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SUBLAMINATE DAMAGE MECHANISMS IN COMPOSITE STRUCTURES
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ENGINEERING L W RENFIELD ET AL JUL 87

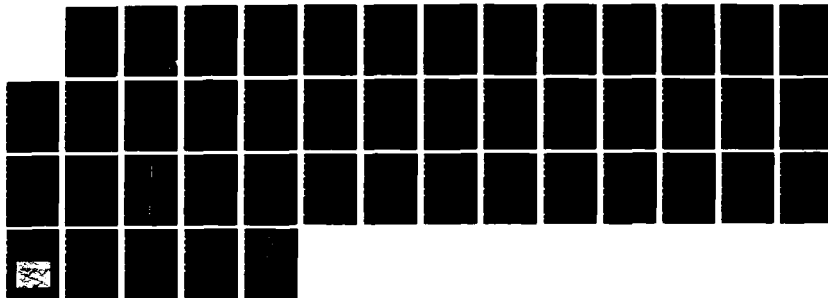
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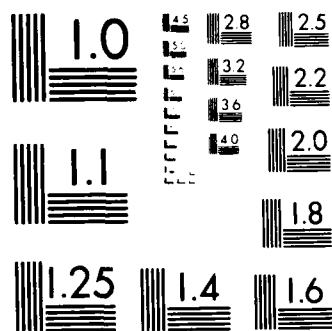
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This final report summarizes the objectives and accomplishments of research on sublamine damage mechanisms in composite structures.) The work was performed during the period 15 April 1985 - 14 April 1987. It may be separated into three elements. The first is interlaminar fracture analysis methodology development. Existing methods for predicting strain energy release rate components have been assessed, and two new alternative approaches have been developed and illustrated.

The second is the creation of a phenomenologically based criterion for damage tolerance analysis of composite structures. An equivalent damage parameter and a relevant compliance measure are determined from experiments. This methodology has been validated by seven independent experiments.

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SUBLAMINATE DAMAGE MECHANISMS
IN COMPOSITE STRUCTURES

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INTRODUCTION

The work described herein was performed at the School of Aerospace Engineering, Georgia Institute of Technology during the period 15 April 1985 - 14 April 1987. Professor Lawrence W. Rehfield was the Principal Investigator.

This research concerns the mechanisms of damage that occur in composite structures on the sublaminate scale - - - that is the scale of individual plies or groups of plies. The objectives have been to (1) obtain a fundamental understanding of the damage processes from a structural point of view, (2) model them appropriately so that trends or events can be predicted and key parameters identified and (3) use the predictions to provide guidelines, which are hopefully easy to understand and apply, to designers on detailed design issues which influence stress raisers that are common in composite structures.

The usual approach to dealing with localized phenomena is large scale numerical simulation and analysis, mostly by general purpose finite element codes. This approach is often supplemented by a "build and test" demonstration, or series of demonstrations if repeated failures are encountered. While such approaches are often costly and inefficient, their major drawback is that fundamental principles are not discovered which provide the means to produce better results. Furthermore, the steps must be repeated all over again the next time a similar situation arises.

In contrast to the above approach, we have pursued fundamental objectives which have been met in the main. In particular and, to our knowledge, for the first time, an analytical framework has been created which permits the interaction of damage mechanisms in composite laminates

to be predicted and, more importantly, understood. This is believed to be a major contribution. Furthermore, correlation with carefully performed experiments provide convincing evidence of the validity of the analytical methodology.

The second significant contribution is creating a means of relating complex forms of damage directly to load carrying capacity or residual strength on a reliable, physically meaningful basis. Many have believed that observed characteristic damage states commonly found in composites due to fatigue, static loading and low energy impact are so complex that they defy analytical prediction. This may be true if a traditional atomistic, detailed mechanical model is developed and analyzed. Predicting every individual event in order to grasp the overall reality may not produce the desired insight and understanding to control the process in an engineering sense. It is certainly not economical or efficient. A concept which we call "equivalent damage" permits the detailed, atomistic steps to be avoided in making practical predictions on the effects of damage in composites. This approach is supported by data from seven independent experiments.

SUMMARY OF ACCOMPLISHMENTS

Foundation Provided by Previous Work

The present research had its origin in the development and application of new structural models for composites under three previous AFOSR grants, 81-0056, 82-0080 and 83-0056. This modeling technology permitted prediction of interlaminar stresses in composite laminates and strain energy release rates for delamination prediction by elementary means. This is an enabling technology.

Delamination poses some unique problems for the analyst. In practical composite structures built up from many plies, each interply surface is a potential delamination site. Consequently, a complete analysis must be conducted for each interply surface by assuming the crack occurs in that plane. The fact that numerous repetitive analyses must be conducted is of great practical importance. Issues such as the efficiency of the analysis method and the elapsed time required impact both cost and schedule in a major way. This situation provided the motivation for development of this new approach.

Computer codes based upon this work are now used regularly at the NASA Langley Research Center, U.S. Army Aerostructures Directorate, Air Force Materials Laboratory and Bell Helicopter Textron, Inc.

Earlier work, which was completed and published during the current grant period and which contributed to the present research, appears in Accomplishments 1, 2 and 5. The purpose of citing these accomplishments is two-fold: (1) they provide the background that has proved so essential to our modeling efforts, which are key to the present research and (2) effort was expended during the present grant period in order to complete them and bring them to publication.

Overview of the Research

The research program can be separated into three elements. The first is the completion of background work on interlaminar fracture analysis which had its origin in the research conducted under the earlier grant 83-0056. This is a key element as interlaminar fracture or delamination is a very common damage mode in laminated composite structures. It is prevalent because interlaminar planes have minimum fracture toughness.

These planes are not reinforced by fibers. A complete account of this work appears in Accomplishments 3, 4 and 6.

The second is the development of a new approach to damage tolerance analysis and testing of composite structures. It has its origin in experimental observations, and it provides a means of relating damage size to failure. Thus, it is intended to serve the same purpose as fracture mechanics does for metals. This new approach is presented in Appendix I.

The third is the development of the analysis methodology that permits the understanding and prediction of the interaction of sublaminate damage mechanisms. It is presented and applied in Appendix II. Also, it will be presented as indicated in Accomplishment 15.

Each of these three elements will be considered in the following sections.

Interlaminar Fracture Analysis Methodology

Interlaminar fracture in composite laminates can be predicted by an energy release rate analysis based upon fracture mechanics. Several fracture laws for composite structures are expressed in terms of the energy release rate components. Therefore, an accurate knowledge of their values is essential to design against fracture. An extensive investigation of two major approaches which utilize finite element analysis to obtain the energy release rate components has been performed^{3,6}. These approaches are the crack closure technique and the virtual crack extension method. A dependence of the energy release rate components on the mesh and crack extension size is identified. A new approach which utilizes results obtained by the crack closure technique and the virtual crack extension method is presented. This approach leads to improved results which are

independent of the mesh and crack extension size. Improved estimates for a benchmark mode I behavior have been found and compared to an exact solution to prove the efficiency of this approach. This method is also applied successfully to a mixed-mode configuration.

Another new method³, the coupled strain energy method, has been developed for calculating the energy release rate (ERR) components. This approach exploits the superposition of an auxiliary equilibrium state to the mixed mode situation under consideration. Finally, separate ERR components are obtained in terms of the auxiliary solutions and the coupled strain energy. These reliable predictions can be utilized with confidence in appropriate failure laws for composite materials systems.

This work has provided a base of knowledge that has proven of enormous value in the development of the analysis methodology for sublaminar damage. It is pioneering in nature and provides new methods of ERR analysis and the conceptual foundation for the methods.

Damage Tolerance Analysis

A new, promising approach to damage tolerance analysis for composite structures has been created. A damage law relating equivalent damage size and failure has been established which has been validated by seven independent experiments on several specimen configurations. Four generic configurations have been studied. They are:

1. Double cracked-lap-shear (discrete ply dropoff),
2. Taper by dropping or terminating plies,
3. Damaged imbedded plies, and
4. Through thickness holes.

All four produce high interlaminar stresses and delamination accompanied by other forms of damage. These specimens progressively introduce fiber controlled damage in addition to delamination and matrix microcracking.

An equivalent damage parameter, which is monotonically related to the extent of damage, and a relevant compliance measure must be determined from experiments. These are input to the damage law. Complete details are presented in Appendix I.

While this approach is phenomenological in nature, it provides a practical means of assessing the effects of complex states of damage on residual strength or failure. At present the only alternative is empiricism.

Sublamine Damage Analysis

The origin of this work is a series of delamination experiments conducted on double cracked-lap-shear specimens in tension. After the onset of delamination, stable crack growth occurred --- increasing loads were required to extend the delamination crack. There was no known physical mechanism that explained this behavior as the graphite-epoxy material system was quite brittle. After considerable investigation, the interaction of two damage modes --- delamination and matrix microcracking -- was found to provide a rational explanation that is in concert with analysis predictions and physical evidence. To the authors' knowledge, this is the first successful analysis of the interaction between delamination and matrix microcracking.

A key assumption was used in creating the analysis methodology --- matrix microcracking is predicted by strain level only. This is valid for

damage characteristic dimensions greater than a ply thickness. For damage on a smaller scale, fracture mechanics concepts and means for detecting sub-ply microcracks is required. For most engineering applications, strain level predictions are quite satisfactory.

A complete account of this work appears in Appendix II. An application to a double cracked-lap-shear specimen in tension provides a convenient test case where experimental data exists.

ACCOMPLISHMENTS

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2. Armanios, E.A., Rehfield, L.W. and Reddy, A.D., "Design Analysis and Testing for Mixed-Mode and Mode II Interlaminar Fracture of Composites," in Composite Materials: Testing and Design (Seventh Conference), ASTM STP 893. J.M. Whitney, Ed., American Society for Testing and Materials, Philadelphia, 1986, pp. 232-255.
3. Weinstein, F., "Studies in Interlaminar Fracture of Composite Laminates," Ph.D. Thesis, Georgia Institute of Technology, June 1986.
4. Rehfield, L.W., Armanios, E.A. and Weinstein, F., "Analytical Modeling of Interlaminar Fracture in Laminated Composites," Composites '86: Recent Advances in Japan and the United States, Proceedings of the Third Japan-U.S. Conference on Composite Materials, K. Kawata, S. Umekawa, and A. Kobayashi Eds., 1986 pp. 331-340.
5. Reddy, A.D., Rehfield, L.W., Weinstein, F. and Armanios, E.A., "Interlaminar Fracture Processes in Resin Matrix Composites under Static and Fatigue Loading," Composite Materials: Testing and Design (Eighth Symposium), ASTM STP 972, J.S. Whitcomb Ed., American Society for Testing and Materials, Philadelphia, 1987.

Publications Pending

6. Weinstein, F., Armanios, E.A. and Rehfield, L.W., "An Assessment of Methods for Computing Energy Release Rate Components for Interlaminar Fracture," ASTM Second Symposium on Composite Materials: Fatigue and Fracture, Cincinnati, OH, 27-28 April 1987. To appear in an ASTM STP volume.

Presentations

7. Reddy, A.D., Rehfield, L.W., Weinstein, F. and Armanios, E.A., "Interlaminar Fracture Processes in Resin Matrix Composites under Static and Fatigue Loading," ASTM Composite Materials Testing and Design: Eighth Symposium, Charleston, S.C., 28-30 April 1986.
8. Rehfield, L.W., "An Overview of Interlaminar Fracture Research," ASTM Mini-Symposium on Fracture Testing of Composite Materials State of the Art, Charleston, S.C., 28th April 1986.
9. Rehfield, L.W., Armanios, E.A. and Weinstein, F., "Analytical Modeling of Interlaminar Fracture in Laminated Composites," Third Japan-U.S. Conference on Composite Materials, Tokyo, Japan, 23-25 June 1986.

Presentations (continued):

10. Weinstein, F., Armanios, E.A. and Rehfield, L.W., "An Assessment of Methods for Computing Energy Release Rate Components for Interlaminar Fracture," presented at the ASTM Ninth Symposium on Composite Materials: Fatigue and Fracture, Cincinnati, Ohio, 26 April 1987.
- 11-13. Rehfield, L.W., Armanios, E.A. and Weinstein, F., "Understanding and Predicting Sublaminar Damage Mechanisms in Composite Structures, presented at:
 - a. Air Force Office of Scientific Research, Washington, D.C., 7 November, 1986.
 - b. Fracture and Fatigue Research Laboratory, Georgia Institute of Technology, Atlanta, Georgia, 20 January, 1987.
 - c. Centennial Colloquium Series in Structural Mechanics, School of Engineering Science and Mechanics, Georgia Institute of Technology, 30 January, 1987.
14. Armanios, E.A., "Delamination in Composite Structures," Spotlight on Research at Georgia Tech: Advanced Materials and Composites, Georgia Institute of Technology, Atlanta, Georgia, 9-10 June, 1987.
15. Rehfield, W.W., Armanios, E.A. and Weinstein, F., "Understanding and Predicting Sublaminar Damage Mechanisms in Composite Structures," to be presented at the Ninth Symposium on Composite Materials: Testing and Design, Reno, Nevada, 25-26 April, 1988.

APPENDIX I

"DAMAGE TOLERANCE ANALYSIS AND
TESTING OF COMPOSITE AIRCRAFT
STRUCTURES"

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School of Aerospace Engineering
Georgia Institute of Technology

INTRODUCTION

Damage tolerance for composite aircraft structures has an empirical base. There is no unifying framework such as fracture mechanics for metal structures. This is due primarily to the complexity of damage modes in composites which includes contributions with different length scales.

There is a pressing need for a damage tolerance analysis methodology for composites. It is needed not only for design but for supportability. Rational maintenance/repair decisions affect both readiness and life cycle costs. At present, empirical data are mainly used. There are also some current efforts aimed at modeling micromechanisms observed in foreign object impact which utilize test data as input.

The objective of this proposed work is to investigate whether a newly discovered framework and approach can be applied to foreign object impact damage. This new approach is briefly described in the following.

FOUNDATION OF A NEW APPROACH

There are two types of information that are needed for a damage tolerance analysis. The first is a quantitative assessment of the damage in the structure. The second is a relationship between failure and damage size or extent. Damage assessment is straightforward in metal structures --- crack area --- and most cracks reach the exterior surfaces where they can be detected. Fracture mechanics provides the failure criterion in this case.

If residual strength is adequate, that is, there is no immediate static failure for the given damage, the residual lifetime is needed in order to establish rational inspection procedures and repair decisions. Life predictions require additional data. These data characterize damage growth in fatigue and are usually in the form of fatigue damage growth as a function of stress intensity for metals.

The situation for composites is not nearly so neat and well established. Difficulties begin with the complex modes of damage which are difficult to describe and quantify. With the exception of pure interlaminar fracture or delamination, fracture mechanics cannot be used directly. This is because damage growth is not self-similar and mode changes and mode interactions are common in practical laminates.

The new approach presented here is a direct result of experimental observations. A generic situation is depicted in Figure 1. Almost continuous damage, a progressive form of damage that develops as a series of sequential damage increments, is indicated; this is commonly found when delamination and matrix cracking are major damage modes. Also shown is a compliance plot which illustrates compliance change with damage size. Note that a compliance value corresponding to failure is approached.

The compliance-damage relationship indicated in Figure 1 can be modeled by the damage growth law presented in Figure 2. This law serves the same purpose that fracture mechanics does for metals that are damaged by cracking. It is a two parameter model. The parameter a_0 characterizes the integrated mechanical effect of initial microdamage. The parameter C_F is the compliance corresponding to failure.

Figure 1
ALMOST CONTINUOUS DAMAGE

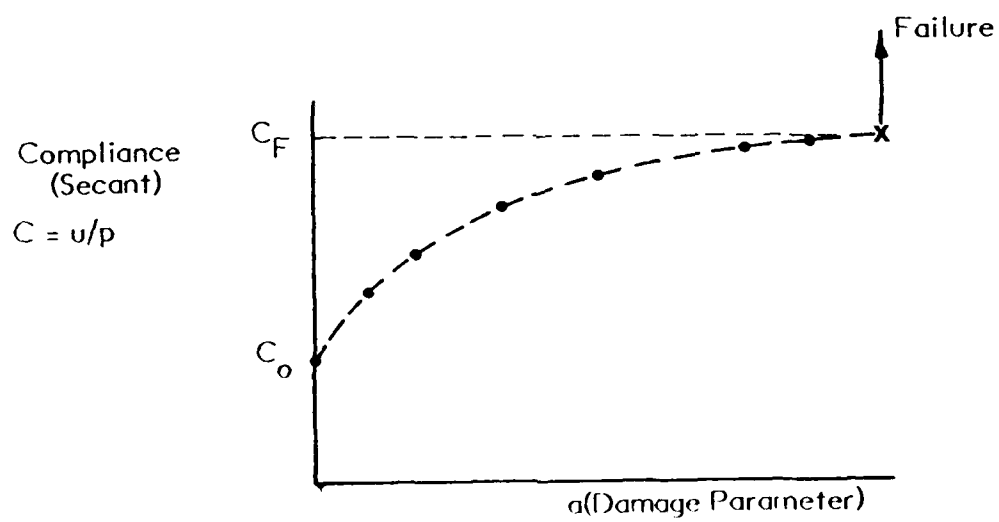
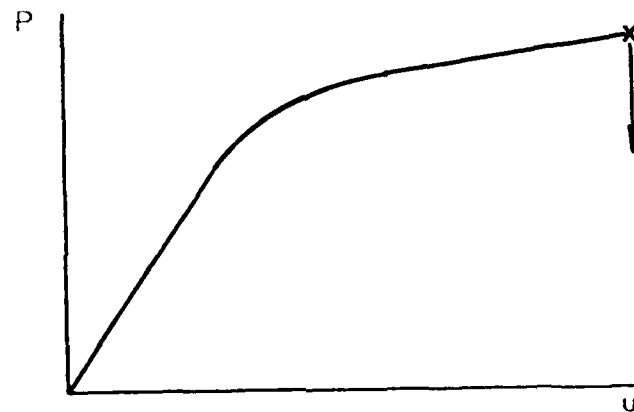


Figure 2

DAMAGE GROWTH LAW

C-a CURVE IS APPROXIMATELY HYPERBOLIC

$$a = a_o \frac{(C - C_o)}{(C_F - C)}$$

$$\text{TOTAL DAMAGE} = a_o + a$$

a_o , CHARACTERIZES INITIAL DAMAGE

a , CHARACTERIZES NEW DAMAGE GROWTH

If the damage growth represents the behavior of the structure, experimental data may be plotted in the particularly convenient manner shown in Figure 3. A linear "Damage Growth Plot" can be constructed. The intercept with the compliance axis corresponds to the failure compliance. The slope of the line is related to the initial damage size and can be used to quantify it.

This approach permits, therefore, failure to be predicted by extrapolation of subcritically obtained data. While this is not a nondestructive test in a strict sense, testing to failure is not required. The ability to quantify the initial damage by test facilitates the establishment of typical values which can be used in damage tolerant design procedures.

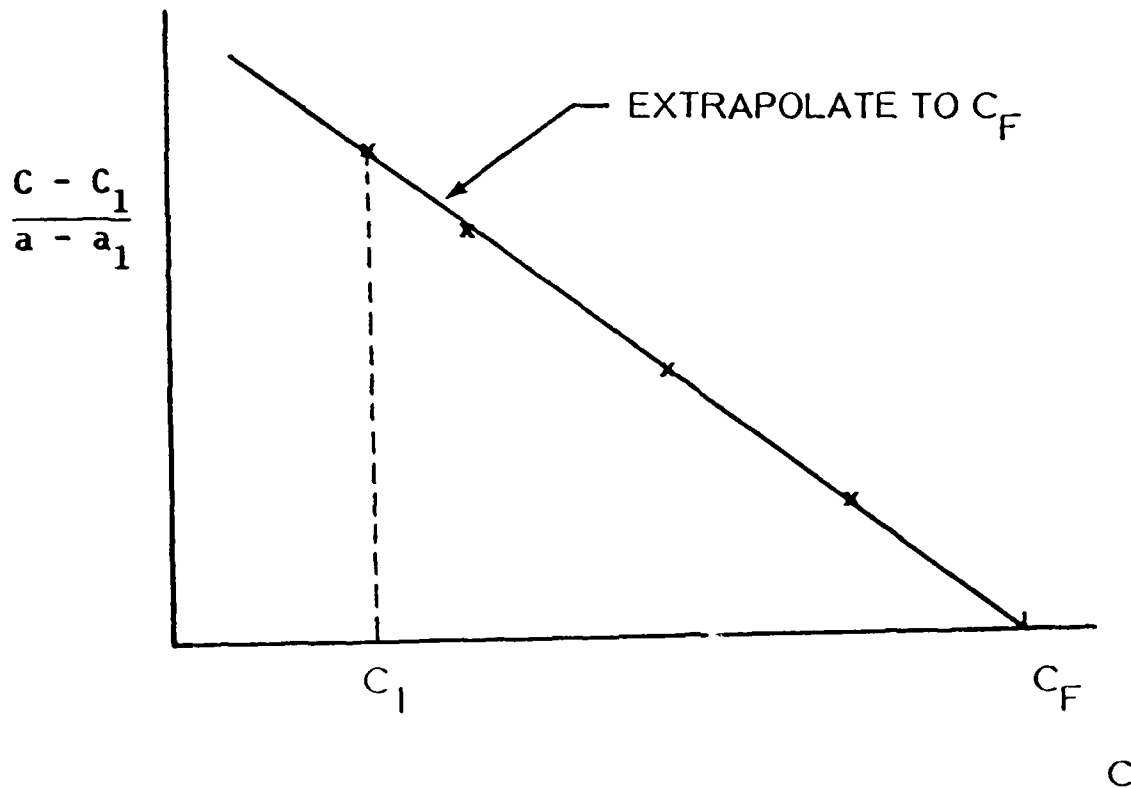
Our methodology was to hypothesize the form of the damage growth law in Figure 2 and to attempt to validate it for a number of generic test bed structures. A total of seven distinct experiments have been conducted on six different configurations. The generic configurations were designed to have a strong delamination damage component. Delamination area was the parameter chosen to characterize the damage. The six specimens are shown in Figures 4-9. A summary of the test results and subcritical data analysis predictions are given in Figure 10.

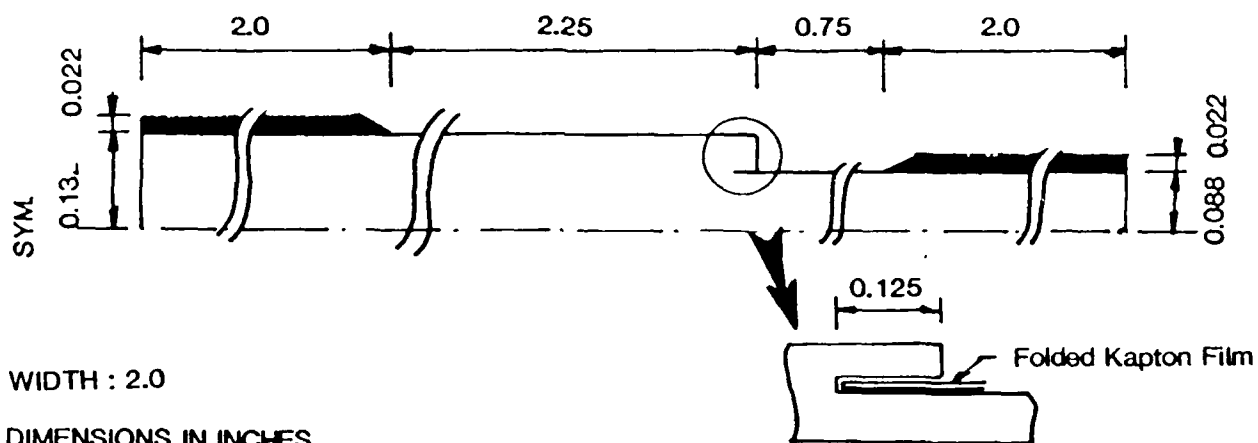
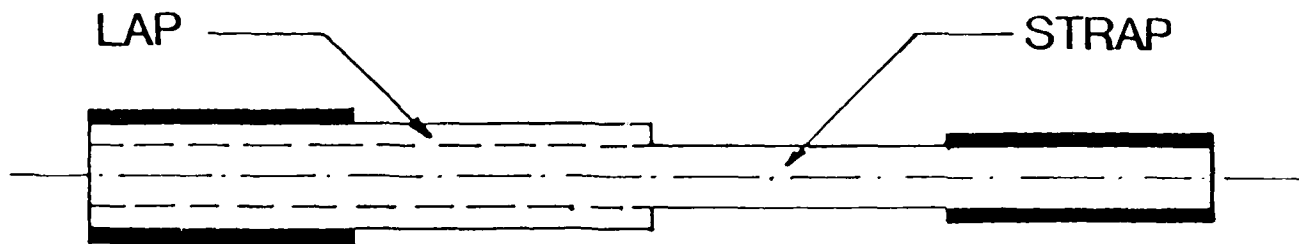
The proposed approach clearly works well for the test bed structures under tensile loading. This establishes a base of favorable experience that justifies pursuing the approach further. Note that the approach is phenomenological in nature. A detailed understanding of micromechanisms and modeling of them is not required.

Figure 3

DAMAGE GROWTH LAW PERMITS
"STIFFNESS PLOT" TO BE USED

$$(C - C_1)/(a - a_1) = [(C_F - C_1)/a_0 C_F](C_F - C)$$





WIDTH : 2.0

DIMENSIONS IN INCHES

LAP : $(-45/45/0/90)_s$

STRAP : $(45/-45/0/90)_s$

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Figure 4

The Double Cracked-lap-shear Specimen

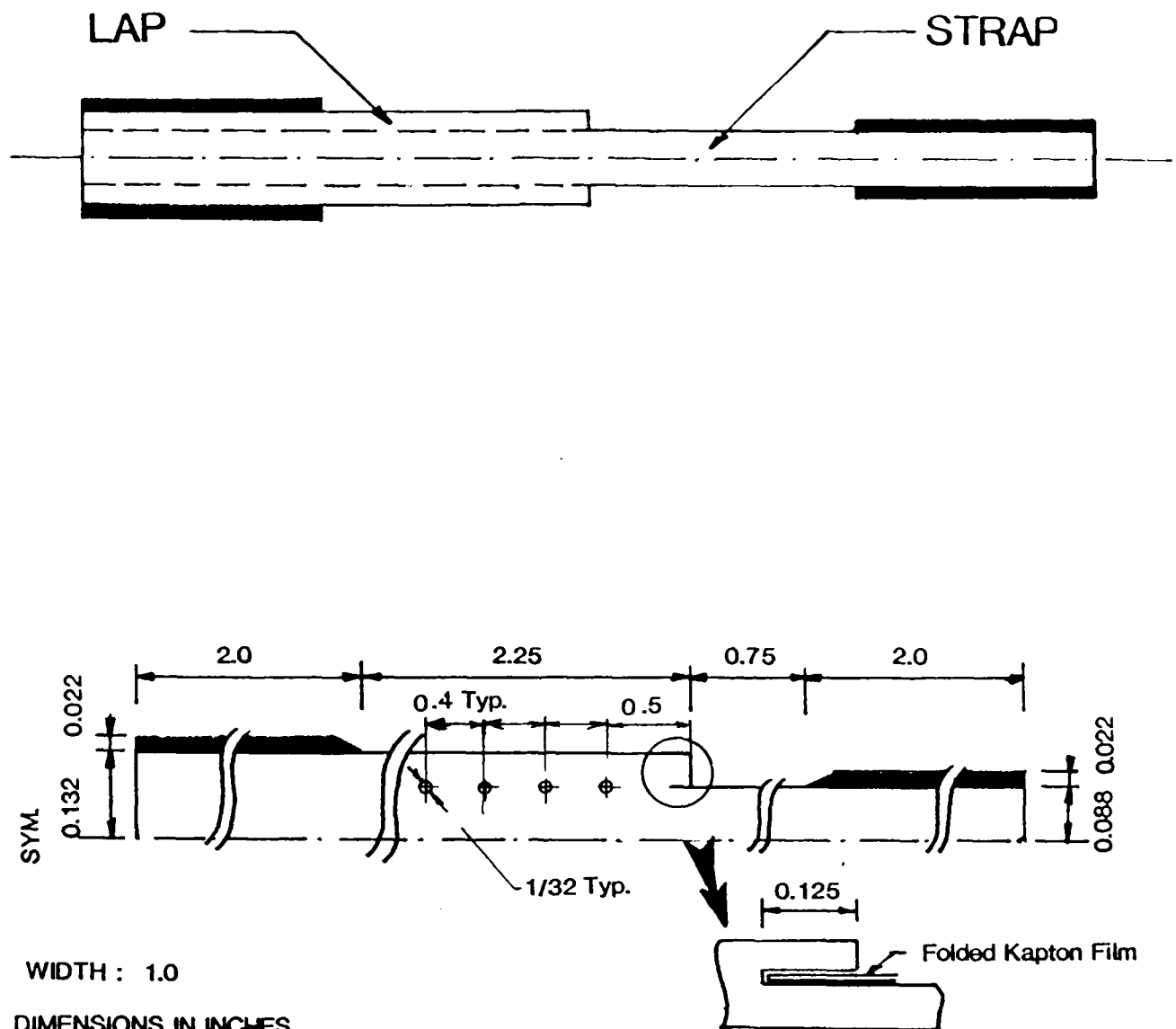
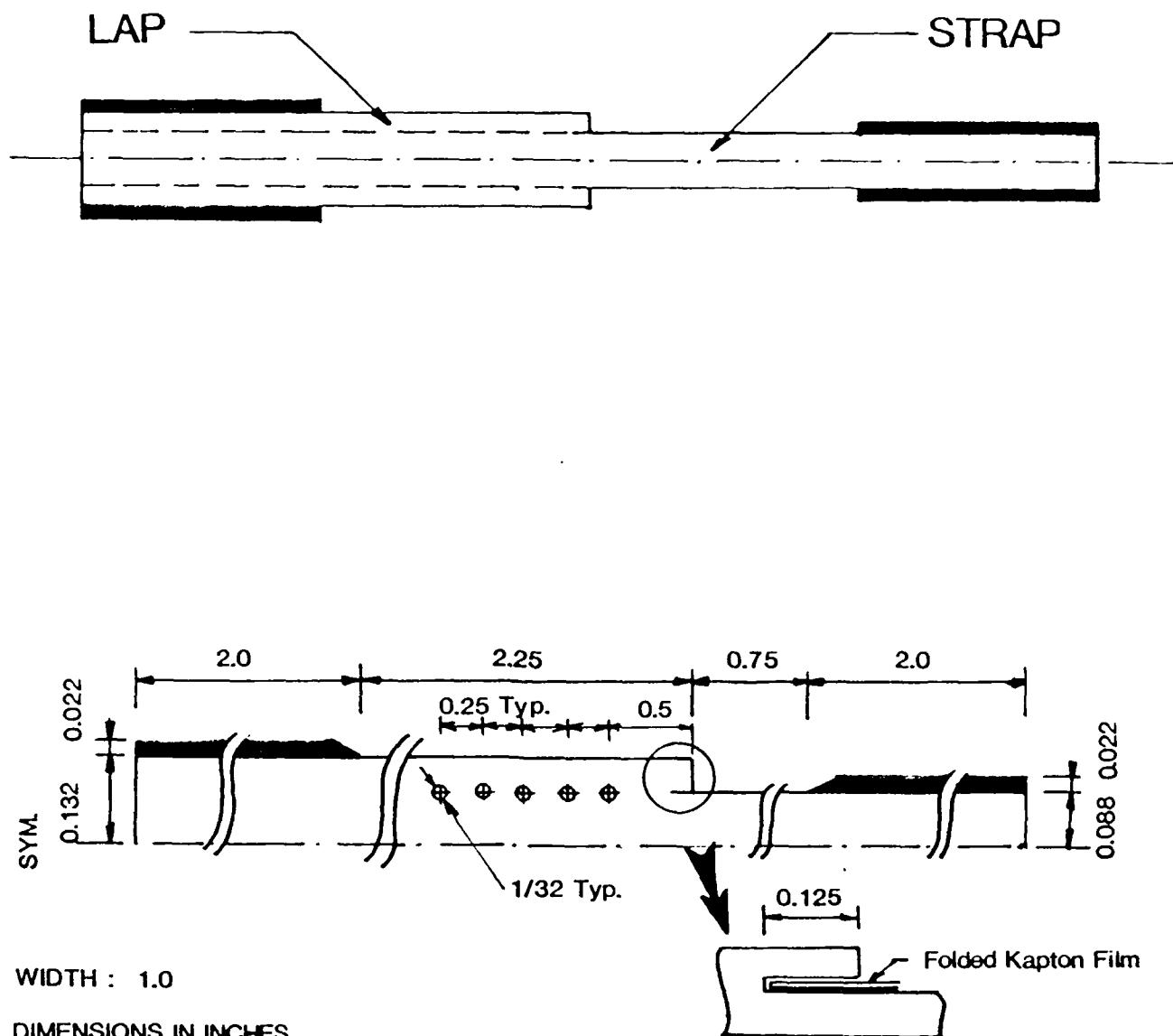


Figure 5

The Double Cracked Lap-shear Specimen
With Internal Ply Damage :
0.4 IN Lateral Hole Spacing, 1/32 IN. DIA.



WIDTH : 1.0

DIMENSIONS IN INCHES

LAP : $(-45/45/0/90)_s$

STRAP : $(45/-45/0/90)_s$

AS4-3501

Figure 6

The Double Cracked-lap-shear Specimen
With Internal Ply Damage :
0.25 IN. Lateral Hole Spacing , 1/32 IN. DIA.

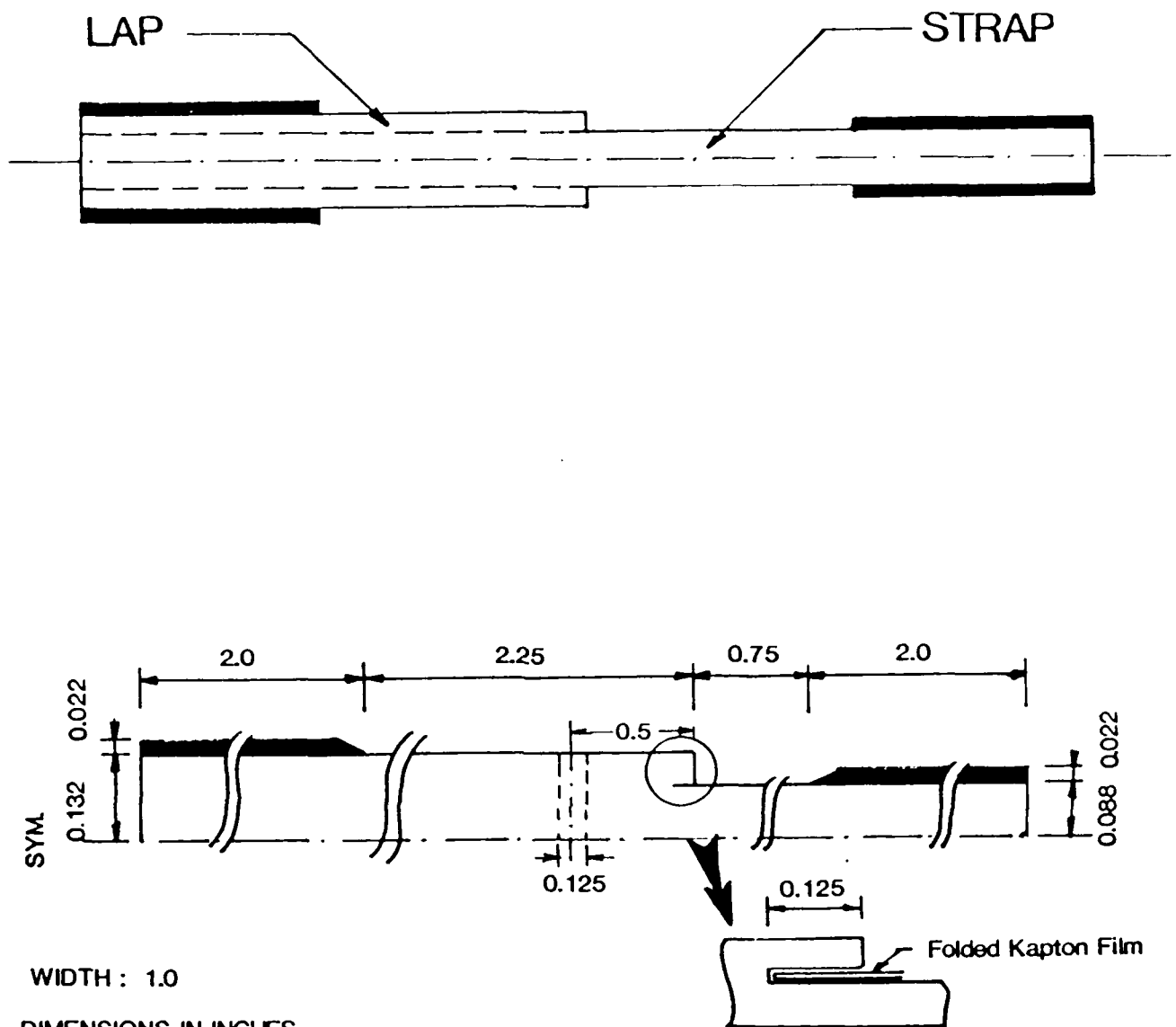
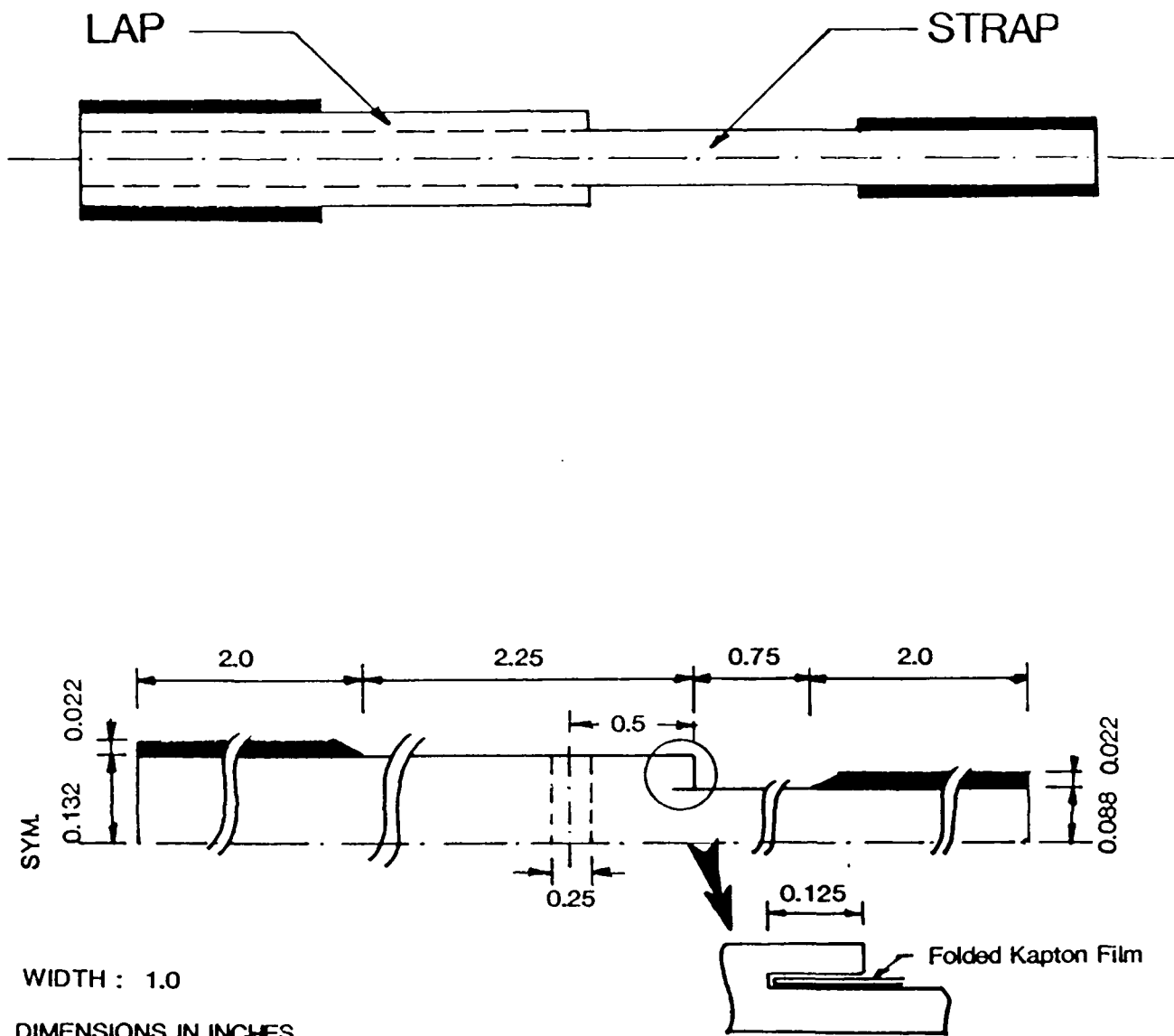


Figure 7
The Double Cracked Lap-shear Specimen
With 1/8 IN. Through Thickness Hole



WIDTH : 1.0

DIMENSIONS IN INCHES

LAP : $(-45/45/0/90)_s$

STRAP : $(45/-45/0/90)_s$

AS4-3501

Figure 8

The Double Cracked Lap-shear Specimen
With 1/4 IN. Through Thickness Hole

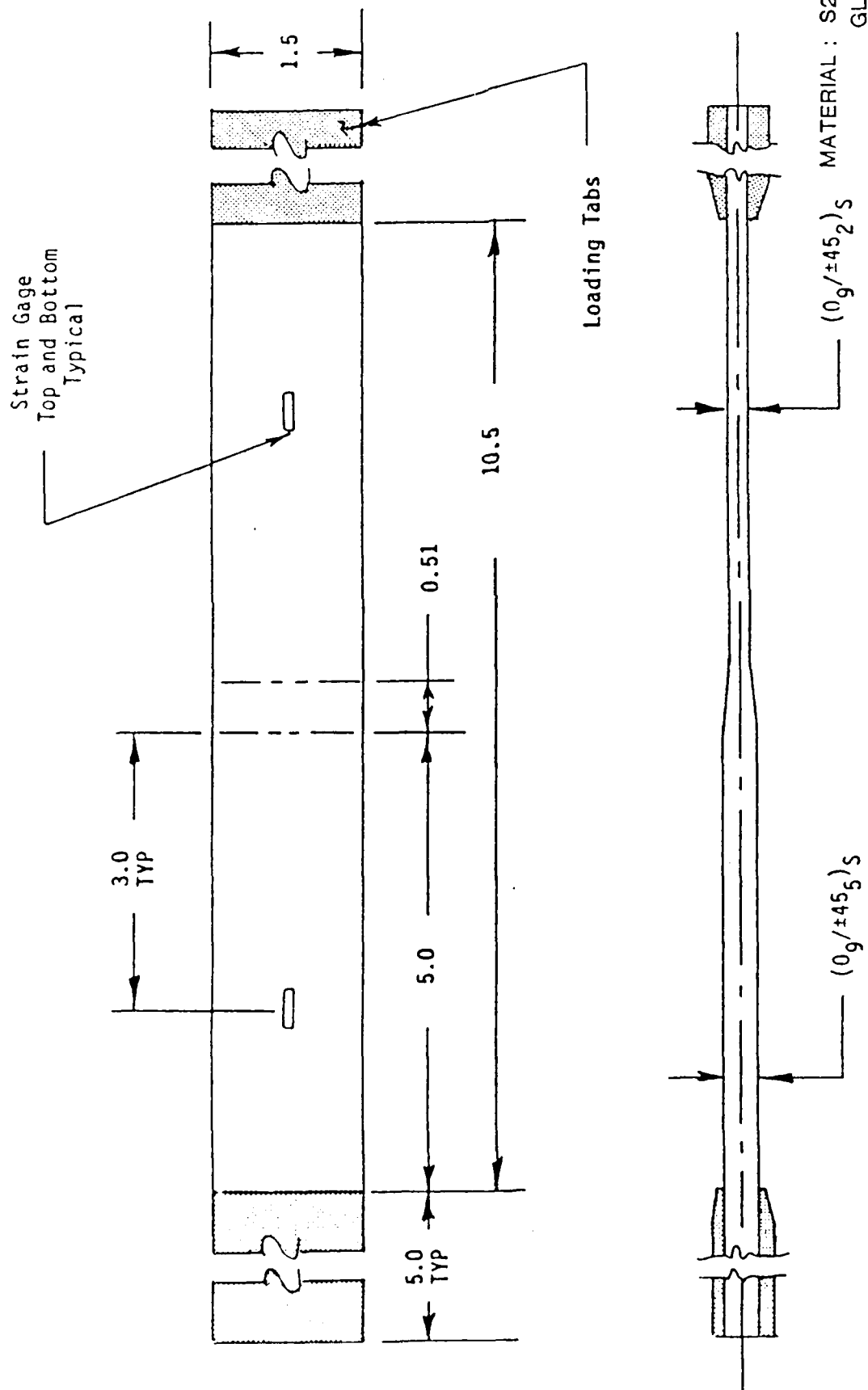


Figure 9

Ply Drop / Taper Specimen

Figure 10

COMPLIANCE FAILURE COMPARISON

SPECIMEN	DESCRIPTION	COMPLIANCE			% DIFFERENCE
		TEST (IN/LB)X10 ⁶	DATA ANALYSIS (IN/LB)X10 ⁶		
0	NO DAMAGE	0.920	0.918		0.2
1	NO DAMAGE	0.681	0.644		5.5
2	LATERAL HOLES	2.424	2.385		1.6
3	LATERAL HOLES	2.597	2.569		1.1
4	THROUGH THICKNESS HOLE	1.925	1.863		3.2
5	THROUGH THICKNESS HOLE	2.000	1.987		0.7
6	TAPER	4.889	4.576		6.4

In a design environment, the designer may establish an allowable strain level. The (secant) compliance at failure and the allowable strain permits a failure load to be predicted.

CONCLUDING REMARKS

In response to the pressing need for a damage tolerance analysis methodology for composite structures, a new framework of a phenomenological type is presented and supported by data from seven experiments. The approach appears promising and further investigation is justified.

APPENDIX II

UNDERSTANDING AND PREDICTING SUBLAMINATE DAMAGE MECHANISMS
IN COMPOSITE STRUCTURES

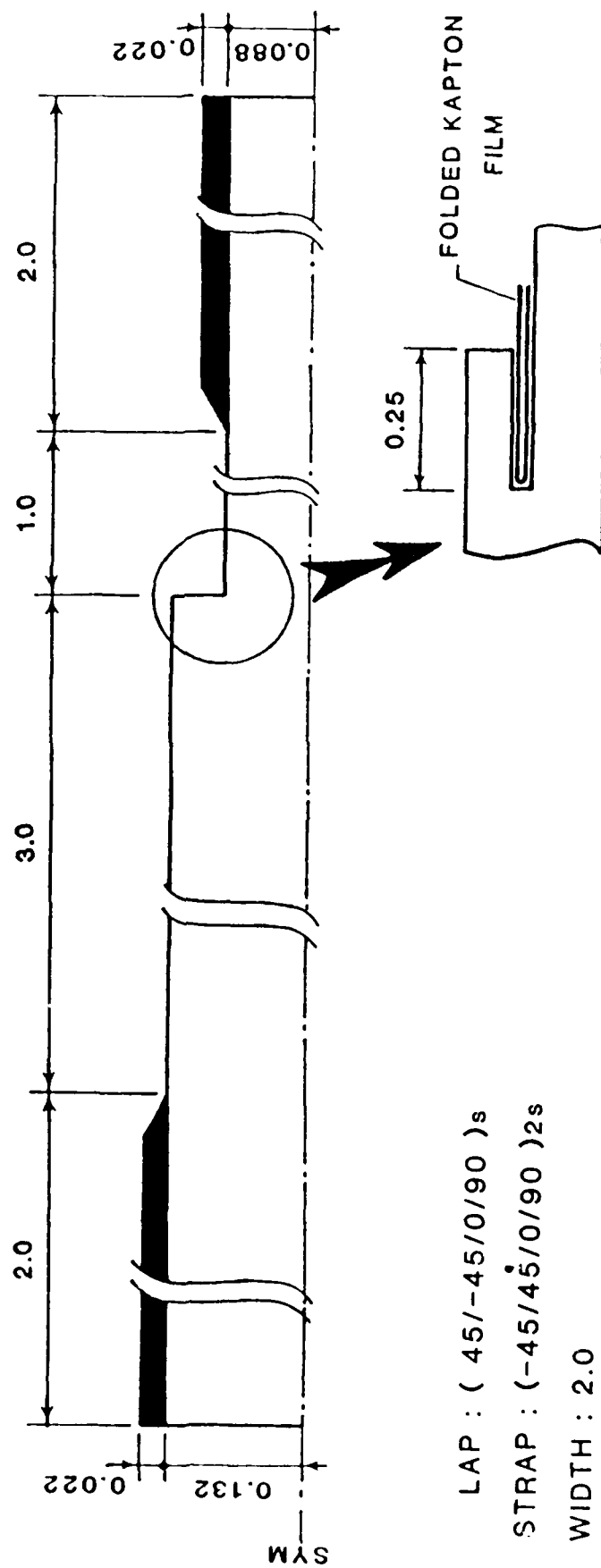
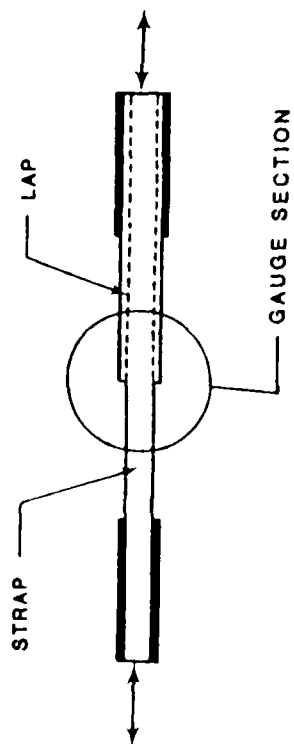
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INTRODUCTION

This work originated from two sources. The first was the desire to create a damage tolerance analysis capability for composite structures --- one that is comparable to its fracture mechanics based counterpart for metallic structures. The second was the paradox posed by some delamination experiments that we performed several years ago. In responding to these inquiries a new conceptual framework for the analysis of damaged laminated composite structures has been created. The method isolates the parameters controlling the initiation and propagation of the damage modes. These include delamination, matrix microcracking and fiber fracture as well as their interaction. Moreover, a rational physical explanation of the observed behavior and quantitative agreement with test results are achieved.

SUMMARY OF EXPERIMENTAL FINDINGS AND EARLY INVESTIGATION

The present research in sublaminar damage mechanisms had its origin in the development of a new design analysis and testing methodology for interlaminar fracture which appear in References 1-3. A double cracked-lap-shear specimen made of AS4/3502 and AS4/3501-6 graphite/epoxy materials was designed and is shown in Fig. 1. The specimen layup is quasi-isotropic, balanced and symmetric with $[+45/0/90]_S$ in the lap portion and



LAP : (45/-45/0/90)s

STRAP : (-45/45/0/90)2s

WIDTH : 2.0

MATERIAL : AS4/3502

FIG. 1

$[\pm 45/0/90]_{4s}$ in the strap portion. The lap interface is at $\pm 45^\circ$ orientation to the loading direction. A fundamental feature of the designed specimen is its ability to be tested under net tensile and compressive loadings. The specimen exhibits mixed-mode or Mode II behavior depending on the loading direction. As a result of the practical configuration selected for the specimen, the test results revealed some new and intriguing phenomena. Under tension loading, delamination is characterized by three stages: an initiation at lower values of the applied load followed by a stable phase where crack growth is only possible under increasing load and a final unstable terminal fracture at higher load values. Under compressive loading no crack growth is observed prior to a single, unstable, catastrophic fracture event which fails the specimen. Also, loads corresponding to failure by unstable fracture under tension and compression testing are nearly the same. The average value of the total energy release rate at initiation is 2.1 in-lb/in^2 and 4.2 in-lb/in^2 at final failure under tensile loading. Under compression the average value corresponding to initiation is 4.6 in-lb/in^2 .

The increasing resistance to crack growth under tensile loading was quite puzzling since the matrix materials are brittle and tests of unidirectional single cracked-lap-shear specimen reported by Russell⁴ and Wilkins⁵ did not show resistance behavior. The single cracked-lap-shear specimen of Reference 4 is made of AS1/3501-6 graphite/epoxy material. The layup is unidirectional with three plies in the lap and strap portions. In Reference 5, the specimens are unidirectional with 4 plies in the

lap and 10 plies in the strap. The material is T300/5208 graphite/epoxy. Our own tests performed on $[\pm 45/0/90]_S$ quasi-isotropic single cracked-lap-shear specimens with 8 plies in the lap and 40 plies in the strap regions show resistance behavior also. These tests confirm that the difference in behavior is not associated with the type of specimen used but rather on the layup.

In order to explain the resistance phenomenon, a systematic approach was utilized. The factors reported earlier to influence delamination behavior such as fiber bridging, fiber breakage, hygrothermal effects and curing stresses were examined to assess their effect in the double cracked-lap shear specimen.

Fiber bridging occurs between plies of similar orientation for specimens exhibiting Mode I behavior. Interfaces separating plies of the same orientation are prone to fiber nesting during fabrication. In this case, delamination resistance is increased as a result of fibers "bridging" between plies. The $\pm 45/-45$ interface at the delamination front in the double cracked-lap-shear specimen prevents fiber nesting. Also, the designed double cracked-lap-shear specimen exhibits a mixed-mode behavior with 68 percent Mode II, and no bridging was observed.

Moisture and curing stress effects can be significant in a laminated composite as the coefficients of thermal and moisture expansions are orientation dependent. However, the balanced and symmetric quasi-isotropic layup used in the designed double cracked-lap-shear specimen tends to minimize these effects

A comparison of the photomicrographs of the fracture surfaces in the stable and unstable regions of the specimen show little or no fiber breakage. However, the fracture surface in the stable growth region is characterized by matrix microcracks. Their presence modifies the local stiffness at the crack front. How important are the effects of these microcracks? Can this effect raise the initiation total energy release rate from 2 to 4 in-lb/in²?

A preliminary answer to these questions can be found from an investigation done on the effects of Mode I suppression³. Test results on double cracked-lap-shear specimens where the opening mode is suppressed through a clamping fixture show an increase in the initiation from 2 to 4 in-lb/in². A striking result is the fact that the clamping force needed to suppress Mode I is one percent of the applied tensile force. This may indicate that although matrix microcracking has a small effect on the overall stiffness of the specimen it may modify the local stiffness resulting in a reduction of the opening mode at the delamination front. This localized stiffness modification can be as effective as the one-percent clamping force.

TOWARD A GENERALIZED ANALYSIS OF DAMAGE MODES

The decision to select a practical configuration in order to investigate the delamination problem provided the opportunity to learn that other damage modes can develop simultaneously. Their interaction can be beneficial if the damage mechanism is understood and controlled.

The damage modes at play here can be expressed in terms of the following:

- (1) Matrix microcracking controlled by the resin controlled transverse strain to failure (ϵ_c);
- (2) Delamination controlled by the fracture toughness (G_c),
and
- (3) Fiber breakage controlled by the fiber strength.

The first two modes interact to produce the resistance behavior observed in the double cracked-lap-shear specimen under tension. As matrix microcracking occurs, the opening and sliding deformations of the delamination front and the matrix stiffness are altered at the local scale. At the global scale, the total energy release and the laminate balance change. The modeling of these phenomena requires the interaction between micro and macro scales. Final failure results when delamination reaches the total length of the lap or when complete fiber breakage occurs.

The quantitative assessment of resistance is based on an engineering intuitive approach. Matrix microcracking is induced by the strain gradient at the crack front. A prerequisite for determining the strain distribution at the crack front is a higher-order theory that includes shear deformation and transverse strain as well. Delamination onset is determined using a fracture mechanics approach based on the total energy release rate and the energy release rate components associated with Mode I (G_I) and Mode II (G_{II}). Mode III (G_{III}) component is negligible in this type of specimen. The interaction between matrix microcracking and delamination is determined from the

loads required to initiate each damage mode separately. This is illustrated in the flow chart of Fig. 2.

At a given value of the applied load, the strain at the delamination front and G_I , G_{II} and G_T are determined from a finite element analysis using EAL (Engineering Analysis Language) code. The element used is the four node constant strain quadrilateral element. A schematic representation of the finite element mesh is shown in Fig. 3. The number of degrees of freedom used is 5490. In order to assess the accuracy of predictions at the delamination front, the axial stress distribution is plotted on a logarithmic scale as shown in Fig. 4. This is a direct method to extract the order of the singularity in the near-field stress distribution. At this stress level the load required to initiate matrix microcracking (P_M) is determined.

The load required for the onset of delamination (P_D) is determined from G_I , G_{II} and G_T using the following law

$$G_{OC} = \xi^n G_{IC} + (1-\xi)^n G_{IIC} \quad (1)$$

where G_{OC} is the strain energy required for the onset of delamination, G_{IC} and G_{IIC} are the fracture toughness associated with Mode I and Mode II, respectively. These are approximately 1 in lb/in² and 4 in lb/in² for AS4/3501-6 graphite/epoxy material. The ratio (G_I/G_T) is denoted by ξ . The exponent n is material dependent⁴. Limited correlation with experimental data indicates that a value of 2 gives satisfactory results for the material used. As a check, the onset of delamination for the designed

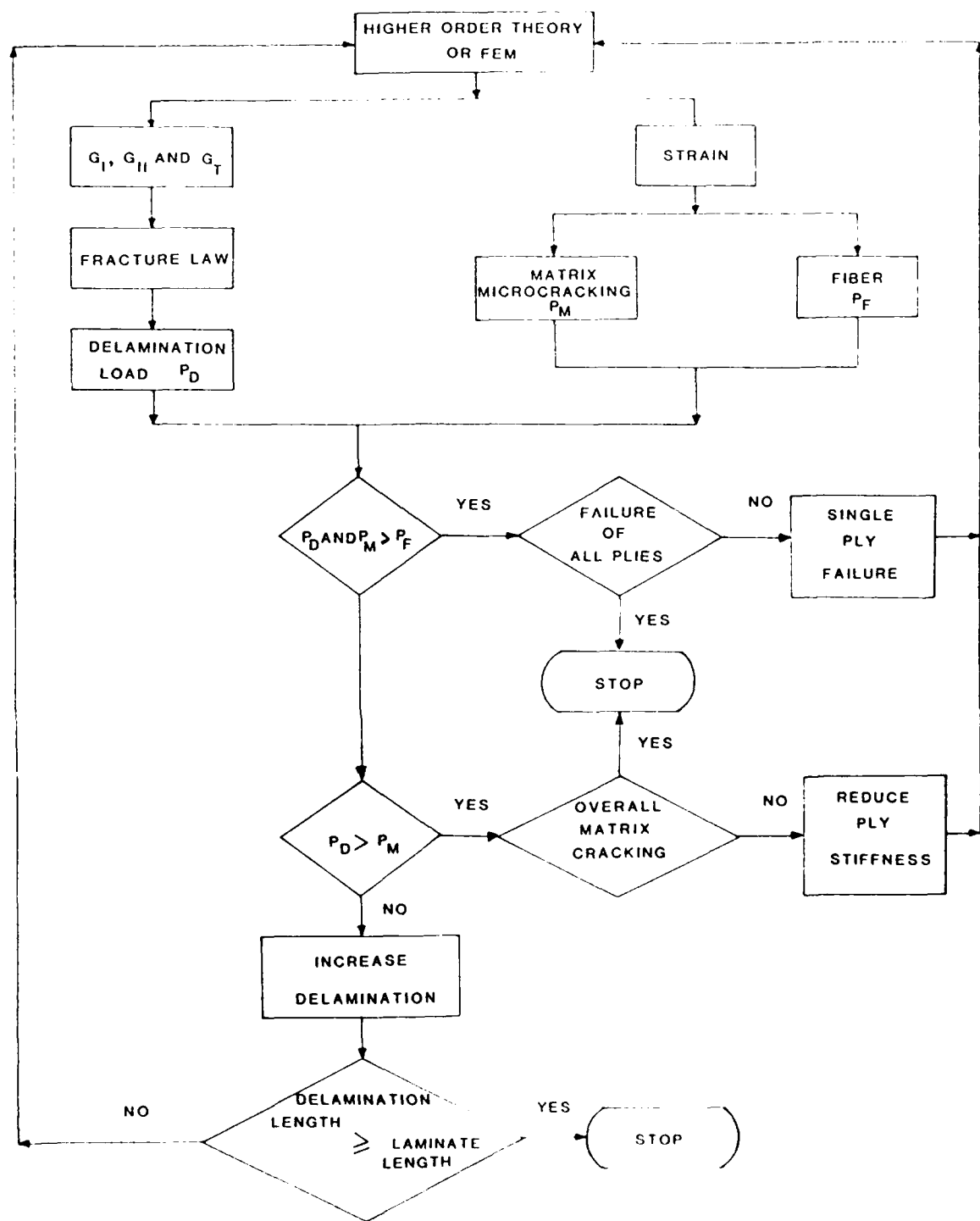
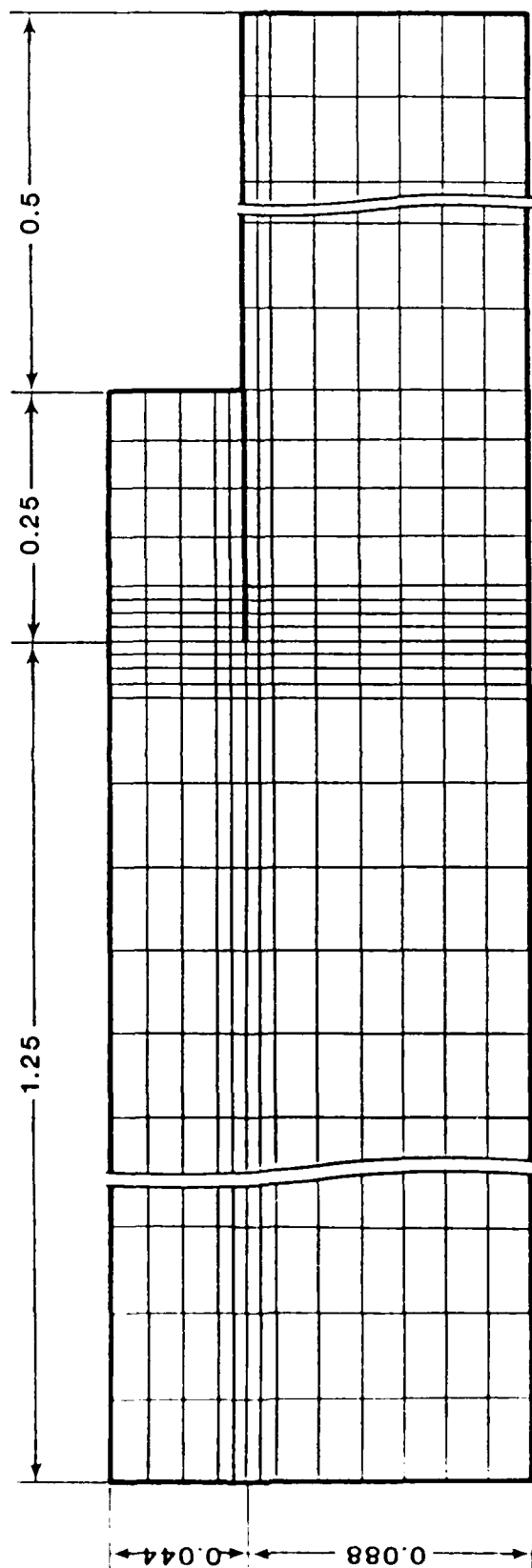


FIG. 2



DIMENSIONS IN INCHES

NDOF : 5490

FIG. 3

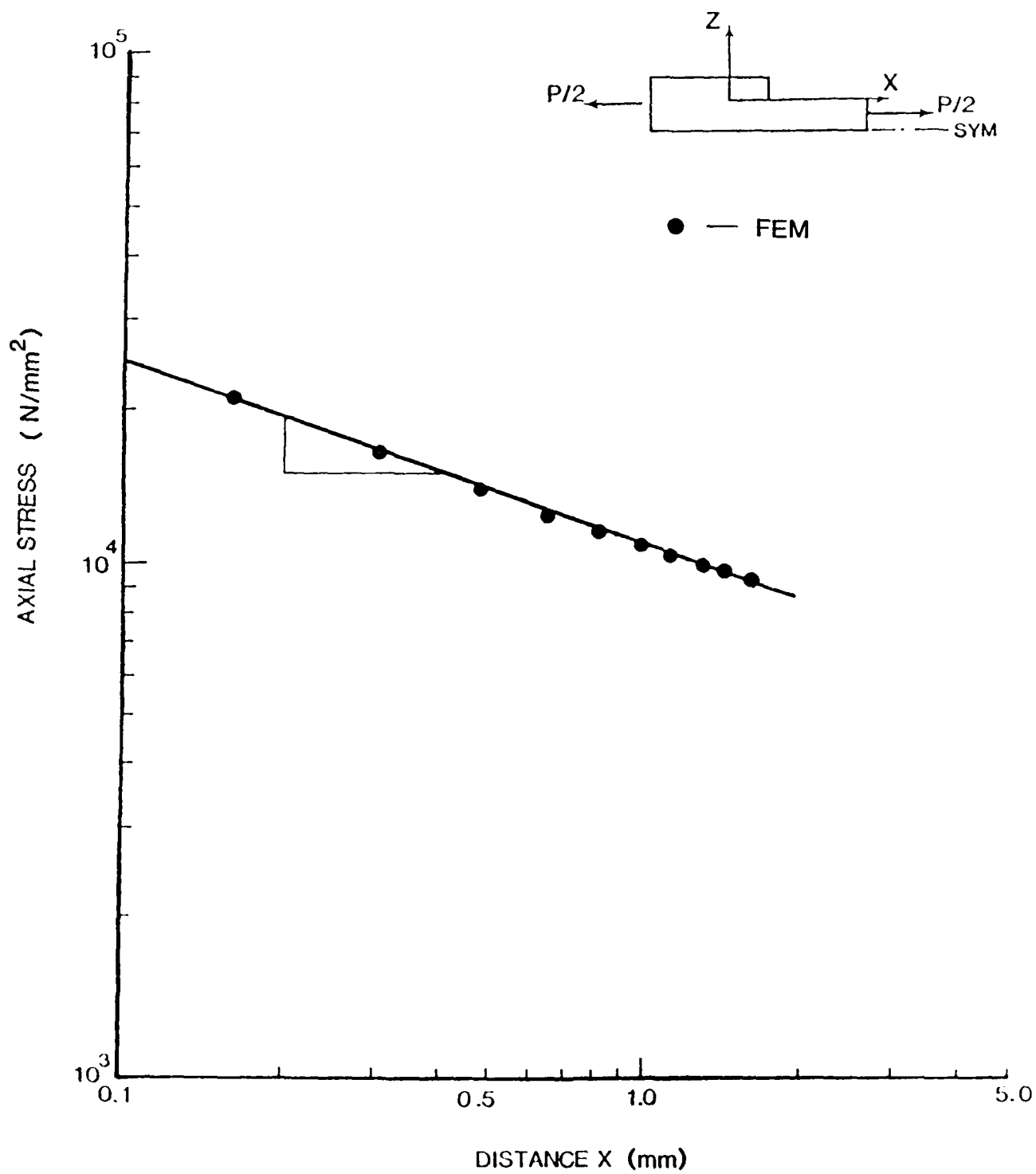


FIG. 4

double cracked-lap-shear specimen (with $G_{II}/G_T = 0.68$), is estimated at 1.95 in lb/in² using equation (1).

The driving damage mode is determined by comparing P_D , P_M and the load corresponding to fiber breakage (P_F). For the designed double cracked-lap-shear specimen under tension loading the driving damage modes are delamination and matrix microcracking. Under compressive loading, delamination is the prevalent damage mode. This situation is depicted in Fig. 5. The load corresponding to a crack extension Δa is denoted by critical load in figure. The solid dots are the analytical predictions. Numbers 1, 2 and 3 correspond to data points from three double cracked-lap-shear specimens generated from the same parent panel.

The numerical values represented by the solid dots in Fig. 4 appear in tabulated form in Fig. 6. A schematic of the prevalent damage modes appear in figure. Delamination is represented by a dashed line while matrix microcracking corresponds to solid semi-circles. Matrix microcracking occurs in the -45° ply in the strap portion at the delamination interface. The 90° plies close to the delamination front exhibit microcracking in the final stages of the resistance curve. A photomicrograph from the lap portion of a failed specimen showing evidence of matrix microcracking appears in Fig. 7. Matrix microcracking occurs at a direction normal to the fiber orientation in the -45° ply. Enhanced x-rays of two failed double cracked-lap-shear specimens tested under tensile and compressive loadings, respectively, indicate the presence of matrix microcracking in the tension specimen while no matrix microcracking appears in the specimen tested under compression.

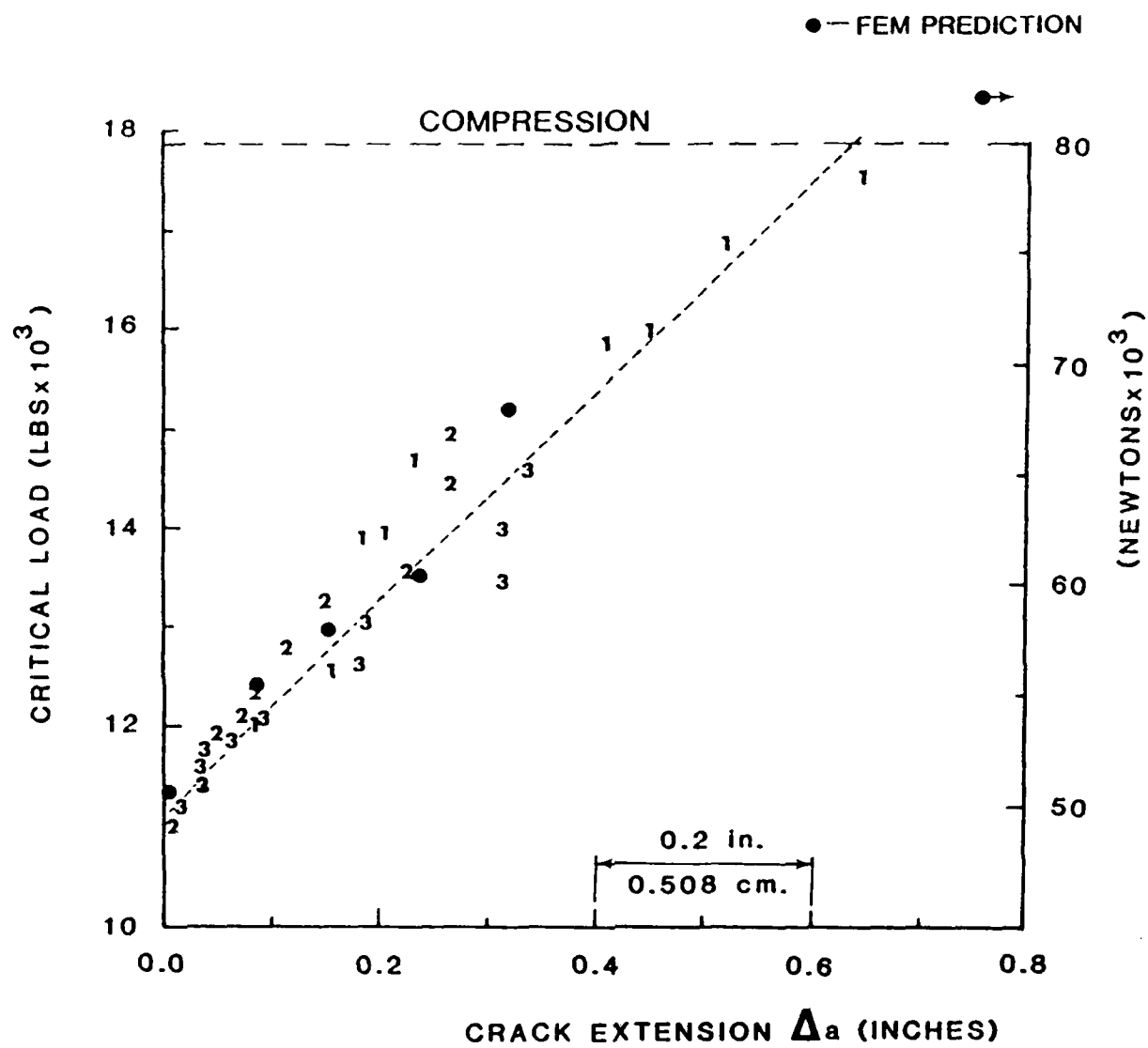
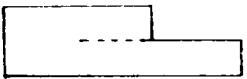
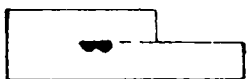
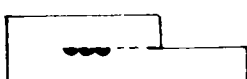
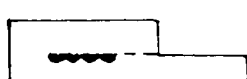
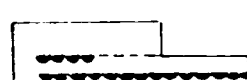
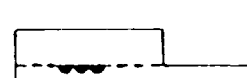


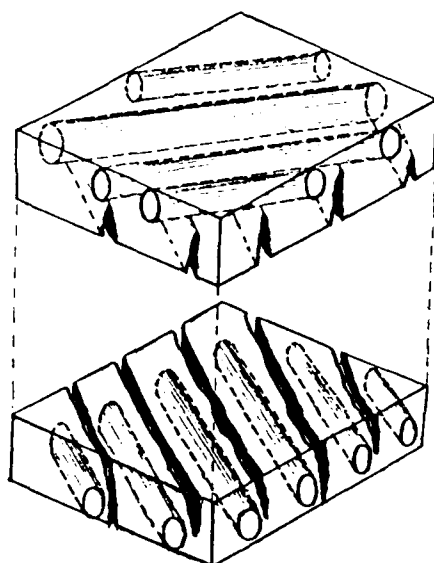
FIG. 5

PREDICTIONS OF DAMAGE GROWTH

LOAD (LBS.)	CRACK LENGTH (INCHES)	% G_{II}/G_T	DAMAGE
11,486	0.44	60	
12,528	0.50	60	
13,020	0.61	60	
13,530	0.67	60	
15,300	0.76	66	
18,301	1.20	85	
18,301	-	-	

 MATRIX CRACKING
 --- DELAMINATION

FIG. 6



MATRIX CRACKING IN THE LAP PORTION
(NORMAL TO FIBERS DIRECTION)



FIG. 7

Under both loading conditions the analysis predicts no fiber breakage. This correlates with the photomicrographs of the failed specimen showing little or no fiber breakage^{1,2}.

CLOSING REMARKS

The decision to select a practical laminate has proved to be necessary to understand toughening mechanisms in real structures. Delamination actually does not occur in isolation---it is accompanied by other damage modes. In the present context the interaction between the damage modes is beneficial as it results in a resistance to delamination growth raising the energy onset value from 2 to 4 in-lb/in².

This finding establishes a new basis for the design of laminated composites---toughening can be designed-in using the interaction of the damage modes that exist in practical structures. The outcome is an efficient damage tolerant structural concept where the micro and macro scale characteristics of a composite are fully utilized. This concept can be extended to other material systems such as metal matrix composites. The prerequisite is a fundamental understanding of the damage modes at play. The framework can be based on the analysis methodology outlined in this work. The final outcome is a control of the damage modes and the use of the composite structure to its full potential.

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