Progressive Damage Analysis of Laminated Composite (PDALC) - (A Computational Model Implemented in the NASA COMET Finite Element Code) Version 2.0

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Abstract

A method for analysis of progressive failure in the Computational Structural Mechanics Testbed is presented in this report. The relationship employed in this analysis describes the matrix crack damage and fiber fracture via kinematics-based volume-averaged damage variables. Damage accumulation during monotonic and cyclic loads is predicted by damage evolution laws for tensile load conditions. The implementation of this damage model required the development of two testbed processors. While this report concentrates on the theory and usage of these processors, a complete listing of all testbed processors and inputs that are required for this analysis are included. Sample calculations for laminates subjected to monotonic and cyclic loads were performed to illustrate the damage accumulation, stress redistribution, and changes to the global response that occurs during the loading history. Residual strength predictions made with this information compared favorably with experimental measurements.

Introduction

Laminated composite structures are susceptible to the development of microcracks during their operational lives. While these microcracks tend to aggregate in high stress regions and result in localized regions of reduced stiffness and strength, the microcracks can affect the global response of the structure. This change in the global structure in turn can create high stresses and increase damage accumulation in another part of the structure. Thus to accurately predict the structural response and residual strength of a laminated composite structure, the effects of the accumulating damage must be incorporated into the global analysis. The approach taken is to develop damage-dependent constitutive equations at the ply level. These equations are then employed in the development of the lamination equations from which the constitutive module of the structural analysis algorithm is constructed. This algorithm is executed in a stepwise manner in which the damage-dependent ply-level results are used in the calculation of the global response for the next load step. This report will describe two Computational Structural Mechanics (CSM) Testbed (COMET) processors that were developed for the performance of such an analysis. A brief review of the theory behind the processors is first presented. The usage of these processors is then demonstrated. Since this analysis requires the use of other COMET processors, this report serves as a supplement to the Computational Structural Mechanics Testbed User's Manual (ref. 1).

It should be noted that the current damage model capability, computer code version 1.1, is limited to matrix cracking and fiber fracture under tensile loads.

Symbols and Abbreviations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>laminate extensional stiffness matrix</td>
</tr>
<tr>
<td>B</td>
<td>laminate coupling stiffness matrix</td>
</tr>
<tr>
<td>β</td>
<td>mode I matrix cracking scale factor</td>
</tr>
<tr>
<td>D</td>
<td>laminate bending stiffness matrix</td>
</tr>
<tr>
<td>dpara</td>
<td>material parameter determined from experimental data</td>
</tr>
<tr>
<td>E11</td>
<td>lamina longitudinal modulus</td>
</tr>
<tr>
<td>E22</td>
<td>lamina transverse modulus</td>
</tr>
<tr>
<td>F</td>
<td>applied force</td>
</tr>
<tr>
<td>G12</td>
<td>lamina shear modulus</td>
</tr>
<tr>
<td>γ</td>
<td>tensile fiber fracture scale factor</td>
</tr>
<tr>
<td>k</td>
<td>material parameter determined from experimental data</td>
</tr>
<tr>
<td>Nx</td>
<td>applied load</td>
</tr>
<tr>
<td>n</td>
<td>material parameter determined from experimental data</td>
</tr>
<tr>
<td>PDALC</td>
<td>Progressive Damage Analysis of Laminated Composites</td>
</tr>
<tr>
<td>R</td>
<td>percent of maximum load</td>
</tr>
<tr>
<td>σ11</td>
<td>lamina longitudinal critical stress</td>
</tr>
<tr>
<td>σ12</td>
<td>lamina shear critical stress</td>
</tr>
<tr>
<td>σ22</td>
<td>lamina transverse critical stress</td>
</tr>
<tr>
<td>ψ</td>
<td>mode II matrix cracking scale factor</td>
</tr>
<tr>
<td>tply</td>
<td>ply thickness</td>
</tr>
<tr>
<td>u</td>
<td>longitudinal extension</td>
</tr>
<tr>
<td>w, v, w</td>
<td>undamaged midplane displacements</td>
</tr>
<tr>
<td>x, y, z</td>
<td>displacement fields</td>
</tr>
<tr>
<td>v12</td>
<td>lamina Poisson's ratio</td>
</tr>
</tbody>
</table>
Damage-Dependent Constitutive Relationship

The damage-dependent constitutive relationship employed in the COMET analysis is based on a continuum damage mechanics model proposed by Allen, Harris, and Groves (refs. 2 and 3). Rather than explicitly modeling each matrix crack in the material, the averaged kinematic effects of the matrix cracks in a representative volume are modeled by internal state variables. These internal state variables for matrix cracks are defined by the volume-averaged dyadic product of the crack face displacement, \( u_i \), and the crack face normal, \( n_j \), as proposed by Vakulenko and Kachanov (ref. 4):

\[
\alpha_{ij}^M = \frac{1}{V_L} \int u_i n_j \, ds, \quad (1)
\]

where \( \alpha_{ij}^M \) is the second order tensor of internal state variables, \( V_L \) is the local representative volume in the deformed state, and \( S \) is the crack surface area. This product can be interpreted as additional strains incurred by the material as a result of the internal damage. From micromechanics it has been found that the effects of the matrix cracks can be introduced into the ply-level constitutive equation as follows (ref. 5):

\[
\sigma_L = [Q] (\varepsilon_L - \alpha_L^M), \quad (2)
\]

where \( \sigma_L \) are the locally averaged components of stress, \([Q]\) is the stiffness matrix in ply coordinates, and \( \{\varepsilon_L\} \) are the locally averaged components of strain. The laminate constitutive relationships are obtained by integrating the ply constitutive equations through the thickness of the laminate to produce

\[
\begin{align*}
\{N\} &= [A] \{\varepsilon_L^0\} + [B] \{\kappa_L\} + \{f_L^M\}, \quad (3) \\
\{M\} &= [B] \{\varepsilon_L^0\} + [D] \{\kappa_L\} + \{g_L^M\}, \quad (4)
\end{align*}
\]

where \( \{N\} \) and \( \{M\} \) are the resultant force and moment vectors, respectively; \([A], [B], \) and \([D]\) are the well known laminate extensional, coupling, and bending stiffness matrices, respectively (ref. 6); \( \{\varepsilon_L^0\} \) is the midplane strain vector; and \( \{\kappa_L\} \) is the midplane curvature vector; \( \{f_L^M\} \) and \( \{g_L^M\} \) are the damage resultant force and moment vectors for matrix cracking, respectively (ref. 7). The application of \( \{f_L^M\} \) and \( \{g_L^M\} \) to the undamaged material will produce midplane strain and curvature contributions equivalent to those resulting from the damage-induced compliance increase.

As the matrix cracks accumulate in the composite, the corresponding internal state variables must evolve to reflect the new damage state. The rate of change of these internal state variables is governed by the damage evolutionary relationships. The damage state at any point in the loading history is thus determined by integrating the damage evolutionary laws. Based on the observation that the accumulation of matrix cracks during cyclic loading is related to the strain energy release rate \( G \) in a power law manner (ref. 8), Lo et al. (ref. 9) have proposed the following evolutionary relationship for the internal state variable corresponding to mode I (opening mode) matrix cracks:

\[
d\alpha_{L_{12}}^M = \frac{d\alpha_{L_{12}}^M}{dS} = k G^n dN, \quad (5)
\]

The term \( d\alpha_{L_{12}}^M \) reflects the changes in the internal state variable with respect to changes in the crack surfaces. This term can be calculated analytically from a relationship that describes the average crack surface displacements in the pure opening mode (mode I) for a medium containing alternating 0° and 90° plies (ref. 5). The term \( G \) is the strain energy release rate calculated from the ply-level damage-dependent stresses. The material parameters, \( \tilde{k} \) and \( \tilde{n} \), are phenomenological in nature and must be determined from experimental data (refs. 10 and 11). Because \( \tilde{k} \) and \( \tilde{n} \) are assumed to be material parameters, the values determined from one laminate stacking sequence should be valid for other laminates as well. Since the interactions with the adjacent plies and damage sites are implicitly reflected in the calculation of the ply-level response through the laminate averaging process, equation 5 is not restricted to any particular laminate stacking sequence.

When the material is subjected to quasi-static (monotonic) loads, the incremental change of the internal state variable is assumed to be

\[
d\alpha_{kl}^M = \begin{cases} 
   f(\varepsilon_L, \beta, \gamma, \psi) & \text{if } \varepsilon_L > \varepsilon_{kl_{\text{low}}}; \\
   0 & \text{if } \varepsilon_L < \varepsilon_{kl_{\text{low}}} 
\end{cases} \quad (6)
\]
where $\varepsilon_{\text{k}c_{\text{crit}}}$ is the critical tensile failure strain and $\beta, \gamma, \text{and } \psi$ are scale factors that describe the load carrying capability of the material after the occurrence of mode I (opening mode) matrix cracking, fiber fracture, and mode II (shear mode) matrix cracking, respectively. The physical interpretation of equation (2) is as follows: as long as the strains in a material element (local volume element or finite element) are less than the critical strains, $\varepsilon_{\text{k}c_{\text{crit}}}$, no damage exists and the internal state variables have a zero value. When the strains reach their critical value, the element is damaged and this damage is represented by an internal state variable whose value is proportional to the local strain. The proportionality is dependent on the scale factors $\beta, \gamma, \text{and } \psi$. Currently, the scale factors are chosen such that when fiber fracture, mode II matrix cracking, or mode I matrix cracking occur in a ply within an element, the longitudinal, shear, and transverse stresses for that ply in that element are

$$
\sigma_{11} = \gamma \sigma_{11}^{c} \\
\sigma_{12} = \psi \sigma_{12}^{c} \\
\sigma_{22} = \beta \sigma_{22}^{c},
$$

(7) (8) (9)

where $\sigma_{11}^{c}, \sigma_{12}^{c}, \text{and } \sigma_{22}^{c}$ are the lamina longitudinal, shear, and transverse critical stresses, respectively.

**Structural Analysis Formulation**

In order to simplify the formulation, it is expedient to consider the special case of symmetric laminates. With this assumption, the coupling stiffness matrix, $[B]$, becomes the null matrix and the in-plane and out-of-plane laminate equations are decoupled. The laminate equations (3) and (4) are then substituted into the plate equilibrium equations to yield the following governing differential equations for the plate deformations:

$$
-p_x = A_{11} \frac{\partial^2 u}{\partial x^2} + 2A_{16} \frac{\partial^2 u}{\partial x \partial y} + A_{66} \frac{\partial^2 u}{\partial y^2} \\
+ A_{16} \frac{\partial^2 v}{\partial x^2} + (A_{12} + A_{66}) \frac{\partial^2 v}{\partial x \partial y} \\
+ A_{26} \frac{\partial^2 v}{\partial y^2} + \frac{\partial f_{1}^{M}}{\partial x} + \frac{\partial f_{2}^{M}}{\partial y}
$$

(10)

-$$p_z = A_{16} \frac{\partial^2 u}{\partial x^2} + (A_{12} + A_{66}) \frac{\partial^2 u}{\partial x \partial y} + A_{26} \frac{\partial^2 u}{\partial y^2} \\
+ A_{22} \frac{\partial^2 v}{\partial y^2} + 2A_{26} \frac{\partial^2 v}{\partial x \partial y} + A_{66} \frac{\partial^2 v}{\partial x^2} \\
+ \frac{\partial f_{3}^{M}}{\partial x} + \frac{\partial f_{4}^{M}}{\partial y}.
$$

(11)

These governing differential equations are integrated against variations in the displacement components to produce a weak form of the damage dependent laminated plate equilibrium equations. By substituting the corresponding displacement interpolation functions into the weak form of the plate equilibrium equations, the following equilibrium equations in matrix form are produced (ref. 12 and 13)

$$
[K] \{\delta\} = \{FA\} + \{FM\}
$$

(13)

where $[K]$ is the element stiffness matrix, $\{\delta\}$ is the displacement vector, $\{FA\}$ is the applied force vector, and $\{FM\}$ is the damage-induced force vector resulting from matrix cracking. Note that the effects of the internal damage now appear on the right hand side of the equilibrium equations as damage-induced force vectors.

**Structural Analysis Scheme**

The progression of damage is predicted by an iterative and incremental procedure outlined in the flow chart shown in figure 1. The first block of figure 1 is a description of the finite element model. Block numbers are shown in the right hand corner of each box in the flowchart. Blocks 2 and 3 are processors that calculate the element stiffness matrices and assemble and factor the global stiffness matrix. The compliance changes due to damage are accounted for by combining the damage induced force vector with the applied force vector and solving for the global displacements in equation (6). This solution process occurs in block 4 and 5 and then the element stress resultants are computed in block 6.
The ply-level strains and stresses are computed in block 7 and as long as the strains in a material element (local volume element or finite element) are less than the critical strains, \( E_{k\text{crit}} \), no damage exists and the internal state variables have zero values. When the strains reach their critical value, the element is damaged and this damage is represented by an internal state variable. The damage state is updated and the ply-level stresses and strains are post-processed in block 8. The analysis iterates over blocks 4 through 8 until equilibrium is established, and then the next load step is applied.

The implementation of this analysis into the COMET code can be accomplished with the development of processors DRF and DGI. These processors, as with other COMET processors, are semi-independent computational modules that perform a specific set of tasks. Processor DRF first calculates the damage resultant forces and moments and then incorporates them into the global force vectors. The second processor, DGI, post-processes the elemental stress resultants into ply level stresses and strains using the damage dependent constitutive relationship. With this information, the processor computes the damage evolution and updates the damage state for the next series of calculations. The remaining calculations can be performed with existing COMET processors. The following is a listing in order of COMET processor executions for this analysis:

1. Procedure ES defines element parameters.
2. Processor TAB defines joint locations, constraints, reference frames.
3. Processor AUS builds tables of material and section properties and applied forces.
4. Processor LAU forms constitutive matrix.
5. Processor ELD defines elements.
9. Processor RSEQ resequences nodes for minimum total execution time.
10. Processor TOPO forms maps to guide assembly and factorization of system matrices.
11. Processor K assembles system stiffness matrix.
12. Processor INV factors system stiffness matrix.
13. Continue
14. Processor DRF forms damage resultant force vectors.
15. Processor SSOL solves for static displacements.
17. Processor DGI calculates ply level stresses and damage evolution.
18. For next load cycle, go to step 13; else stop.

The usage and theory behind each of the existing processors can be found in The Computational Structural Mechanics Testbed User's Manual (ref. 1). The processors DRF and DGI are described in Appendices A and B of this report, respectively. With the exception of processor DRF and DGI, other processors from the COMET processor library can be substituted into the listing above to perform the tasks specified.

Example Calculations

Example calculations were conducted using COMET to illustrate the features of the progressive damage code. The first example demonstrates the effects of the evolving matrix damage on a crossply laminated composite plate subjected to constant amplitude fatigue loads. The dimensions and boundary conditions for the laminated plate are shown in figure 2. This plate was discretized into 24 four-node quadrilateral EX47 shell elements (ref. 14). In this example, the plate has a \([0/90]_4\) laminate stacking sequence and the ply-level mechanical properties are listed in table 1. These properties corresponded to those measured for IM7/5260 (ref. 11). A maximum load of 2500 lb/in at an R-ratio of 0.1 was applied to the laminate. The COMET runstream and input, as well as a segment of the output, for this example can be found in the section entitled "Progressive Failure Analysis Input" of Appendix B.

The predicted distribution of the mode I matrix crack damage \( M \alpha_{22} \) in the 90° plies is shown in figure 3. The damage was greatest at the narrow end of the plate since the component of stress normal to the fiber was highest in this region. The higher stresses further translated to a greater amount of energy available for the initiation and propagation of additional damage. This was reflected in the damage evolution along the length of the plate. However as damage accumulated in the plate, the stress gradient in the 90° plies became less steep as shown in figure 4. The similarity in stress resulted in relatively uniform changes to the damage state at the higher load cycles. For this laminate stacking sequence, the load shed by the damaged 90° plies was absorbed by the 0° plies. The consequence of this load redistribution is an increase in the global displacements as illustrated in figure 5. The redistribution of load to the adjacent plies will affect the interlaminar shear stresses as well. This could create favorable conditions for the propagation of delamination.
The second example examines the effects of damage accumulation during cyclic fatigue loads on the stiffness of notched laminates. In this example, the notched laminates are tension fatigue loaded for 100,000 cycles. The notched (central circular hole) laminate was shown in figure 6. Symmetry was assumed about the length and width of the laminate so that only a quarter of the laminate was modeled by the finite element model. This model, also shown in figure 6, consisted of 320 four-node quadrilateral EX47 shell elements. Two laminate stacking sequences, a cross-ply $[0/90]$, and a quasi-isotropic $[0/\pm 45/90]$, were considered. These laminates possessed the same ply-level material properties as the first example. (See table 1.) The maximum fatigue loads employed in sample calculations are listed in table 2. The COMET runstream for the fatigue loading is similar to the previous example which is listed in Appendix B. In figure 7, the predicted stiffness loss for the open-hole geometry is compared to experimentally measured values of stiffness loss measured over a 4-in. gage length, symmetric about the open hole.

The final example considers the effects of monotonically increasing loads on the residual strength of AS4/938, AS4/8553-40, and AS4/3501-6 notched laminates (ref. 15). The notched laminate shown in figure 8 is considered in this example. Symmetry was assumed about the length and width of the laminate so that only a quarter of the laminate was modeled by the finite element model. The four inch wide panels with one inch notches had a mesh (figure 8) that consisted of 278 four node quadrilateral EX47 shell elements. All of the elements on the x=0 centerline from the notch-tip to the edge of the panel were the same size for the 4, 12, and 36 inch wide panels. The laminate stacking sequence was orthotropic $[\pm 45/0/90/\pm 30/0]$. These laminates possessed the ply-level material properties shown in table 3 (ref. 16 and 17). The applied load is incrementally increased with each load step to simulate a ramp up load input. Failure of the component is assumed to have occurred when the elements that span the width of the laminate have sustained a level of fiber fracture such that the analysis cannot reach equilibrium within a given load step. The load at which this condition exists is used to calculate the residual strength. The COMET runstream for this example is listed in Appendix C. The predicted residual strengths are shown along with experimental measurements in figure 9.

The load redistribution due to damage progression is simulated using monotonic damage growth parameters ($\beta$, $\psi$, and $\gamma$). These parameters can be complicated algebraic functions describing the complex behavior of load redistribution due to matrix cracking and fiber fracture. However, for the purpose of developing the framework for this progressive damage methodology, simple constants were chosen for the parameters. So for this analysis, the damage growth law parameters govern the load redistribution in a way that is similar to the ply discount method. It is not reasonable to assume a 100% load redistribution at the instant of failure for mode I matrix cracking and tensile fiber fracture. Therefore, a 90% load redistribution was assumed, i.e. the local ply stress is only 10% of the critical ply strength ($\beta = 0.1$ and $\gamma = 0.1$). As the applied load increases, mode I matrix cracking and tensile fiber fracture internal state variables increase in proportion to the local strains. This results in a constant stress level (10% of the critical ply strength) in the damaged plies, illustrated in figure 10, with the load redistributing to the surrounding plies and elements.

Based on Losipescu shear data (ref. 18) there is a shear strain ($\gamma_{12}$) where the behavior is no longer linear and becomes almost perfectly plastic. At this strain level, $\psi$ is equal to 1.0 to simulate elastic-perfectly plastic shear stress/strain behavior as illustrated in figure 10. This implies that as the applied load increases, the damaged ply carries 100% of the critical shear strength while the additional stress transfers to the surrounding plies and elements. When the shear strain becomes catastrophic ($\gamma_{12}$), $\psi$ is assumed to be equal to 0.1. The load redistribution for shear is now similar to the case for mode I matrix cracking.

Concluding Remarks

This report describes a progressive failure analysis for laminated composites that can be performed using the Computational Structural Mechanics (CSM) Testbed (COMET) finite element code. The present analysis utilizes a constitutive model that describes the kinematics of the matrix cracks via volume averaged internal state variables. The evolution of these internal state variables is governed by an experimentally based damage evolutionary relationship. The nonlinearity of the constitutive relationship and of the damage accumulation process requires that this analysis be performed incrementally and iteratively.

Two processors were developed to perform the necessary calculations associated with this constitutive model. In the analysis scheme, these processors were called upon to interact with existing COMET processors to perform the progressive failure analysis. This report, which serves as a guide for performing progressive failure analysis on
COMET, provides a brief background on the constitutive model and the analysis methodology in COMET. The description and usage of the two progressive failure processors can be found in the appendices of this report.

The results from the example problems illustrated the stress redistribution that occurred during the accumulation of matrix cracks and fiber fracture. This in turn influenced the damage evolution characteristics, the global displacements, and the residual strengths. It should be noted that the current damage model capability is limited to mode I (opening mode) and mode II (shearing mode) matrix cracking and fiber fracture under tensile loading conditions. The inclusion of other damage modes such as delamination and compression failure mechanisms will provide a more complete picture of the failure process.
Appendix A

Processor DRF

A1. General Description

This processor calculates the damage resultant forces and moments caused by matrix cracking in laminated composites. These resultant forces and moments when applied to an undamaged laminate will produce an equivalent amount of displacements and curvatures to those resulting from the matrix crack surface kinematics in a damaged laminate. This enables an analysis of the response of a damaged laminate without having to update the stiffness matrix each time the damage state changes. Matrix crack damage is modeled in this processor by volume averaged crack surface kinematics using internal state variables (refs. 2 and 3).

Processor DRF and processor DGI, which is described in appendix B, were developed to perform progressive failure analysis of quasi-static and fatigue loaded laminates in Computational Structural Mechanics (CSM) Testbed (COMET). Analyses from these processors are stored in two formats. One is in standard format that is accessed by opening the output file. The other is a data set, which is stored in a testbed data library, and provides data to processors and post-processors (ref. 1). In this analysis, processor DRF is used in conjunction with COMET analysis processors to determine the static displacement and elemental stress resultants for a laminated composite structure containing matrix crack damage. Processor DGI then calculates the damage-dependent ply stresses. The damage state is updated based on the ply stresses and this procedure is repeated for the next load cycle.

A1.1. Damage Dependent Constitutive Relationship

In this processor, the effects of the matrix cracks are introduced into the ply-level constitutive equations as follows (ref. 3):

\[
\sigma_L = [Q](\varepsilon_L - \alpha_L^M),
\]

where \(\sigma_{Lij}\) are the locally averaged components of stress, \([Q]\) is the ply level reduced stiffness matrix, and \(\varepsilon_{Lij}\) are the locally averaged components of strain. \(\alpha_L^M\) are the components of the strain-like internal state variable for matrix cracking and are defined by

\[
\alpha_L^{MK} = \frac{1}{V_L} \int_{V_L} u_i n_j ds,
\]

where \(V_L\) is the volume of an arbitrarily chosen representative volume of ply thickness which is sufficiently large that \(\alpha_L^{MK}\) do not depend on \(V_L\), \(u_i\) are the crack opening displacements, \(n_j\) are the components of the vector normal to the crack face, and \(S\) is the surface value of the volume \(V_L\). The present form of the model assumes that \(\alpha_L^{MK}, \alpha_L^{K2},\) and \(\alpha_L^{2K}\), the internal state variables representing the tensile fiber fracture, mode II (shear mode) matrix cracking, and mode I (opening mode) matrix cracking, respectively, are the only nonzero damage components.

A1.2. Damage Dependent Laminate Equations

The ply level strains are defined as follows:
\[ \varepsilon_{Lx} = \varepsilon_{Lx}^0 - \gamma \kappa_{Lx} \]  
(A3)

\[ \varepsilon_{Ly} = \varepsilon_{Lyy}^0 - \gamma \kappa_{Lyy} \]  
(A4)

\[ \varepsilon_{Lz} = \varepsilon_{Lz}^0 - \kappa_{Lz} \]  
(A5)

where \( \varepsilon_{L}^0 \) and \( \kappa_{L} \) are the midplane strains and curvatures, respectively. The aforementioned ply strains are then substituted into equation (A1) to produce the ply-level stresses. Damage-dependent lamination equations are obtained by integrating these ply stresses through the thickness of the laminate (ref. 15). Next, the stiffness matrix in the laminate equation is inverted to produce

\[
\begin{bmatrix}
\varepsilon_L^d \\
\kappa_L
\end{bmatrix} = 
\begin{bmatrix}
A & B \\
B & D
\end{bmatrix}^{-1}
\begin{bmatrix}
N - f^M \\
M - g^M
\end{bmatrix}
\]  
(A6)

where \([A], [B],\) and \([D]\) are, respectively, the undamaged laminate extensional, coupling, and bending stiffness matrices. They are defined by the following equations from reference 6:

\[
[A] = \sum_{k=1}^{n} [\bar{Q}]_k (z_t - z_i) 
\]  
(A7)

\[
[B] = \frac{1}{2} \sum_{k=1}^{n} [\bar{Q}]_k (z_i^2 - z_i) 
\]  
(A8)

\[
[D] = \frac{1}{2} \sum_{k=1}^{n} [\bar{Q}]_k (z_i^2 - z_i) 
\]  
(A9)

where \([\bar{Q}]_k\) is the transformed reduced elastic modulus matrix for the \(k^{th}\) ply in laminate coordinates. In equation (A6), \(N\) are the components of the resultant force per unit length and \(M\) are the components of the resultant moments per unit length. The variables \(\{ f^M \}\) and \(\{ g^M \}\) represent the contribution to the resultant forces and moments from matrix cracking and are calculated from,

\[
\{ f^M \} = -\sum_{k=1}^{n} [\bar{Q}]_k (z_t - z_i) \{ \alpha'^M \}_k 
\]  
(A10)

\[
\{ g^M \} = -\frac{1}{2} \sum_{k=1}^{n} [\bar{Q}]_k (z_i^2 - z_i) \{ \alpha'^M \}_k 
\]  
(A11)

where \(\{ \alpha'^M \}_k\) contains the matrix cracking internal state variables for the \(k^{th}\) ply. Thus given the forces \(N\) and moments \(M\), as well as the damage variables in each ply, equation (A6) can be utilized to calculate the midsurface strains \(\varepsilon_{L}^0\) and curvature \(\kappa_{L}\).

A2. Processor SYNTAX

This processor uses keywords and qualifiers along with the CLIP command syntax (ref. 1). Two keywords are recognized: SELECT and STOP.
A2.1 Keyword SELECT

This keyword uses the qualifiers listed below to control the processor execution.

<table>
<thead>
<tr>
<th>Qualifier</th>
<th>Default</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIBRARY</td>
<td>1</td>
<td>Input and output library.</td>
</tr>
<tr>
<td>ELEMENT</td>
<td>ALL</td>
<td>Element type (EX47, EX97) used in the analysis. Default is all element types found in LIBRARY.</td>
</tr>
<tr>
<td>SREF</td>
<td>1</td>
<td>Stress reference frame. Stress resultants may have been computed in the element stress/strain reference frame (SREF=0) or in one of three alternate reference frames. For SREF=1, the stress/strain x-direction is coincident with the global y-direction. For SREF=3 the stress/strain x-direction is coincident with the global z-direction. Note that the processor currently must have the stress/strain coincident with the global x-direction (SREF=1).</td>
</tr>
<tr>
<td>PRINT</td>
<td>1</td>
<td>Print flag. May be 0, 1, or 2; 2 results in the most output.</td>
</tr>
<tr>
<td>MEMORY</td>
<td>2 000 000</td>
<td>Maximum number of words to be allocated in blank common. This is an artificial cap on memory put in place so that the dynamic memory manager does not attempt to use all of the space available on the machine in use.</td>
</tr>
<tr>
<td>DSTATUS</td>
<td>1</td>
<td>Damage state flag. If no damage, DSTATUS = 0. If matrix cracking (cyclic load), DSTATUS = 1. If matrix cracking (monotonic load), DSTATUS = 22222.</td>
</tr>
<tr>
<td>XFACTOR</td>
<td>0.0</td>
<td>Increases the specified applied forces by this factor at every load step. This is used in the residual strength calculations.</td>
</tr>
</tbody>
</table>

A2.2 Keyword STOP

This keyword has no qualifiers.

A3. Subprocessors and Commands

Processor DRF does not have subprocessors

A4. Processor Data Interface

A4.1. Processor Input Datasets

Several datasets, listed below, are used as input for processor DRF.

<table>
<thead>
<tr>
<th>Input Dataset</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELTS.NAME</td>
<td>Element names</td>
</tr>
<tr>
<td>OMB.DATA.1.1</td>
<td>Material properties including strain allowables</td>
</tr>
</tbody>
</table>
A4.2 Processor Output Datasets

These Datasets used as output for processor DRF.

<table>
<thead>
<tr>
<th>Output Dataset</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>APPL.FORC</td>
<td>Applied force and moments at joints</td>
</tr>
<tr>
<td>DFCT.xxxx.<em>.</em></td>
<td>Temporary damage resultant force dataset</td>
</tr>
<tr>
<td>DRFC.xxxx.<em>.</em></td>
<td>Damage resultant force dataset</td>
</tr>
</tbody>
</table>

A5. Limitations

Only EX47 and EX97 elements implemented with the generic element processor ES1 will be processed by processor DRF. All other elements will be ignored. The stress reference frame must be coincident with the global x-direction.

A6. Error Messages

Fatal errors will occur when any of the required datasets are missing from the input data library or when the stress resultants at the integration points are missing.

Warning messages will be written and execution will continue when there is a missing or unreadable keyword or qualifier or if any of the original SPAR elements are encountered.

A7. Usage Guidelines and Examples

A7.1 Runstream Organization

The following listing illustrates the organization of a progressive failure analysis that uses COMET. Because of the nonlinear nature of the damage-dependent constitutive equation, this analysis is performed in a stepwise manner.

1. Procedure ES  Define element parameters.
2. Processor TAB  Define joint locations, constraints, reference frames.
3. Processor AUS  Build tables of material and section properties and applied forces.
4. Processor LAU  Form constitutive matrix.
5. Processor ELD  Define elements.
6. Processor E    Initialize element datasets, create element datasets.
8. Processor RSEQ Resequence nodes for minimum total execution time.
9. Processor TOPO Form maps to guide assembly and factorization of system matrices.
11. Processor INV Factor system stiffness matrix.
12. Continue
13. Processor DRF Form damage resultant force vectors.
14. Processor SSOL Solve for static displacements
15. Procedure STRESS Calculate element stress resultants
16. Processor DGI Calculate ply level stresses and damage evolution
17. For next load cycle, go to step 13; else stop.

A7.2. Progressive Failure Analysis Input and Output

Please refer to Processor DGI for usage example (Appendix 1.2).

A8. Structure of Datasets Unique to Processor DRF

A8.1. DRFC.xxxx

This data set is created by processor DRF and uses the SYSVEC format. See APPL.FORC.iset.1 This dataset contains the damage resultant forces and moments corresponding to the given matrix cracking state.

A8.2. DFCT.xxxx

Data set DFCT.xxx is created by processor DRF and uses the SYSVEC format. See APPL.FORC.iset.1 This dataset contains the damage resultant forces and moments from the previous load step and is used to restore the applied force vector to the initial value.

A8.3. ISV.xxxx

This data set contains the matrix cracking internal state variables at each layer. The xxxx is the element name. The data is stored in a record named ALPAM.1. This record contains \( n \) items, where
\[
\text{\( n = n_{\text{layer}} \times n_{\text{intgpt}} \times n_{\text{elt}} \)}
\]
and \( n_{\text{layer}} \) is the number of layers in the model, \( n_{\text{intgpt}} \) is the number of integration points for the element, and \( n_{\text{elt}} \) is the number of elements.

The data is stored in the following order:
1. \( \alpha_{L_1}^M \), internal state variable associated with fiber fracture.
2. \( \alpha_{L_2}^M \), internal state variable associated with mode I opening of the matrix crack.
3. \( \alpha_{L_3}^M \), internal state variable associated with mode II opening of the matrix crack.

The data storage occurs for every layer, every integration point, and every element.
Appendix B

Processor DGI

B1. General Description

Processor DGI predicts the evolution of matrix crack damage in laminated composites for monotonical loads and cyclic fatigue loads. The processor also calculates fiber fracture under tensile load conditions. The matrix crack damage is represented in this processor by volume-averaged crack surface kinematics that use internal state variables (refs. 2 and 3). The evolution of these internal state variables is governed by a phenomenological growth law.

This processor was designed to perform progressive failure analysis of laminated composite structures in the Computational Structural Mechanics (CSM) Testbed (COMET). At each load cycle, the elemental stress resultants for a laminated composite structure are obtained from COMET with the effects of matrix crack damage accounted for by Processor DRF. Processor DGI then postprocesses this information and uses the ply-level stresses to determine the evolution of matrix crack damage in each ply of the laminate. This procedure is repeated until the specified number of load cycles has been reached.

B1.1 Damage Dependent Constitutive Relationship

In this processor, the effects of the matrix cracks are introduced into the ply-level constitutive equations as follows (ref. 5):

\[
\{\sigma_L\} = [Q]\{\varepsilon_L - \alpha_M^M\}
\]  

(B1)

where \(\{\sigma_L\}\) are the locally averaged components of stress, \([Q]\) is the ply level reduced stiffness matrix, and \(\{\varepsilon_L\}\) are the locally averaged components of strain. \(\{\alpha_M^M\}\) are the components of the strain-like internal state variable for matrix cracking and are defined by

\[
\alpha_M^L = \frac{1}{V_L} \int u_i n_j dS
\]  

(B2)

where \(V_L\) is the volume of an arbitrarily chosen representative volume of ply thickness that is sufficiently large that \(\alpha_M^L\) do not depend on \(V_L\), \(u_i\) are the crack opening displacements, and \(n_j\) are the components of the vector normal to the crack face. The present form of the model assumes that \(\alpha_M^M, \alpha_M^{12}\), and \(\alpha_M^{22}\), the internal state variables representing the tensile fiber fracture, mode II (shear mode) matrix cracking, and mode I (opening mode) matrix cracking, respectively, are the only nonzero damage components.

For a uniaxially loaded medium containing alternating 0° and 90° plies, \(\alpha_M^{12}\) has been found from a micromechanics solution to be related to the far field normal force and crack spacing as follows (ref. 5):

\[
\alpha_M^{12} = \frac{\rho}{2\bar{T}}
\]  

(B3)

where

\[
\frac{\pi^4}{64\xi} C_{222}
\]
\[ \xi = \frac{1}{\sum_{m=1}^{2} \sum_{n=1}^{2} C_{2222}(2m-1)^2(2n-1)^2 + C_{1212}(\bar{a}/\bar{h})^2(2m-1)^4} \]  

\( \rho \) is the force per unit length that is applied normal to the fibers and \( 2\bar{h} \) and \( 2\bar{a} \) are the layer thickness and crack spacing, respectively. The \( C_{2222} \) is the modulus in the direction transverse to the fibers and \( C_{1212} \) is the in-plane shear modulus. Both moduli are the undamaged properties.

**B1.2. Damage Evolution Relationship**

Equation (B3) is used when the matrix crack spacing is known in each ply of the laminate. Since it is usually necessary to predict the damage accumulation and response for a given load history, damage evolutionary relationships must be utilized to determine the values of the internal state variables. The following relationship was used for the rate of change of the internal state variable \( \alpha_{L22}^M \) in each ply during fatigue loading conditions (ref. 9):

\[ \frac{d\alpha_{L22}^M}{dS} = \frac{d\alpha_{L22}^M}{dN} \]  

where \( d\alpha_{L22}^M \) describes the change in the internal state variable for a given change in the crack surface areas, \( \bar{K} \) and \( \bar{n} \) are material parameters (refs. 10 and 11), \( N \) is the number of load cycles, and \( G \) is the damage-dependent strain energy release rate for the ply of interest and is calculated from the following equation:

\[ G = V_L C_{ijkl}(\varepsilon_{Lij} - \alpha_{Lij}^M) \frac{d\alpha_{Lij}^M}{dS} \]  

where \( V_L \) is the local volume. Interactions with the adjacent plies will result in ply strains \( \varepsilon_{Lij} \), that are affected by the strains in adjacent plies. Thus, the strain energy release rate \( G \) in each ply will be implicitly reflected in the calculation of the ply-level response, so that equation (B5) is not restricted to a particular laminate stacking sequence. Substituting equation (B6) in equation (B5) and integrating the result in each ply over time gives the current damage state in each ply for any fatigue load history.

When the material is subjected to monotonically increasing loads, the rate of change of the internal state variable \( \alpha_{Lij}^M \) is described by

\[ d\alpha_{11} = \begin{cases} \varepsilon_{11} - \alpha_{11}^{sd} + \frac{1}{Q_{11}Q_{22} - Q_{12}^2} \left( Q_{12} \beta S_{cr}^{v} - Q_{22} \gamma S_{cr}^{v} \right) & \text{if } \alpha_{22} > 0; \\ \varepsilon_{11} - \alpha_{11}^{sd} + \frac{Q_{12}}{Q_{11}} \varepsilon_{22} - \frac{\gamma S_{cr}^{v}}{Q_{11}} & \text{if } \alpha_{22} = 0 \end{cases} \]  

\[ d\alpha_{22} = \begin{cases} \varepsilon_{22} - \alpha_{22}^{sd} + \frac{1}{Q_{11}Q_{22} - Q_{12}^2} \left( Q_{12} \gamma S_{cr}^{v} - Q_{22} \beta S_{cr}^{v} \right) & \text{if } \alpha_{11} > 0; \\ \varepsilon_{22} - \alpha_{22}^{sd} + \frac{Q_{12}}{Q_{22}} \varepsilon_{11} - \frac{\beta S_{cr}^{v}}{Q_{22}} & \text{if } \alpha_{11} = 0 \end{cases} \]  

\[ d\alpha_{12} = \frac{\psi S_{cr}^{v}}{Q_{66}} + \gamma_{12} - \alpha_{12}^{sd} \]  

13
for strains exceeding \( e_{11m} \), \( e_{22m} \), and \( \gamma_{12m} \), respectively. If none of the critical strains are exceeded, there is no damage. The \( a_{kl} \) is the updated internal state variable, \( a_{kl}^{old} \) is the internal state variable for the previous damage state, and \( da_{11}, da_{22}, \) and \( da_{12} \) are the incremental changes in the internal state variables for tensile fiber fracture, mode I matrix cracking, and mode II matrix cracking, respectively. The monotonic damage growth parameters (\( \beta, \psi, \) and \( \gamma \)) can be complicated algebraic functions describing the complex behavior of load redistribution due to matrix cracking and fiber fracture. However, for the purpose of developing the framework for this progressive damage methodology, simple constants were chosen for the parameters. So for this analysis, the damage growth law parameters govern the load redistribution in a way that is similar to the ply discount method. It is not reasonable to assume a 100% load redistribution at the instant of failure for mode I matrix cracking and tensile fiber fracture. Therefore, a 90% load redistribution was assumed, i.e. the local ply stress is only 10% of the critical ply strength (\( \beta = 0.1 \) and \( \gamma = 0.1 \)). As the applied load increases, mode I matrix cracking and tensile fiber fracture internal state variables increase in proportion to the local strains. This results in a constant stress level (10% of the critical ply strength) in the damaged plies, illustrated in figure 10, with the load redistributing to the surrounding plies and elements.

Based on Iosipescu shear data (ref. 16) there is a shear strain (\( \gamma_{12}^{o} \)) where the behavior is no longer linear and becomes almost perfectly plastic. At this strain level, \( \psi \) is equal to 1.0 to simulate elastic-perfectly plastic shear stress/strain behavior as illustrated in figure 10. This implies that as the applied load increases, the damaged ply carries 100% of the critical shear strength while the additional stress transfers to the surrounding plies and elements. When the shear strain becomes catastrophic (\( \gamma_{12}^{cr} \)), \( \psi \) is assumed to be equal to 0.1. The load redistribution for shear is now similar to the case for mode I matrix cracking.

B2. PROCESSOR SYNTAX

This processor uses keywords and qualifiers along with the CLIP command syntax. Two keywords are recognized: SELECT and STOP.

B2.1 Keyword SELECT

This keyword uses the qualifiers listed below to control the processor execution.

<table>
<thead>
<tr>
<th>Qualifier</th>
<th>Default</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIBRARY</td>
<td>1</td>
<td>Input and output library.</td>
</tr>
<tr>
<td>ELEMENT</td>
<td>ALL</td>
<td>Element type (EX47, EX97) used in the analysis. Default is all element types found in LIBRARY.</td>
</tr>
<tr>
<td>LOAD_SET</td>
<td>1</td>
<td>Load set; i of input data set STRS.xxxx.i.j.</td>
</tr>
<tr>
<td>SREF</td>
<td>1</td>
<td>Stress reference frame. Stress resultants may have been computed in the element stress/strain reference frame (SREF=0) or in one of three alternate reference frames. For SREF=1, the stress/strain x-direction is coincident with the global y-direction. For SREF=3 the stress/strain x-direction is coincident with the global z-direction. Note that the processor currently must have the stress/strain coincident with the global x-direction (SREF=1).</td>
</tr>
<tr>
<td>PRINT</td>
<td>1</td>
<td>Print flag. May be 0, 1, or 2; 2 results in the most output.</td>
</tr>
<tr>
<td>STEP</td>
<td>0</td>
<td>Step number in nonlinear analysis (i.e., i in the STRS.xxxx.i.0 data set for nonlinear analysis).</td>
</tr>
</tbody>
</table>
**MEMORY**  
2 000 000  
Maximum number of words to be allocated in blank common.  
This is an artificial cap on memory put in place so that the dynamic memory manager does not attempt to use all of the space available on the machine in use.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSTATUS</td>
<td>1</td>
<td>Damage state flag. If no damage, DSTATUS = 0. If matrix cracking (cyclic load), DSTATUS = 1. If matrix cracking (monotonic load), DSTATUS = 22222.</td>
</tr>
<tr>
<td>INC_SIZE</td>
<td>1.0</td>
<td>Increment size used in damage growth law.</td>
</tr>
<tr>
<td>NCYCLE</td>
<td>1</td>
<td>Cycle number</td>
</tr>
<tr>
<td>NINCR</td>
<td>1</td>
<td>Increment number</td>
</tr>
</tbody>
</table>

**B2.2 Keyword STOP**

This keyword has no qualifiers.

**B3. Subprocessors and Commands**

None. Processor DGI does not have subprocessors.

**B4. Processor Data Interface**

**B4.1 Processor Input Datasets**

Several datasets, listed below, are used as input for processor DGI.

<table>
<thead>
<tr>
<th>Input Dataset</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELTS.NAME</td>
<td>Element names</td>
</tr>
<tr>
<td>STRS.xxx.xxx.i</td>
<td>Element stress resultants. Record named INTEG_PTS must exist.</td>
</tr>
<tr>
<td>OMB.DATA.1.1</td>
<td>Material properties including strain allowables</td>
</tr>
<tr>
<td>LAM.OMB.**.*</td>
<td>Laminate stacking sequence</td>
</tr>
<tr>
<td>ES.SUMMARY</td>
<td>Various element information</td>
</tr>
<tr>
<td>PROP.BTAB.2.102</td>
<td>ABD matrix</td>
</tr>
<tr>
<td>WALL.PROP.1.1</td>
<td>Shell wall dataset</td>
</tr>
<tr>
<td>DIR.xxx.xxx.*</td>
<td>Element directory dataset</td>
</tr>
<tr>
<td>DEF.xxx.xxx.*</td>
<td>Element definition (connectivity) dataset</td>
</tr>
<tr>
<td>ISV.xxx.xxx.*</td>
<td>Internal state variable dataset</td>
</tr>
<tr>
<td>DGP.DATA.1.1</td>
<td>Damage growth law parameters data set</td>
</tr>
</tbody>
</table>

**B4.2 Processor Output Datasets**

<table>
<thead>
<tr>
<th>Output Dataset</th>
<th>Contents</th>
</tr>
</thead>
</table>
B5. Limitations

Only EX47 and EX97 elements implemented with the generic element processor ES1 will be processed by processor DGI. All other elements will be ignored. The stress reference frame must be coincident with the global x-direction.

B6. Error Messages

Fatal errors will occur when any of the required datasets are missing from the input data library or when the stress resultants at the integration points are missing. (See section B4.1.)

Warning messages will be written and execution will continue when there is a missing or unreadable keyword or qualifier or if any of the original SPAR elements are encountered.

B7. Usage Guidelines and Examples

B7.1 Organization of Progressive Damage Analysis on Testbed

The organization of the COMET processors for a progressive failure analysis is shown below. The nonlinear nature of the damage-dependent constitutive equation requires that this analysis be performed in a stepwise manner.

1. Procedure ES  Define element parameters.
2. Processor TAB  Define joint locations, constraints, reference frames.
3. Processor AUS Build tables of material and section properties and applied forces.
4. Processor LAU  Form constitutive matrix.
5. Processor ELD  Define elements.
6. Processor E    Initialize element datasets, create element datasets.
9. Processor RSEQ Resequence nodes for minimum total execution time.
10. Processor TOPO Form maps to guide assembly and factorization of system matrices.
12. Processor INV  Factor system stiffness matrix.
13. Continue
14. Processor DRF  Form damage resultant force vectors.
15. Processor SSOL Solve for static displacements
16. Procedure STRESS Calculate element stress resultants
17. Processor DGI  Calculate ply level stresses and damage evolution
18. For next load cycle, go to step 13; else stop.

B7.2. Progressive Damage Analysis Input

The following listing illustrates the input from a progressive failure analysis. The problem being solved is the uniaxially tensile loaded tapered laminated plate, figure 2, described in the main body of this report. The listing contains the main runstream plus a procedure file to perform the calculations for each load cycle.

```
# @S-me
# cp $CSM_PRC/proclib.gal proclib.gal .Copy procedure library
chmod u+w proclib.gal
```

16
tapered panel
24 nodes, 14 elements

*add pffc.clp .Add procedure for repeating calculations
*def/a es_name = EX47 .Element name
*def/a es_proc = ES1 .Element processor name
*call ES ( function='DEFINE ELEMENTS'; es_proc = <es_proc>; es_name = <es_name> )

[xtab]
START 24 .24 nodes
JOINT LOCATIONS .Enter joint locations
  1  0.0  0.0  0.0  20.0  2.0  0.0  8  1  3
  8  0.0 10.0  0.0  20.0  8.0  0.0
CONSTRAINT DEFINITION 1 .Constraints:
  zero 1,2,3,4,5: 1,17,8 .Fixed end
  zero 6: 1,24 .Supress drilling DOF

[xaus]
SYSVEC : appl forc .Create input datasets
  I=1 : J=8 : 3750.0
  I=1 : J=16 : 7500.0
  I=1 : J=24 : 3750.0

TABLE(NI=16,NJ=1): OMB DATA I J .Ply level material data
  IM7/5260
  I=1,2,3,4,5
  J=1: 22.162E+6 0.333 1.262E+6 0.754E+6 0.754E+6
  I=6,7,8,9
  J=1: 0.754E+6 1.0E-4 1.0E-4 0.01
  I=10,11,12,13,14,15,16
  J=1: 0.0 0.0 0.0 0.014 0.014 0.014 0.0

TABLE(NI=3,NJ=3,ITYPE=0): DGP DATA I J .Section properties
  J=1: 1.1695 5.5109 3.8686E-7
  J=2: 1.006 0.0
  J=3: 1.006 0.0

TABLE(NI=3,NJ=1,ITYPE=0): DGP DATA I J .Damage evolution data
  J=1: 1.1695 5.5109 3.8686E-7

[xlaus]
ONLINE=2 .Create constitutive matrix

<xel>
<es_expe_cmd>
NSECIT = 1 : SREF=1
  1  2 10  9
  2  3 11 10
  3  4 12 11
  4  5 13 12
  5  6 14 13
  6  7 15 14
  7  8 16 15
  9 10 18 17
 10 11 19 18
 11 12 20 19
 12 13 21 20
 13 14 22 21
 14 15 23 22
15 16 24 23

.xqt E .Initialize element datasets
  stop
  *call ES (function='INITIALIZE') .initialize element matrices
  *call ES (function='FORM STIFFNESS/MATL') .Form stiffness matrices
  .xqt RSEQ .Resequence
  reset maxcon=12
  .xqt TOPO .Create maps
  .xqt K .Assemble global stiffness matrix
  .xqt INV .Factor the global stiffness matrix
  .def ns_overwrite=<true>

  Call procedure to perform calculations at each cycle
  *call PFFC ( es_proc=<es_proc> ; es_name=<es_name> ; --
    N_fcycl=1 ; N_lcycl=2000 ; N_cylinc=5 ; --
    NPRT=100 )
  .pack 1
  .xqt exit
  .endinput

  B7.2.1. Procedure to perform the loop through the calculations for each load cycle
  (file name pffc.clp)
  *
  procedure PFFC ( es_proc ; es name ; --
    N_fycl ; N_lycl ; N_cylinc ; --
    NPRT )
  *
    N_fycl: first fatigue cycle
    N_lycl: last fatigue cycle
    N_cylinc: cycle increment
    NPRT: output storage cycle increment

    begin loop here
  *
  .set echo=off
  .def icount = 0 .Initialize print counter
  .DO :CYCLOOP $NCYL = ![N_fycl], ![N_lycl], ![N_cylinc]>
    .def icount = ( <icount> + 1 )
    .if < <icount>/eq <[NPRT]> >/then
      .def iprint = 1
      .def icount = 0
    .else
      .def iprint = 0
    .endif
    .def delinc = <[N_cylinc]>
  *.xqt DRF .Calculate damage resultant forces
    select /PRINT = 0
    stop
  *.xqt SSOL .Solve for static displacements
    Calculate elemental stress resultants
  *call STRESS (direction=1; location= INTEG_PTS; print=<false> )
  *.if < <IPRINT> /eq 1 > /then
    *.xqt VPRT .Print static displacements
      format = 4
      print STAT DISP
      stop
B7.3. Progressive Damage Analysis Output

The following is a partial list of a progressive failure analysis output produced by processor DGI. Data for postprocessing is stored in dataset PLYDT.xxxx.xxx.1.

** BEGIN DGI ** DATA SPACE= 2000000 WORDS
CYCLE NUM. = 496

ELEMENT NUMBER 1 TYPE EX47
EVALUATION (INTG) POINT NUMBER 1
REFERENCE SURFACE STRAINS AND CURVATURES
   E0-X  E0-Y  E0-XY  K-X  K-Y  K-XY
0.4619E-02 -0.6946E-04 0.1180E-02 0.0000E+00 0.0000E+00 0.0000E+00
COMBINED BENDING AND MEMBRANE STRESSES, STRAINS, AND MATRIX CRACK DAMAGE VARIABLE
FOR EACH LAYER OF ELEMENT 1 TYPE EX47

<table>
<thead>
<tr>
<th>LAYER</th>
<th>THETA</th>
<th>SIG-1</th>
<th>SIG-2</th>
<th>TAU-12</th>
<th>STRAIN-1</th>
<th>STRAIN-2</th>
<th>GAMMA-12</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0.103E+06</td>
<td>0.187E+04</td>
<td>0.890E+03</td>
<td>0.462E-02</td>
<td>-0.695E-04</td>
<td>0.118E-02</td>
</tr>
<tr>
<td>2</td>
<td>90</td>
<td>0.384E+03</td>
<td>0.578E+04</td>
<td>-0.890E+03</td>
<td>-0.695E-04</td>
<td>0.462E-02</td>
<td>-0.118E-02</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0.103E+06</td>
<td>0.187E+04</td>
<td>0.890E+03</td>
<td>0.462E-02</td>
<td>-0.695E-04</td>
<td>0.118E-02</td>
</tr>
</tbody>
</table>

** BEGIN DGI ** DATA SPACE= 2000000 WORDS
CYCLE NUM. = 996

** BEGIN DGI ** DATA SPACE= 2000000 WORDS
CYCLE NUM. = 996

19
ELEMENT NUMBER 1 TYPE EX47
EVALUATION (INTG) POINT NUMBER 1
REFERENCE SURFACE STRAINS AND CURVATURES
E0-X E0-Y E0-XY K-X K-Y K-XY
0.4625E-02 -0.6839E-04 0.1184E-02 0.0000E+00 0.0000E+00 0.0000E+00
COMBINED BENDING AND MEMBRANE STRESSES, STRAINS, AND MATRIX CRACK DAMAGE VARIABLE
FOR EACH LAYER OF ELEMENT 1 TYPE EX47
LAYER THETA SIG-1 SIG-2 TAU-12 STRAIN-1 STRAIN-2 GAMMA-12
1 0. 0.103E+06 0.187E+04 0.892E+03 0.462E-02 -0.688E-04 0.118E-02
2 90. 0.382E+03 0.573E+04 -0.892E+03 -0.688E-04 0.462E-02 -0.118E-02
3 0. 0.103E+06 0.187E+04 0.892E+03 0.462E-02 -0.688E-04 0.118E-02
LAYER ALPM-11 ALPM-22 ALPM-12
1 0.000E+00 0.246E-11 0.000E+00
2 0.000E+00 0.901E-04 0.000E+00
3 0.000E+00 0.246E-11 0.000E+00
STRAIN-1 STRAIN-2 GAMMA-12
0.893E+03 0.463E-02 -0.684E-04 0.118E-02
-0.893E+03 -0.684E-04 0.463E-02 -0.118E-02
0.893E+03 0.463E-02 -0.684E-04 0.118E-02
** BEGIN DGI ** DATA SPACE= 2000000 WORDS
CYCLE NUM. = 1496

ELEMENT NUMBER 1 TYPE EX47
EVALUATION (INTG) POINT NUMBER 1
REFERENCE SURFACE STRAINS AND CURVATURES
E0-X E0-Y E0-XY K-X K-Y K-XY
0.4625E-02 -0.6839E-04 0.1184E-02 0.0000E+00 0.0000E+00 0.0000E+00
COMBINED BENDING AND MEMBRANE STRESSES, STRAINS, AND MATRIX CRACK DAMAGE VARIABLE
FOR EACH LAYER OF ELEMENT 1 TYPE EX47
LAYER THETA SIG-1 SIG-2 TAU-12 STRAIN-1 STRAIN-2 GAMMA-12
1 0. 0.103E+06 0.187E+04 0.893E+03 0.463E-02 -0.684E-04 0.118E-02
2 90. 0.376E+03 0.568E+04 -0.893E+03 -0.684E-04 0.463E-02 -0.118E-02
3 0. 0.103E+06 0.187E+04 0.893E+03 0.463E-02 -0.684E-04 0.118E-02
LAYER ALPM-11 ALPM-22 ALPM-12
1 0.000E+00 0.372E-11 0.000E+00
2 0.000E+00 0.129E-03 0.000E+00
3 0.000E+00 0.372E-11 0.000E+00
STRAIN-1 STRAIN-2 GAMMA-12
0.894E+03 0.463E-02 -0.681E-04 0.119E-02
-0.894E+03 -0.681E-04 0.463E-02 -0.119E-02
0.894E+03 0.463E-02 -0.681E-04 0.119E-02
** BEGIN DGI ** DATA SPACE= 2000000 WORDS
CYCLE NUM. = 1996

ELEMENT NUMBER 1 TYPE EX47
EVALUATION (INTG) POINT NUMBER 1
REFERENCE SURFACE STRAINS AND CURVATURES
E0-X E0-Y E0-XY K-X K-Y K-XY
0.4627E-02 -0.6806E-04 0.1185E-02 0.0000E+00 0.0000E+00 0.0000E+00
COMBINED BENDING AND MEMBRANE STRESSES, STRAINS, AND MATRIX CRACK DAMAGE VARIABLE
FOR EACH LAYER OF ELEMENT 1 TYPE EX47
LAYER THETA SIG-1 SIG-2 TAU-12 STRAIN-1 STRAIN-2 GAMMA-12
1 0. 0.103E+06 0.187E+04 0.894E+03 0.463E-02 -0.681E-04 0.119E-02
2 90. 0.376E+03 0.566E+04 -0.894E+03 -0.681E-04 0.463E-02 -0.119E-02
3 0. 0.103E+06 0.187E+04 0.894E+03 0.463E-02 -0.681E-04 0.119E-02
LAYER ALPM-11 ALPM-22 ALPM-12
1 0.000E+00 0.372E-11 0.000E+00
2 0.000E+00 0.129E-03 0.000E+00
3 0.000E+00 0.372E-11 0.000E+00
STRAIN-1 STRAIN-2 GAMMA-12
0.895E+03 0.463E-02 -0.680E-04 0.119E-02
-0.895E+03 -0.680E-04 0.463E-02 -0.119E-02
0.895E+03 0.463E-02 -0.680E-04 0.119E-02
20
B8. Structure of Datasets Unique to Processor DGI

B8.1. PDAT.xxxx

Data set PDAT.xxxx contains ply-level damage dependent stresses, strains, and internal state variables. Data are centroidal values. The variable xxxx is the element name. The data for each element is stored in a record named DAT_PLY.ielt, where ielt is the element number. Each record contains $n$ items, where

$$n = n\text{layer} \times 9$$

and $n\text{layer}$ is the number of layers in the model.

The data is expressed with respect to ply coordinates and is stored in the following order:

1. $\sigma_{11}$ normal stress in the fiber direction.
2. $\sigma_{22}$ normal stress transverse to the fibers.
3. $\sigma_{12}$ shear stress.
4. $\varepsilon_{11}$ strain in the fiber direction.
5. $\varepsilon_{22}$ strain transverse to the fibers.
6. $\varepsilon_{12}$ shearing strain.
7. $\alpha_{L,11}$ internal state variable associated with fiber fracture.
8. $\alpha_{L,22}$ internal state variable associated with mode I opening of the matrix crack.
9. $\alpha_{I,12}$ internal state variable associated with mode II opening of the matrix crack.

Repeated $n\text{layer}$ times.

B8.2. DGP.DATA.1.1

This data set is created by AUS/TABLE and contains the growth law parameters for the matrix cracking evolutionary relationship. The following variables are used to specify table size:

NI = number of material parameters, for this case 3
NJ = number of material systems, for this case 1
Type = numerical format such as real or integer

where NI and NJ are the number of columns and rows, respectively and Type specifies numerical format, real or integer.

Each entry contains the following:

1. Growth law parameter, $\bar{\kappa}$ .
2. Growth law parameter, $\bar{\eta}$ .
3. Parameter for determining $\frac{d\alpha_{L,ij}}{dS}$, $d\text{para}$

These entries are repeated NJ times.

B8.3. ISV.xxxx

This data set contains the matrix cracking internal state variables at each layer. The variable xxxx is the element name. The data is stored in a record named ALPAM.1.

This record contains $n$ items, where

$$n = n\text{layer} \times n\text{intgpt} \times n\text{elt}$$
and \( n_{layer} \) is the number of layers in the model, \( n_{intgpt} \) is the number of integration points for the element, and \( n_{elt} \) is the number of elements.

The data is stored in the following order:

1. \( M_{L11} \), internal state variable associated with fiber fracture.
2. \( M_{L22} \), internal state variable associated with mode I opening of the matrix crack.
3. \( M_{L12} \), internal state variable associated with mode II opening of the matrix crack.

The data storage occurs for every layer, every integration point, and every element.
Appendix C

Residual Strength Runstream

C1. General Description

This appendix lists a sample runstream that was used to calculate the residual strength of an orthotropic center-notched laminate that was monotonically loaded to failure.

C2. Residual Strength Analysis Input

The following listing illustrates the input from a residual strength analysis. The problem being solved is the uniaxially tensile loaded center-notched orthotropic laminated plate shown in figure 8. The listing contains the main runstream plus a procedure file. The procedure file calculates the response during the monotonic loading to failure and is presented in this appendix. The finite element mesh was created using PATRAN. The file PT2T.PRC was created using the testbed PATRAN To Testbed (PT2T) neutral file converter. This file contains all of the nodal locations, connectivity matrix, boundary conditions, and applied forces.

```plaintext
cp $CSM_PRC/proclib.gal proclib.gal
chmod u+w proclib.gal
testbed > cct.o << 'endinput
*set echo=off
*set plib=28
*open 28 proclib.gal /old
*open/new 1 cct.101
  rectangular panel with center-cut slit
  quarter panel mesh
  EX47 4 node quad elements
  *
*add pffdm.clp
*add initialize.clp
*ADD PT2T.PRC
*def/a es_name = EX47
*def/a es_proc = ES1
*call ES ( function = 'DEFINE ELEMENTS'; es_proc = <es_proc>;--
  es_name=<es_name> )
[xqt TAB]
START 800
*call PT2T_JLOC

CONTRINT DEFINITION 1
  *call PT2T_BC

[xqt AUS]
SYSVEC : appl forc
  *
call PT2T_AF

TABLE(NI=16,NJ=1): OMB DATA 1 1
  AS4/938
  J=1: 1,2,3,4,5
  J=1: 19.60E+6 0.32 1.36E+6 0.72E+6 0.72E+6
  J=5,7,8,9
  J=1: 0.72E+6 1.0E-4 1.0E-4 0.01
  J=10,11,12,13,14,15,16
  J=1: 0.0 0.0 0.0 0.0148 0.005 0.010 0.0
  TABLE(JI=3,NJ=13,itype=0): LAM OMB 1 1
  J=1: 1 0.0072 -45.0
```

23
C2.1 Procedure to perform the monotonic loading calculations (file name pffdm.clp)

*procedure PFFDM ( es_proc ; es_name ; --
   N_fcycl ; N_lcycl ; N_cylinc ;--
   NSUB ; NSTRT ; NS_lcycl ; NPRT )

File to control monotonic loading to failure
   N_fcycl: first cycle number
   N_lcycl: last cycle number
   N_cylinc: cycle increment
   NSUB: subincrement flag (=0, to bypass)
   NSTRT: cycle to start subincrements(=0, to bypass)
   NS_lcycl: number of subincrements(=1, to bypass)
   NPRT: output storage cycle increment

begin loop here

*set echo=off
*def icount = 0
   *def icount = ( <icount> + 1 )
   *if < <icount>/eq <[NPRT]> > /then
      *def iprint = 1
      *def icount = 0
   *else
      *def iprint = 0
      *endif
   *def/i $ITCYCL = 1
   *def/i DUMIT = i
   *def/i $SNCYL = 1

24
*def delinc = <[N_cylinc]>*
*def/d st_disp == STAT.DISP.*
*def/d ap_forc == APPL.FORC.*
*def/a nst Disp == NST.DISP
*def/a ost Disp == OST.DISP
*def/a dst Disp == DST.DISP
*DO $ITCYCL = 1,1000
*def/i drfit = 1
[xtq DRF:MNR
   select /PRINT = 0
   select /DSTATUS = 22222
   select /XFACTOR = 1.0
   select /DUMIT = <$ITCYCL>
stop

******************************************************
 postpone iterations until damage occurs

*G2M/name=drfit/type=D/maxn=1--
   1, DRFITU.EX47.*, DRFDAT.1
*if < <drfit>/eq 0.0 >/then
*def/i $ITCYCL = 1000
*endif

******************************************************
 iterate until change in damage resultant
 forces are small

*G2M/name=drfitn/type=I/maxn=1--
   1, DRFITV.EX47.*, DRFDAT.1
*print 1 DRFITV.EX47.* DRFDAT.1 /m=1
*if < <$ITCYCL>/ge 2 >/then
*if < <drfitn>/eq 0 >/then
*deffi $ITCYCL = 1000
*endif
*endif

******************************************************
*if < <$ITCYCL>/ge 2 >/then
*G2M/name=ddisp/type=D/maxn=1--
   1, DST.DISP, DATA.1 /m=49
*endif

*if < <$NCYL>/ge 2 >/then
[xtq vec
   COMBINE <ost Disp> <- <st Disp>
*if < <$NCYL>/eq 2 >/then
   COMBINE <dst Disp> <- <st Disp>
*endif
*endif

[xtq SSOL

*if < <drfit>/ne 0.0 >/then
*if < <$ITCYCL>/ge 2 >/then
[xtq vec
   COMBINE <dst Disp> <- <st Disp>
   COMBINE <nst Disp> <- <dst Disp> + <ost Disp>
   COMBINE <st Disp> <- <nst Disp>
*endif
*endif

*call STRESS (direction=1; location= INTEG_PTS; print=<false> )
[xtq DGI
   select /PRINT = 0
   select /INC_SIZE = <delinc>
   select /N_CYCLE = <$NCYL>

25
**C3. Residual Strength Analysis Output**

Centroidal values of the ply stresses, strains, and internal state variables for each element can be found in the PDAT.xxxx data set (renamed as PLYDTM.EX47.xxxx.yyyy). Nodal displacements are located in the STAT.DISP.xxxx data set (renamed as DISPM.EX47.xxxx.yyyy). These data sets are located in the *.101 output file and can be retrieved as separate individual files. An example of data output for one damaged element from one of the PDAT.xxxx data sets is given below.

Record DAT_PLY.97 of dataset PLYDTM.EX47.190.50

<table>
<thead>
<tr>
<th>Record</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.9230D+05 6.8000D+02 7.2000D+03 9.8001D-03 1.0500D-02 3.1344D-02</td>
</tr>
<tr>
<td>7</td>
<td>0.0000D+00 1.3139D-02 2.1344D-02 2.0601D+05 6.8000D+02 7.2000D+03</td>
</tr>
<tr>
<td>13</td>
<td>1.0500D-02 9.8001D-03-3.1344D-02 0.0000D+00 1.2664D-02-4.1344D-02</td>
</tr>
<tr>
<td>19</td>
<td>2.9008D-04-6.8656D-03 5.0370D-02 2.5822D-02-5.5218D-03 6.9959D-04</td>
</tr>
<tr>
<td>25</td>
<td>2.4230D-02 0.0000D+00 0.0000D+00-1.0801D+05 6.8000D+02-5.0370D+04</td>
</tr>
<tr>
<td>31</td>
<td>-5.5218D-03 2.5822D-02-6.9958D-04 0.0000D+00 2.3558D-02 0.0000D+00</td>
</tr>
<tr>
<td>37</td>
<td>1.4610D+05 5.0053D+03 7.2000D+03 1.7683D-02 2.6170D+03 2.7494D-02</td>
</tr>
<tr>
<td>43</td>
<td>1.0311D-02 1.3219D-03 1.7494D-02 1.5110D+05 1.8871D-03 7.2000D+03</td>
</tr>
<tr>
<td>49</td>
<td>1.8289D-02 2.0111D-03-2.6794D-02 1.0610D-02 3.0960D-03-3.6794D-02</td>
</tr>
<tr>
<td>55</td>
<td>2.9008D-04-6.8656D-03 5.0370D-02 2.5822D-02-5.5218D-03 6.9959D-04</td>
</tr>
<tr>
<td>61</td>
<td>2.4230D-02 0.0000D+00 0.0000D+00 1.5110D+05 1.8871D-03 7.2000D+03</td>
</tr>
<tr>
<td>67</td>
<td>1.8289D-02 2.0111D-03-2.6794D-02 1.0610D-02 3.0960D-03-3.6794D-02</td>
</tr>
<tr>
<td>73</td>
<td>1.4610D+05 5.0053D+03 7.2000D+03 1.7683D-02 2.6170D+03 2.7494D-02</td>
</tr>
<tr>
<td>79</td>
<td>1.0311D-02 1.3219D-03 1.7494D-02-1.0801D+05 6.8000D+02-5.0370D+02</td>
</tr>
<tr>
<td>85</td>
<td>-5.5218D-03 2.5822D-02-6.9958D-04 0.0000D+00 2.3558D-02 0.0000D+00</td>
</tr>
<tr>
<td>91</td>
<td>2.9008D-04-6.8656D-03 5.0370D-02 2.5822D-02-5.5218D-03 6.9959D-04</td>
</tr>
<tr>
<td>97</td>
<td>2.4230D-02 0.0000D+00 0.0000D+00 2.0601D+05 6.8000D+02 7.2000D+03</td>
</tr>
<tr>
<td>103</td>
<td>1.0500D-02 9.8001D-03-3.1344D-02 0.0000D+00 1.2664D-02-4.1344D-02</td>
</tr>
<tr>
<td>109</td>
<td>1.9230D+05 6.8000D+02 7.2000D+03 9.8001D-03 1.0500D-02 3.1344D-02</td>
</tr>
<tr>
<td>115</td>
<td>0.0000D+00 1.3139D-02 2.1344D-02</td>
</tr>
</tbody>
</table>

This data is for element number 97 at load step number 190 and at the 50th (or last) iteration. Based on the structure of data sets in Appendix B Section 8, the underlined data is the output for the third ply (in this case that would be the 0° ply). The number 2.9008D+04 means that \( \sigma_{11} \), the normal stress in the fiber direction, is 29,008 psi. This is 10% of the failure strength because we know that fiber fracture has occurred from the value of \( \sigma_{11} \), 2.4230D-02.

An example of the nodal displacements for the first nine nodes are listed below. Each row of data belongs to one node. The order of data is such that the x-direction translation is listed first, then the y and z translations followed by the rotations about the x, y, and z axes, respectively.

Record DATA.1 of dataset DISPM.EX47.190.50

<table>
<thead>
<tr>
<th>Record</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.9339E-02 3.7506E-03 0.0000E+00 0.0000E+00 0.0000E+00</td>
</tr>
</tbody>
</table>

26
<table>
<thead>
<tr>
<th></th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
<th>Value 4</th>
<th>Value 5</th>
<th>Value 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>1.9377E-02</td>
<td>3.2392E-03</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
</tr>
<tr>
<td>13</td>
<td>1.9422E-02</td>
<td>2.7315E-03</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
</tr>
<tr>
<td>19</td>
<td>1.9666E-02</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
</tr>
<tr>
<td>25</td>
<td>1.9475E-02</td>
<td>2.2355E-03</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
</tr>
<tr>
<td>31</td>
<td>1.9656E-02</td>
<td>4.2360E-04</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
</tr>
<tr>
<td>37</td>
<td>1.9532E-02</td>
<td>1.7568E-03</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
</tr>
<tr>
<td>43</td>
<td>1.9628E-02</td>
<td>8.5391E-04</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
</tr>
<tr>
<td>49</td>
<td>1.9585E-02</td>
<td>1.2969E-03</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
<td>0.0000E+00</td>
</tr>
</tbody>
</table>

How often such data is stored in data sets is up to the user and is controlled by the NPRT variable in the runstream and the *copy 1 command in the procedure pffdm.clp.
References


Table 1. Material Properties of Unidirectional Ply of IM7/5260

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{11}$ (Msi)</td>
<td>22.16</td>
</tr>
<tr>
<td>$E_{22}$ (Msi)</td>
<td>1.26</td>
</tr>
<tr>
<td>$G_{12}$ (Msi)</td>
<td>0.75</td>
</tr>
<tr>
<td>$v_{12}$</td>
<td>0.333</td>
</tr>
<tr>
<td>$t_{ply}$, in.</td>
<td>0.006</td>
</tr>
<tr>
<td>$\varepsilon_{11crit}$</td>
<td>0.015</td>
</tr>
<tr>
<td>$\varepsilon_{22crit}$</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Growth law parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k$</td>
<td>1.1695</td>
</tr>
<tr>
<td>$\bar{n}$</td>
<td>5.5109</td>
</tr>
<tr>
<td>$d_{para}$</td>
<td>3.8686 x 10^7</td>
</tr>
</tbody>
</table>

Table 2. Maximum Fatigue Loads Employed in Sample Calculations

<table>
<thead>
<tr>
<th>Layup</th>
<th>Specimen geometry</th>
<th>Maximum fatigue load (R = 0.1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0/±45/90]_s</td>
<td>unnotched</td>
<td>3300 lb/in</td>
</tr>
<tr>
<td></td>
<td>open hole</td>
<td>2000 lb/in</td>
</tr>
<tr>
<td>[0/90]_s</td>
<td>unnotched</td>
<td>2480 lb/in</td>
</tr>
<tr>
<td></td>
<td>open hole</td>
<td>1572 lb/in</td>
</tr>
</tbody>
</table>

Table 3. Lamina Material Properties

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_{11}$ (Msi)</th>
<th>$E_{22}$ (Msi)</th>
<th>$G_{12}$ (Msi)</th>
<th>$\nu_f$ (%)</th>
<th>$\nu_{12}$</th>
<th>$\varepsilon_{12}$ (°)</th>
<th>$\varepsilon_{cr}$ (°)</th>
<th>$\gamma_{12}$ (°)</th>
<th>$\gamma_{cr}$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a_AS4/8553-40</td>
<td>19.7</td>
<td>1.31</td>
<td>0.65</td>
<td>58.2</td>
<td>0.34</td>
<td>0.87</td>
<td>1.56</td>
<td>1.00</td>
<td>10.00</td>
</tr>
<tr>
<td>a_AS4/938</td>
<td>19.6</td>
<td>1.36</td>
<td>0.72</td>
<td>57.2</td>
<td>0.32</td>
<td>0.50</td>
<td>1.48</td>
<td>1.00</td>
<td>10.00</td>
</tr>
<tr>
<td>b_AS4/3501-6</td>
<td>20.0</td>
<td>1.36</td>
<td>0.87</td>
<td>60.3</td>
<td>0.28</td>
<td>0.50</td>
<td>1.50</td>
<td>1.00</td>
<td>10.00</td>
</tr>
</tbody>
</table>

a $E_{11}$, $E_{22}$, $G_{12}$, $\nu_{12}$, $\varepsilon_{12}$, and $\varepsilon_{cr}$ measured by Boeing (ref. 16)

b $E_{11}$, $E_{22}$, $G_{12}$, $\nu_{12}$, $\nu_{90}$, $\varepsilon_{cr}$, and $\varepsilon_{cr}$ measured by Lagace et al. (ref. 17)

* $\gamma_{12}$ and $\gamma_{cr}$ are approximations from Iosipescu shear test data (ref. 18)
Figure 1. Progressive failure analysis scheme.
Figure 2. Conditions and model of cross-ply laminated composite plate. All linear dimensions are in inches.
Figure 3. Averaged distribution of mode I matrix crack damage variable $\alpha_{22}^M$ in 90° plies.

Figure 4. Distribution of stress component normal to fibers in 90° plies.
Figure 5. Global displacements resulting from load redistribution.

Figure 6. Finite element model for a laminate with a central circular hole.
Figure 7. Stiffness loss of IM7/5260 laminates with central circular notch.

Figure 8. Finite Element Mesh of the Center-Crack Tension Panel.
Residual Strength (ksi)

Figure 9. Residual Strength Predictions for the Center-Crack Tension Panels.

Figure 10. Load Carrying Capability After Ply Failure.
Progressive Damage Analysis of Laminated Composite (PDALC) - (A Computational Model Implemented in the NASA COMET Finite Element Code) Version 2.0

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Hampton, VA 23681-2199

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A method for analysis of progressive failure in the Computational Structural Mechanics Testbed is presented in this report. The relationship employed in this analysis describes the matrix crack damage and fiber fracture via kinematics-based volume-averaged damage variables. Damage accumulation during monotonic and cyclic loads is predicted by damage evolution laws for tensile load conditions. The implementation of this damage model required the development of two testbed processors. While this report concentrates on the theory and usage of these processors, a complete listing of all testbed processors and inputs that are required for this analysis are included. Sample calculations for laminates subjected to monotonic and cyclic loads were performed to illustrate the damage accumulation, stress redistribution, and changes to the global response that occurs during the loading history. Residual strength predictions made with this information compared favorably with experimental measurements.

Composites; Damage tolerance; Fracture mechanics; Progressive damage; Residual strength