTRODUCTION

It is generally accepted that flawed structures fail when the flaws grow or coalesce to a critical dimension such that (1) the structure cannot safely perform as designed and qualified or (2) catastrophic fracture is imminent. This is true for structures either made from traditional homogeneous materials or fiber composites. One difference between fiber composites and traditional materials is that composites have multiple fracture modes that initiate local flaws compared to only a few for traditional materials. Any predictive approach to simulate structural fracture in fiber composites needs to formally quantify: (1) these multiple fracture modes, (2) the types of flaws they initiate, and (3) the coalescing and propagation of these flaws to critical dimensions for imminent structure fracture.

An ongoing research activity at NASA Lewis Research Center is directed toward the development of a methodology for the computational simulation of structural fracture in fiber composites. A part of this methodology consists of step-by-step procedures to simulate individual and mixed mode fracture in a variety of generic composite components. Another part has been incorporated into an integrated computer code identified as CODSTRAN for Composite Durability Structural Analysis. The objective of the proposed paper is to describe the fundamental aspects of this methodology and to illustrate its application to a variety of generic composite structures.

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The generic types of composite structural fracture include: (1) single and combined mode fracture in beams, (2) laminate free-edge delamination fracture, and (3) laminate center flaw progressive fracture. Structural fracture is assessed in one or all of the following: (1) the displacements increase very rapidly, (2) the frequencies decrease very rapidly, (3) the buckling loads decrease very rapidly, or (4) the strain energy release rate increases very rapidly. These rapid changes are herein assumed to denote imminent structural fracture. Based on these rapid changes, parameters/guidelines are identified which can be used as criteria for (1) structural fracture, (2) inspection intervals, and (3) retirement for cause.

In the present study, computational simulation is defined in a specific way. Also general remarks are included with respect to (1) generalization of the procedure to large structures and/or structural systems, (2) experience gained about conducting such a long duration research activity, and (3) research needs in order to increase its computational efficiency, gain confidence, and expedite its application.

COMPUTATIONAL SIMULATION-DEFINITION

During the course of this research activity computational simulation has evolved to have a specific meaning which is defined as follows:

> "Description and quantification of the physics by progressive/multiple application of elementary math models, which are derivable from fundamental concepts, through the use of computers to obtain the desired structural response with acceptable engineering accuracy."

In the context of the above definition, computational simulation is not limited to:

(1) Applied Mathematics
(2) Approximate Analysis
(3) Numerical Analysis
(4) Numerical Testbed
(5) Solution Algorithm

However, it may include some or all of the above, plus many others.

END-NOTCH BEAM FRACTURE

In this section we describe the application of the structural fracture concept to beams with end notches. Specifically, we describe structural fracture as either: (1) Mode I, (2) Mode II, (3) combined Modes I and II, and (4) combined Modes I, II, and III. The general procedure for the computational simulation of structural fracture for beams with these types of fracture modes are summarized in figure 1. This general procedure is complemented with progressive finite element substructuring as will be described later in some detail. The beams are assumed to be made from AS-graphite fiber/epoxy matrix (AS/E) with 0.6 fiber volume ratio (FVR).

Mode I

A schematic depicting the strain-energy release rate (SERR) in a double cantilever is shown in figure 2. Two curves are shown in this figure: (1) the solid line for global SERR is determined using the displacement at the point where the load is applied, and (2) the local SERR is determined by the crack closure technique. For this case, structural fracture is imminent when the crack length progresses to about 1.15 in. This length is determined by the intercept of the tangents near the rapidly increasing portion of the SERR curve (fig. 1). The important observation is that the general concept is applicable to even this relatively simple structure.

Mode II

A schematic of the end-notches inducing Mode II and combined Modes I and II is shown in figure 3. The finite element model and the local progressive substructuring are shown in figures 4 and 5, respectively. The details are described in reference 1. Typical results obtained for Mode II are shown in figure 6 where the measured range (ref. 2) is also shown. The crack length for imminent structure fracture is about 1.18 in. based on the global SERR curve.

Three points are worth noting:

(1) Mode II fracture exhibited some stable growth.

(2) The local approach predicts optimistic results relative to "critical" crack length but conservative results relative to the critical SERR magnitude. The reason is that the global approach incorporates the overall readjustment of the structure while the local does not.

(3) The SERR (G) is within the measured range (ref. 2).

The important observation is that the computational simulation procedure captures the whole history of the process which leads to structural fracture induced by Mode II fracture.

Combined Modes I and II

Typical results for combined modes I and II fracture in end notch beams are shown in figure 7. Structural fracture is imminent when the crack length progresses to about 1.14 in. (global SERR curve). The local curve, again, predicts optimistic magnitudes for critical crack length but conservative magnitudes for the critical SERR.

The decomposition to Modes I and II is also shown. These curves were determined using the local closure technique (ref. 1). Interestingly, structural fracture for this condition is driven by Mode I. Also, the curves for Modes I and II resemble their respective independent parts in figures 2 and 6. Furthermore, superposition of Modes I and II appears to apply to the local mixed mode curve but not to the global curve. The important observation is that structural fracture in beams subjected to combined (mixed) modes I and II fracture can be computationally simulated and the respective "critical" parameters quantified from the general procedure in figure 1.

Mixed Modes I, II, and III

The schematic used to computationally simulate structural fracture in beams subjected to mixed Modes I, II, and III fracture is illustrated in figure 8. Mode III is induced by the bending-shear coupling present in the unsymmetric $(+\theta_m/-\theta_n)$ laminate. An enlargement of the regions modeled in the vicinity of the crack tip, and used for progressive substructuring, is shown in figure 9. The details are described in reference 3. Typical results of SERR versus crack length for various unsymmetric laminate angles are shown in figure 10. The important observations to be made is that the Mode III contribution to structural fracture is relatively insignificant compared to the other two. Also, use of the global SERR is inclusive of the individual modes as well as any influences of integrated structural effects. The influences of integrated structural effects are not easily or, even at all, captured by local crack-closure techniques.

Collectively the four different types of structural fracture described demonstrate that structural fracture can be computationally simulated with respect to:

(1) Its history from initiation to the onset of rapid (unstable) propagation;

(2) Its critical parameters (for imminent rapid propagation);

(3) Its predominant fracture modes that drive it

The very important point to be noted is that all of the above were obtained without resort to the multitude of experiments that are usually required in traditional fracture mechanics.

LAMINATE FREE-EDGE DELAMINATION FRACTURE

In this section we summarize the application of the structural fracture to components subjected to free-edge delaminations under in-plane loading. Specifically, we describe the following types of delaminations: center, pocket, and internal. Detailed descriptions on the simulation procedural steps are given in references 4 and 5. Also the effects of delamination on buckling will be briefly described. A schematic illustrating the origin of the interlaminar free edges that induce free-edge delamination is shown in figure 11. A typical simulation result is shown in figure 12 where the global strain energy release rate (SERR) is plotted versus percent area delaminated. Although the SERR initially rises very rapidly, it levels off by the 10 percent delamination and settles into a stable delamination growth up to 70 percent.

Center Delamination

A photograph of a C-scan of a laboratory specimen with edge delamination (ref. 6) and a schematic of its corresponding one obtained by computational simulation are shown in figure 13 (ref. 5). The corresponding SERR for three different composite systems is shown in figure 14. The behavior of all three curves in figure 14 is similar to that in figure 12--early rapid rise followed by subsequent stable growth.

The observations to be made are: (1) free-edge delamination in the presence of in-plane loads is benign; (2) different materials can be readily evaluated with respect to their structural fracture resistance; and (3) substantial area may delaminate simultaneously with no change in the in-plane stress states.

Pocket Delaminations

These delaminations are believed to occur as follows: first, transply splits develop simultaneously at several places along the free edge; second, local delaminations develop in the vicinity of these splits due to high local stresses. These local delaminations are called, herein, pocket delaminations. Upon subsequent loading, these pocket delaminations merge to center delaminations.

Computational simulation results for these types of delaminations are shown in figure 15 for three different composite systems. The merging of pocket delaminations to center delamination is identified by the "jump" in the SERR curve followed by a rapid decrease and subsequent stable growth similar to that for center delamination in the previous section. The important observation is that computational simulation captures the progression of this complex delamination. The "jump" and subsequent "rapid decrease" can be used to guide strategic experiments to verify this sequence of events. They can also be used to interpret "stick-slip" type of progressive fracture prevalent in adhesively bonded joints.

Interior/Center Delamination

These types of delaminations may result from lack of bonding during fabrication; or they may occur as a result of inadvertent damage. Their growth to imminent structural fracture can be computationally simulated as the other types of delaminations. Results from these types of simulations for in-plane tensile stress are shown in figure 16 (ref. 5). As can be seen, their influence is negligible until large areas (greater than 50 percent) have delaminated. Whereupon the delaminations have reached the free edges. From here on, it behaves like a center-edge delamination.

The very important point to be noted is that internal delaminations are benign in-plane tensile stress fields.

Delamination Effects on Structural Response

The delamination effects on structural response can be computationally simulated as descried in reference 5. Typical results for the effects of center-edge delamination on buckling load are shown in figure 17 for three different composite systems. The decrease in buckling load appears to be linear and is relatively small (about 20 percent for 7-percent delaminated area). The observation to be made is that local delaminations have negligible effect on buckling loads. Although results are now shown here, internal/embedded delaminations have even less effect. The same observations hold for delamination effects on vibration frequencies.

CENTER-FLAW PROGRESSIVE FRACTURE

Flaws in plate/shell type structures propagate to critical sizes for imminent structural fracture. Research activities on progressive composite fracture at Lewis during the last 10 years have culminated in the development of the CODSTRAN computer code (ref. 7). CODSTRAN (Composite Durability Structural Analysis) has been specifically developed for the computational simulation of progressive fracture in fiber composites (refs. 7 to 9). The modules comprising CODSTRAN are: (1) the executive module, containing communication links to all other modules; (2) the I/O module; (3) the analysis module; (4) The composite mechanics module; and (5) the fracture mechanics module.

A schematic showing the logic of the code, with an analysis model and typical results is shown in figure 18 (ref. 8). The code tracks the damage growth flaw propagation up to structural fracture. Simulation of progressive fracture for different flaw types is shown in figure 18, and for different loading conditions in figure 19. The structural degradation in terms of vibration frequencies and buckling load is shown in figure 20 (ref. 9). The collective results from figures 18 to 20 demonstrate that progressive fracture in composites can be computationally simulated: (1) to any level of detail, (2) for any loading condition, and (3) for any structural response.

GENERAL REMARKS

Based on the continuing research effort described, some general remarks are appropriate. These remarks include: (1) generalization, (2) experience gained, and (3) future research needs.

Generalization

The computational simulation procedures described previously can be generalized for structural fracture in composites as follows:

(1) Develop global structural/stress analysis model
(2) Apply specified loading conditions
(3) Identify hot spots for these loading conditions
(4) Introduce flaws in the hot spots
(5) With specified loads on the global model propagate flaws
(6) Monitor structural performance degradation (displacement, buckling loads, frequencies) versus flaw propagation
(7) Identify flaw size for unacceptable performance degradation level
(8) Set qualification, inspection intervals, and retirement-for-cause criteria based on the simulated history of structural performance degradation versus flaw propagation.

Experience Gained

The experience gained during this rather extensive research effort, lead to the emergence of a suitable environment in order to successfully conduct loosely-defined long-term research. This research environment includes the following essential features:

(1) Continuity in research activity
(2) Collection of participants' with composite knowledge in:
   (i) Structural mechanics principles
   (ii) Finite element analysis
   (iii) Composite mechanics
   (iv) Fracture mechanics concepts
(3) Participants willing to question traditional approaches
(4) Participants willing to adopt/invent new approaches
(5) Continuing and unwavering management support
(6) Availability of computer facilities and supporting personnel

These features can serve as guidelines to conduct long-term research in computational simulation in general.

Future Research Needs

Assuming the state-of-the-art on composite structural fracture is as described herein, the authors consider the following as near-future research needs:

(1) Incorporation of uncertainties in the simulation
(2) Development of specialty: (1) finite elements, (2) boundary elements, and (3) functions, all of which include local details and capable of capturing steep gradients and thereby provide computational efficiency
(3) Efficient self-adaptive global/multilocal scale methods
(4) Time dependence and multiline scaling (local events simulated in different time scales compared to global)
(5) Formulation/programming for parallel processors
(6) Adaptation to smart structures and health monitoring systems

CONCLUSIONS

Based on the results of the research on computational simulation for structural fracture in composite the following conclusions are made:

1. Computational simulation of structural fracture in composite structures is ready for extension to wide use applications.

2. Reluctance to adopt it is natural because of: (i) unfamiliarity and (ii) attachment to traditional approaches.

3. Reluctance can be overcome by: (i) education, (ii) using it first in parallel with traditional approaches, and (iii) make it a specification requirement by the procuring agencies in new designs.

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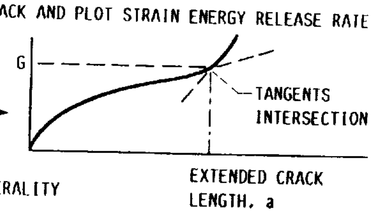
- DETERMINE REQUISITE COMPOSITE PROPERTIES AT DESIRED CONDITIONS USING COMPOSITE MICROMECHANICS AND LAMINATE THEORY
- RUN 3-D FINITE ELEMENT ANALYSIS FOR AN ARBITRARY LOAD
- SCALE LOAD UNTIL ONE OF LOCAL STRESSES AT ELEMENT(S) NEXT TO CRACK-TIP REACHES ITS CORRESPONDING STRENGTH
- WITH SCALED LOAD EXTEND CRACK AND PLOT STRAIN ENERGY RELEASE RATE VS CRACK LENGTH
- SELECT CRITICAL "G" AND CRITICAL "a" FROM THE INTERSECTION OF THE TANGENTS



- METHOD HAS VERSATILITY/GENERALITY

FIGURE 1. - GENERAL PROCEDURE FOR PREDICTING COMPOSITE STRUCTURES FRACTURE TOUGHNESS.

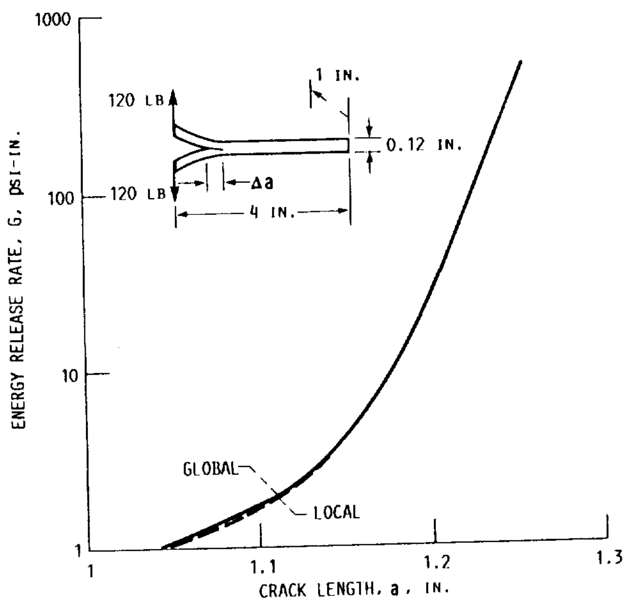


FIGURE 2. - DOUBLE-CANTILEVER ENERGY RELEASED RATE COMPARISONS.

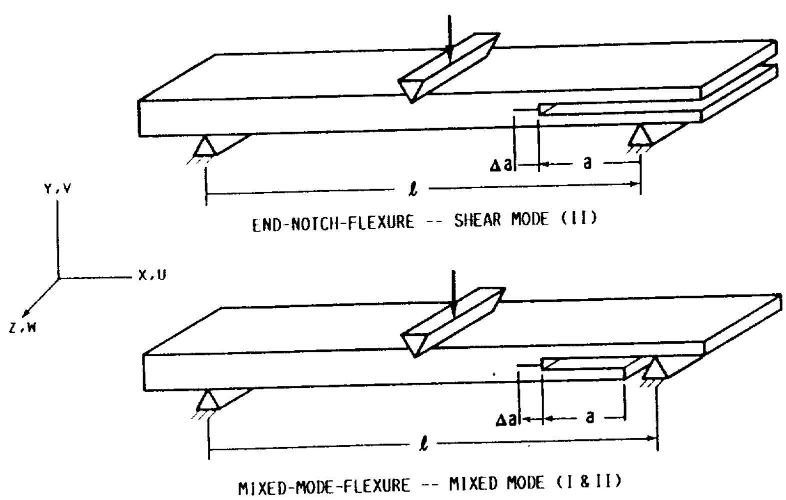


FIGURE 3. - SCHEMATIC OF FLEXURAL TEST FOR INTERLAMINAR FRACTURE MODE TOUGHNESS.

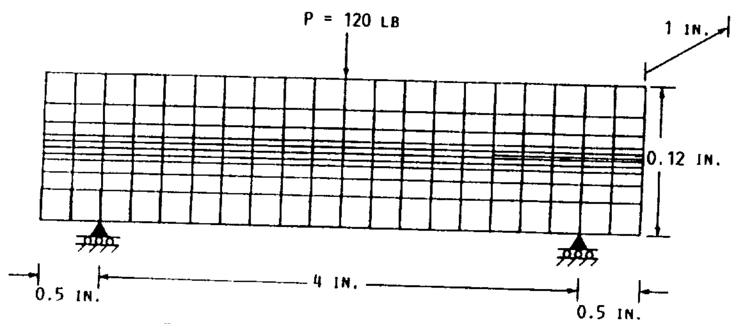


FIGURE 4. - MODEL GEOMETRY AND F.E. SCHEMATIC.

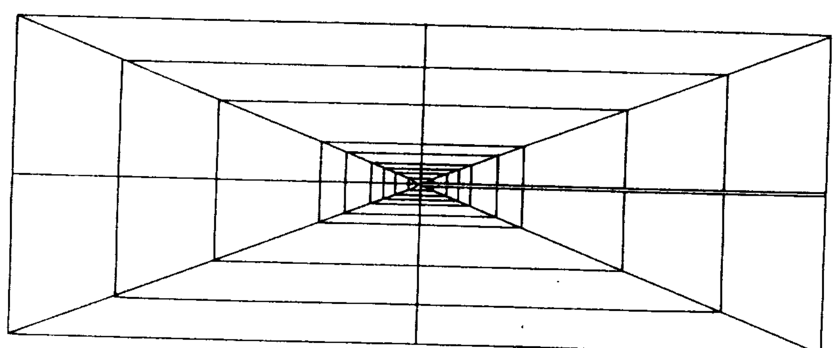


FIGURE 5. - CRACK REGION ELEMENT MODEL DETAILS FRONT VIEW.

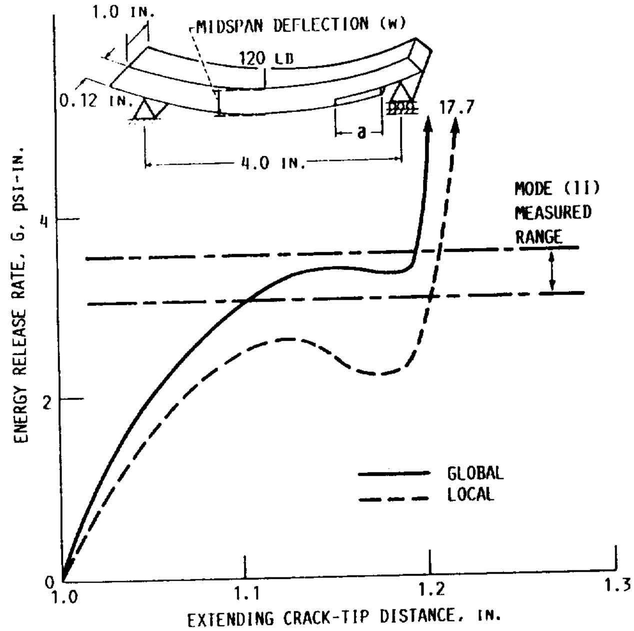


FIGURE 6. - END-NOTCH-FLEXURE ENERGY RELEASE RATE COMPARISONS.

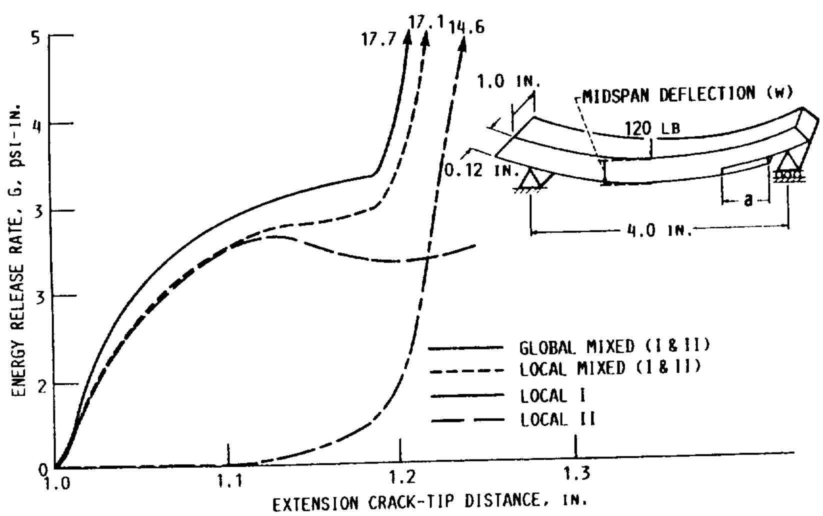


FIGURE 7. - MIXED-MODEL-FLEXURE ENERGY RELEASE RATE AND COMPONENTS (AS/E) (SINGLE POINT CONSTRAINED (LEWIS) METHOD).

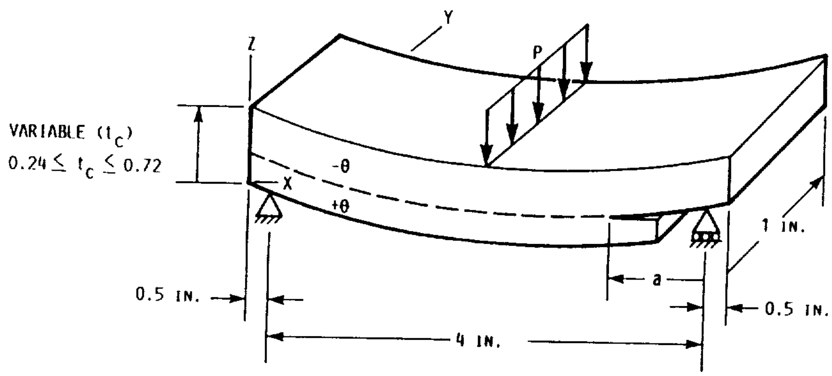


FIGURE 8. - UNSYMMETRIC LAMINATE GEOMETRY AND LOADING FOR MIXED MODE I, II, AND III FRACTURE.

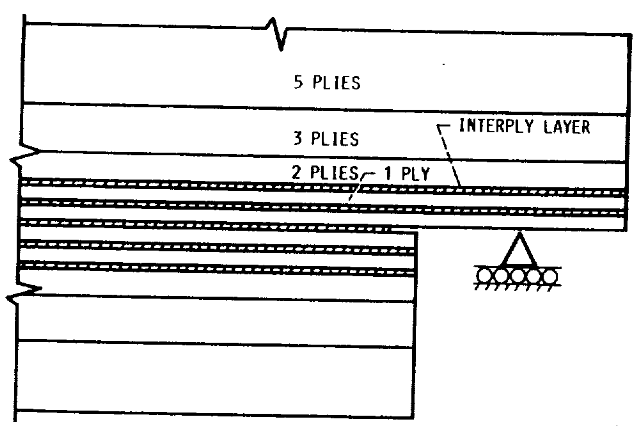


FIGURE 9. - SCHEMATIC OF F.E. MODEL THROUGH-THE-THICKNESS DETAILS (LOCAL PROGRESSIVE SUBSTRUCTURING).

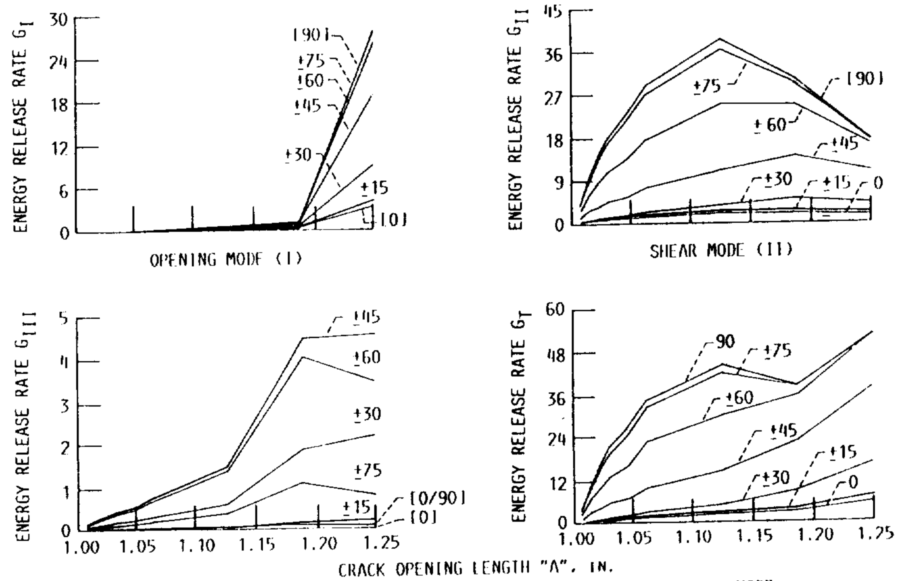


FIGURE 10. - EFFECTS OF CRACK LENGTH AND PLY ORIENTATION ON STRAIN ENERGY RELEASE RATES (IN.-LB/IN.^{2}) $[-\theta_{36}/+\theta_{12}]$.

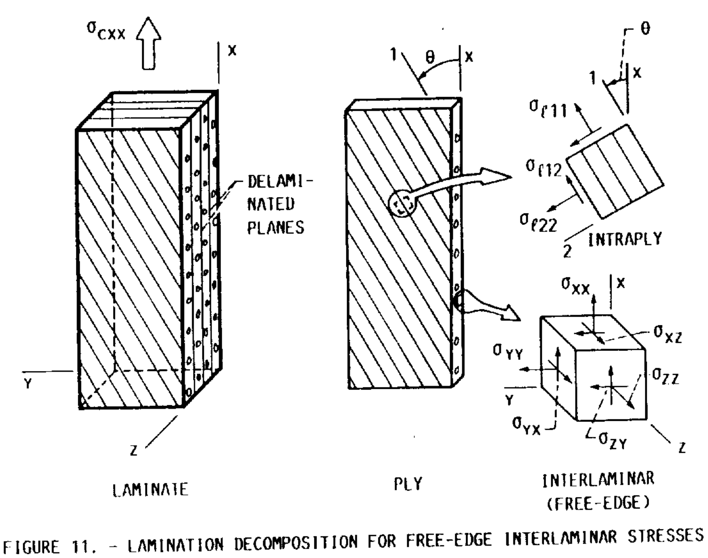


FIGURE 11. - LAMINATION DECOMPOSITION FOR FREE-EDGE INTERLAMINAR STRESSES.

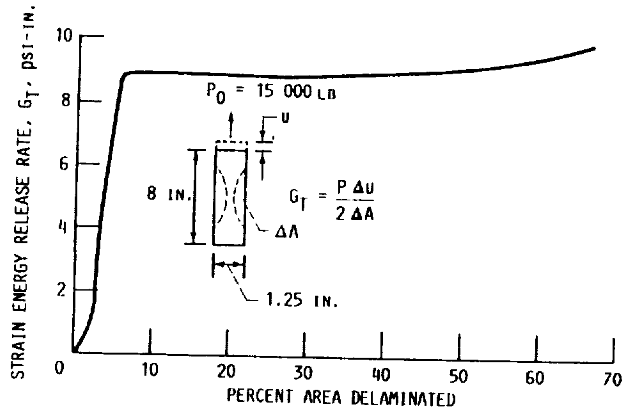


FIGURE 12. - STRAIN ENERGY RELEASE RATE FOR A "TYPICAL" LAB SPECIMEN (AS/E $[\pm 30/90]_s$ 0.6 FVR COMPOSITE).

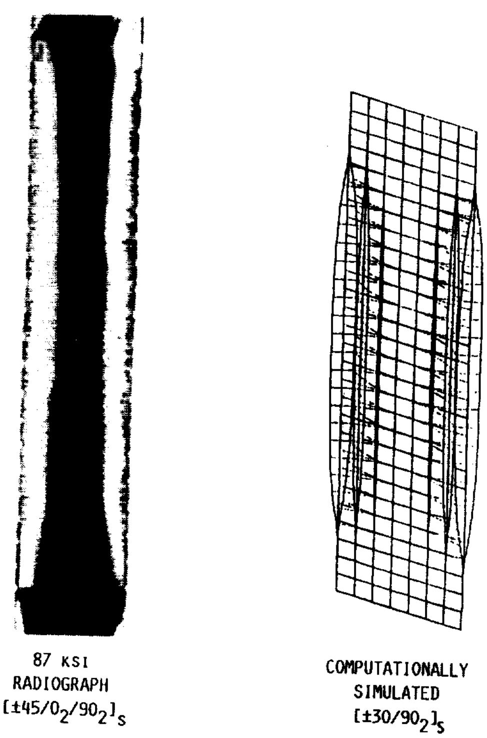


FIGURE 13. - FREE-EDGE PROGRESSIVE DELAMINATION CAN BE COMPUTATIONALLY SIMULATED.

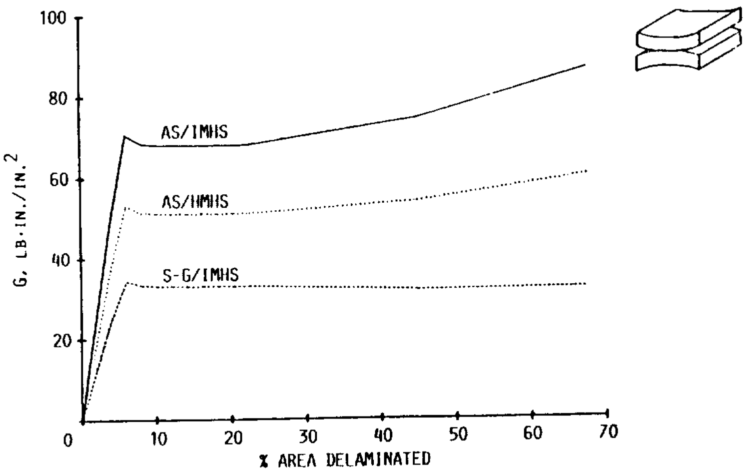


FIGURE 14. - STRAIN ENERGY RELEASE RATE (6-PLY CENTER DELAMINATION).

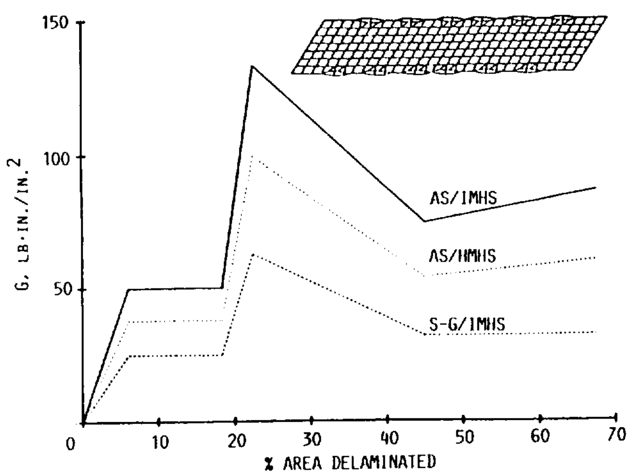


FIGURE 15. - STRAIN ENERGY RELEASE RATE (6-PLY CENTER/POCKET DELAMINATION).

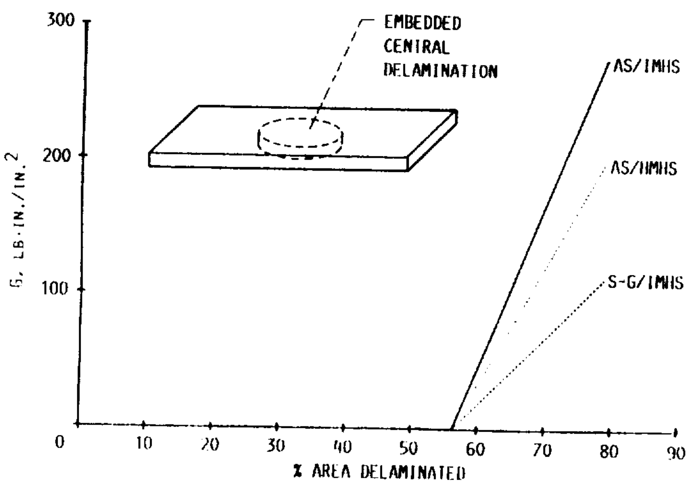


FIGURE 16. - STRAIN ENERGY RELEASE RATE (6-PLY INTERIOR/CENTER DELAMINATION).

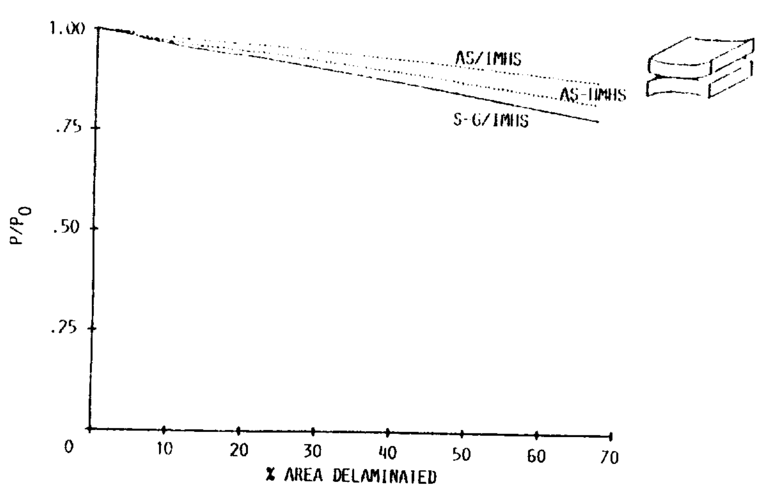
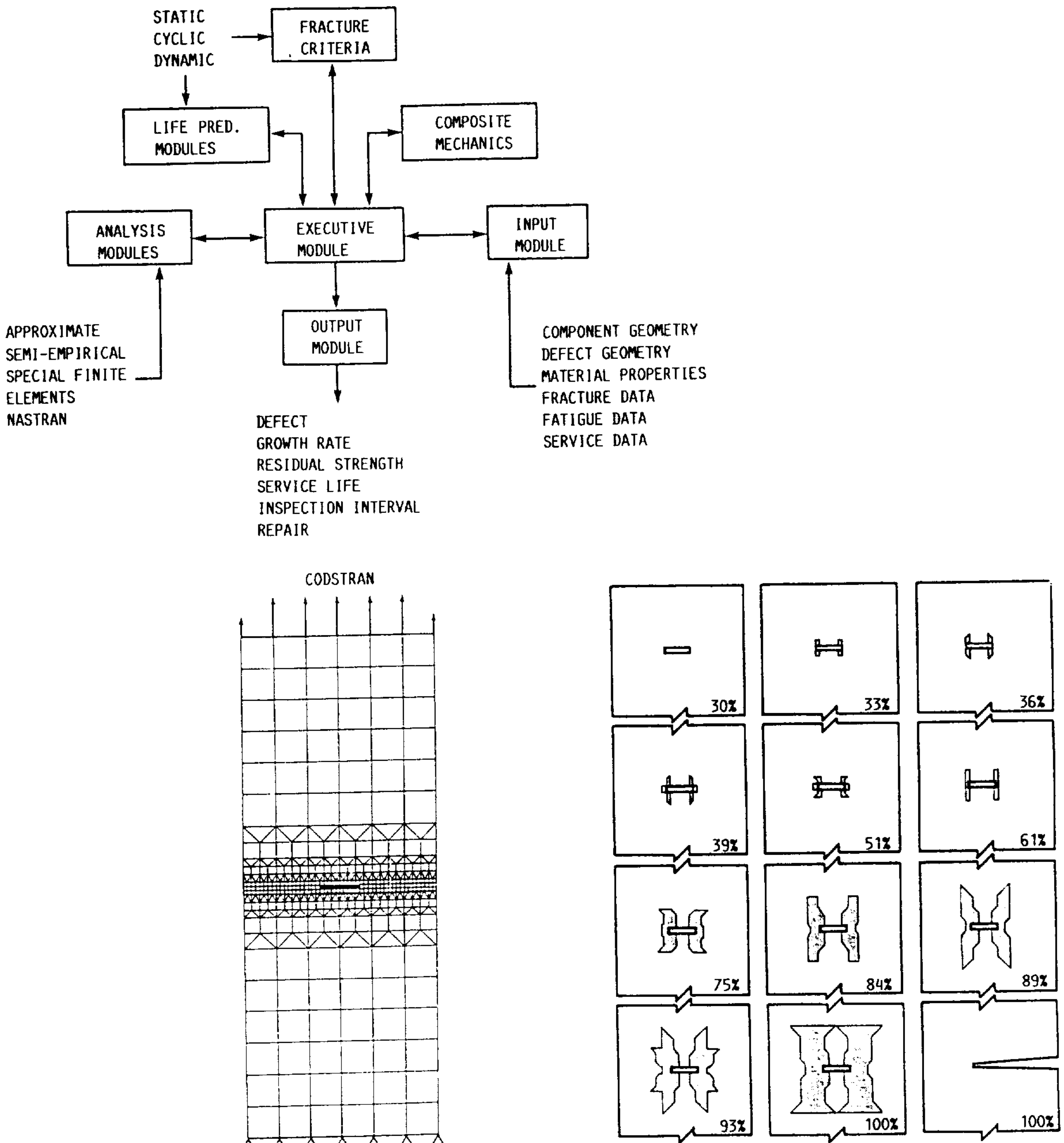


FIGURE 17. - BUCKLING LOAD (6-PLY CENTER DELAMINATION).



FINITE ELEMENT MODEL OF A

PROGRESSIVE FRACTURE AT VARIOUS PERCENTAGES OF FRACTURE LOAD

FIGURE 18. - COMPUTATIONAL SIMULATION OF PROGRESSIVE FRACTURE IN FIBER COMPOSITES.

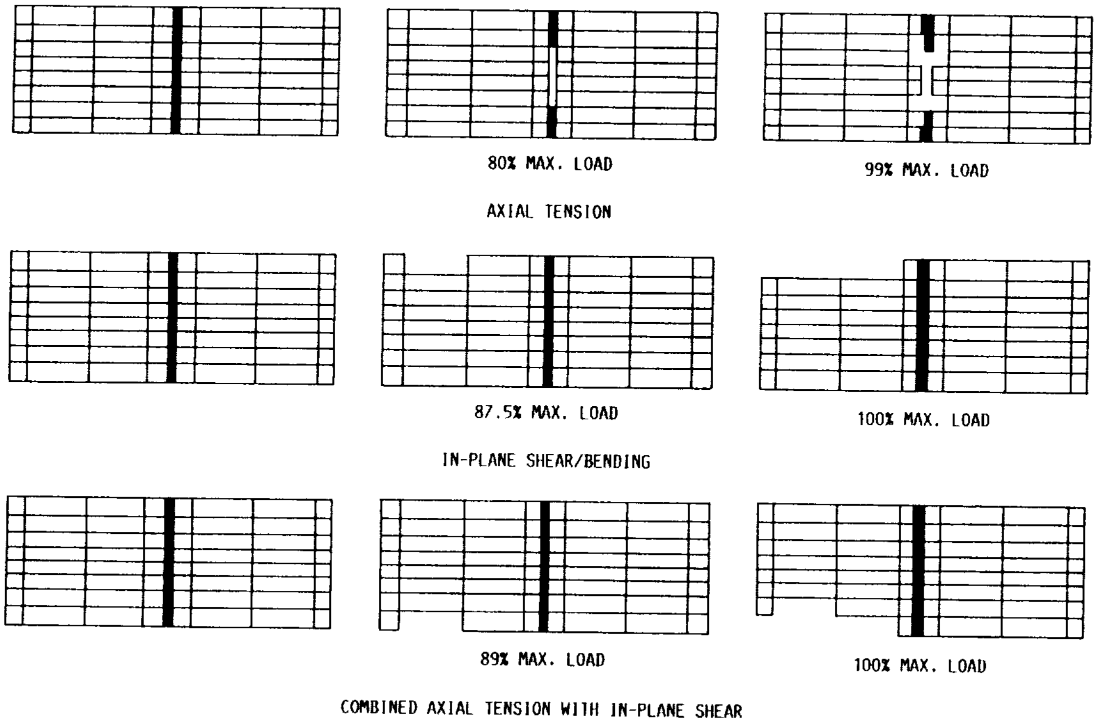


FIGURE 19. - PROGRESSIVE FRACTURE FOR INDIVIDUAL AND COMBINED LOADING.

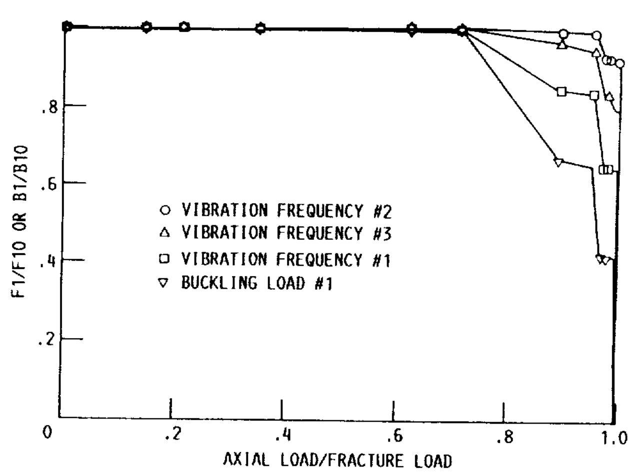


FIGURE 20. - THE EFFECT OF STRUCTURAL DEGRADATION ON NATURAL FREQUENCIES AND BUCKLING LOAD. COMPOSITE: T-300/EPOXY. (SUPPORT COND. 1 - EDGES PARALLEL TO LOADING FREE)

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16. Abstract

A methodology has been developed for the computational simulation of structural fracture in fiber composites. This methodology consists of step-by-step procedures for mixed mode fracture in generic components and of an integrated computer code CODSTRAN (Composite Durability Structural Analysis). The generic types of composite structural fracture include: (1) single and combined mode fracture in beams, (2) laminate free-edge delamination fracture, and (3) laminate center flaw progressive fracture. Structural fracture is identified by rapid changes in one or all of the following: (1) displacements, (2) frequencies, (3) the buckling loads, or (4) the strain energy release rate. These rapid changes are herein assumed to denote imminent structural fracture. Based on these rapid changes, parameters are identified which can be used as guidelines for (1) structural fracture, (2) inspection intervals, and (3) retirement for cause.

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