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# Progressive Fracture of Polymer Matrix Composite Structures: A New Approach


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# PROGRESSIVE FRACTURE OF POLYMER MATRIX COMPOSITE STRUCTURES:

# A NEW APPROACH

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## SUMMARY

A new approach independent of stress intensity factors and fracture toughness parameters has been developed and is described for the computational simulation of progressive fracture of polymer matrix composite structures. The damage stages are quantified based on physics via composite mechanics while the degradation of the structural behavior is quantified via the finite element method. The approach accounts for all types of composite behavior, structures, load conditions, and fracture processes starting from damage initiation, to unstable propagation and to global structural collapse. Results of structural fracture in composite beams, panels, plates, and shells are presented to demonstrate the effectiveness and versatility of this new approach. Parameters and guidelines are identified which can be used as criteria for structural fracture, inspection intervals and retirement for cause. Generalization to structures made of monolithic metallic materials are outlined and lessons learned in undertaking the development of new approaches, in general, are summarized.

## 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 global fracture is imminent. This is true for structures made from traditional homogeneous materials as well as fiber composites. The 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 for simulating structural fracture in fiber composites needs to formally quantify: (1) all possible fracture modes, (2) the types of flaws they initiate, and (3) the coalescing and propagation of these flaws to critical dimensions for imminent structural fracture.

One of the ongoing research activities 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 (refs. 1 to 3). Another part has been to

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incorporate these methodologies into an integrated computer code identified as CODSTRAN for Composite Durability Structural Analysis (refs. 4 and 5). The objective of this proposed report is to describe the fundamental aspects of this new approach and to illustrate its application to a variety of generic composite structures.

The generic types of composite structural fracture illustrated in this report are: (1) single and combined mode fracture in beams, (2) laminate free-edge delamination fracture, (3) laminate center flaw progressive fracture, and (4) plate and shell structural fractures. Structural fracture is assessed by one or all of the following indicators: (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 rates increase very rapidly. These rapid changes are herein assumed to denote imminent global structural fracture. Based on these rapid changes, parameters and guidelines are identified which can be used as criteria for (1) structural fracture, (2) inspection intervals, and (3) retirement for cause.

In the present approach, computational simulation is defined in a specific way. Also general remarks are included with respect to (1) application of this new approach to large structures and/or structural systems and (2) lessons learned about conducting such a long duration research activity, with regard to increasing computational efficiency, gaining confidence, and expediting its application. Sample case results are included for composite beams, panels, plates, and shells to illustrate the effectiveness and versatility of this new approach.

## FUNDAMENTALS

This new approach to structural fracture is based on the following concepts.

1. Any structure or structural component can sustain a certain amount of damage prior to structural fracture (collapse).

2. During damage propagation, the structure exhibits progressive degradation of structural integrity as measured by <u>global</u> structural behavior variables such as loss in frequency, loss in buckling resistance, or excessive displacements.

3. The critical damage can be characterized as the amount of damage beyond which a small additional damage or loading increase will cause a rapid degredation in the structural integrity.

4. Structural damage is characterized by the following five sequential stages: (1) initiation, (2) growth, (3) accumulation, (4) stable or slow propagation (up to critical amount), and (5) unstable or very rapid propagation (beyond the critical amount) to collapse.

These concepts are fundamental to developing formal procedures to (1) identify the five different stages of damage, (2) quantify the amount of damage at each stage, and (3) relate the degradation of <u>global</u> structural behavior to the amount of damage at each stage.

The formal procedures included in this new approach are as follows:

<u>Damage-stage identification</u>.—(1) Damage initiates when the local stress state exceeds the corresponding material resistance. (2) Initial damage grows when the stress exceeds the corresponding material

resistance on the damaged periphery for every possible failure mode. (3) Damage accumulates when multiple sites of damage coalesce. (4) Damage propagation is stable or slow when small increases, in either the damage propagation or loading condition, produce insignificant or relatively small degradation in the structural behavior (frequencies, buckling resistance, and displacements). (5) Damage propagation is unstable or very rapid when small increases in the damage propagation or in loading conditions produce significant or very large changes in the global structural behavior variables (frequencies, buckling resistance, and displacements).

Damage quantification.—The amount of damage is formally quantified by modeling the physics, in the periphery of the damaged region, to keep the structure in equilibrium for the specified loading conditions, structural configuration, and boundary conditions. This part of the procedure is most conveniently handled by using computational simulation in conjunction with incremental/iterative methods as will be described later.

Structural behavior degradation.—This part of the procedure is quantified by using composite mechanics in conjunction with the finite element analysis. The damage stages are quantified by the use of composite mechanics while degradation of the structural behavior is quantified by the finite element method where the damaged part of the structure does not contribute to the resistance but is carried along as a parasitic material. It is very important to note that nowhere in this approach mention of either stress intensity factors or fracture toughness parameters was made. This new approach bypasses both of them. However, use is made of the structural fracture toughness in terms of global Strain Energy Release Rate (SERR) because it is a convenient parameter to identify the "critical damage amount." The critical global SERR in the context of present approach is described subsequently.

The fundamental concepts described previously are concisely summarized in figure 1. The steps are few and simple and the parameters for "critical damage" are readily identifiable.

The combination of composite mechanics with the finite element method to permit formal description of local conditions to global structural behavior is normally handled through an integrated computer code as shown schematically in figure 2. The bottom of this figure describes the conditions of the material (microstress versus resistance) and where the criteria for damage initiation, growth, accumulation, and propagation are examined. The left part integrates (synthesizes) local damage conditions to global structural behavior (response). The right part of the figure tracks (decomposes) the effects of global changes (loading conditions for example) on the local (micro) material stress/resistance. Increases in damage are induced at the micro level while increases in the load conditions are applied at the global structural model. Overall structural equilibrium is maintained by iterations around this simulation (cartwheel type) cycle until a specified convergence is reached. Implementation of the new approach to track the various stages of damage is illustrated schematically in figure 3. The final result in terms of load versus global displacement is shown in figure 4. The schematics in figures 1 to 4, collectively summarize the fundamentals and implementation of this new approach to composite structural fracture and also to structural fracture in general. Applications to specific structures and components are described in subsequent sections.

## BEAMS

The new approach has been applied to three different types of beams: (1) double cantilever for opening mode delamination, (2) end-notch-shear for shear mode delamination, and (3) mixed mode delamination. Typical results obtained are summarized below. The details are described in the references cited for each specific application.

Double cantilever.—A typical result from applying this new approach to a double cantilever for opening mode delamination is shown in figure 5 (ref. 1). For this simulation, a preexisting damage (1 in. long) was assumed across the beam width. A small amount of damage growth/accumulation (about 0.05 in.) had severe effect on the strain energy release rate (SERR-G). Rapid damage occurred to about 1.12 in., beyond which the SERR increased very rapidly indicating unstable damage propagation to complete delamination. Referring to figure 1, the critical damage for this beam is less than 1.0 in. long (a) and less than 1.0 psi-in. structural fracture toughness (G). These values are in the range of those experimentally measured by using the double cantilever test method (about 0.8 psi-in. at 1-in. crack length).

End-notch-shear.—Typical results for shear-mode delamination in a beam, as can be measured by end-notch-flexure, are shown in figure 6 (ref. 1). A preexisting damage of 1 in. across the width was assumed for the simulation. A rapid damage growth/accumulation took place to about 1.1 in. followed by a stable damage propagation to about 1.18 in. Beyond this point, the damage propagation became unstable. Note that the range of measured data is indicated by the horizontal dashed lines. Note also that the local crack closure technique, which is commonly used, is also shown as a dashed curve. Applying the criteria in figure 1, the critical fracture toughness parameters are from the global curve about 1.18 in. for "a" and about 3.5 psi-in. for "G." Those from the local curve are about 1.2 in. for "a" and 2.5 psi-in. for "G". This example illustrates the difference between local and global quantities. It is worth noting that the local method requires about three times the computer time compared to the global.

Mixed mode delamination.—Two types can be simulated: (1) Shear mode (Mode II) combined with opening mode (Mode I) and (2) opening mode (Mode I) combined with shear mode (Mode II) and with tearing mode (Mode III). A typical result for the first type is shown in figure 7 (ref. 1). This figure illustrates that the global method does not distinguish how much each mode contributes. It is necessary to use the local closure technique to quantify the simultaneous contribution of each mode. An interesting observation is that the opening mode drives the delamination to beam splitting while the shear mode reaches a stable propagation state and remains there. Referring to figure 1, the critical structural fracture parameters are about 1.18 in. for "a" and about 3.3 psi-in. for "G." These are about 5 and 8 percent smaller, respectively, compared to shear mode (Mode II) fracture.

A typical result for the second type of mixed mode delamination is shown in figure 8 (ref. 2). The curves plotted in this figure are for critical values obtained from figure 1, that is, when the damage propagation state becomes unstable. The individual mode contributions were obtained by the local "crack closure" technique. A few interesting observations are: (1) the tearing mode (Mode III) is insignificant compared to the other two; (2) Mode I contributes the most; and (3) superposition of the three modes does not equal that of the total. This again indicates that the global fracture parameters appear to be more representative indicators of structural fracture. The other important observation is that the unsymmetric laminate configuration can be used in the end-notch mixed mode beam to measure the tearing mode. This is a simple test method indeed. The authors are not aware of any measured results obtained by using this test method. Collectively, the results from the different beams demonstrate that the new approach is readily applicable to these types of composite structures. Through-the-thickness damage and embedded damage can be simulated just as readily.

## PANELS

The new approach has been applied to computationally simulate structural fracture of composite panels subjected to in-plane loads. Typical results for three types of delamination are described to demonstrate application of the procedure (ref. 3).

Edge delamination.—The physics and stress state of edge delamination in composite laminates are schematically illustrated in figure 9. The delamination processes and their quantification using global parameters is shown in the schematic in figure 10. Typical results obtained for laminates from three different composite systems are shown in figure 11. This type of delamination grows and accumulates rapidly to about 6 percent of the area and then reaches a stable state. This stable state implies: (1) that a specific composite laminate will have a unique critical delamination parameter and (2) edge delamination, induced by predominently tensile in-plane stress, will not lead to panel collapse or disintegration.

Referring to figure 11, the parameters for stable damage state are about 7 percent area delamination for all composite systems and about 35, 50, and 70 psi-in. for S-G/IMHS, AS/HMHS, and AS/IMHS composites, respectively. Additional observations from figure 11 are that the structure fracture toughness depends on fiber type (difference in S-G and AS for the same matrix IMHS) and matrix (HMHS and IMHS for the same fiber AS). An important conclusion is that this new approach provides a relatively simple formal procedure to evaluate and/or identify fiber/matrix combinations for specified structural fracture toughness.

Edge-pocket-delamination.—Edge delamination is usually preceded by transply cracks which can occur in several locations simultaneously thus forming pocket-type delaminations along the edge. These types of delaminations can be simulated the same way as described previously except that they represent a form of multisite damage initiation, growth, accumulation, and propagation. Typical results for structural fracture toughness are shown in figure 12 for three different composite systems. Several interesting aspects of fracture progression can be observed in this figure. (1) Pocket delaminations grow rapidly inward to about 5 percent in delaminated area. (2) Stable delamination occurs inward to about 20 percent in delaminated area. (3) The pocket delaminations coalesce as indicated by the jump in "G." (4) The accumulated delamination grows with a decreasing rate to a stable level of about 45 percent in delaminated area. (5) The propagation exhibits stable behavior beyond this delaminated area. The structural fracture toughness value after stabilization is the same as that for stable edge delamination. The important conclusions are: (1) this new approach provides sufficient information to identify and quantify the fracture process from initiation to structure/component collapse and (2) it is readily adaptable to multiple site fracture initiation.

Internal or embedded delamination.—This type of delamination is a result of the fabrication process or damage sustained by inadvertent normal impact. In either case the damage growth, accumulation, and propagation can be simulated by using this new approach. Typical results are shown in figure 13 for the three different composite systems. An important observation is that substantial internal damage (up to 55 percent in delaminated area) occurs with negligible increase in the global SERR. Keep in mind that this panel and delamination results are for tensile in-plane load which does not cause local buckling.

The results from the panel clearly demonstrate that the new approach for structural fracture is readily adaptable to these types of delamination fractures including those initiated at internal hidden sites.

Through-the-thickness defects.—The previous examples were special cases of structural fracture. A panel with through-the-thickness defects is a more general case because 14 different failure modes are possible including fiber fractures. Three specific cases are simulated using the computer code CODSTRAN (fig. 2). These specific cases are selected to illustrate the similarities in fracture growth accumulation and propagation. Schematics of the three different cases (no defect (a), crack-like-defect (b), and hole-like-defect (c)) are shown in figure 14 with respective schematics depicting the damage propaga-tion extent by element annihilation (ref. 6).

The damage extent for all three cases is approximately the same. The load that induced the damage is not the same. That, for the crack-like and hole-like initial defects, are about the same (figs. 14(b) and (c)). However, the load for the case without initial defects (fig. 14(a)) is about twice as high as that for the defective laminates. The failure modes for each panel with different angle ply laminates are summarized in figure 15. As can be seen, the failure modes for all defect (notch) types are practically identical. The important observation is that irrespective of the initial defect shape, the damage growth, damage accumulation, and propagation appear to remain constant at least for uniform tensile load. An important conclusion is that this new approach to composite structural fracture simulates all aspects of the fracture process.

## PLATES

This case is selected to illustrate the effects of damage propagation on vibration frequencies and buckling resistance as well as the effects of hygrothermal environments. Typical results obtained by using CODSTRAN (fig. 2) are shown in figures 16 and 17 (refs. 7 to 9) where the schematics of the plate and the various hygrothermal environments are also shown. The important observations are: (1) the reference case, at room temperature and without moisture, exhibits the least amount of damage accumulation to fracture compared to the other cases; (2) moisture alone has a negligible effect on fracture load but increases the damage extent to fracture (fig. 16(b)); (3) combined temperature and moisture (hygrothermal) decrease the load to fracture but permit substantial damage accumulation to fracture (fig. 16(b)); (4) both the vibration frequency and the buckling resistance decrease very rapidly as the fracture load (structual collapse) is approached (fig. 16(c)); (5) the hygrothermal environments degrade the structural behavior of the plate (figs. 17(b), (c), and (d)); and (6) the buckling resistance is the most discriminating structural behavior for hygrothermal degradation (fig. 17(d)).

The important conclusion is that this new approach provides the formalism to simulate complex environmental effects from the micromechanics to structural behavior. That is, the temperature and moisture affect the matrix locally while the composite mechanics and the finite element method integrate these local effects to structural behavior (buckling resistance in this case).

## SHELLS

CODSTRAN is used to simulate the damage initiation, growth accumulation, and propagation to fracture in a composite shell with through-the-thickness as well as partial initial defects and subjected to internal pressure with hygrothermal environment.

Through-the-thickness defect.—Typical results for a through-the-thickness initial defect are shown in figure 18 (ref. 9). The results in this figure show that: (1) shells subjected to internal pressure sustain relatively low damage accumulation to fracture compared to other structural components (fig. 18(b)); (2) shells are less tolerant to hygrothermal effects compared to other structural components (fig. 18(c)); (3) the vibration frequencies of the shell do not degrade rapidly as the fracture pressure is approached (fig. 18(c)), and (4) hygrothermal environments have a significant effect on the higher vibration frequencies of the shell (fig. 18(c)). The effects on frequencies depends on specific shell/defect combination. An important observation is that composite shells with through-the-thickness defects subjected to internal pressure, exhibit a brittle type behavior to fracture. This explains, in part, the successful application of Linear Elastic Fracture Mechanics to these types of structures.

Partial-thickness defects.—The composite shell shown in figure 19 is investigated with initial fiber defects in two adjacent hoop plies occurring as (1) surface ply defects and (2) internal ply defects, as depicted in figure 20 (ref. 10). Computational simulation results for these two cases are summarized in figure 21. Case (1) exhibits results in a gradual damage growth and propagation with local degradation. There is sufficient local distortion of the shell geometry during the damage propagation to serve as a warning of approaching structural fracture. On the other hand, in case (2) damage propagation to structural fracture occurs without warning as a sudden catastrophic fracture of the shell. Figure 22 summarizes damage initiation and structural fracture pressures for the two cases with reference to the fracture pressure of a defect-free shell. It is noteworthy that surface ply defects reduce the ultimate fracture pressure by 15 percent whereas interior or midthickness ply defects reduce the ultimate fracture pressure by 23 percent. The important conclusion is that the complex structural behavior of shells with damage accumulation can be computationally simulated for any type of defects as well as for defect-free shells.

## GENERALIZATION AND LESSONS LEARNED

The discussion of this new approach focussed on its application to composite structures which are far more complex than conventional metallic structures. However, the approach is readily adaptable to structures made from any material or any combination of materials. Based on the experience and success to date, it can be readily generalized as is outlined in figure 23. The steps in the outline are the same for any structure. The difference is only in the description and history-tracking of the material behavior.

The important lessons learned in developing this new approach are generic and should be instructive for undertaking the development of new approaches in general. These lessons are summarized in figure 24. The authors firmly believe (they are convinced) that all the items in this summary are necessary for the successful development of new approaches. The authors are also convinced that the development of any new approach is not and should not be a short term activity because the developers increase their knowledge with continuous feedback and mature with the accumulation of experience during the development stage.

## SUMMARY

A new approach independent of stress intensity factors and fracture toughness parameters has been developed and described for the computational simulation of the fracture of composite structures. This approach is inclusive in that it integrates composite mechanics (for composite behavior) with finite element analysis (for global structural response). The integration of these two disciplines permits: (1) quantification of the fracture progression from local damage initiation to structural fracture (collapse), (2) accommodation of any loading conditions including temperature and moisture, and (3) the effects of material degradation due to hygrothermal environments. The versatility of the approach is demonstrated by using it to computationally simulate fracture in typical structures (beams, panels, plates, and shells) in a variety of fracture conditions. Parameters and guidelines are identified which can be used as criteria for structural fracture, inspection intervals, and retirement for cause. Generalization to structural systems and structures made from other components is outlined. Important lessons learned from undertaking the development of new approaches are summarized.

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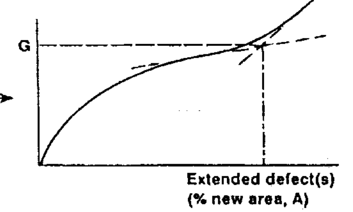
- Determine requisite properties at desired conditions using composite mechanics.
- Run 3-D finite element analysis for an arbitrary loading condition.
- Scale loading condition to match ply stress (or microstresses) at the maximum stress element(s) adjacent to defect(s).
- With scaled loading condition extend defect(s) and plot strain energy release rate vs extended defects(s).
- Select critical "G" and critical "A" →




- Method is versatile/general.

Figure 1.—General procedure for predicting fracture toughness in composite structures with defects.

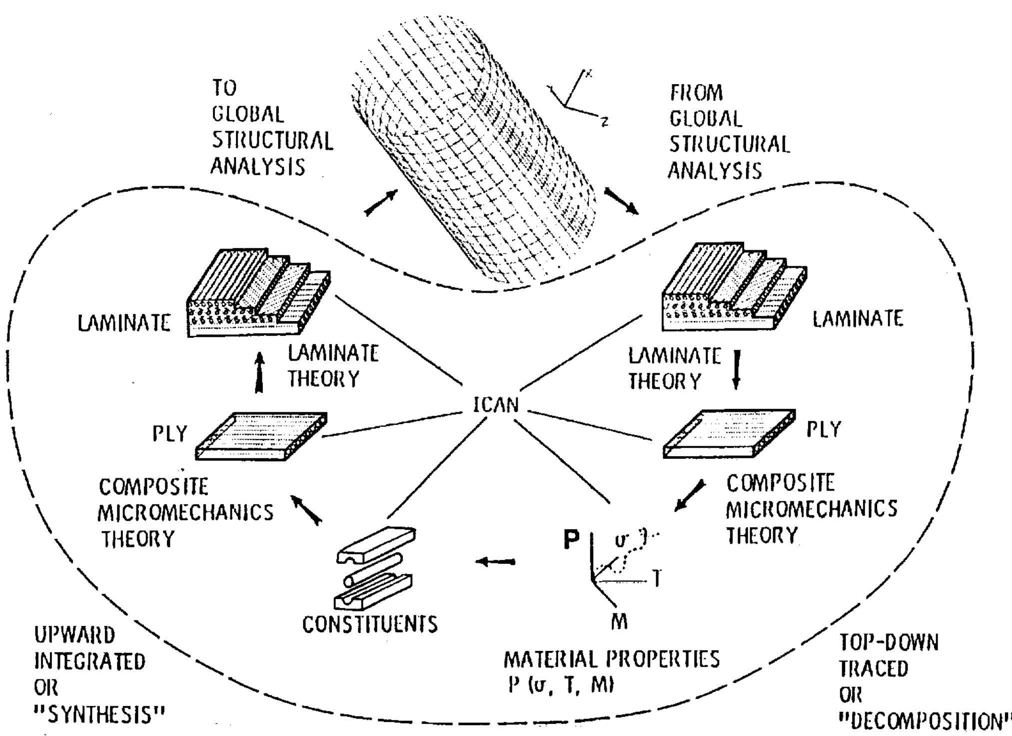



Figure 2.—CODSTRAN analysis cycle.

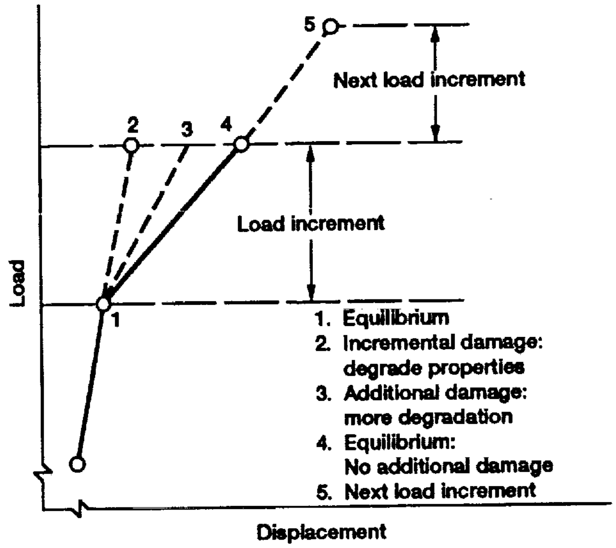



Figure 3.—CODSTRAN load incrementation.

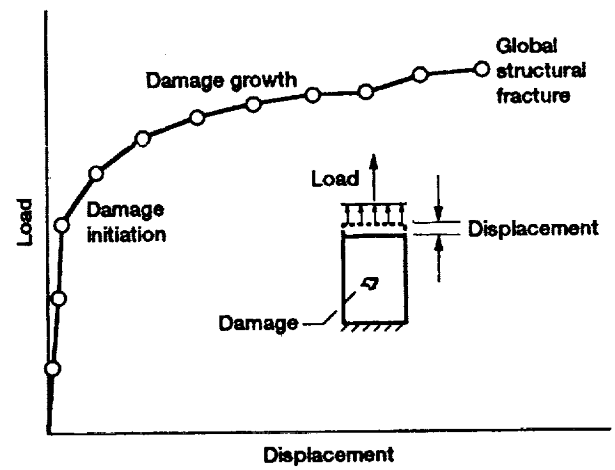



Figure 4.—Overall CODSTRAN simulation.

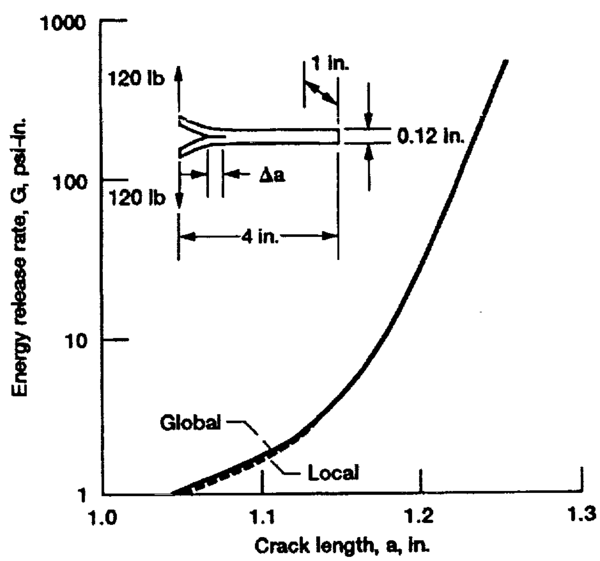



Figure 5.—Double-cantilever energy release rate-comparisons (AS/E).

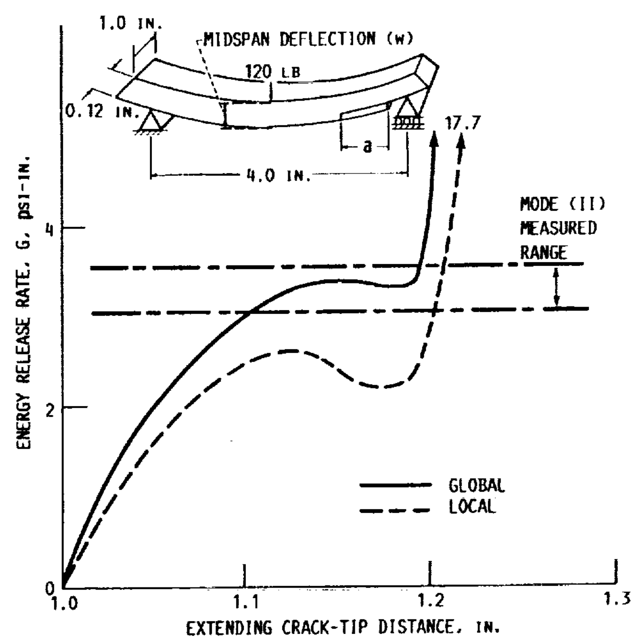



Figure 6.—End-notch-flexure energy release rate-comparisons.

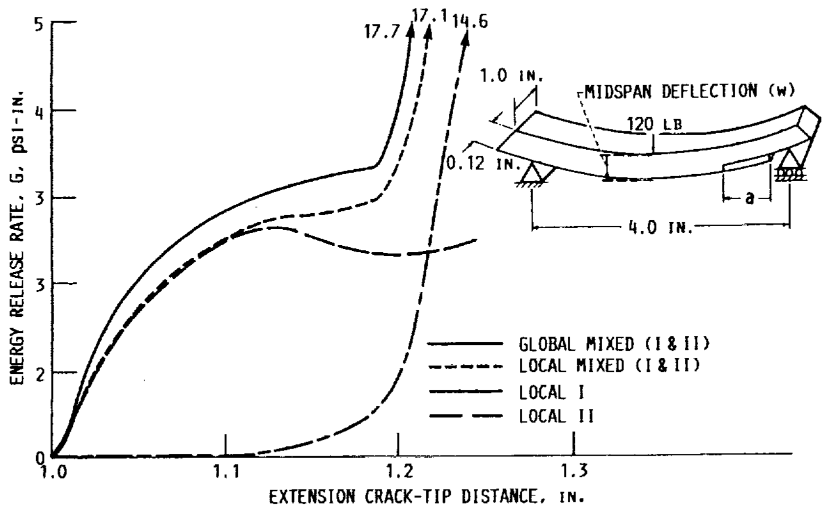



Figure 7.—Mixed-mode-flexure energy release rate and components (AS/E) (single point constrained (Lewis) method).

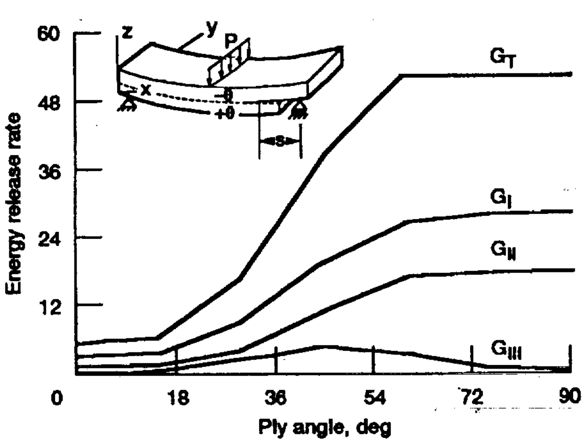



Figure 8.—Ply orientation effects on maximum strain energy release rates (in.-lb/in.$^2$) for constant load $[-\theta_{36}/+\theta_{12}]$.

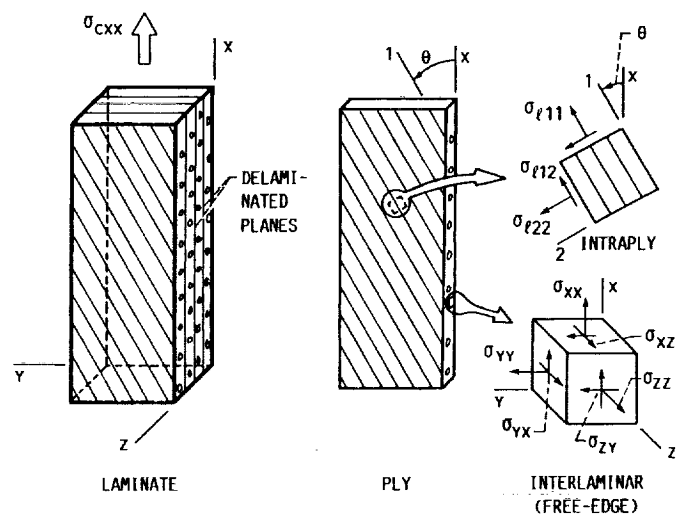



Figure 9.—Lamination decomposition for free-edge interlaminar stresses.

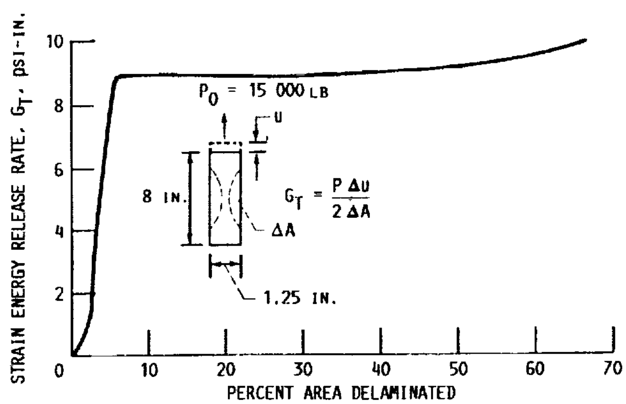



Figure 10.—Strain energy release rate for a "typical" lab specimen (AS/E [±30/90]$_S$ 0.6 FVR composite).

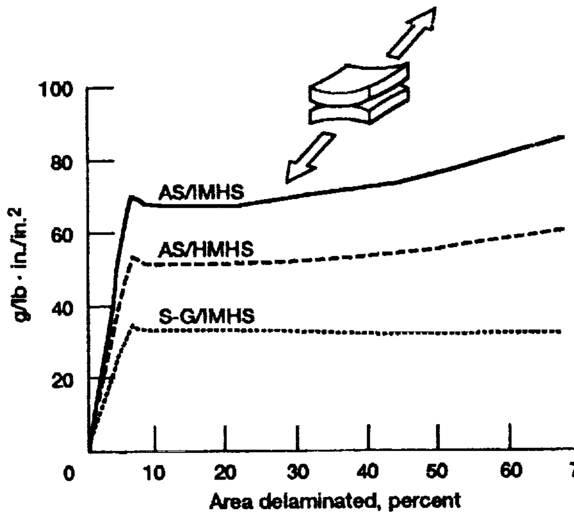



Figure 11.—Strain energy release rate. 6-ply center delamination.

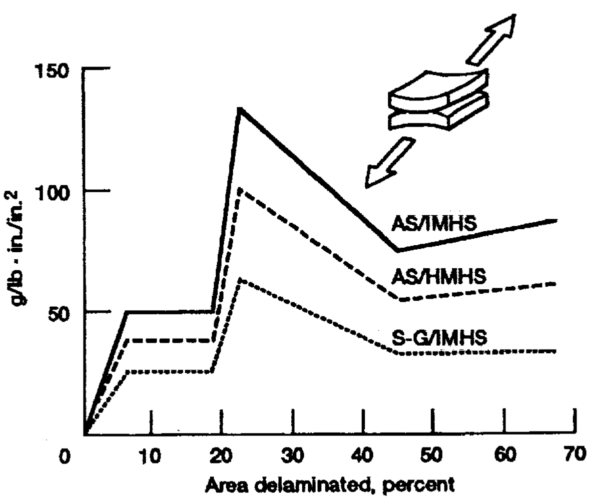



Figure 12.—Strain energy release rate. 6-ply center/pocket delamination.

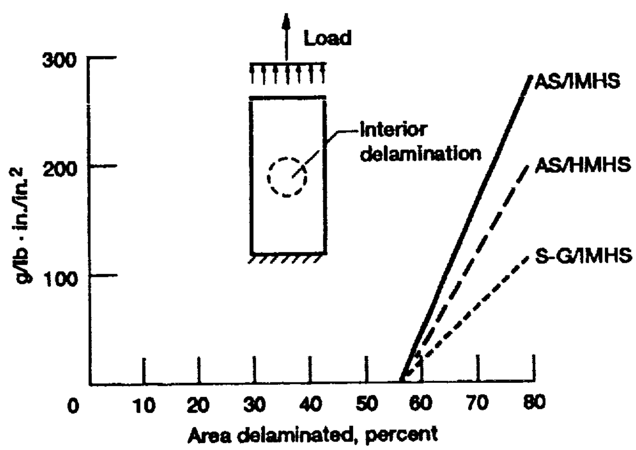
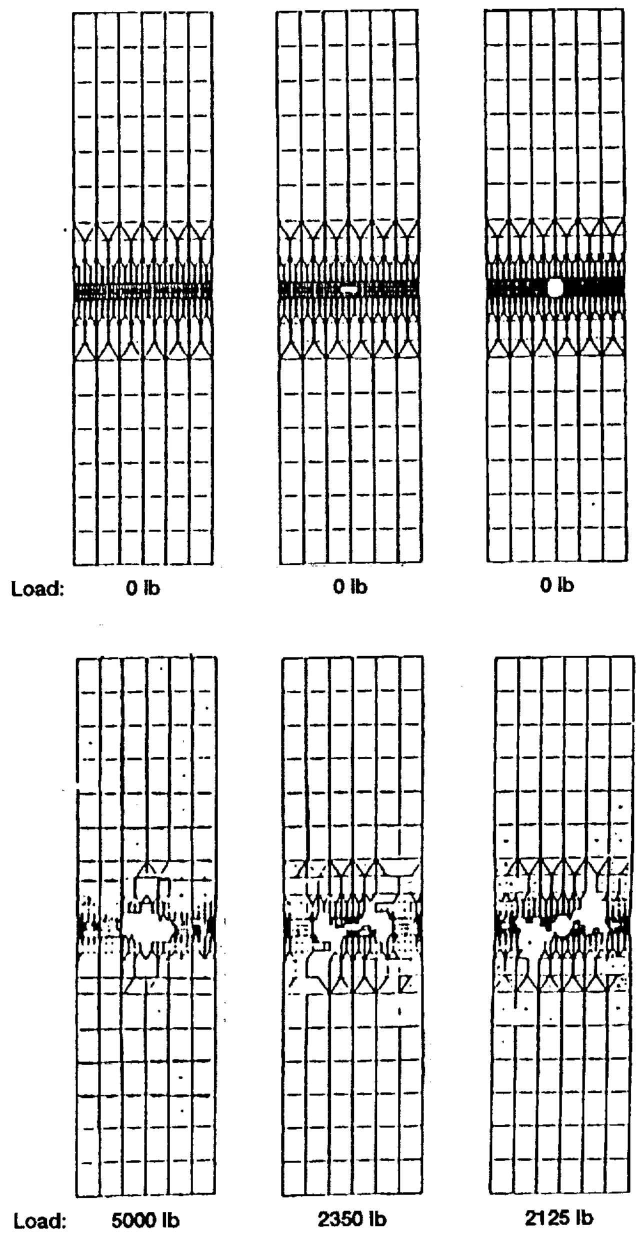



Figure 13.—Strain energy release rate. 6-ply interior/center delamination.




(a) No defect. (b) Crack-like defect. (c) Hole-like defect.

Figure 14.—Computationally simulated progressive fracture of laminates with different types of defects (Gr/E $[\pm 15]_s$) and subjected to in-plane tensile loading.

| Notch type | Ply orientation; $[\pm\theta]_s$; $\theta$ in degrees | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 3 | 5 | 10 | 15 | 30 | 45 | 60 | 75 | 90 |
| Unnotched--<br>solid | LT | LT<br>S[3] | LT<br>S[3] | LT<br>S[3] | I<br>S | S | I<br>S | TT | TT | TT |
| Notched--<br>thru slit | S[1]<br>LT | S[1]<br>LT | S[1]<br>LT | S | S | I[4]<br>S | I[4]<br>S | I[4]<br>TT<br>S[2] | TT | TT |
| Notched--<br>thru hole | S[1]<br>LT | S[1]<br>LT | S[1]<br>LT | S | S<br>LT | I[4]<br>S | I[4]<br>S<br>TT | I[4]<br>TT | TT | TT |

* LT = Longitudinal Tension
TT = Transverse Tension
S = Interply Shear: 1) Initial fracture due to intraply shear in the notch tip zone
2) Minimal intraply shearing during fracture
3) Some intraply shear occurring near constraints (grips)
4) Delaminations occur in notch tip zone prior to any intraply damage
I = Interply Delamination

Figure 15.—Fracture modes* of $[\pm\theta]_s$ G/E laminates (predicted by CODSTRAN).

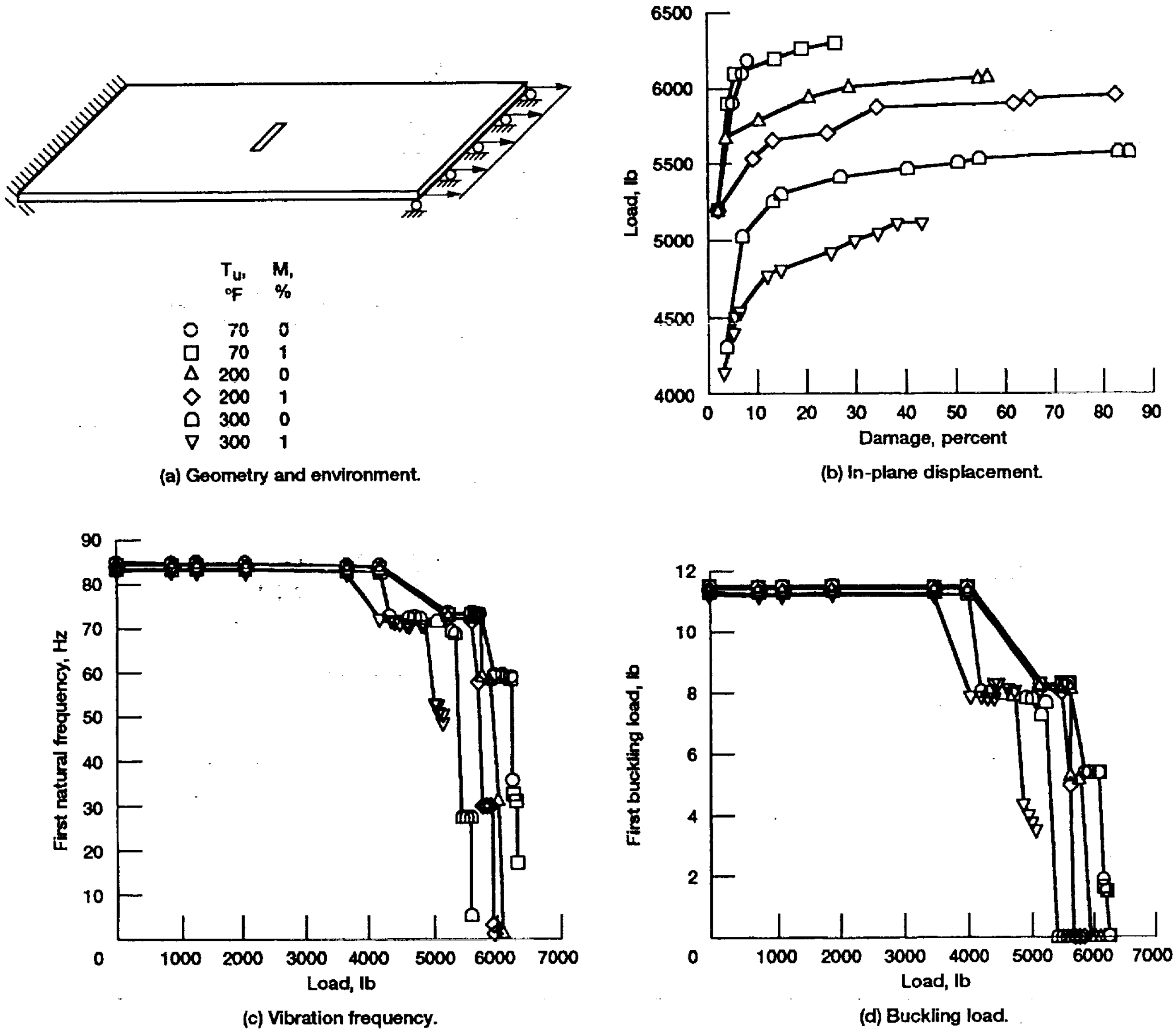



Figure 16.—Load induced progressive damage and effects on composite (T300/EP $[\pm 15]_{2s}$) plate structural response including hygrothermal environment.

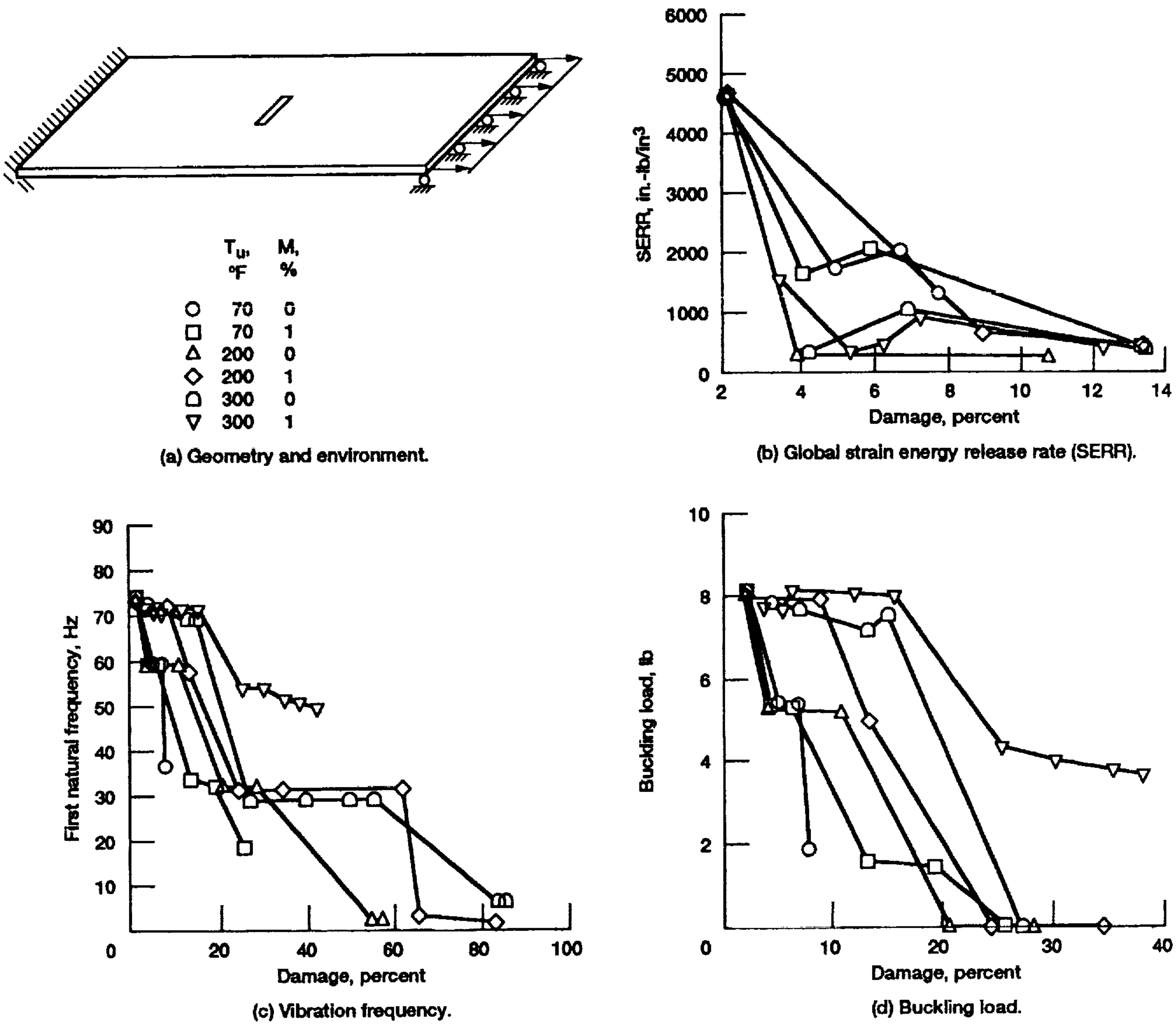



Figure 17.—Progressive damage degradation effects on composite plate (T300/EP $[\pm 15]_{2s}$) plate structural behavior including hygrothermal environment.

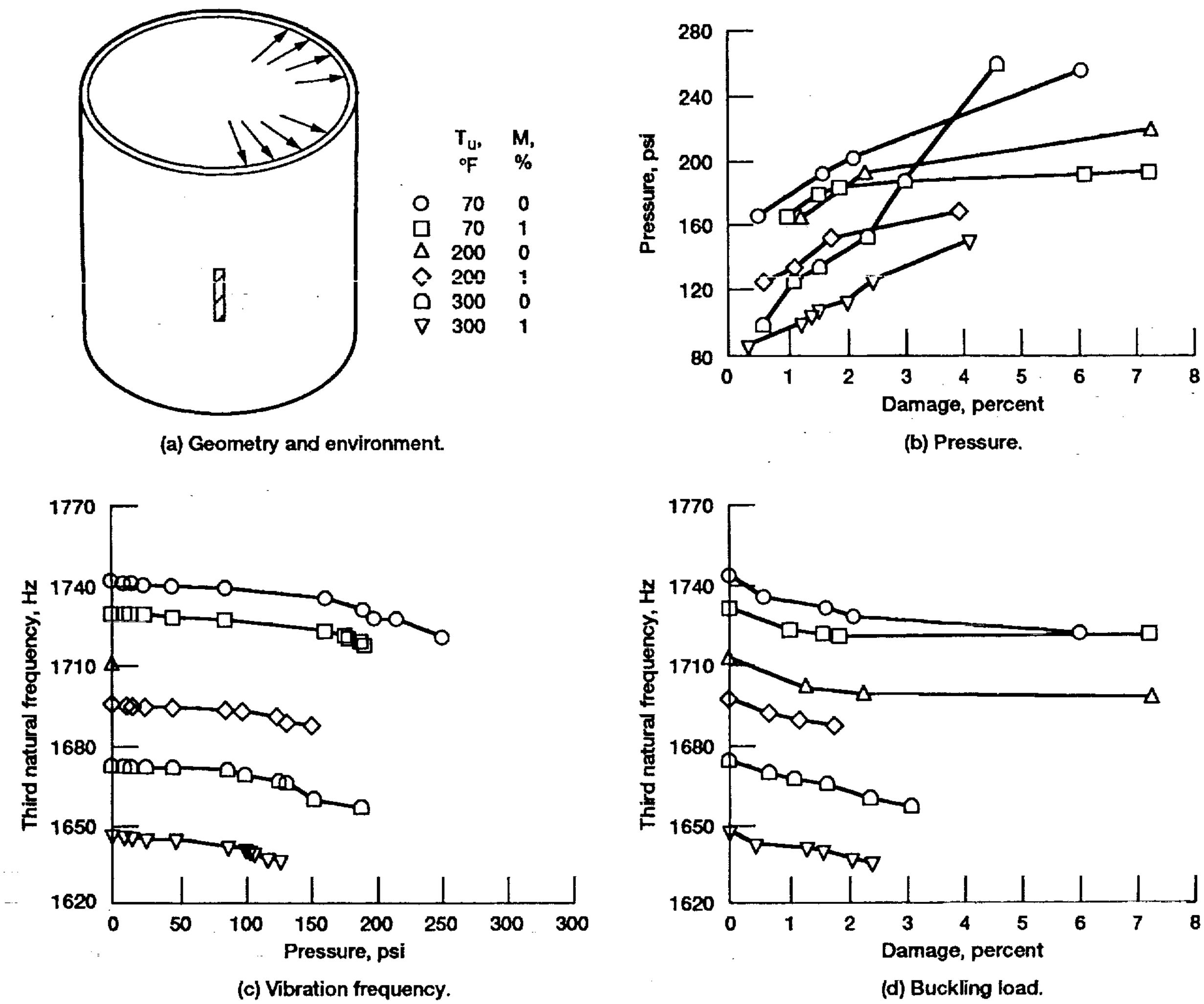
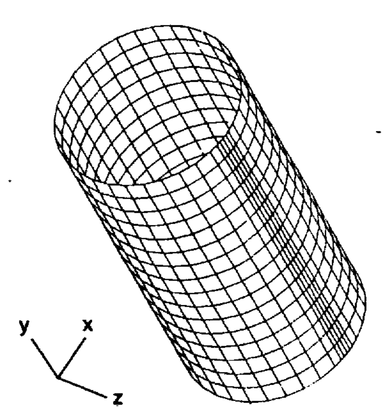



Figure 18.—Load induced progressive damage and effects on composite shell (T300/EP $[90_2/\pm15/90_2/\pm15/90_2/\pm15/90_2]$) structural behavior including hygrothermal environment.




Composite Shell T300/Epoxy$[90_2/\pm15/90_2/\pm15/90_2/\mp15/90_2]$
Shell diameter = 40 in., Length = 80 in.
612 nodes, 576 quadrilateral elements
Initial fiber defect in 2 adjacent hoop plies
Defect extends 5 in. along axial direction of shell

Figure 19.—Shell structure evaluated.

Pre-existing defect before loading assumed

Cases considered:
- Surface defect (plies 1 and 2 or plies 13 and 14)
- Mid-thickness defect (plies 9 and 10)

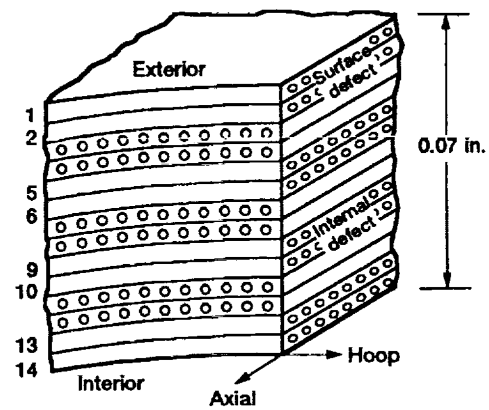



Figure 20.—Shell laminate structure schematic indicating initial defects. Composite Shell T300/Epoxy $[90_2/\pm15/90_2/\pm15/90_2/\mp15/90_2]$.

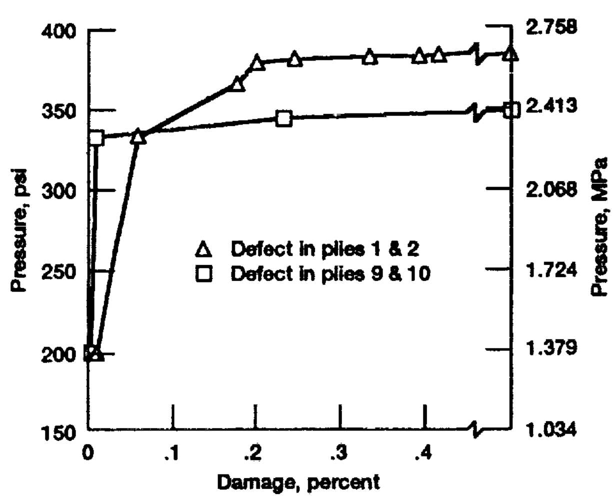



Figure 21.—Damage propagation with pressure. Composite Shell T300/Epoxy $([90_2/\pm15]_2//90_2/\mp15/90_2)$.

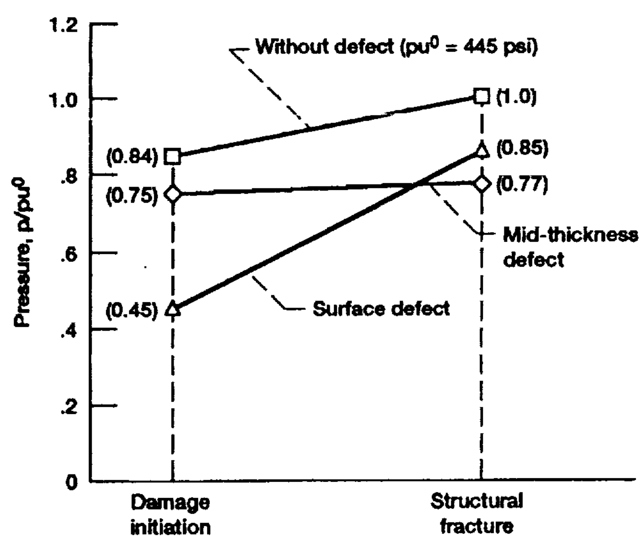
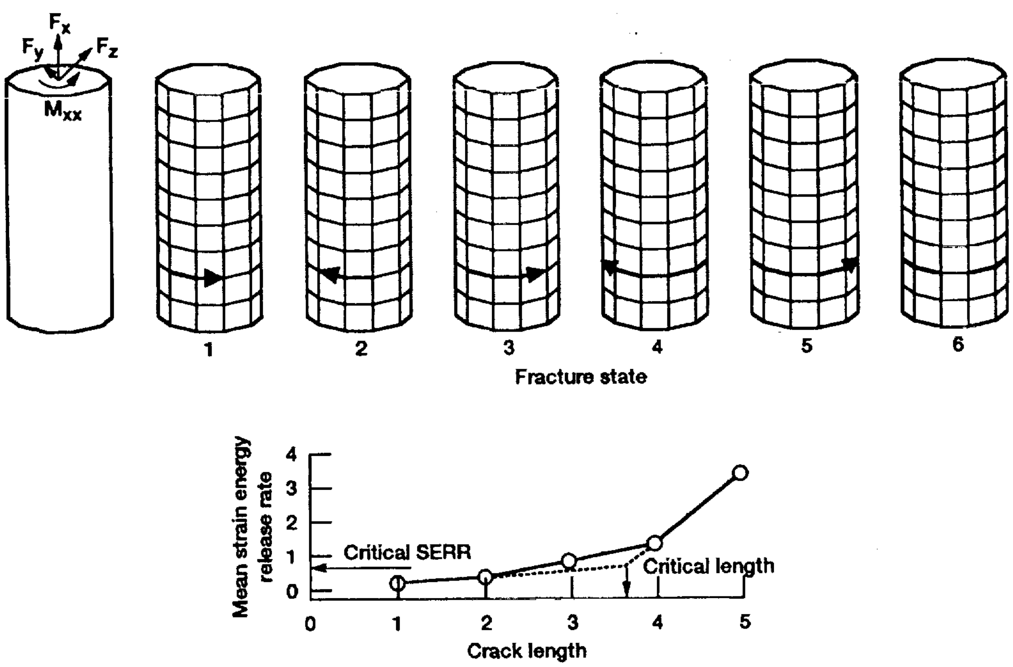



Figure 22.—Summary of results. Composite Shell T300/Epoxy $[90_2/\pm15/90_2/\pm15/90_2/\mp15/90_2]$.




Computational simulation of structural fracture
- Develop global finite element structural/stress analysis model
- Apply spectra loads
- Identify hot spots for spectra loads
- Introduce flows
- With spectra loads on structure grow flaws
- Monitor structural performance degradation versus flaw growth
- Identify flaw size for unacceptable performance degradation
- Set qualification, inspection, and retirement-for-cause criteria

Figure 23.—Generalization.

- Continuity in research activity
- Participants' composite knowledge:
  - Structural mechanics principles
  - Finite element analysis
  - Composite mechanics
  - Fracture mechanics concepts
  - Software development
- Participants willing to question traditional approaches adopt/invent new ones
- Management support
- Availability of computer facilities and support

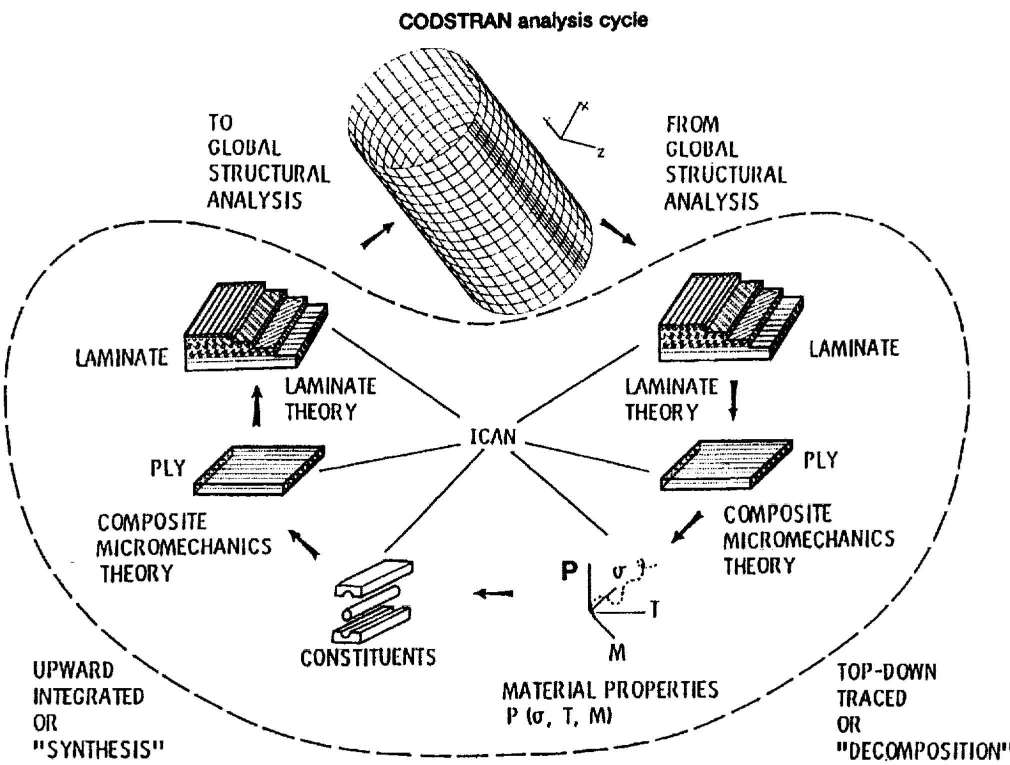



Figure 24.—Lessons learned.

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**13. ABSTRACT** ***(Maximum 200 words)***

A new approach independent of stress intensity factors and fracture toughness parameters has been developed and is described for the computational simulation of progressive fracture of polymer matrix composite structures. The damage stages are quantified based on physics via composite mechanics while the degradation of the structural behavior is quantified via the finite element method. The approach accounts for all types of composite behavior, structures, load conditions, and fracture processes starting from damage initiation, to unstable propagation and to global structural collapse. Results of structural fracture in composite beams, panels, plates, and shells are presented to demonstrate the effectiveness and versatility of this new approach. Parameters and guidelines are identified which can be used as criteria for structural fracture, inspection intervals and retirement for cause. Generalization to structures made of monolithic metallic materials are outlined and lessons learned in undertaking the development of new approaches, in general, are summarized.

**14. SUBJECT TERMS**
Damage initiation; Growth; Accumulation; Stable; Unstable; Propagation; Collapse; Beams; Panels; Plates; Shells; Fracture modes; Hygrothermal environment; Frequencies; Buckling resistance; Strain-energy release

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