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RESTRAN: Residual Strength  
Analysis of Impact Damaged  
Composite Laminates  
Volume II: User's Manual

by Erik Saether

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## RESTRAN: Residual Strength Analysis of Impact Damaged Composite Laminates Volume II: User's Manual

Erik Saether

Weapons and Materials Research Directorate, ARL

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## Abstract

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A general predictive methodology for determining residual strength in impact damaged composite laminates has been developed and incorporated into a computer code designated RESTRAN (REsidual STrength ANalysis). RESTRAN is a finite element based design tool that can analyze composite structures with arbitrary three-dimensional (3-D) geometry, loading and support conditions, material properties, and initial material and delamination damage. Material failure modes are predicted using a robust suite of failure criteria and damage laws. Structural failure due to sequential sublaminates buckling of delaminated layers is also accounted for. A progressive failure analysis is performed until ultimate structural failure is predicted, thereby yielding an estimate of the residual strength. This report contains a user's manual for the RESTRAN program with complete descriptions of input statements and program output. Several examples are shown to illustrate the use of the RESTRAN computer code.

## Table of Contents

	<u>Page</u>
List of Figures .....	vii
List of Tables .....	ix
1. Introduction .....	1
2. RESTRAN Input Statements .....	1
2.1 Executive Control .....	3
2.1.1 Preliminary Model Evaluation .....	3
2.1.2 Analysis Procedures .....	3
2.2 System Resources .....	5
2.3 Model Description .....	5
2.3.1 Node Definition and Generation .....	5
2.3.2 Element Definition and Generation .....	7
2.3.3 Node and Element Sets .....	8
2.3.4 Boundary Constraints and Load Conditions .....	9
2.3.5 Model Generation .....	11
2.3.6 Material Property Input .....	17
2.3.6.1 Linear Elastic Material Moduli .....	17
2.3.6.2 Nonlinear Elastic Material Moduli .....	18
2.3.7 Failure Mode Selection .....	21
2.3.7.1 Material Failure Criteria .....	21
2.3.7.2 User-Defined Failure Criteria .....	22
2.3.8 Material Damage Laws .....	24
2.3.8.1 Damage Law Selection .....	24
2.3.8.2 User-Defined Damage Law .....	25

2.3.9	Initial Damage Description .....	25
2.3.9.1	Initial Material Damage .....	25
2.3.9.2	Delamination Description .....	27
2.3.10	Coordinate Transformation .....	28
2.4	Execution Modification .....	30
2.4.1	User-Defined Buckling Mode Interpretation .....	30
2.4.2	Element Failure Exclusion .....	33
2.4.3	Job Execution Status .....	33
2.5	Output Control .....	34
2.6	Graphics .....	35
2.7	Miscellaneous .....	37
3.	RESTRAN Error Checking .....	38
3.1	Tests on Initial Input .....	38
3.2	Run-Time Error Determination .....	38
4.	Input File Format .....	38
5.	Computer Implementation of RESTRAN .....	38
6.	Computational Efficiency .....	39
7.	Numerical Examples .....	40
7.1	Linear Static Analysis .....	40
7.1.1	Input Data File for a Linear Static Problem .....	41
7.1.2	Timing Summary of Job Execution .....	47
7.1.3	Linear Static Solution Output File .....	48
7.2	Linear Buckling Analysis .....	55
7.2.1	Input Data File for a Linear Buckling Problem .....	56

7.2.2	Solution Timing Summary for Linear Buckling Analysis .....	62
7.2.3	Linear Buckling Solution Output File .....	63
7.3	Residual Strength Analysis .....	70
7.3.1	Input Data File for a Residual Strength Problem .....	72
7.3.2	Output Data File for a Residual Strength Problem .....	77
7.3.3	Graphical Output using MATHEMATICA .....	86
8.	Conclusion .....	89
9.	References .....	91
	Appendix A: Sample User-Defined Subroutine to Compute Nonlinear Material Properties .....	93
	Appendix B: Sample User-Defined Subroutine to Compute Material Failure .....	99
	Appendix C: Sample User-Defined Subroutine to Assign Initial Material Damage .....	105
	Appendix D: Sample User-Defined Subroutine to Interpret Buckling Modes .....	109
	Appendix E: Sample User-Defined Subroutine to Assign Material Degradation Due to Buckling .....	113
	Appendix F: Sample Generated MATHEMATICA Input File .....	117
	Appendix G: Sample User-Defined Subroutine to Output Model Data for Graphical Display .....	121
	Distribution List .....	127
	Report Documentation Page .....	145

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## List of Figures

<u>Figure</u>	<u>Page</u>
1. One-dimensional node generation .....	6
2. Two-dimensional node generation .....	7
3. Hexahedral element geometry .....	7
4. Generation of a one-, two-, or three-dimensional field of elements .....	8
5. Translational degrees of freedom .....	10
6. Convention for element face numbering .....	11
7. Controlling the level of discretization using the NDIV parameter .....	13
8. Discretization of outer corner regions .....	13
9. Variable delamination size through thickness .....	13
10. Relative model sizes .....	15
11. Selection of quadrants to model symmetry conditions .....	15
12. Rotated plate in space with an open elliptical hole .....	15
13. Sample format of file <i>restran.elg</i> .....	16
14. Nonlinear elastic material .....	19
15. <b>USERNL</b> subroutine format .....	19
16. Storage format for stresses and strains .....	20
17. Calculation of secant moduli .....	20
18. Linear approximation to nonlinear elastic moduli .....	21
19. <b>USERFC</b> subroutine format .....	23
20. <b>USERID</b> subroutine format .....	26
21. Global (x,y,z), element (x',y',z'), and local ( $\bar{x}$ , $\bar{y}$ , $\bar{z}$ ) coordinate systems .....	28
22. Local coordinate system generation .....	29

23.	Complex delamination states .....	30
24.	<b>USERB1</b> subroutine format .....	31
25.	<b>USERB2</b> subroutine format .....	32
26.	Format of user-defined subroutine <b>USRGRF</b> .....	36
27.	MAXRAM parameter in RESTRAN .....	39
28.	Model used for linear static analysis .....	41
29.	Deformation under applied static loads .....	55
30.	Model used for linear buckling analysis .....	56
31.	Global and local buckling mode shapes .....	70
32.	Geometry and loading an elastically supported composite plate .....	71

## List of Tables

<u>Table</u>		<u>Page</u>
1.	RESTRAN input statements. ....	2
2.	Parameters required for various failure criteria. ....	22
3.	Cascade failure in residual strength analysis. ....	88

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# 1 Introduction

The development of the RESTRAN (*RE*sidual *ST*rength *AN*alysis) computer program represents a significant contribution as a design tool to predict the reduction in structural strength due to impact damage. The numerical finite element basis provides the greatest versatility for modeling structures of arbitrary geometry, support, and load conditions while accounting for both material and structural failure modes. Although designed specifically for the analysis of advanced fibrous composites, the support of a layered media permits additional material systems to be modeled such as sandwich-type constructions, piecewise linear approximations of homogeneous materials with varying properties along a thickness direction, and isotropic materials modeled as a single layer. For composites, material failure may be differentiated into fiber and matrix modes, while structural failure involves buckling of local sublaminates due to the presence of delamination damage. In addition to built-in features, a suite of user-defined subroutine interfaces are available for problem-specific tailoring of the analysis. Optional graphics may be requested and output as input files for display using MATHEMATICA [1], TECPLOT [2], or in a user-defined format. The analysis capabilities of RESTRAN are thoroughly discussed in the Theoretical Manual [3]. The current report details the use of the RESTRAN code. Complete descriptions are given of the program input statements to define the structural geometry, support and load conditions, material behavior, and solution procedures. Finally, a series of demonstration problems showing program input and output are provided to illustrate the use and capabilities of RESTRAN.

## 2 RESTRAN Input Statements

The following sections detail the syntax and basic format of input statements available to describe the model geometry and invoke program options. Some degree of flexibility has been implemented in the parsing of these statements such that either upper or lower case letters can be used, and arbitrary space or comma delimiters can be used in listing statement options and data items. The basic format of all input statements is:

$$\begin{aligned} &*\text{STATEMENT}, \text{OPTION}_1 = \text{X}, \text{OPTION}_2 = \text{Y}, \dots, \text{OPTION}_n = \text{Z} \\ &\text{DATA}_1, \text{DATA}_2, \text{DATA}_3, \dots, \text{DATA}_n \end{aligned}$$

One requirement, however, is that the **\*STATEMENT** entry must begin in the first field in the record or line of the input file. The input statements may generally occur in any order and are parsed sequentially as contained in the input file. Statements may be repeated to supersede prior instructions or to append additional quantities to the input database such as nodes or elements.

In developing syntax for RESTRAN input, many of the primary statements such as node, element, boundary, and mesh generation are based on the syntax used in the commercial finite element analysis programs ABAQUS [4]. Other statements have a parallel in NASTRAN [5]. This was implemented so that preprocessor programs such as PATRAN [6], which facilitate the preparation of input for these commercial codes, could be used to create the majority of the input data for RESTRAN. The addition of a small set of RESTRAN-specific statements completes the input description to perform the various analysis options. The input statements supported are listed in Table 1.

Table 1: RESTRAN input statements.

STATEMENT	CATEGORY	PAGE	
* PREPASS	EXECUTIVE	3	
* SOLUTION		3	
* MEMORY ALLOCATION	SYSTEM RESOURCES	5	
* NODE	MODEL DESCRIPTION	5	
* NGEN		6	
* NFILL		6	
* ELEMENT		7	
* ELGEN		8	
* NSET		8	
* NSET2		8	
* ELSET		9	
* ELSET2		9	
* BOUNDARY		9	
* BOUNDARY2		9	
* CLOAD		10	
* PRESSURE		10	
* MODEL GENERATION		11	
* LAYER		17	
* MATERIAL		17	
* NONLINEAR MATERIAL		18	
* FAILURE CRITERION		21	
* DAMAGE LAW		24	
* INITIAL DAMAGE		25	
* DELAMINATION		27	
* POSTBUCKLED MATERIAL		27	
* ORIENTATION		28	
* DEFORMED GEOMETRY		29	
* EQUIVALENCE		29	
* INCLUDE		37	
* EXCLUDE ELEMENT		30	
* ENDDATA		30	
* PARAMETER USRBKL		EXECUTION MODIFICATION	31
* PARAMETER STATUS			33
* PARAMETER LAPFAIL	33		
* PARAMETER DIRECTORY	34		
* NODE PRINT	OUTPUT CONTROL	34	
* ELEMENT PRINT		34	
* PLY FAILURE PRINT		34	
* GRAPHICS		35	
* ECHO		37	
* HEADING		37	

## 2.1 Executive Control

Two statements are available to dictate executive control over the execution of RESTRAN. These statements are used to invoke preliminary model checking or initiate various analysis procedures.

### 2.1.1 Preliminary Model Evaluation

To perform a detailed check on the inputted model, the following executive control statement can be included anywhere in the input stream.

**\*PREPASS**

This statement causes RESTRAN to process the input file, perform error checking, assess memory requirements, and generate optional graphics of the model. This option overrides any other specified solution procedure and is used to assess the validity of the inputted model prior to performing any further analysis.

### 2.1.2 Analysis Procedures

Several solution procedures are available in RESTRAN. The executive control statement to request specific analysis procedures is given by

**\*SOLUTION, METH = PROC  
LIM<sub>1</sub>, LIM<sub>2</sub>, ACCEL  
PROC, ITERB, CVAL, MTOL, RTOL**

This statement selects the analysis procedure to be invoked by RESTRAN by assigning the mandatory parameter **METH**. Two linear analyses and three residual strength procedures may be selected. For linear static analysis, the method parameter is set as

**METH = LSA**

This directs RESTRAN to perform a linear static analysis to determine the basic elastic response of the structure. This option may be used to check displacements, stresses and strains, and an optional graphical depiction of deformation state, to assess applied loads and support conditions imposed on the model. In addition, the inclusion of the **\*PLY FAILURE PRINT** option will output first-ply failure statistics. The data list following the **\*SOLUTION** statement can be omitted.

**METH = LBA**

This option directs RESTRAN to perform a linear buckling analysis. This procedure may be used to analyze stability in a multiply-delaminated composite with all delaminations considered simultaneously. The predominant buckling mode can then be determined such that only a single, critical delamination may be input for a subsequent residual strength analysis. This would greatly speed execution because the residual strength algorithm will consider each delamination in sequence to automatically choose the critical delamination involved in sublaminates buckling. Optional graphical output can be selected to view the buckled mode shape. As with the **LSA**

solution procedure, the data list following the **\*SOLUTION** statement can be omitted.

To invoke an incremental/iterative residual strength analysis, the following options are available.

$$METH = \begin{cases} MTL \\ BKL \\ CMB \end{cases} \quad (1)$$

These options specify the range of failure modes to be accounted in the analysis. The **METH = MTL** parameter is used to specify that only material failure modes are to be processed. **METH = BKL** causes only sublaminar buckling failures to be analyzed, and **METH = CMB** directs the solution algorithm to consider both material and buckling failure modes.

The control parameters set basic iteration bounds in the residual strength analysis. **LIM<sub>1</sub>** is the maximum number of sequential load increments to be calculated in the prediction of residual strength. These loads are automatically determined as scalar factors applied to the initial set of external loads, and this limit may be set arbitrarily high. In certain cases where user-defined subroutines are used to degrade material properties undergoing failure, arbitrary degradation laws may be input which could, in some situations, cause internal tests performed by **RESTRAN** to avoid determining catastrophic failure. An upper bound on the number of total analysis cycles is therefore needed to stop runaway execution. **LIM<sub>2</sub>** is thus used to set the maximum number of iterations to converge the damage state at the current load level. For each iteration, failures are accounted and internal loads redistributed, which may cause additional failures to occur. Although most failure events tend to converge rapidly to an equilibrium damage state or cascade to ultimate structural collapse, this limit sets bounds on possible slow failure cascades which may warrant changes in other input parameters. The optional **ACCEL** parameter is used to accelerate the prediction of failure by encompassing larger groups of local failures per analysis cycle. **RESTRAN** automatically determines a scale factor applied to the vector of initial input loads to identically satisfy selected failure criteria for a critical ply in a particular element. This set of loads is then increased by a default value of 1% to cause other plies to fail which may have calculated failure indices near unity. The value of the **ACCEL** parameter overrides the default value such that, for example, an input value of 1.1 will cause all plies within 10% of the critical ply load to fail in the current cycle and thus accelerate the prediction of local failures. Care must be given in setting the value of this parameter, as it directly modifies the applied loads and therefore the predicted value of the residual strength. A value less than unity would preclude material failure and is therefore automatically reset to the default value. A large value would cause an overprediction of the residual strength and would have to be manually factored out of the final predicted strength measure by the user.

For residual strength analysis involving sublaminar buckling failure, **PROC** may be set equal to 'SIMULTANEOUS' to analyze all delaminations as a single group or 'ITERATIVE' to analyze each delamination separately and to iterate **ITERB** times to obtain a solution to the constrained buckling contact problem of an embedded delamination. To approximately solve the contact constraints involved with sublaminar buckling, iterations are performed to minimize the degree of interpenetration of a buckling mode to surrounding layers. This is performed by repeated solution of a linear buckling analysis of a particular delamination. The complete satisfaction of constraints is impractical and unnecessary to obtain reasonable local buckling loads. The parameters **CVAL**, **MTOL**, and **RTOL** specify specific treatment of delamination buckling and range from 0 to 1 due

to an internal normalization of the buckling mode vector. To limit the number of iterations and to specify a criteria for accepting a particular buckling mode, the fraction of nodes exhibiting a physical opening mode is required. The default value of **CVAL** is 0.9, indicating that a mode is accepted if only 10 % of nodes in the delamination plane are involved in nonphysical interpenetrating displacements. The entry **MTOL** indicates the ratio of maximum local modal displacements across the delamination plane with the maximum overall buckling mode displacement. This ratio is used to predict whether a mixed-mode instability is occurring wherein the delamination being analyzed may be undergoing an opening mode; however, the overall structure is exhibiting a greater deflection indicating a global mode. The default value for **MTOL** is 0.5. Setting this tolerance to zero will preclude a mixed global-local buckling mode from being predicted. Finally, the **RTOL** entry indicates the threshold below which the relative motion of opposing delamination surfaces are to be considered zero, and coincident nodes are to be condensed out of the current delamination plane. Unless specified, the default value for **RTOL** is 0.0.

## 2.2 System Resources

A single large array is used within RESTRAN to perform numerical operations on global-sized matrices. This in-core array is used to provide working storage to perform fast matrix operations with the bulk of generated internal data stored in external scratch files. In the normal default execution mode, RESTRAN uses a half bandwidth storage scheme internally. In order to run large jobs, an out-of-core solution algorithm may be invoked. This causes additional processing and will slow down the execution speed. The internal algorithm for memory usage is specified using the following entry:

```
*MEMORY ALLOCATION  
SType
```

where **SType** = '**BANDWIDTH**' for half bandwidth storage and '**OUT-OF-CORE**' for fully external storage. A storage format of '**FULL**' is recognized which causes all operations to be performed using full matrix storage. The only practical use of this feature is to speed execution of small problems in which the connectivity unavoidably yields a global stiffness matrix that is densely populated as opposed to sparse. If this statement is omitted, the default storage mode is **BANDWIDTH**.

## 2.3 Model Description

The following subsections detail the RESTRAN input statements used to define a structural model.

### 2.3.1 Node Definition and Generation

Nodes are input using the following statement:

```
*NODE, SETID = NSD  
  NODE ID, X, Y, Z
```

where the node number and position in global x, y, z coordinates are repeated for each node

in the model. The optional parameter **SETID** is used to include the specified nodes into a new or existing set. The node set ID must be numerical; general character strings are not supported.

To automatically generate nodes, two utility routines may be invoked to generate a linear and planar field of nodes. These are specified by the commands **\*NGEN** and **\*NFILL**.

To generate a linear array of nodes, the following statement is used

```
*NGEN, SETID = NGI  
  NODE1, NODE2, INCR
```

As shown in Figure 1, **\*NGEN** generates a line of nodes between two previously defined nodes, **NODE<sub>1</sub>** and **NODE<sub>2</sub>**. The increment value, **INCR**, specifies the increment in the node numbers of equally spaced nodes to be generated between the two existing nodes. This increment thereby specifies the number of nodes generated, which is given by

$$NUMGEN = (|NODE_2 - NODE_1| / INCR) - 1 \quad (2)$$

The generated nodes may optionally be assigned to a node set by including the **SETID** parameter. This option must be specified if the **\*NFILL** command is to be used with these generated nodes.

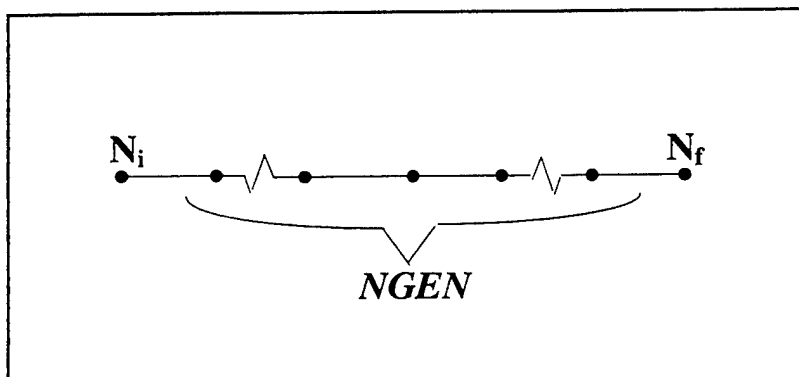


Figure 1. One-dimensional node generation.

A two-dimensional plane of nodes may be generated using the following statement:

```
*NFILL, SETID = NFD  
  NSET1, NSET2, NUMGEN, INCR
```

As shown in Figure 2, two lines of nodes with specified set identification numbers **NSET<sub>1</sub>**, **NSET<sub>2</sub>** are used to generate a plane of nodes. In generating the two-dimensional field of nodes, **NUMGEN** indicates the number of equally spaced nodes to be generated between bounding nodes in each set, and **INCR** indicates the increment in node numbering between each set. The node set parameter is optional.

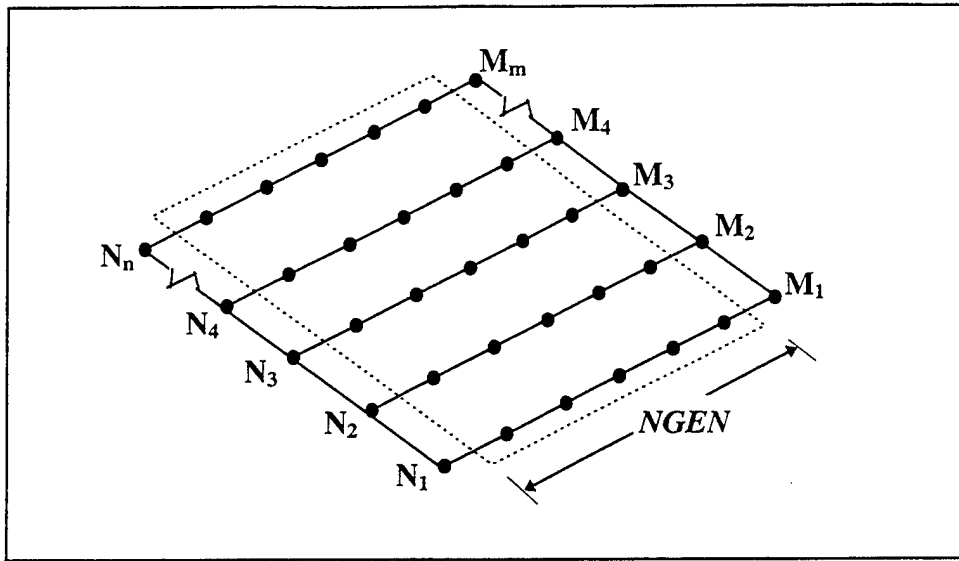


Figure 2. Two-dimensional node generation.

### 2.3.2 Element Definition and Generation

Element definitions are input using the following statement:

```
*ELEMENT, LAYUP = L, ORIENTATION = M, ELSET = EID
EID, N1, N2, N3, N4, N5, N6, N7, N8
```

The data list gives the element number and the node numbers of the nodes defining the element geometry as shown in Figure 3. The mandatory parameter, **LAYUP = L**, associates the elements with a particular input sublaminar. The optional orientation parameter designates the identification number of an inputted local coordinate system to be assigned to these elements. The **ELSET** parameter is also optional to assign each inputted element to an element set. The data list is repeated for all elements associated with the specified layup and local coordinate system. The **\*ELEMENT** data block is repeated for each group of elements with a unique assigned layup and spatial orientation.

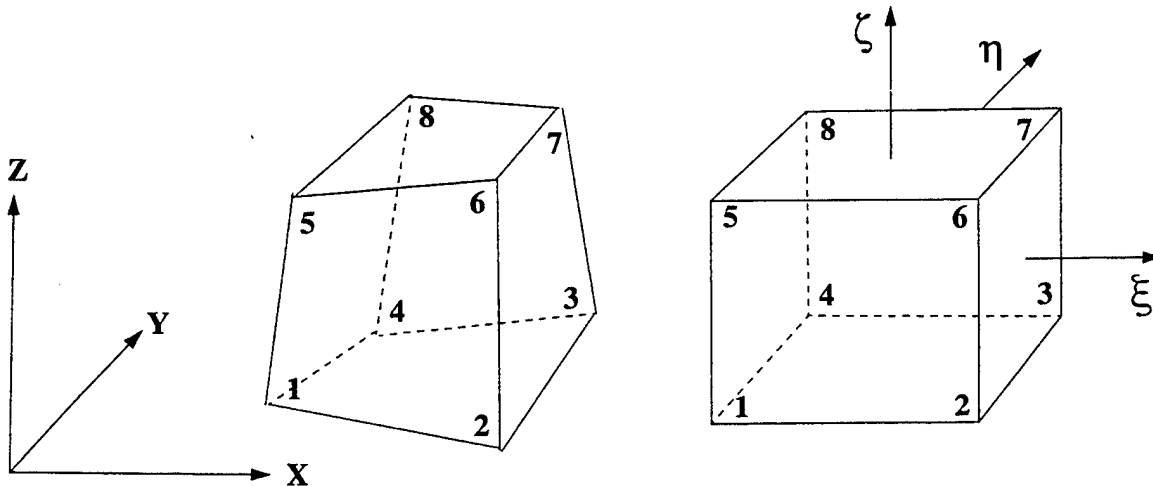


Figure 3. Hexahedral element geometry.

Automated generation of elements is supported by the following input statement:

```
*ELGEN, ELSET = EID  
ELID, NGNX, NODX, NIDX, NGNY, NODY, NIDY, NGNZ, NODZ, NIDZ
```

**ELID** indicates the starting element from which other elements are to be generated. The parameters **NGN<sub>X,Y,orZ</sub>** indicate the number of elements to be generated along the global X, Y, or Z directions, **NOD<sub>X,Y,orZ</sub>** indicates the increment in node numbers, and **NID<sub>X,Y,orZ</sub>** indicates the increment in element numbers along the X, Y, or Z directions, respectively. The optional parameter **ELSET** may be used to add the generated elements to a new or existing element set. Element generation is depicted in Figure 4.

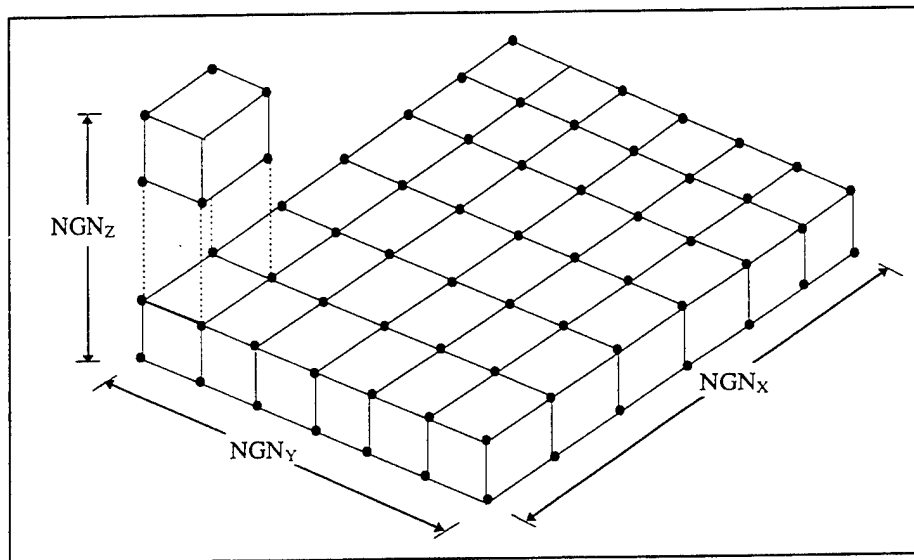


Figure 4. Generation of a one-, two- or three-dimensional field of elements.

### 2.3.3 Node and Element Sets

Node and element sets are used to define delamination planes, initial damage, and in print request statements. Node sets are declared using the following statements.

```
*NSET, SETID = NID  
N1, N2, ... ,Nk
```

Where **SETID = NID** gives the set identification number, and **N<sub>1</sub>, N<sub>2</sub>, ... ,N<sub>k</sub>** are the set of node numbers. The list of nodes can contain any number per line delimited by either commas or blanks and continued on an arbitrary number of additional lines. An alternate statement is available for nodes defined within bounds.

```
*NSET2  
NID, N1, N2
```

where **NID** is the set number, and  $N_1$  and  $N_2$  give an inclusive range of node numbers to be formed into a set. Only nodes within the given range that are actually used in the model will be stored. This line may be repeated to define multiple sets.

The **\*NSET** and **NSET2** statements can be used to exclusively define node sets or used in conjunction with the optional node set parameters on the **\*NODE**, **\*NGEN**, or **\*NFILL** statements. Depending on the order in which the input records are parsed, any statement can initiate the creation of a new node set while subsequent statements referencing the same node set will be accumulated into the existing set.

Element sets are defined using the following command.

```
*ELSET, SETID = EID  
E1, E2, E3, ... ,Ek
```

where **EID** is the assigned element set number, and  $E_1 \rightarrow E_k$  is the sequence of element numbers to be included in the set. The number of element ID's per line is arbitrary, and any number of additional lines may be used to complete the set definition.

Element sets may additionally be defined using the following command.

```
*ELSET2  
EID E1, E2
```

where **EID** is the assigned element set number, and  $E_1$  and  $E_2$  give a range of element numbers to be included in the set. An arbitrary number of element sets may be defined using this statement.

As with node sets, element sets may be defined or built up using any combination of **\*ELEMENT**, **\*ELGEN**, **\*ELSET**, and **\*ELSET2** statements.

### 2.3.4 Boundary Constraints and Load Conditions

Specific point constraints on displacement degrees of freedom may be applied to enforce fixity conditions at any node. Two input statements are available to apply these conditions.

```
*BOUNDARY  
NODE, DOF1, DOF2
```

where **NODE** is the node number. **DOF<sub>1</sub>** and **DOF<sub>2</sub>** specify the range of degrees of freedom to be fixed. This line may be repeated for all nodes with applied displacements constraints. The three degrees of freedom at each node are denoted by 1,2,3 and correspond to the global (x,y,z) coordinate or the **u**, **v**, and **w** translational motions with respect to the global coordinate system. This is shown in Figure 5. The second statement allows a node set to be used to define fixity conditions.

```
*BOUNDARY2  
NID, DOF1, DOF2
```

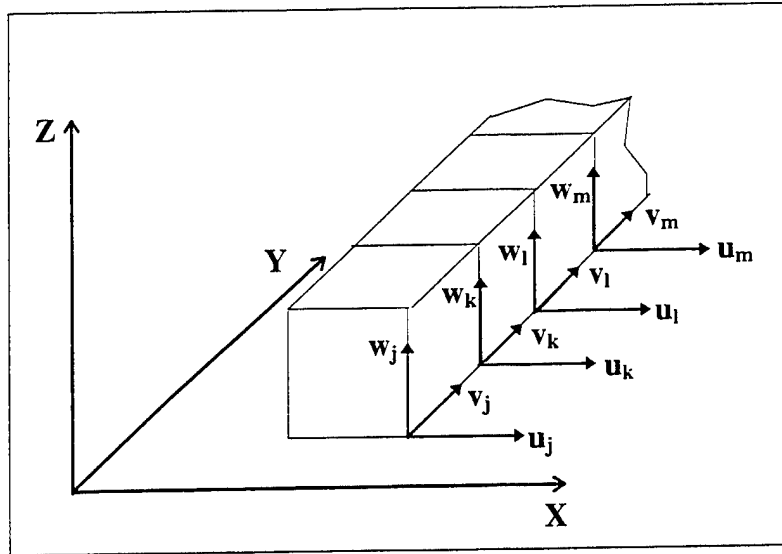


Figure 5. Translational degrees of freedom.

where **NID** is a node set number, and **DOF<sub>1</sub>** and **DOF<sub>2</sub>** define the range of degrees of freedom to be removed from each node in the set.

External loads may be applied as either concentrated forces at nodes or as pressure distributions over an element face. For concentrated loads the input entry is given by

**\*CLOAD**  
**NODE, DOF, MAG**

where **NODE** is the node number at the point of application, **DOF** is the direction of the load along the (1,2,3) degree of freedom directions which correspond to the global (x,y,z) coordinate system, and **MAG** is the magnitude of the load. The direction of the load is specified by the sign of the applied force. This line may be repeated for all nodes with applied concentrated loads.

Uniform distributed loading is applied using the **\*PRESSURE** statement. This internally integrates the applied pressures and forms a consistent load vector which is included with any other applied point loads. The syntax is given by

**\*PRESSURE**  
**ELID, F<sub>i</sub>, P<sub>o</sub>**

where **ELID** is the element number, **F<sub>i</sub>** is the element face number as shown in Figure 6, and **P<sub>o</sub>** is the applied pressure. The sign on **P<sub>o</sub>** dictates whether the distributed tractions are applied opposite to the direction of the outward normal to the face yielding compressive loads (**+P<sub>o</sub>**), or in the same sense as the outer normal yielding tensile loading (**-P<sub>o</sub>**).

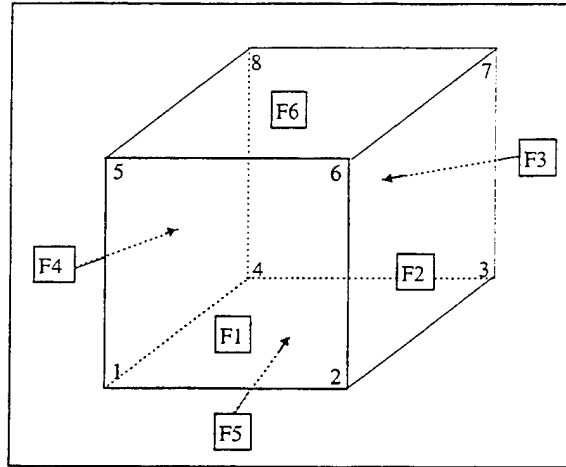


Figure 6. Convention for element face numbering.

### 2.3.5 Model Generation

It is expected that most models input to RESTRAN will be generated using preprocessing software such as PATRAN, which supports templates for output of a finite element model in various formats. The bulk of an input file typically consists of node and element definitions; for that reason, the adopted form of RESTRAN input syntax for node, element, force, and displacement constraint conditions is based on a simplified form of ABAQUS input formats. Thus, for example, output from a preprocessor in ABAQUS format can be cut and pasted into a RESTRAN input file with only minor modification, and only those statements specific to RESTRAN need be added to complete a job description. Alternatively, the **\*INCLUDE** statement can be used to temporarily redirect input to an alternate file containing statements to be used by RESTRAN.

However, in the absence of preprocessing software to facilitate the creation of a finite element model, an input option is available to create a simple layered plate model containing a central circular or elliptical region which may be assigned reduced moduli and/or used to define delamination planes. The use of this rudimentary feature has been assumed within a prepass mode after which the output may be incorporated into a complete RESTRAN input file. This statement is given as follows

```

*MODEL GENERATION
NDIV, NSURF, A, B, ND1, ND2, ND3, ND4
SFCT, NQ1, NQ2, NQ3, NQ4, NI, NORIENT
T11, T12, T13
T21, T22, T23
T31, T32, T33
1) SCLi, ZOi
2) MATIi, MATOi, NSIDi, NOFi, NEFi

```

where the various input parameters are identified next and will be discussed subsequently.

<b>NDIV</b>	=	Number of inner divisions
<b>NSURF</b>	=	Number of surfaces
<b>A</b>	=	Length of rectangle
<b>B</b>	=	Width of rectangle
<b>ND<sub>i</sub></b>	=	Number of divisions in outer regions
<b>SFCT</b>	=	Sizing parameter
<b>NQ<sub>i</sub></b>	=	Flag to remove elements in quadrants
<b>NI</b>	=	Flag to remove elements within ellipse
<b>NORIENT</b>	=	ID of orientation vector
<b>T<sub>ij</sub></b>	=	Coordinate transformation matrix
<b>SCL<sub>i</sub></b>	=	Scale factor for the <i>i</i> <sup>th</sup> surface
<b>Z0<sub>i</sub></b>	=	Z-Coordinate of surface
<b>MATI<sub>i</sub></b>	=	Layup number for material properties in inner elliptical region
<b>MATO<sub>i</sub></b>	=	Layup number for material properties in outer elliptical region
<b>NSID<sub>i</sub></b>	=	Node set number for nodes within elliptical region
<b>NOF<sub>i</sub></b>	=	Starting node sequence number
<b>NEF<sub>i</sub></b>	=	Starting element sequence number

The input mixes data for surfaces and layers such as starting node number, **NOF**, and starting element number, **NEF**, respectively. The number of surfaces for each node plane is equal to the number of layers plus one. Element data is assumed to correspond to the layer below the current surface. Therefore, input lines **1** and **2** are repeated for each surface starting at the top of the laminate and, for the last surface, arbitrary values for layer quantities associated with elements, such as material properties, must be entered to avoid null values on the input line but are not used internally.

The model is formed in several stages for each layer. The orientation is initially assumed parallel with the global (x,y,z) coordinates with the z-coordinate defining the thickness direction. First, an inner square region defined on  $-1 \leq x, y \leq 1$  with side dimensions equal to two units is meshed containing an inner circular region with a radius fixed at 0.65. The degree of discretization is determined by specifying the number of divisions, **NDIV**, as shown in Figure 7. Next, a larger outer square region is created using corner vertices located at  $(\pm \text{SFCT}, \pm \text{SFCT})$ , yielding a square with side dimensions  $2 \times \text{SFCT}$ . As shown in Figure 8, the corner regions are discretized according to the input values **ND<sub>1</sub>**, **ND<sub>2</sub>**, **ND<sub>3</sub>**, **ND<sub>4</sub>** which specify the number of divisions to be made in each region. For each surface, the scale factor **SCL<sub>i</sub>** may be used to shrink or expand the size of the delamination through the thickness. This value is applied to the node coordinates within the inner region such that  $(x', y') = \text{SCL}_i(x, y)$  for  $-1 \leq (x, y) \leq 1$ . Acceptable values for this magnification factor should be positive and less than or equal to unity. Figure 9 shows an enlarged side view of a four-layered plate with a varying delamination radius created by using **SCL** = 1.0, 0.9, 0.8, 0.7 and 0.6 in the five different surfaces. The relative size of the inner square to the outer square region can be varied through the selection of **SFCT** and **SCL**, and is given by the ratio **SCL/SFCT**. A final transformation is performed wherein the coordinates of the entire node field is multiplied by

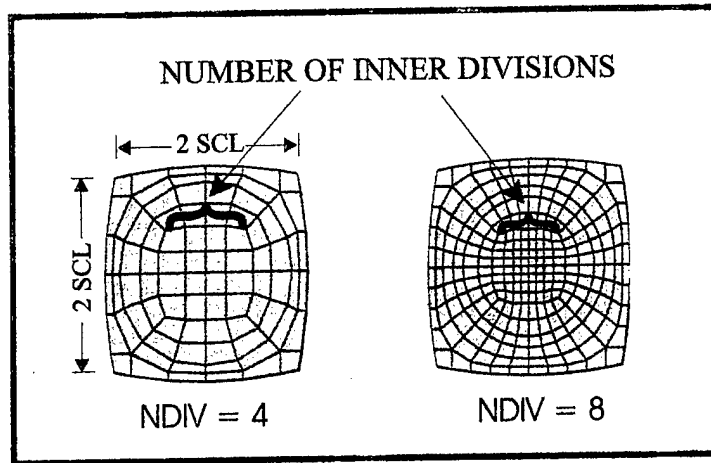


Figure 7. Controlling the level of discretization using the NDIV parameter.

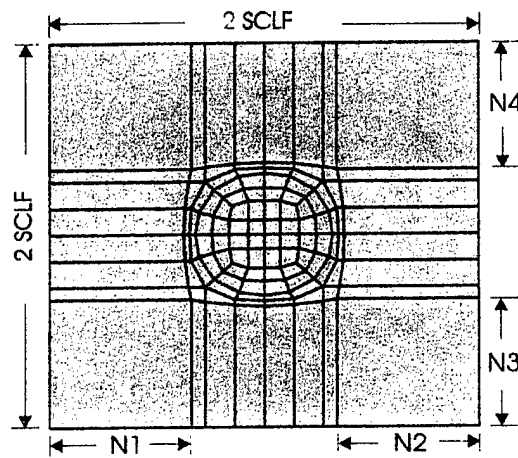


Figure 8. Discretization of outer corner regions.

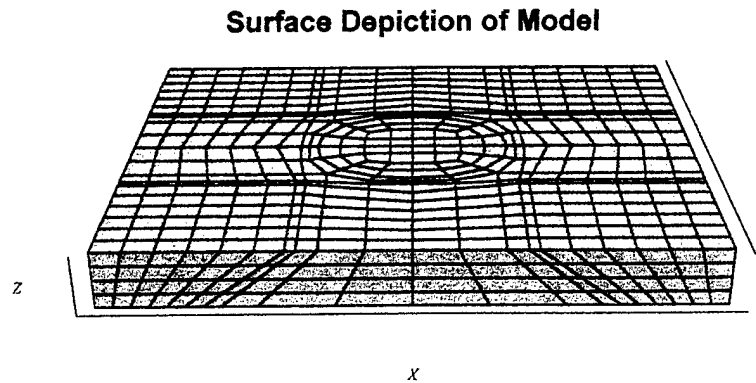


Figure 9. Variable delamination size through thickness.

the factor  $1/\mathbf{SFCT}$  and then scaled according to the stretch factors  $\mathbf{A}$  and  $\mathbf{B}$  to give the desired overall plate dimensions. For  $\mathbf{A} = \mathbf{B}$ , the inner region remains circular, while for  $\mathbf{A} \neq \mathbf{B}$ , different elliptical regions may be generated. As shown in Figure 10, various input values for  $\mathbf{SFCT}$ ,  $\mathbf{SCL}$ ,  $\mathbf{A}$ , and  $\mathbf{B}$  can yield significantly different models.

The starting numbers for nodes in each surface and elements in each layer must be specified such that the last generated node in a surface or element number in a layer does not exceed the starting number assigned to the node or element in the next surface or layer. For each surface, a node set number,  $\mathbf{NSID}$ , is input to identify the nodes within the inner circular region. These nodes are automatically stored as a node set and can be used to define an inner delamination node plane. For each layer, material property identification numbers are given for elements within and outside the elliptical region in the  $\mathbf{MATI}$  and  $\mathbf{MATO}$  parameters, respectively.

If symmetry can be used to reduce the size of the model, quadrants may be selected for removal using the flags  $\mathbf{NQ}_1$ ,  $\mathbf{NQ}_2$ ,  $\mathbf{NQ}_3$ ,  $\mathbf{NQ}_4$  in which a value of zero causes all elements and nodes in the corresponding quadrant to be deleted. The designation for the quadrants and models exploiting various symmetry conditions obtained using different values for the flags  $\mathbf{NQ}_i$  is shown in Figure 11. To create a model with an open hole, setting the modeling flag  $\mathbf{NI}$  equal to zero will cause all elements within the ellipse to be removed.

Finally, the coordinate transformation matrix is used to orient the model in space. This matrix maps the coordinates as

$$\begin{Bmatrix} \bar{x} \\ \bar{y} \\ \bar{z} \end{Bmatrix} = \begin{bmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{bmatrix} \begin{Bmatrix} x \\ y \\ z \end{Bmatrix} \quad (3)$$

Figure 12 shows an example with a transformation matrix given by

$$[T] = \begin{bmatrix} 0.0 & 0.0 & 1.0 \\ 0.0 & 1.0 & 0.0 \\ 1.0 & 0.0 & 0.0 \end{bmatrix} \quad (4)$$

together with the modeling option flag  $\mathbf{NI} = 0$  which creates a layered model of a vertical plate with an open elliptical hole.

This routine has been included to create a simple model and was designed to be used in a **\*PREPASS** execution mode with graphics outputted to show the generated model. The generated elements and nodes are output to the file *restran.elg*, which is formatted to list elements and nodes together with nodes identified along the various boundaries. This format is shown in Figure 13. Upon completion, the node and element definitions that are generated may be subsequently included into a new input file with all loads and boundary conditions specified in order to perform an analysis.

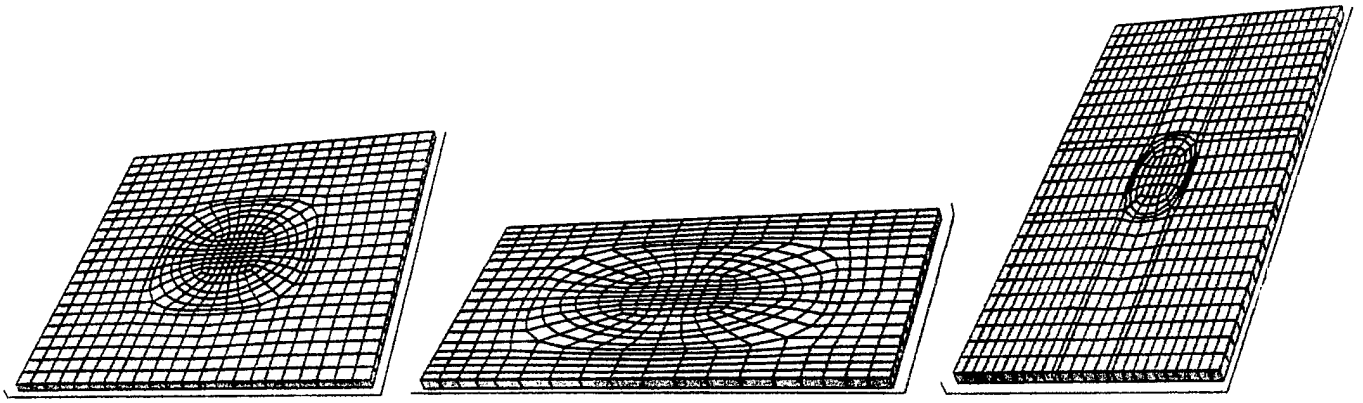


Figure 10. Relative model sizes.

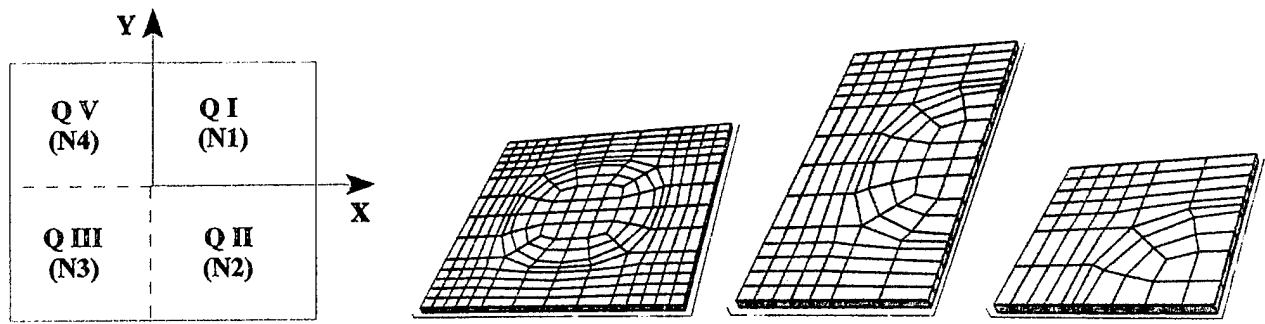


Figure 11. Selection of quadrants to model symmetry conditions.

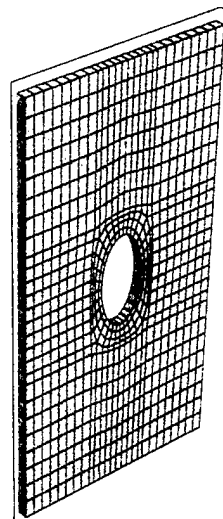


Figure 12. Rotated plate in space with an open elliptical hole.

```

*NODE
  1  0.000000E+00  0.000000E+00  0.300000E+01
  2  0.000000E+00  0.100000E+01  0.300000E+01
  3  0.200000E+01  0.100000E+01  0.300000E+01
  4  0.200000E+01  0.000000E+00  0.300000E+01
  5  0.200000E+01 -0.100000E+01  0.300000E+01
  6  0.000000E+00 -0.100000E+01  0.300000E+01
 10  0.000000E+00  0.266667E+01  0.300000E+01

*NSET, NSID =      55
 1002  1003  1004  1005  1006  1007  1008  1009
 1010  1011  1012  1013  1014  1015  1016  1017
 1018  1019  1020  1021  1022  1023  1024

*NSET, NSID =      60
 2002  2003  2004  2005  2006  2007  2008  2009
 2010  2011  2012  2013  2014  2015  2016  2017
 2018  2019  2020  2021  2022  2023  2024

*NSET, NSID =      65
 3002  3003  3004  3005  3006  3007  3008  3009
 3010  3011  3012  3013  3014  3015  3016  3017
 3018  3019  3020  3021  3022  3023  3024

*NSET, NSID =      70
 4002  4003  4004  4005  4006  4007  4008  4009
 4010  4011  4012  4013  4014  4015  4016  4017
 4018  4019  4020  4021  4022  4023  4024

*ELEMENT, LAYUP =      1
  1  1001  1004  1003  1002  1  4  3  2
  2  1006  1005  1004  1001  6  5  4  1
  5  1002  1003  1011  1010  2  3  11  10
  6  1003  1013  1012  1011  3  13  12  11
  7  1004  1014  1013  1003  4  14  13  3
  8  1005  1015  1014  1004  5  15  14  4
  9  1017  1016  1015  1005  17  16  15  5
 10  1018  1017  1005  1006  18  17  5  6

*ELEMENT, LAYUP =      2
 65  1058  1059  1075  1074  58  59  75  74
 66  1059  1060  1076  1075  59  60  76  75
 67  1060  1078  1077  1076  60  78  77  76
 68  1061  1079  1078  1060  61  79  78  60
 69  1062  1080  1079  1061  62  80  79  61
 70  1063  1081  1080  1062  63  81  80  62
 71  1064  1082  1081  1063  64  82  81  63

```

NODES CONTAINED ON OUTER SIDE BOUNDARIES

NODES ALONG (0.000E+00,0.100E+02) <-> (0.200E+02,0.100E+02)

Figure 13. Sample format of file *restran.elg*.

266	267	268	269	270	271	272	273	1266	1267
1268	1269	1270	1271	1272	1273	2266	2267	2268	2269
2270	2271	2272	2273	3266	3267	3268	3269	3270	3271

NODES ALONG (0.000E+00,-.100E+02) <-> (0.000E+00,0.100E+02)

2	6	10	18	26	34	42	50	58	66
74	86	105	120	135	150	221	236	251	266
1001	1002	1006	1010	1018	1026	1034	1042	1050	1058

NODES ALONG (0.200E+02,-.100E+02) <-> (0.200E+02,0.100E+02)

112	127	142	157	165	173	181	189	197	205
213	228	243	258	273	1112	1127	1142	1157	1165
1173	1181	1189	1197	1205	1213	1228	1243	1258	1273
2112	2127	2142	2157	2165	2173	2181	2189	2197	2205

Figure 13. Sample format of file *restran.elg* (continued).

### 2.3.6 Material Property Input

The complete specification of material properties encompasses the description of lamination layup, elastic moduli, failure criteria, initial material damage, and property degradation laws. The input of these quantities is described in the following subsections.

#### 2.3.6.1 Linear Elastic Material Moduli

The assumption of a layered material media in RESTRAN requires that a sequence of plies be specified even in the case of a homogeneous material. This is inputted through the following statement

```
*LAYER, LAYUP = M
    MATIDi, THKi, THETAi
```

where the mandatory parameter **LAYUP = M** designates the layer identification number which is matched to the **LAYUP = M** parameter on the **\*ELEMENT** data entry. **MATID<sub>i</sub>** is the identification number of a **\*MATERIAL** statement which gives the material moduli for the *i*<sup>th</sup> ply. The **THK<sub>i</sub>** and **THETA<sub>i</sub>** entries give the layer thickness and ply orientation angle with respect to the global or local coordinate system, respectively. This data line is repeated for each ply in the sublaminates.

Each layer may assume different orthotropic material properties with nine independent material moduli. These moduli are input using the following statement:

```
*MATERIAL, MATID = Mi
    E1, E2, E3, G13, G23, G12
    V13, V23, V12
```

where the subscripts (1,2,3) refer to the principle fiber coordinates for composite materials or

general material axes for homogeneous orthotropic materials.

### 2.3.6.2 Nonlinear Elastic Material Moduli

The support of nonlinear material behavior in RESTRAN is restricted to materials which exhibit a nonlinear-elastic stress-strain relationship. For residual strength characterization, nonlinear inelastic behavior such as plastic deformation is considered a failure mechanism and may be accounted through selected failure criteria and damage laws. Nonlinear elastic materials, which follow the same deformation path under loading and unloading as shown in Figure 14, are indicated through the following statement.

```
*NONLINEAR MATERIAL  
ITLIM, CVMTOL, CVBTOL  
P1, P2, P3, ... , PN
```

where **ITLIM** is the maximum number of iterations permitted to obtain a converged solution. **CVMTOL** is the tolerance of the difference in the norm of the residual load vector between iterations below which convergence of material failure is determined.

$$\|\Delta \mathbf{R}_i\| \leq \mathbf{CVMTOL} \quad (5)$$

**CVBTOL** is the corresponding prescribed tolerance for predicting convergence of buckling eigenvalues such that

$$\|\lambda_i - \lambda_{i-1}\| \leq \mathbf{CVBTOL} \quad (6)$$

The **\*NONLINEAR MATERIAL** statement additionally alerts RESTRAN to treat material properties specified on the **\*MATERIAL** entry as initial values and to subsequently access a user-defined subroutine denoted **USERNL** to obtain nonlinear moduli under increasing applied loads. A user-defined subroutine mode of input was selected as the most general and straightforward method of defining nonlinear elastic properties. As opposed to tabular entry formats, **USERNL** allows all material moduli to be varied independently provided that the resulting constitutive matrix remains positive definite. Also, specific moduli may be written as a function of individual stress or strain components, or based on combined measures of unit elastic energy or strain energy density. RESTRAN passes interpolated stress and strain data at each ply transformed into the local material coordinate system of the current element and requires that the user routine return scale factors to be applied to the initial moduli to approximate secant material properties. The input of the number of iterations and convergence tolerance parameters is optional, and default values of **ITLIM** = 5, **CVMTOL** = 0.01, and **CVBTOL** = 2 are internally assigned. The constants **P<sub>N</sub>** are optional input parameters that are passed into the user-defined subroutine and may be used to define secant properties. A maximum of 25 parameters may be input on as many additional lines as needed.

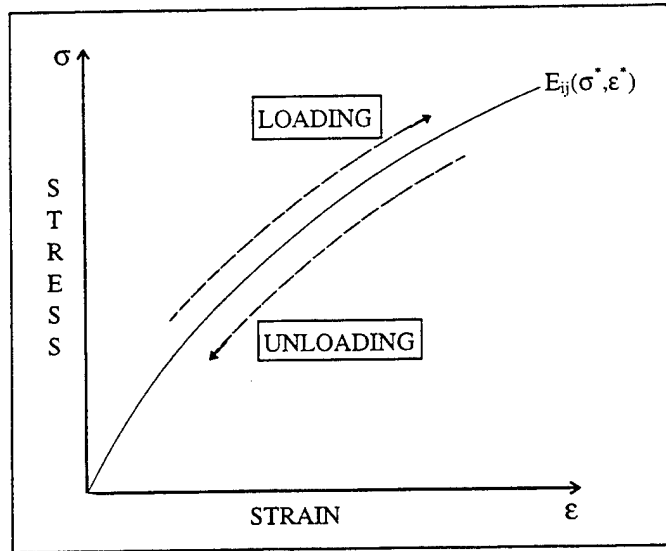


Figure 14. Nonlinear elastic material.

The subroutine interface written in FORTRAN is described next. The current implementation in RESTRAN assumes a single nonlinear material that can be described by a maximum of 25 parameters specified in the input file (any number can be 'built-in' to the user written subroutine). With proper consideration of the argument call interface, this and all user-defined subroutines may be developed in selected languages, compiled, and linked with the main RESTRAN executable prior to job execution. Figure 15 shows the required subroutine format.

```

SUBROUTINE USERNL ( STRESS,STRAIN,SXX,SYY,SZZ,TYZ,TZX,TTY,EXX,EYY,
1                   EZZ,GYZ,GZX,GXY,PARAM,THKN,ATHK,TLM,THETA,FE1,
2                   FE1,FE2,FE3,FG31,FG23,FG12,FV31,FV23,FV12,NORD )
C
C *****
C **                                     **
C **  USER-DEFINED ROUTINE TO COMPUTE SECANT  **
C **  MODULI IN NONLINEAR MATERIAL ANALYSIS  **
C **                                     **
C *****
C
C  IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
C  DIMENSION STRESS(27,6),STRAIN(27,6),PARAM(25)
C
C  *** USER DEFINED CODE FOR COMPUTING ***
C  *** SECANT MATERIAL MODULI          ***
C
RETURN
END

```

Figure 15. USERNL subroutine format.

This routine is called for each layer in each element for the calculation of material properties as a function of stress/strain state. Stresses and strains are passed to the user subroutine calculated at Gauss points and at the midpoint of each element layer rotated into the local coordinate system if one has been specified. Gauss-point tensor quantities are stored in the STRESS and STRAIN arrays for which the storage order depicted in Figure 16 is the same for both stresses and strains. Interpolated layer stresses are provided in the scalar variables  $SXX \rightarrow TXY$ , while corresponding strain values are stored in  $EXX \rightarrow GXY$ . The total laminate and layer thicknesses are given by the TLM and ATHK variables. The accumulated thickness to the current ply is stored in the THKN variable. THETA contains the orientation angle of the current ply. PARAM is an array containing input parameters to define the material nonlinearity. The user routine must return scalar factors  $FE1 \rightarrow FV12$  which RESTRAN uses to compute secant moduli as depicted in Figure 17 for the current load level.

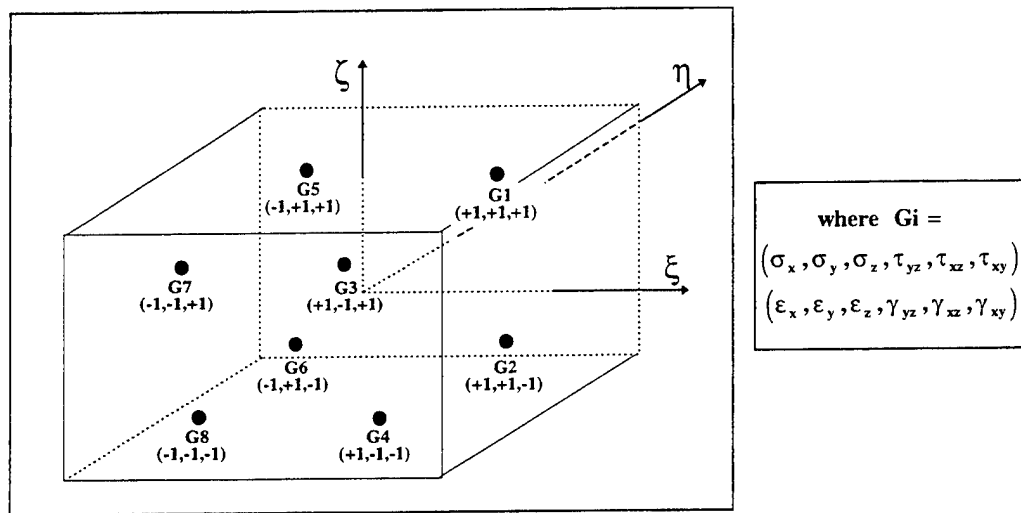


Figure 16. Storage format for stresses and strains.

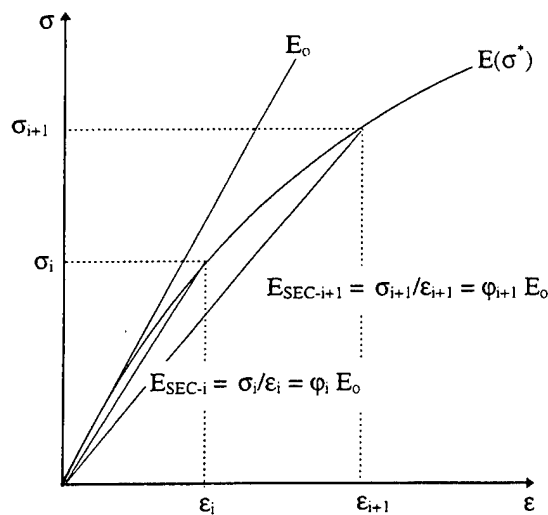


Figure 17. Calculation of secant moduli.

These factors are applied to the initial moduli as

$$\begin{aligned}
 \bar{E}_1^k &= F_{E1} E_{1o}^k & \bar{\nu}_{31}^k &= F_{V31} \nu_{31o}^k \\
 \bar{E}_2^k &= F_{E2} E_{2o}^k & \bar{\nu}_{23}^k &= F_{V23} \nu_{23o}^k \\
 \bar{E}_3^k &= F_{E3} E_{3o}^k & \bar{\nu}_{12}^k &= F_{V12} \nu_{12o}^k \\
 \bar{G}_{23}^k &= F_{G23} G_{23o}^k \\
 \bar{G}_{31}^k &= F_{G31} G_{31o}^k \\
 \bar{G}_{12}^k &= F_{G12} G_{12o}^k
 \end{aligned}
 \tag{7}$$

This user-defined subroutine must be compiled and linked into the RESTRAN executable prior to performing residual strength analysis. An example of the user-written subroutine **USERNL** for returning secant moduli is presented in Appendix A. Finally, it must be noted that if increased execution time in converging nonlinear material response is problematic or nonlinear properties are slight or inaccurately characterized, the nonlinear solution algorithm and the use of this subroutine may be avoided by inputting initial moduli as effective secant approximations based on measured ultimate failure strength and strain data as depicted in Figure 18.

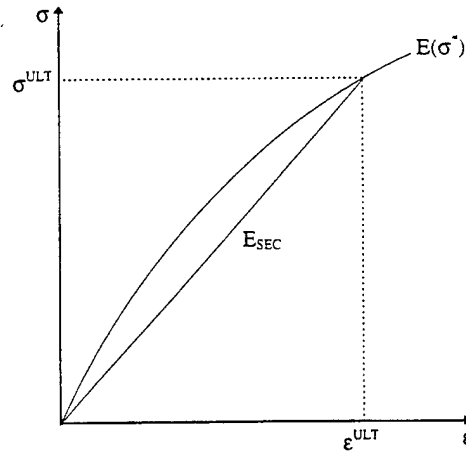


Figure 18. Linear approximation to nonlinear elastic moduli.

### 2.3.7 Failure Mode Selection

For residual strength prediction, the selection of the **METH** parameter on the **\*SOLUTION** entry determines whether material failure modes and/or buckling failure modes are to be calculated in the algorithmic assessment of progressive failure.

#### 2.3.7.1 Material Failure Criteria

RESTRAN supports a robust suite of material failure criteria. The specific failure criterion to be associated with an input material labeled **Mi** is specified using

```

*FAILURE CRITERION, MATID = Mi
FCTYPE
P1, P2, P3, P4, P5, P6
P7, P8, P9, P10

```

where **FCTYPE** is a character string which denotes the name of the criterion, and **P<sub>1</sub>** through **P<sub>10</sub>** are used to input up to 10 material constants required by the criterion. For the various input parameters, compressive material strengths may be input as positive or negative, the sign is internally corrected. The criteria designations and required constants are listed in Table 2.

Table 2: Parameters required for various failure criteria.

Criterion	Parameters
MAX-STRESS	$X_t, X_c, Y_t, Y_c, Z_t, Z_c, R, S, T$
MAX-STRAIN	$X_t, X_c, Y_t, Y_c, Z_t, Z_c, R, S, T$
BELTRAMI	$S^{ult}$
VON MISES	$S^{ult}$
HOFFMAN(1,2,3)	$X_t, X_c, Y_t, Y_c, Z_t, Z_c, R, S, T$
HILL(1,2,3)	$X_t, X_c, Y_t, Y_c, Z_t, Z_c, R, S, T$
TSAI-WU(1,2,3)	$X_t, X_c, Y_t, Y_c, Z_t, Z_c, R, S, T$
CHRISTENSEN	$X_t, X_c, K, \alpha$
FENG	$A_1, A_2, A_3, A_4, A_5, A_6$
HASHIN	$X_t, X_c, Y_t, Y_c, S$
USER-DEFINED	NRCHK, $P_1 \rightarrow P_{10}$

A complete description of the various failure criteria, including the required material constants, is presented in the RESTRAN theoretical manual [3]. In summary,  $X_t, X_c, Y_t, Y_c, Z_t,$  and  $Z_c$  are the normal tensile and compressive strengths in the principle 1, 2, and 3 directions, respectively, and  $R, S,$  and  $T$  are the shear strengths defined in the 23, 13, and 12 planes, respectively. For the isotropic Beltrami and Von Mises criteria,  $S^{ult}$  is the combined stress measure at which yielding occurs or the proportional limit reached. The constants required in the Christensen, Feng, and Hashin criteria are explained in the RESTRAN Theoretical Manual [3]. The variations on the Hoffman, Hill, and Tsai-Wu criteria involve specialization of these criteria to account for two-dimensional or three-dimensional stress states and whether they predict a single unspecified failure mode or differentiate between fiber and matrix modes. The variations are specified by the appended numerical suffix in which '1' designates 3-D single mode failure, '2' designates 2-D plane stress, single mode failure, and '3' specifies 3-D mixed mode failure. The user-defined option is discussed in the following subsection.

### 2.3.7.2 User-Defined Failure Criteria

Specifying a user-defined failure criteria alerts RESTRAN to access a user-supplied subroutine designated USERFC. The output from this subroutine is an unaltered or degraded set of material properties for the current ply depending on whether the user-defined criterion has predicted material failure. The input parameter NRCHK controls error checking in a subroutine driver for USERFC. If NRCHK is equal to zero, all checks will be bypassed. A nonzero entry will cause the following tests to be performed:

- 1) If moduli or Poisson ratios have increased, a warning will be issued and execution will con-

tinue.

2) If moduli have been set to negative values, an error message will be printed and execution will continue with moduli set equal to zero.

3) If scale factors are returned less than or equal to zero, an error message will be printed and an absolute value of the scale factor will be used in subsequent calculations.

The parameters  $P_1 \rightarrow P_{10}$  are optional and may be used to pass required data into the user-defined subroutine. The format of USERFC is shown in Figure 19.

```
      SUBROUTINE USERFC ( SGPTS,EGPTS,STRESS,STRAIN,PTHK,THETA,IPLY,
1          NELID,PARAM,E1,E2,E3,G12,G23,G31,V12,V23,
2          V13,EM,EF,NORD,NSTAT,NFSTAT,NACCS )
C
C *****
C **                                     **
C ** USER-DEFINED FAILURE CRITERION TO COMPUTE **
C ** MATERIAL FAILURE UNDER APPLIED LOAD **
C **                                     **
C *****
C
C      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
C      DIMENSION SGPTS(27,6),EGPTS(27,6),STRESS(6),STRAIN(6),PARAM(15)
C
C      *** SOURCE CODE FOR USER-DEFINED FAILURE ***
C      *** CRITERION AND DAMAGE LAW **
C
C      RETURN
C      END
```

Figure 19. USERFC subroutine format.

The input and output data passed into the routine through the argument list will be explained subsequently. STRESS, and STRAIN are vectors of stress and strain interpolated to the current ply and transformed into the local material coordinate system. The storage convention for the stress/strain vectors is given by  $[E_{11}, E_{22}, E_{33}, E_{23}, E_{31}, E_{12}]$ . SGPTS and EGPTS are arrays which store the untransformed stresses and strain components at the element integration or Gauss points. PTHK and THETA are ply thickness and orientation angle, respectively. IPLY and NELID are ply number and element number, respectively. The PARAM array contains a list of parameters from the \*FAILURE CRITERIA entry.  $E_1 - \nu_{31}$  are material moduli and Poisson ratios. EM, and EF are scale factors for matrix- and fiber-dominated failure modes. NSTAT is the ply status flag in which  $NSTAT = 1$  or  $2$  for matrix- or fiber-dominated failure mode, respectively, and  $NSTAT = 3$  for total ply failure. In addition, the option exists to set  $NSTAT = 4$ , which causes the element to be excluded from further degradation. The new failure status is returned in the variable NFSTAT.

NACCS is set to zero if no failure is predicted during the current iteration and to unity if failure is predicted. An example of a user-written subroutine for determining ply failure indices is presented in Appendix B.

This user-defined subroutine must be compiled and linked into the RESTRAN executable prior to performing residual strength analysis.

### 2.3.8 Material Damage Laws

Independent of the selected failure criterion, several types of material damage laws may be invoked to degrade material properties. These damage laws are available to selectively apply varying degrees of material degradation to simulate progressive ply damage modes. For complete generality, a user-written subroutine may be used.

#### 2.3.8.1 Damage Law Selection

A specific damage law is selected using the following statement.

```
*DAMAGE LAW, MATID = Mi
  APPLIED-DAMAGE-LAW
  P1, P2, P3, P4, P5, P6
```

where  $MATID = M_i$  associates the damage law with a material property set identification number. The following parameter, **APPLIED-DAMAGE-LAW**, may be given as 'NULL', 'MIXED', or 'PARTIAL' to invoke specific damage laws. Information regarding failure mode determination by the selected failure criterion is stored and used in applying the selected damage law. The parameters,  $P_1, P_2, P_3, P_4, P_5, P_6$ , may be used in the computing degraded material properties. Currently, only  $P_1$  is used when specifying a 'PARTIAL' degradation in properties. The 'NULL' option causes all properties of the current ply to be set to zero as

$$\begin{array}{lll} E_1 = 0.0 & G_{31} = 0.0 & \nu_{12} = 0.0 \\ E_2 = 0.0 & G_{23} = 0.0 & \nu_{13} = 0.0 \\ E_3 = 0.0 & G_{12} = 0.0 & \nu_{23} = 0.0 \end{array} \quad (8)$$

When selecting a single-mode failure criteria, specifying 'PARTIAL' will cause properties to first be degraded according to

$$\begin{array}{lll} E_1 = \alpha E_1 & G_{31} = \alpha G_{31} & \nu_{12} = \alpha \nu_{12} \\ E_2 = \alpha E_2 & G_{23} = \alpha G_{23} & \nu_{13} = \alpha \nu_{13} \\ E_3 = \alpha E_3 & G_{12} = \alpha G_{12} & \nu_{23} = \alpha \nu_{23} \end{array} \quad (9)$$

For differentiating between fiber and matrix failure modes, the options **MIXED** or **PARTIAL** may be selected. Both degrade selected material properties depending on predicted failure mode. For a partial degradation, a reduction factor,  $\alpha$ , is entered through the  $P_1$  parameter. In specifying a mixed mode degradation, the factor  $\alpha$  is automatically taken as zero. The degradation laws are given by the following.

For fiber failure mode

$$\begin{aligned} E_1 &= \alpha E_1 \\ G_{31} &= \alpha G_{31} \\ G_{12} &= \alpha G_{12} \\ \nu_{12} &= \alpha \nu_{12} \\ \nu_{13} &= \alpha \nu_{31} \end{aligned} \tag{10}$$

For matrix dominated failure

$$\begin{aligned} E_2 &= \alpha E_2 \\ E_3 &= \alpha E_3 \\ G_{23} &= \alpha G_{23} \\ \nu_{23} &= \alpha \nu_{23} \end{aligned} \tag{11}$$

For interlaminar shearing mode failure

$$\begin{aligned} G_{23} &= \alpha G_{23} \\ G_{31} &= \alpha G_{31} \end{aligned} \tag{12}$$

For inplane shearing failure mode

$$G_{12} = \alpha G_{12} \tag{13}$$

After initial partial ply failure is accounted, subsequent failure is assumed total.

### 2.3.8.2 User-Defined Damage Law

A user-defined damage law is applied through selecting the **USER-DEFINED** failure criterion on the **\*FAILURE CRITERIA** entry. The USERFC subroutine detailed in Figure 19 is then accessed to apply the specific failure criteria and return reduced material properties using the user-defined damage law encoded into this subroutine.

### 2.3.9 Initial Damage Description

RESTRAN has been specifically designed to predict residual strength of composite laminates which contain initial damage due to impact events. The input of the initial damage state is critical in the prediction of residual strength and is, perhaps, the most difficult data to obtain from a user's standpoint. The following section describes the input requirements.

#### 2.3.9.1 Initial Material Damage

The input of initial damage in RESTRAN is performed using the following data entry:

```
*INITIAL DAMAGE  
ELSET, DAMAGE-TYPE  
P1, P2, ... ,P10
```

where **ELSET** specifies an element set to which the initial damage is to be applied. Damage is assumed to apply equally to all plies in the element. Initial property degradation may be applied

by setting the the **DAMAGE-TYPE** parameter equal to 'FIBER', 'MATRIX', 'TOTAL', 'USER-DEFINED', or 'EXCLUDED' to specify the initial effects of various damage modes. For fiber failure, the following properties are degraded:

$$\begin{aligned}
 E_1 &= 0 \\
 G_{31} &= 0 \\
 G_{12} &= 0 \\
 \nu_{13} &= 0 \\
 \nu_{12} &= 0
 \end{aligned}
 \tag{14}$$

For matrix failure, the following properties are degraded:

$$\begin{aligned}
 E_2 &= 0 \\
 E_3 &= 0 \\
 G_{23} &= 0 \\
 \nu_{23} &= 0
 \end{aligned}$$

For total failure, all material properties are set equal to zero such that

$$\begin{aligned}
 E_1 &= 0.0 & G_{31} &= 0.0 & \nu_{12} &= 0.0 \\
 E_2 &= 0.0 & G_{23} &= 0.0 & \nu_{13} &= 0.0 \\
 E_3 &= 0.0 & G_{12} &= 0.0 & \nu_{23} &= 0.0
 \end{aligned}
 \tag{15}$$

Specifying 'USER-DEFINED' on the \*INITIAL DAMAGE entry, the input parameters,  $P_1 \rightarrow P_{10}$ , are passed into the user-defined subroutine USERID for initial calculation of reduced material properties to simulate initial damage. The format of USERID is shown in Figure 20.

```

SUBROUTINE USERID (PTHK,THETA,E1,E2,E3,G13,G23,G12,V13,V23,V12,
1          P1,P2,P3,P4,P5,P6,P7,P8,P9,NELID,IPLY,NSTAT )
C
C *****
C **                                     **
C **   USER-DEFINED SUBROUTINE TO ASSIGN   **
C **   INITIAL ELEMENT MATERIAL DAMAGE.     **
C **                                     **
C *****
C
C   IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
C   *** USER-DEFINED INITIAL MATERIAL ***
C   *** DAMAGE SOURCE CODE           ***
C
RETURN
END

```

Figure 20. **USERID** subroutine format.

PTHK and THETA are the current ply thickness and orientation angle, E1 through V12 are material moduli, P1 through P9 are input parameters provided on the \*MDAMAGE data entry, and NELID and IPLY are the current element and ply number. NSTAT is a ply failure status flag which is set to '1' or '2' for matrix or fiber (or general) failure, respectively. This permits additional material failure to be predicted. If total failure is predicted, NSTAT is set equal to '3'. This is usually assigned when the material moduli have been reduced to zero. If NSTAT is set equal to '4,' then the current damage state is maintained and further degradation is excluded. This may be enforced initially through a damage-type specification discussed next. An example of a user-written subroutine to assign initial material damage is contained in Appendix C.

The specification of 'EXCLUDED' is provided to indicate that the current element set is free of initial damage and is excluded from accumulating damage during subsequent residual strength analysis. This feature permits, in perhaps the easiest manner, an arbitrary set of elements to be declared failure free or indestructible. This option may be used to prevent elements from failing at which external loads are applied - which will normally terminate the analysis - or to avoid failing some internal structure which is deemed not to influence residual strength predictions. The use of this method for protecting elements or by the parameter LAMPFAIL is advocated over defining a set of elements with high material moduli or strength measures because these approaches could, in uncommon situations, cause these exaggerated element properties to be used in predicting ultimate failure, thus yielding incorrect measures of residual strength.

### 2.3.9.2 Delamination Description

A delamination is defined by a node set which identifies the node points lying within the delamination plane. RESTRAN automatically generates a corresponding set of coincident nodes and redefines element connectivity to sever connection between elements lying above and below this plane defined by the normal to the delamination surface. The input statement used to define delamination planes is given by

```
*DELAMINATION  
  NSET1, NSET2, NSET3, ... ,NSETn
```

where NSET<sub>i</sub> lists node set identification numbers defined in the \*NODE SET entry. Any number of node sets may be listed per line, and this line may be repeated as many times as needed to define the delaminations present in the model.

RESTRAN currently calculates buckling loads based on a linear stability analysis. To approximate structural behavior in the post-buckled regime, modifications to the material properties of those elements participating in the buckling mode must be specified. A full description of allowable post-buckled element response is discussed in the RESTRAN Theoretical Manual [3]. The following statement is mandatory for residual strength analysis which includes potential sublaminar buckling failure. The entry statement is given by

```
*POSTBUCKLED MATERIAL  
  CLFAC, PBFAC, NITER
```

where CLFAC specifies whether a constant load at buckling failure is to be approximately maintained in the buckled elements during the additional progressive failure analysis. This parameter

is a real number ranging from 0.0 to 1.0. For **CLFAC** = 0.0, no internal scaling is performed to approximate the constant load state, and for values greater than 0.0 up to 1.0, varying degrees of maintaining the internal element loads present at failure are enforced. The parameter **PBFAC** is used to reduce element material properties to account for buckling failure. This factor is used to reduce the constitutive properties as

$$[\bar{C}_{ij}] = \text{PBFAC}[C_{ij}] \quad (16)$$

Both **CLFAC** and **PBMFAC** may be specified to account for assumed post-buckled sublaminates behavior. For **CLFAC** > 0, the global stiffness matrix becomes a nonlinear function of loads at which prior sublaminates have undergone buckling failure, and an iterative procedure is invoked to converge subsequent eigen-analyses. The parameter **NITER** is used to specify the maximum number of iterations to be performed in calculating further sublaminates buckling loads.

### 2.3.10 Coordinate Transformation

An arbitrary coordinate system  $(\bar{x}, \bar{y}, \bar{z})$  may be specified for each element in **RESTRAN** to define a local reference system. This local coordinate system may be used to define ply material properties and account for any laminate orientation with respect to the element  $(x', y', z')$  system which is aligned with the global coordinate system. On output, element or layer stresses and strains may be output in this local system. These Cartesian coordinate systems are depicted in Figure 21.

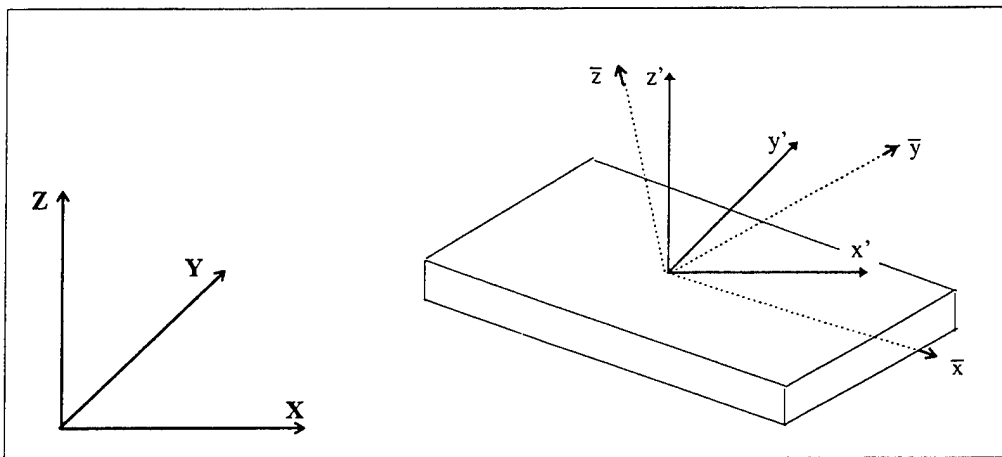


Figure 21. Global  $(x,y,z)$ , element  $(x',y',z')$  and local  $(\bar{x}, \bar{y}, \bar{z})$  coordinate systems.

A local coordinate system is defined using the following input statement

```
*ORIENTATION
CID, Vx1, Vx2, Vx3, Vy1, Vy2, Vy3
```

where **CID** is the coordinate system number, and  $V_{x_1} \rightarrow V_{y_3}$  are the components of two vectors defined in the global coordinate system that define a plane. If these two vectors are not orthogonal, the  $V_y$  vector is made orthogonal to  $V_x$  and the third coordinate  $V_z$  is determined from the vector cross product  $V_z = V_x \times V_y$ . The coordinate system is associated with selected elements using the **ORIENTATION** parameter on the **\*ELEMENT** data entry. The generation of a local coordinate system is depicted in Figure 22.

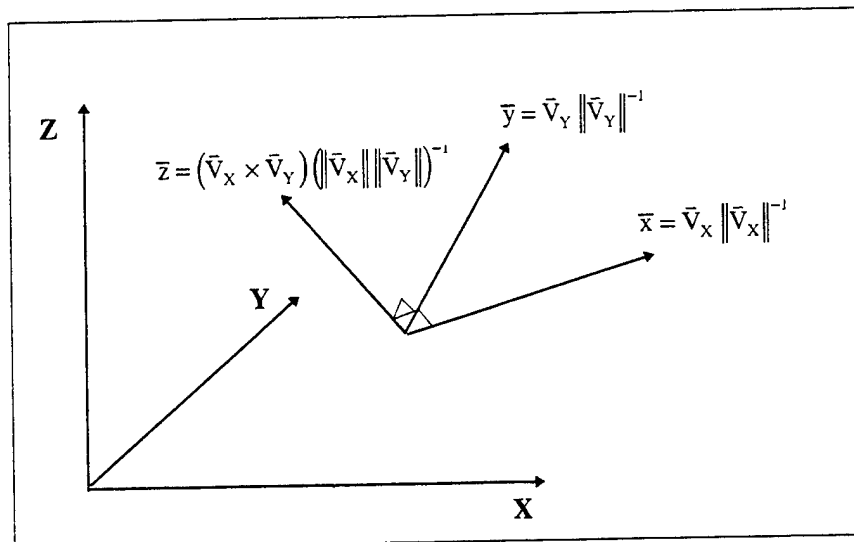


Figure 22. Local coordinate system generation.

To set a tolerance for deformed geometry check, the following statement is required:

**\*DEFORMED GEOMETRY**  
**TOL**

where **TOL** is the angular tolerance in degrees such that warnings will be issued if the calculated internal element angles,  $\theta$ , are outside the bounds

$$\text{TOL} \leq \theta \leq 180 - \text{TOL} \quad (17)$$

The default value for the tolerance is  $45^\circ$ . This will only alert the user to possibly incorrect element definitions or excessive element distortions but will not stop execution.

Nodes may be equivalenced through the following command

**\*EQUIVALENCE**  
**NSET1, NSET2**

where **NSET1** and **NSET2** are node set identifiers. Any number of node set pairs may be entered on separate lines and must be of equal size. This command specifies that each node in sequence in the first node set is to be replaced by the associated node in the second set. This operation may be used to join separate portions of a finite element model.

Elements may be excluded from failure using the following general statement

```
*EXCLUDE ELEMENT  
ELSET1, ELSET2, ... , ELSETn
```

where **ELSETi** are element set identifiers. Any number of element sets may be entered on each line. The total number of input sets is currently limited to 100. This command specifies that all elements specified in the various sets be excluded from failure. This feature may be used for models where only failure in a portion of the model is of interest, or regions of the overall model may be coarsely modeled and local failure in these regions is not to be accounted for in the prediction of residual strength.

To terminate parsing of the input file, the following statement is required:

```
*ENDDATA
```

Any statements following **\*ENDDATA** in the input file are ignored.

## 2.4 Execution Modification

Various modifications to the execution of solution procedures may be specified through the use of the **\*PARAMETER** statement.

### 2.4.1 User-Defined Buckling Mode Interpretation

RESTRAN has built-in algorithms for processing and interpreting sublaminar buckling modes. These algorithms, however, assume that delaminations form a planar surface. As described in the RESTRAN users manual [3], this surface need not be continuous, but a delamination which cannot be described by a sequence of plane sections cannot be processed. To overcome this limitation, a user-written subroutine may be used to analyze the buckling mode of complicated delamination configurations. Specialized interpretation of simultaneous buckling of multiple delaminations or stepped fracture surfaces, such as depicted in Figure 23, may then be performed.

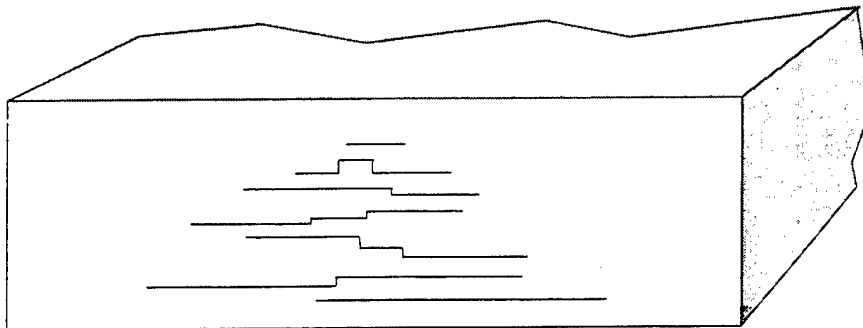


Figure 23. Complex delamination states.

To invoke the access of a user-written subroutine to analyze buckling modes, the following entry is included anywhere in the input stream.

**\*PARAMETER USRBKL**

This causes RESTRAN to bypass the existing interpretive algorithms and access two user-defined routines. These subroutine are designated **USERB1** and **USERB2**. The routine **USERB1** is accessed to analyze the current buckling mode shape and determine whether the buckling mode is acceptable and should be used as a possible instability failure mode. The format of this routine is given in Figure 24.

```

SUBROUTINE USERB1 ( EMODE,NELEM,NDSET,NXSET,NDID,EIGV,NUMNOD,
1                 NBPRC,LCNSL,ITERB,NUMEXC,NACC,NSURF,NINC,
2                 MDX0,MDX1,MAXB,MDX3 )
C
C *****
C **                                     **
C **   USER-DEFINED SUBROUTINE TO EVALUATE   **
C **   BUCKLING FAILURE MODE                 **
C **                                     **
C *****
C
C   IMPLICIT DOUBLE PRECISION(A-H,O-Z)
C
C   DIMENSION EMODE(MDX0,MAXB),NELEM(MDX3,12),NDSET(MDX1)
C   DIMENSION NXSET(MDX1)
C
C   *** SOURCE CODE FOR EVALUATING BUCKLING FAILURE ***
C
C   RETURN
C   END

```

Figure 24. **USERB1** subroutine format.

This routine is passed the mode shape contained in the emode array stored as

NODE POSITIVE NORMAL				NODE NEGATIVE NORMAL			
ID	U	V	W	ID	U	V	W
$N_1$	$U_1$	$V_1$	$W_1$	$M_1$	$U_1$	$V_1$	$W_1$
$N_2$	$U_2$	$V_2$	$W_2$	$M_2$	$U_2$	$V_2$	$W_2$
$N_3$	$U_3$	$V_3$	$W_3$	$M_3$	$U_3$	$V_3$	$W_3$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$N_n$	$U_n$	$V_n$	$W_n$	$M_n$	$U_n$	$V_n$	$W_n$

where the displacements are stored in each record as coincident node pairs,  $N_i$  &  $M_i$ , corresponding to the positive and negative normal to the delamination surface. NDSET is a linear array containing node numbers defining the current delamination, NXSET is an array to store NUMEXC nodes in the delamination set at which coincident nodes are to be removed to satisfy contact constraints. NDID is the node set ID, EIGV is the eigenvalue of the buckling mode, NODNUM is the total number of nodes in the model, NBPRC and ITERB store the buckling mode interpretation procedure flag and number of iterations, and LCNSL is the current iteration count for the delamination. NACC is set equal to zero if the mode shape is unacceptable and equal to one if this buckling mode is to be considered in determining the next failure mode. NSURF is a parameter that will be passed into the user-written subroutine USERB2 which will assess element failures in the buckled sublaminates. The format of the USERB2 user-defined subroutine is given in Figure 25.

```

SUBROUTINE USERB2 ( NELEM,NODSET,NSETI,NDELM,NDID,NELFL,
1                 ELFAC,NFAIL,NUMELF,NSURF,MAX1,MAX2,
2                 MAX3,MAX4 )
C
C *****
C **                                     **
C **      USER DEFINED SUBROUTINE TO DETERMINE      **
C **      ELEMENT FAILURE DUE TO BUCKLING           **
C **                                     **
C *****
C
C      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
C      DIMENSION NELEM(MAX3,12),NODSET(MAX2)
C      DIMENSION NELFL(MAX1),ELFAC(MAX1),NDELM(MAX4)
C
C      *** USER DEFINED CODE TO SET ELEMENT ***
C      *** FAILURE DUE TO BUCKLING           ***
C
C      RETURN
C      END

```

Figure 25. USERB2 subroutine format.

The array NELEM contains the element connectivity data. The format of this array is

NELID	N1	N2	N3	N4	N5	N6	N7	N8
-------	----	----	----	----	----	----	----	----

in which NELID is the element number, and  $N1 \rightarrow N8$  are the node numbers. These node numbers have been renumbered internally. To obtain the input node numbers, the conversion table, NSETI, can be used. The original input node number for the  $j^{th}$  node and the  $i^{th}$  element is obtained as

$$MPDE = MSETI(NELEM(I,J+1))$$

The nodset array contains the node ID's defining the current delamination. This array has the form:

$$NODSET(NSID, N1, N2, \dots, N_n)$$

where NSID is the node set ID, and  $N_i$  are the node numbers. The routine assigns element failure such that NELFM(I) stores the  $i^{th}$  element ID, and the property reduction factor for this element is stored in ELFAC(I). NDID is the delamination ID number. NUMELF is the total number of elements that have been determined to fail, which is set by the user subroutine.

Examples of user-written subroutines to interpret buckling modes and assign element failures are presented in Appendices D and E.

#### 2.4.2 Element Failure Exclusion

##### **\*PARAMETER LAPFAIL**

This parameter causes the elements to which external loads are applied to not be analyzed for failure. If an element is completely failed to which external forces are applied, the definition of residual strength used in RESTRAN involving a scalar multiplier to the initial load vector loses definition and the analysis is terminated. Although these particular elements may be identified and assigned moduli and/or strength ultimates to preclude failure, in certain cases where elements in this set are involved in the final catastrophic failure event, RESTRAN will use the material constants associated with these elements and predict an erroneously large strength measure before terminating. Thus, the use of this parameter is generally recommended but is maintained as an option.

#### 2.4.3 Job Execution Status

In running an iterative solution sequence which may involve lengthy execution times for large models, the following entry can be included to request an intermediate record of where execution is proceeding

##### **\*PARAMETER STATUS**

The additional output containing execution description and timing information is written to the file *restran.log*.

## 2.5 Output Control

Depending on the operating system used to run RESTRAN, partitions set up for scratch files may be inadequate to hold the temporary files generated during solution. A parameter may be input to direct the directory in which scratch files are to be stored. This parameter is given by

**\*PARAMETER DIRECTORY = FPATH**

where **FPATH** may be set equal to **CURRENT** or **SCRATCH**. If the **CURRENT** option is used, all temporary files are created in the current directory in the **fort.\*** format and must be manually deleted. The default is **SCRATCH**.

Nodal displacement output is specified using the following statement:

**\*NODE PRINT, NODSET = NDS  
NSTRING**

where **NSTRING** is a character string containing the characters **D** and/or **M** in any order to print displacements and/or buckling mode shapes, respectively, after convergence of the  $i^{th}$  load increment. The optional parameter **NDS** may be used to specify a node set number to limit output.

Output of element stress and strain data is requested using the statement

**\*ELEMENT PRINT, OUTPUT=LOC, SYSTEM=CRD, ELSET=NES  
ESTRING**

where **ESTRING** is a character string containing the characters **S** and/or **E** in any order to print stresses and/or strains, respectively. The optional character parameter **LOC** may be set to 'GAUSS' (default) or 'LAYER' for output at element Gauss points or at the midpoint of ply layers, respectively. The character parameter **CRD** may be set to 'LOCAL' for output in the local element coordinate system or 'GLOBAL' (default) for output in the global coordinate system. The integer parameter **NES** may be used to specify an element set to limit output.

In an iterative residual strength analysis, ply failure statistics can be output after convergence at each analysis cycle through the following statement:

**\*PLY FAILURE PRINT, NELSET=NPS**

where ply failures in each element are output showing the percentages of failures due to matrix, fiber, general, and buckling failure. The optional parameter **NPS** may be used to specify an element set number to limit output. This statement may also be used in a linear static analysis to cause the computation of element failure indices after stress recovery is completed. Output is limited to the element ply exhibiting the maximum failure index, the predicted failure mode, and the associated factor to scale the applied loads to cause failure of the ply. At the end of the list, the minimum scale factor is identified and may be considered a residual strength measure based on an overall first-ply failure criterion.

## 2.6 Graphics

The graphics option in RESTRAN has been developed with two primary aims. First, because of the specialized nature of RESTRAN in predicting progressive failure, the graphical information of interest is assumed to concentrate on the element level failure depictions together with overall deformation and/or local buckling mode shapes. This consideration limited the need to provide detailed graphical information on local stress/strain/deformation contours as is available using commercial pre- and postprocessing programs such as PATRAN, which are designed for general structural analysis. Secondly, a commercial software package in widespread use with graphical capabilities and available for use on computer platforms down to the PC level was also of interest. This would free the essential operations of the RESTRAN analysis program from being linked to built-in, platform-dependent graphics routines which would require several versions of the program to be released. Therefore, graphics output can be selected in two formats: MATHEMATICA and TECPLOT. Both are common commercial codes which offer a robust capability in processing primitive graphical objects such as polygonal surfaces and wireframe meshes. The generated output file can be directly input into the selected external code for viewing. The MATHEMATICA format offers more parameters for viewing the input structural model and progressive failure through a color coding and gray-scale scheme. This input file contains complete information on the structural geometry and can be edited to change any viewing parameters such as those effecting view orientation, lighting, and magnification factor for deformation/mode shape depiction. The graphics option is invoked by including the following statement in the input file:

```
*GRAPHICS, FORMAT = FMT  
NDFRM, NWTRN, GMFAC
```

where the parameter, **FMT**, is set equal to 'MATHEMATICA', 'TECPLOT', or 'USER-DEFINED' to specify the required format of the output file. Additional optional parameters are given by

```
NDFRM = 1 For only undeformed geometry  
          = 2 For both deformed and undeformed geometry  
NWTRN = 1 For a wireframe depiction in PREPASS  
          = 2 For surface depiction in PREPASS  
GMFAC = Magnification factor for deformed plots
```

In Prepass, RESTRAN will generate a solid or wireframe depiction of the model, and output is written to a file designated *restran.prp*. In any other solution option, RESTRAN will generate deformation/mode shape graphics for linear static or instability analysis. For residual strength analysis, a visual depiction of damage state and deformation plot will be generated at the end of each converged progressive failure cycle. This information is stored in a file designated *restran.grf*. These files may then be directly input into the selected graphics program to generate the graphical display. An example of a generated graphics file in MATHEMATICA format is presented in Appendix F.

The "USER-DEFINED" option causes RESTRAN to call the user-written subroutine USRGRF. The format of this subroutine is shown in Figure 26.

```

SUBROUTINE USRGRF (NELEM,COORDS,U,NSETI,NELNUM,NUMNOD,
1          NWTRN,NDFRM,GMFAC,SCALE,NPATH,NTG,
2          NFLAG,NDEV,MDX1,MDX2,MDX3 )
C
C *****
C **                                     **
C **  USER-DEFINED GRAPHICS OUTPUT ROUTINE  **
C **                                     **
C *****
C
C      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
C
C      DIMENSION NELEM(MDX3,12),COORDS(MDX2,4),U(MDX1)
C      DIMENSION NSETI(MDX1)
C
C      NODE CONVENTION
C
C
C          Z,W          Y,V
C          |            /
C          | 8-----7   SURFACE
C          | /|          /|   FACE  NODES
C          | /|          /|   F1: (1,2,6,5)
C          | /|          /|   F2: (2,3,7,6)
C          | /|          /|   F3: (3,4,8,7)
C          5-----6   |   F4: (1,5,8,4)
C          | }          | |   F5: (1,4,3,2)
C          | 4-----|---3   F6: (5,6,7,8)
C          | /          | /
C          | /          | /
C          | /          | /
C          1-----2 ----- X,U
C
C      <<< PROGRAM STATEMENTS TO OUTPUT GRAPHICAL >>>
C      <<< INFORMATION IN A USER-DEFINED FORMAT >>>
C
C      RETURN
C      END

```

Figure 26. Format of user-defined subroutine **USRGRF**.

In **USRGRF**, the storage format of element connectivity, coordinate data, and node number conversion contained in the **NELEM**, **COORDS**, and **NSETI** arrays have been previously defined in Section 2.4.1. Other quantities passed into the user-defined routine are the **U** array which contains

the displacement or mode shape vector and a sequence of scalar parameters. NELNUM and NODNUM contain the number of elements and nodes, respectively. SCALE and NTG store the current load multiplier and global analysis cycle number. NPATH stores the solution procedure currently being processed. This is given by

$$NPATH = \begin{cases} 1 & \textit{MaterialFailureCalculation} \\ 2 & \textit{BucklingFailureCalculation} \\ 4 & \textit{LinearStaticAnalysis} \\ 5 & \textit{LinearBucklingAnalysis} \end{cases} \quad (18)$$

NFLAG = 1 or 2, depending on whether the solution is in a PREPASS or ANALYSIS mode, respectively. The remaining parameters, MDX1, MDX2, and MDX3 are size parameters set internally by RESTRAN and must not be altered. An example of a **USRGRF** subroutine is presented in Appendix G.

## 2.7 Miscellaneous

To include a heading or title to the program output, the following input record is used:

```
*HEADING
JOB TITLE
```

where the job title may be up to 80 characters in length.

For convenience, the input file may be included with the program output by including the following statement

```
*ECHO
```

This will echo the input file verbatim to the output stream.

Comments may be inserted between statements anywhere in the input file using a **\*\*\*** format in fields 1 and 2. For example

```
** This line is a comment
```

will cause the input file interpreter to skip this line. Comments may also be inserted within the range of input statements that have a fixed number of entries per record and can have an arbitrary number of records or lines. These include the **\*NODE**, **\*ELEMENT**, and **\*BOUNDARY** statements.

Model data created in programs such as PATRAN in ABAQUS format may be directly included by using the following statement

```
*INCLUDE, FILE='filename.inp'
```

This will cause input to be read from the specified file. The filename must be enclosed in quotes. The included file may contain any input statements that are equivalent to ABAQUS format such as **\*NODE**, **\*ELEMENT**, **\*BOUNDARY**, or **\*CLOAD**. All optional parameter inputs should

be in accordance with RESTRAN input formats and, in addition, the \*ENDDATA or \*END STEP line must be present in the included file to return IO processing to the standard RESTRAN input file *restran.inp*.

### 3 RESTRAN Error Checking

An extensive set of internal testing of initial input and run-time operations has been incorporated into RESTRAN to alert the user to inconsistencies and errors encountered in the model generation and execution of the various RESTRAN analysis options. The range of error testing is described in the following subsections.

#### 3.1 Tests on Initial Input

The essential tests on the basic input involve checking whether the RESTRAN size parameters are adequate to process the current model and verify that a valid model has been input. Testing of model validity includes checking node definition, element connectivity, assigned material properties, support conditions, and failure criteria. These tests are designed to ensure that a viable model can be created for performing subsequent analyses. Fatal errors are determined as those that preclude the subsequent operation of an analysis algorithm and will cause program execution to cease. Warnings are issued if inconsistencies are detected, such as unused nodes, but execution is allowed to proceed.

#### 3.2 Run-Time Error Determination

A valid, consistent structural model may still be ill-posed and produce meaningless results. During execution, numerous tests are made to assess elastic and differential stiffness properties, eigenmode determination and interpretation, material degradation, and processing performed by user-defined subroutines. Although any set of error checking is bound to be incomplete, the internal testing in RESTRAN will alert the user to the most simple and to many subtle errors in the analysis of residual strength.

### 4 Input File Format

The RESTRAN input file is designated *restran.inp*. The file format has been implemented with a degree of flexibility in the parsing of input such that all statements are case insensitive, and arbitrary space or comma delimiters can be used in listing statement options and data items. The input stream in RESTRAN is parsed sequentially and may generally be input in any order. The only exceptions are the node and element generation statements \*NGEN, \*NFILL, \*ELGEN, and \*MODEL GENERATION, which are invoked during the input parsing. The routines that are invoked require node or element data to have been read prior to performing the requested node or element generation. Termination of input is specified by the \*ENDDATA entry.

### 5 Computer Implementation of RESTRAN

RESTRAN is written in FORTRAN 77 with the aim of providing maximum portability across different computer platforms. There is no overriding driver or script to automate various support

or implementation functions, such as setting array size parameters and processing user-defined sub-routines. The installation of RESTRAN requires that a master memory size parameter be set in the preface to the MAIN section of the RESTRAN code. This parameter is denoted MAXRAM and represents the maximum number of double precision words that can be held in core memory. This segment of code is shown in Figure 27.

```

C  @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
C  @@@                                                                                               @@@
C  @@@ RESTRAN, REsidual STREngth ANalysis, IS A FINITE @@@
C  @@@ ELEMENT BASED PROGRAM TO PREDICT THE RESIDUAL @@@
C  @@@ STRENGTH OF IMPACT DAMAGED COMPOSITE LAMINATES @@@
C  @@@                                                                                               @@@
C  @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
C
C      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
C
C      @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
C      @@@                                                                                               @@@
C      @@@          RESTRAN MEMORY PARMETERS @@@
C      @@@                                                                                               @@@
C      @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
C
C <<<          SIZE PARAMETERS USED IN PROGRAM:          >>>
C <<<                                                                                               >>>
C <<< MAXRAM:  MAXIMUM AVAILABLE RAM STORAGE IN          >>>
C <<<          DOUBLE PRECISION WORDS                    >>>
C
C      PARAMETER ( MAXRAM = 16500000 )

```

Figure 27. MAXRAM parameter in RESTRAN.

During program execution, judicious segments of RAM memory are internally allocated to perform the preface operations involving model input and processing. Minimum array sizes are automatically determined, and memory is reallocated to minimize both internal storage requirements and the size of external disk files to streamline the execution of a RESTRAN analysis.

User-defined subroutines must be created using a standardized subroutine parameter interface. For convenience, sample routines are provided in separate appendices. These routines need not be written in FORTRAN, but if other languages are used, care must be given to differences in conventions such as how arrays are ordered as in C. These routines must then be compiled and linked with the RESTRAN object code to form an executable module.

## 6 Computational Efficiency

The computational efficiency of RESTRAN is primarily dictated by the matrix operations associated with decomposition and eigenvalue extraction. As discussed in more detail in the RESTRAN Theoretical Manual [3], the finite element basis naturally leads to the generation of large, sparse,

banded matrices in representing the complete model. Internal algorithms have been created to process matrix storage modes in various formats. These include full matrix storage for small problems, half-bandwidth storage format (default), and out-of-core storage for large problems that exceed the internal RAM memory capacity and require most data storage to be resident in external disk files. The basic determinant of execution speed is the selection of internal data storage format required to hold sufficient data in high-speed in-core memory. Bandwidth storage assumes enough RAM memory to store a complete global matrix at any one time with intermittent I/O operations to swap one global matrix quantity for another. The out-of-core solution mode is slowest due to the high I/O overhead of transferring data between core and external files which must be performed constantly during program execution.

Additional considerations pertain to the direct assembly procedure currently used, which is more computationally and I/O costly than frontal solution methods, and to the condensation of internal equations involved in isolating individual delaminations and imposition of applied displacement boundary conditions. These constraints are applied using row and column shifting, which is more intensive than simple equation isolation using unit diagonal-zeroed row/column procedures that are straightforward in linear equation solution but introduce difficulties in performing eigenanalyses.

Thus, the execution time of performing an analysis using RESTRAN is significantly higher than that obtained in performing similar solution procedures in the widely used commercial codes such as NASTRAN, ABAQUS, and ANSYS, and may be addressed in future enhancements. The specialized analysis of residual strength accounting for combined progressive material and structural failure performed by the RESTRAN code is, however, simply not available in a single commercial program.

## 7 Numerical Examples

The following subsections present sample problems illustrating the use of the RESTRAN code. Each problem uses a model of a simple laminated composite casing in order to contrast different finite element discretizations, applied loading, existing damage, and analysis procedures. Timing summaries are provided to demonstrate the performance of RESTRAN in a Linux environment on a Carrera workstation with a 530 MHz Alpha cpu.

### 7.1 Linear Static Analysis

A static analysis of the finite element model shown in Figure 25 is performed. An arbitrary layup based on a nominal ply thickness of 0.0052in was selected for the various model sections. The top and bottom plates were composed of  $(90_6/\pm 45_4 | \pm 45/0_{28} |)_s$  laminates where '|' designates element layer interfaces. The vertical panel laminate was modeled as  $(0_6/\pm 45_4/90_5/\pm 45_5 | 0_6/\pm 45_5/0_4 |)_s$ . Ply properties were selected as

$$\begin{array}{llll} E_1 & = & 2.48E6 & E_2 & = & 2.48E6 & E_3 & = & 0.71E6 \\ G_{23} & = & 3.0E5 & G_{13} & = & 3.0E5 & G_{12} & = & 9.9E5 \\ \nu_{23} & = & 0.28 & \nu_{13} & = & 0.28 & \nu_{12} & = & 0.243 \end{array}$$

For first ply failure, the maximum stress criterion was selected with the following material strengths

$$\begin{aligned}
 X_t &= 21.3E3 & Y_t &= 21.3E3 & Z_t &= 21.2E3 \\
 X_c &= 47.8E3 & Y_c &= 47.8E3 & Z_c &= 21.0E3 \\
 R &= 1.65E3 & S &= 1.65E3 & T &= 7.0E3
 \end{aligned}$$

The model input, job log, and abbreviated output are shown subsequently, together with the resulting deformed plot.

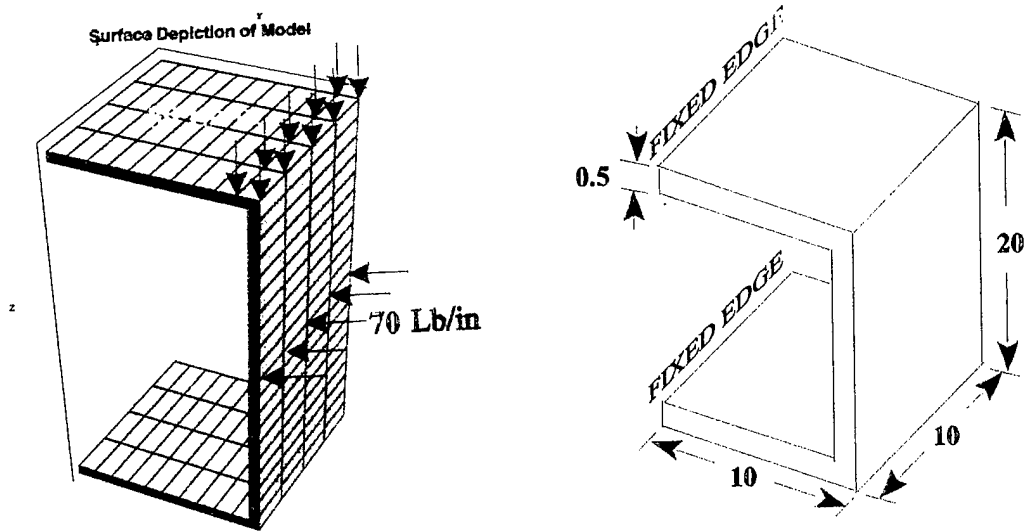


Figure 28. Model used for linear static analysis.

### 7.1.1 Input Data File for a Linear Static Problem

```

*HEADING
  MODEL OF A COMPOSITE CASING
*SOLUTION, METH = LSA
  6,15
**ECHO
**PREPASS
*NODE PRINT
  D,M
*PLY FAILURE PRINT
*MEMORY ALLOCATION
  BAND
*GRAPHICS, format = mathematica
  2, 2, 1.0
**
**
**  NODE DEFINITIONS
**
*node
  1      0.0      0.0      20.0
  5      0.0      10.0     20.0

```

51	10.0	0.0	20.0
55	10.0	10.0	20.0
151	10.0	0.0	0.0
155	10.0	10.0	0.0
201	0.0	0.0	0.0
205	0.0	10.0	0.0
1001	0.0	0.0	19.875
1005	0.0	10.0	19.875
1051	9.875	0.0	19.875
1055	9.875	10.0	19.875
1151	9.875	0.0	0.125
1155	9.875	10.0	0.125
1201	0.0	0.0	0.125
1205	0.0	10.0	0.125
2001	0.0	0.0	19.75
2005	0.0	10.0	19.75
2051	9.75	0.0	19.75
2055	9.75	10.0	19.75
2151	9.75	0.0	0.25
2155	9.75	10.0	0.25
2201	0.0	0.0	0.25
2205	0.0	10.0	0.25
3001	0.0	0.0	19.625
3005	0.0	10.0	19.625
3051	9.625	0.0	19.625
3055	9.625	10.0	19.625
3151	9.625	0.0	0.375
3155	9.625	10.0	0.375
3201	0.0	0.0	0.375
3205	0.0	10.0	0.375
4001	0.0	0.0	19.5
4005	0.0	10.0	19.5
4051	9.5	0.0	19.5
4055	9.5	10.0	19.5
4151	9.5	0.0	0.5
4155	9.5	10.0	0.5
4201	0.0	0.0	0.5
4205	0.0	10.0	0.5

\*\*

\*\* GENERATE NODE SETS

\*\*

\*NGEN, NID=10

1, 5, 1

\*NGEN, NID=20

51, 55, 1

\*NGEN, NID=30

151, 155, 1

\*NGEN, NID=40

201, 205, 1

\*NGEN, NID=50

1001, 1005, 1

\*NGEN, NID=60

1051, 1055, 1

\*NGEN, NID=70

```

1151, 1155, 1
*NGEN, NID=80
1201, 1205, 1
*NGEN, NID=90
2001, 2005, 1
*NGEN, NID=100
2051, 2055, 1
*NGEN, NID=110
2151, 2155, 1
*NGEN, NID=120
2201, 2205, 1
*NGEN, NID=130
3001, 3005, 1
*NGEN, NID=140
3051, 3055, 1
*NGEN, NID=150
3151, 3155, 1
*NGEN, NID=160
3201, 3205, 1
*NGEN, NID=170
4001, 4005, 1
*NGEN, NID=180
4051, 4055, 1
*NGEN, NID=190
4151, 4155, 1
*NGEN, NID=200
4201, 4205, 1
**
** GENERATE NODE PLANES
**
*NFILL
10, 20, 9, 5
20, 30, 19, 5
30, 40, 9, 5
50, 60, 9, 5
60, 70, 19, 5
70, 80, 9, 5
90, 100, 9, 5
100, 110, 19, 5
110, 120, 9, 5
130, 140, 9, 5
140, 150, 19, 5
150, 160, 9, 5
170, 180, 9, 5
180, 190, 19, 5
190, 200, 9, 5
**
**          DEFINE GENERATOR ELEMENTS
**
** top horizontal component
**
*ELEMENT, LAYUP = 1
    1, 1001, 1006, 1007, 1002,    1,    6,    7,    2
*ELEMENT, LAYUP = 2

```

```

100, 2001, 2006, 2007, 2002, 1001, 1006, 1007, 1002
*ELEMENT, LAYUP = 3
200, 3001, 3006, 3007, 3002, 2001, 2006, 2007, 2002
*ELEMENT, LAYUP = 4
300, 4001, 4006, 4007, 4002, 3001, 3006, 3007, 3002
**
** bottom horizontal component
**
*ELEMENT, LAYUP = 1
400, 201, 196, 197, 202, 1201, 1196, 1197, 1202
*ELEMENT, LAYUP = 2
500, 1201, 1196, 1197, 1202, 2201, 2196, 2197, 2202
*ELEMENT, LAYUP = 3
600, 2201, 2196, 2197, 2202, 3201, 3196, 3197, 3202
*ELEMENT, LAYUP = 4
700, 3201, 3196, 3197, 3202, 4201, 4196, 4197, 4202
**
** vertical component
**
*ELEMENT, LAYUP = 5, orientation = 1
800, 1151, 151, 152, 1152, 1146, 146, 147, 1147
*ELEMENT, LAYUP = 6, orientation = 1
900, 2151, 1151, 1152, 2152, 2146, 1146, 1147, 2147
*ELEMENT, LAYUP = 7, orientation = 1
1000, 3151, 2151, 2152, 3152, 3146, 2146, 2147, 3147
*ELEMENT, LAYUP = 8, orientation = 1
1100, 4151, 3151, 3152, 4152, 4146, 3146, 3147, 4147
**
** ELEMENT GENERATION
**
*ELGEN, ELID = 10
1,10,5,1,4,1,10,,
100,10,5,1,4,1,10,,
200,10,5,1,4,1,10,,
300,10,5,1,4,1,10,,
*ELGEN, ELID = 20
800,0,0,0,4,1,1,20,-5,4
900,0,0,0,4,1,1,20,-5,4
1000,0,0,0,4,1,1,20,-5,4
1100,0,0,0,4,1,1,20,-5,4
*ELGEN, ELID = 30
400,10,-5,5,4,1,4,,
500,10,-5,5,4,1,4,,
600,10,-5,5,4,1,4,,
700,10,-5,5,4,1,4,,
**
** DEFINE SET OF ELEMENTS AT UPPER AND LOWER PLATE JUNCTIONS
**
*ELSET, ESID = 500
10 20 30 40 109 119 129 139 209 219 229 239
309 319 329 339 445 449 453 457 545 549 553 557
645 649 653 657 745 749 753 757 800 801 802 803
900 901 902 903 1000 1001 1002 1003 1100 1101 1102 1103
876 877 878 879 976 977 978 979 1076 1077 1078 1079

```

```
1176 1177 1178 1179
**
** EXCLUDE ELEMENT SET 500 FROM FIRST PLY FAILURE PREDICTION
**
*EXCLUDE ELEMENTS
  500
**
** RELAX TOLERANCE IN DEFORMED GEOMETRY CHECKS
**
*DEFORMED GEOMETRY
20.0
**
** LAMINATE DESCRIPTION
**
*LAYER, LAYUP = 1
  1, 0.0416,  90.0
  1, 0.0208,  45.0
  1, 0.0208, -45.0
*LAYER, LAYUP = 2
  1, 0.0208,  45.0
  1, 0.0208, -45.0
  1, 0.1456,   0.0
*LAYER, LAYUP = 3
  1, 0.1456,   0.0
  1, 0.0208, -45.0
  1, 0.0208,  45.0
*LAYER, LAYUP = 4
  1, 0.0208, -45.0
  1, 0.0208,  45.0
  1, 0.0416,  90.0
**
*LAYER, LAYUP = 5
  1, 0.0312,   0.0
  1, 0.0208,  45.0
  1, 0.0208, -45.0
  1, 0.0260,  90.0
  1, 0.0260,  45.0
  1, 0.0260, -45.0
*LAYER, LAYUP = 6
  1, 0.0312,   0.0
  1, 0.0260,  45.0
  1, 0.0260, -45.0
  1, 0.0208,   0.0
*LAYER, LAYUP = 7
  1, 0.0208,   0.0
  1, 0.0260, -45.0
  1, 0.0260,  45.0
  1, 0.0312,   0.0
*LAYER, LAYUP = 8
  1, 0.0260, -45.0
  1, 0.0260,  45.0
  1, 0.0260,  90.0
  1, 0.0208, -45.0
  1, 0.0208,  45.0
```

```
1, 0.0312, 0.0
**
** MATERIAL DEFINITION
**
*MATERIAL, MATID = 1
  2.48E6,2.48E6,0.71E6,0.3E6,0.3E6,0.99E6
  0.28,0.28,0.243
*FAILURE CRITERIA, FCID = 1
  MAX-STRESS
  21.2E3, 47.8E3, 21.2E3, 47.8E3, 21.2E3, 21.0E3
  1.65E3, 1.65E3, 7.0E3
*DAMAGE LAW, DLID = 1
  NULL
**
** ESTABLISH LOCAL COORDINATE SYSTEM FOR VERTICAL SECTION
**
*ORIENTATION
  1, 0.0, 1.0, 0.0, 0.0, 0.0, 1.0
**
*BOUNDARY2
  10, 1, 1
  50, 1, 1
  90, 1, 1
  130, 1, 1
  170, 1, 1
*BOUNDARY2
  40, 1, 3
  80, 1, 3
  120, 1, 3
  160, 1, 3
  200, 1, 3
**
*CLOAD
  46, 3, -50.0
  47, 3, -100.0
  48, 3, -100.0
  49, 3, -100.0
  50, 3, -50.0
  51, 3, -50.0
  52, 3, -100.0
  53, 3, -100.0
  54, 3, -100.0
  55, 3, -50.0
  101, 1, -100.0
  102, 1, -200.0
  103, 1, -200.0
  104, 1, -200.0
  105, 1, -100.0
**
*ENDDATA
```

## 7.1.2 Timing Summary of Job Execution

```

@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
@@
@@      U.S. ARMY RESEARCH LABORATORY      @@
@@
@@              R E S T R A N              @@
@@
@@ RESIDUAL STRENGTH ANALYSIS OF IMPACT @@
@@      DAMAGED COMPOSITE LAMINATES      @@
@@
@@              VERSION 1.0              @@
@@
@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@

```

### M O D E L S I Z E P A R A M E T E R S

```

NUMBER OF ELEMENTS =      640
NUMBER OF NODES    =     1025
DEGREES OF FREEDOM =     3075
SYSTEM BANDWIDTH  =      183

```

TOTAL RAM MEMORY AVAILABLE = 14500000 WORDS

TOTAL RAM MEMORY REQUIRED = 784080 WORDS

```

*****
**
** TIMING SUMMARY OF PROGRAM EXECUTION **
**
*****

```

RESTRAN PREFACE OPERATIONS: 5.3739 SECONDS

```

@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
@@@
@@@ BEGINNING LINEAR STATIC ANALYSIS @@@
@@@
@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@

```

```

ELASTIC STIFFNESS ASSEMBLY TIME:      13.8543 SECONDS
BOUNDARY CONSTRAINT PROCESSING TIME:   0.8140 SECONDS
LINEAR SOLUTION TIME:                  2.1745 SECONDS
STRESS RECOVERY TIME:                  13.9383 SECONDS
GRAPHICAL OUTPUT GENERATION TIME:      2.6908 SECONDS

```

TOTAL JOB EXECUTION TIME: 43.2183 SECONDS

### 7.1.3 Linear Static Solution Output File

```

@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
@@                               @@
@@   U.S. ARMY RESEARCH LABORATORY   @@
@@                               @@
@@           R E S T R A N           @@
@@                               @@
@@   RESIDUAL STRENGTH ANALYSIS OF IMPACT   @@
@@   DAMAGED COMPOSITE LAMINATES         @@
@@                               @@
@@           VERSION 1.0                 @@
@@                               @@
@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@

```

\*\*\* WARNING: MATERIAL ID 1 HAS A MIXED MODE FAILURE CRITERIA  
ASSOCIATED WITH A SINGLE MODE DAMAGE LAW (NULL).  
NULL ACCEPTED

```

#####
###                               ###
### M O D E L D E F I N I T I O N ###
###                               ###
#####

```

J O B H E A D I N G :  
-----

MODEL OF A COMPOSITE CASING

S O L U T I O N C O N T R O L :  
-----

S O L U T I O N A L G O R I T H M :

LINEAR STATIC ANALYSIS

M E M O R Y A L L O C A T I O N :

BANDWIDTH STORAGE MODE

\* BANDWIDTH MINIMIZATION WILL BE PERFORMED

P R O G R A M O P T I O N S :  
-----

- \* EXTENDED JOB EXECUTION STATISTICS WILL BE PRINTED
- \* THE FOLLOWING ELEMENT SETS ARE EXCLUDED FROM FAILURE PREDICTION

500

R E Q U E S T E D P R I N T O P T I O N S:

-----

- \* PRINT DISPLACEMENTS AFTER CONVERGENCE AT THE iTH LOAD INCREMENT
- \* PRINT BUCKLING MODE SHAPE CORRESPONDING TO THE LOWEST BUCKLING LOAD MULTIPLIER AT THE iTH ITERATION
- \* PRINT ELEMENT PLY FAILURE STATISTICS

G R A P H I C S:

-----

- @ GRAPHICAL OUTPUT IN MATHEMATICA FORMAT WILL BE GENERATED
- @ BOTH UNDEFORMED AND DEFORMED GEOMETRY IS REQUESTED  
DEFORMATION/MODE MAGNIFICATION FACTOR = 0.1000E+01
- @ RESTRAN GRAPHICS CONTAINED IN FILE: restran.grf

N O D E D E F I N I T I O N S:

-----

NODE ID	X	Y	Z
1	0.000E+00	0.000E+00	0.200E+02
2	0.000E+00	0.250E+01	0.200E+02
3	0.000E+00	0.500E+01	0.200E+02
4	0.000E+00	0.750E+01	0.200E+02
5	0.000E+00	0.100E+02	0.200E+02
	.	.	.
4201	0.000E+00	0.000E+00	0.500E+00
4202	0.000E+00	0.250E+01	0.500E+00
4203	0.000E+00	0.500E+01	0.500E+00
4204	0.000E+00	0.750E+01	0.500E+00
4205	0.000E+00	0.100E+02	0.500E+00

S P E C I F I E D N O D E S E T S:

-----

SET ID 10:

1	2	3	4	5
			SET ID	20:
51	52	53	54	55
			.	
			.	
			.	
			SET ID	190:
4151	4152	4153	4154	4155
			SET ID	200:
4201	4202	4203	4204	4205

E L E M E N T D E F I N I T I O N S :

ELEMENT	N1	N2	N3	N4	N5	N6	N7	N8
1	1001	1006	1007	1002	1	6	7	2
2	1006	1011	1012	1007	6	11	12	7
3	1011	1016	1017	1012	11	16	17	12
4	1016	1021	1022	1017	16	21	22	17
5	1021	1026	1027	1022	21	26	27	22
			.					
			.					
			.					
1175	4064	3064	3065	4065	4059	3059	3060	4060
1176	4056	3056	3057	4057	4051	3051	3052	4052
1177	4057	3057	3058	4058	4052	3052	3053	4053
1178	4058	3058	3059	4059	4053	3053	3054	4054
1179	4059	3059	3060	4060	4054	3054	3055	4055

E L E M E N T S E T S :

					ELEMENT SET ID	10:
2	3	4	5	...		
					ELEMENT SET ID	20:
801	802	803	804	...		
					ELEMENT SET ID	30:
405	410	415	420	...		

ELEMENT SET ID 500:

10 20 30 40 ...

M A T E R I A L P R O P E R T Y D A T A :

MATERIAL ID 1

E1 = 0.248E+07 G23 = 0.300E+06 MU23 = 0.28000  
E2 = 0.248E+07 G13 = 0.300E+06 MU13 = 0.28000  
E3 = 0.710E+06 G12 = 0.990E+06 MU12 = 0.24300

ASSOCIATED FAILURE LAW:

MAXIMUM STRESS CRITERION

XT = 0.212E+05 XC = 0.478E+05 YT = 0.212E+05  
YC = 0.478E+05 ZT = 0.212E+05 ZC = 0.210E+05  
R = 0.165E+04 S = 0.165E+04 T = 0.700E+04

ASSOCIATED DAMAGE LAW:

NULL POST-FAILURE PROPERTIES

M A T E R I A L L A Y E R D E F I N I T I O N S

LAYUP ID = 1  
NUMBER OF PLYS = 3

MATERIAL ID	PLY THICKNESS	ORIENTATION
1	0.04160	90.00000
1	0.02080	45.00000
1	0.02080	-45.00000

LAYUP ID = 2  
NUMBER OF PLYS = 3

MATERIAL ID	PLY THICKNESS	ORIENTATION
1	0.02080	45.00000
1	0.02080	-45.00000
1	0.14560	0.00000

LAYUP ID = 3  
NUMBER OF PLYS = 3

MATERIAL ID	PLY THICKNESS	ORIENTATION
1	0.14560	0.00000
1	0.02080	-45.00000

1 0.02080 45.00000

LAYUP ID = 4  
NUMBER OF PLYS = 3

MATERIAL ID	PLY THICKNESS	ORIENTATION
1	0.02080	-45.00000
1	0.02080	45.00000
1	0.04160	90.00000

LAYUP ID = 5  
NUMBER OF PLYS = 6

MATERIAL ID	PLY THICKNESS	ORIENTATION
1	0.03120	0.00000
1	0.02080	45.00000
1	0.02080	-45.00000
1	0.02600	90.00000
1	0.02600	45.00000
1	0.02600	-45.00000

LAYUP ID = 6  
NUMBER OF PLYS = 4

MATERIAL ID	PLY THICKNESS	ORIENTATION
1	0.03120	0.00000
1	0.02600	45.00000
1	0.02600	-45.00000
1	0.02080	0.00000

LAYUP ID = 7  
NUMBER OF PLYS = 4

MATERIAL ID	PLY THICKNESS	ORIENTATION
1	0.02080	0.00000
1	0.02600	-45.00000
1	0.02600	45.00000
1	0.03120	0.00000

LAYUP ID = 8  
NUMBER OF PLYS = 6

MATERIAL ID	PLY THICKNESS	ORIENTATION
1	0.02600	-45.00000
1	0.02600	45.00000
1	0.02600	90.00000
1	0.02080	-45.00000
1	0.02080	45.00000
1	0.03120	0.00000

MATERIAL COORDINATE SYSTEMS

ID	V11	V12	V13	V21	V22	V23
1	0.000E+00	0.100E+01	0.000E+00	0.000E+00	0.000E+00	0.100E+01

BOUNDARY CONDITIONS:

SINGLE POINT CONSTRAINTS:

NODE	DOF1 TO DOF2
1	1 1
2	1 1
3	1 1
4	1 1
.	.
.	.
.	.
4202	1 3
4203	1 3
4204	1 3
4205	1 3

APPLIED CONCENTRATED FORCES:

NODE	DIRECTION	MAGNITUDE
46	3	-.500E+02
47	3	-.100E+03
48	3	-.100E+03
49	3	-.100E+03
50	3	-.500E+02
51	3	-.500E+02
52	3	-.100E+03
53	3	-.100E+03
54	3	-.100E+03
55	3	-.500E+02
101	1	-.100E+03
102	1	-.200E+03
103	1	-.200E+03
104	1	-.200E+03
105	1	-.100E+03

FORCE/MOMENT RESULTANTS AT ORIGIN:

$|R| = 0.113E+04$      $|M| = 0.567E+04$

$R_x = -.800E+03$      $R_y = 0.000E+00$      $R_z = -.800E+03$

Mx = 0.400E+04 My = 0.400E+03 Mz = -.400E+04

Xo = 0.950E+01 Yo = 0.500E+01 Zo = 0.100E+02

\*\*\* END OF MODEL DEFINITION \*\*\*

MODEL SIZE PARAMETERS

NUMBER OF ELEMENTS = 640  
NUMBER OF NODES = 1025  
DEGREES OF FREEDOM = 3075  
SYSTEM BANDWIDTH = 183

#####  
## ##  
## LINEAR STATIC ANALYSIS ##  
## ##  
#####

DISPLACEMENT FIELD  
(SCALE FACTOR = 0.100E+01)

NODE	U	V	W
1	0.00000E+00	0.27644E-03	-.24278E+00
2	0.00000E+00	0.60853E-04	-.24592E+00
3	0.00000E+00	-.12759E-03	-.24693E+00
4	0.00000E+00	-.31570E-03	-.24594E+00
5	0.00000E+00	-.53044E-03	-.24281E+00
.	.	.	.
4201	0.00000E+00	0.00000E+00	0.00000E+00
4202	0.00000E+00	0.00000E+00	0.00000E+00
4203	0.00000E+00	0.00000E+00	0.00000E+00
4204	0.00000E+00	0.00000E+00	0.00000E+00
4205	0.00000E+00	0.00000E+00	0.00000E+00

MAXIMUM ELEMENT FAILURE INDICES

ELEMENT	PLY	FAILURE INDEX	MODE	MULTIPLIER
1	3	0.614E-01	GENERAL	0.163E+02
2	3	0.613E-01	GENERAL	0.163E+02
3	3	0.610E-01	GENERAL	0.164E+02
4	3	0.610E-01	GENERAL	0.164E+02
5	3	0.603E-01	GENERAL	0.166E+02
.	.	.	.	.
1174	5	0.266E-01	GENERAL	0.377E+02
1175	5	0.322E-01	GENERAL	0.311E+02
1176	1	0.691E-01	GENERAL	0.145E+02

```

1177      1      0.633E-01  GENERAL  0.158E+02
1178      1      0.633E-01  GENERAL  0.158E+02
1179      1      0.692E-01  GENERAL  0.144E+02

```

```

HIGHEST GLOBAL FAILURE INDEX OCCURRED IN ELEMENT    902
IN PLY NUMBER    1 PREDICTING FIRST PLY FAILURE AT A
FACTOR TO APPLIED LOADS EQUAL TO 0.174E+01

```

```

@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
@@                                                                                      @@
@@  S T A T I C  A N A L Y S I S  C O M P L E T E D  @@
@@                                                                                      @@
@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@

```

According to a first ply failure criterion, failure is predicted at a load given by

$$\{P\} = 1.74\{P_{applied}\} \tag{19}$$

A graphical depiction of the deformed shape is shown in Figure 29.

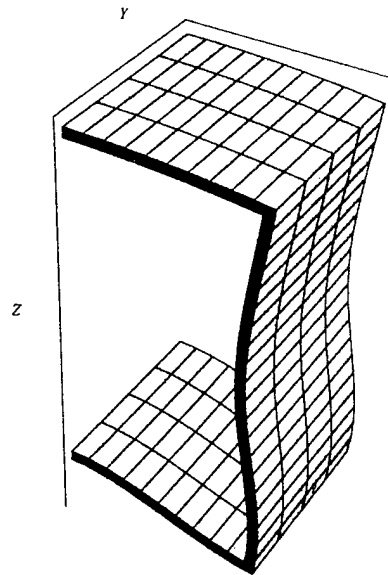


Figure 29. Deformation under applied static loads.

## 7.2 Linear Buckling Analysis

A similar model of a composite casing as shown in Section 7.1 is analyzed for buckling. The same laminate layup and material properties were used. The model, shown in Figure 30, was constructed to model circular delamination at each of the three interior sublaminates interfaces in the vertical plate. The location of these delaminations are indicated by || in the layup description given by  $(0_6/\pm 45_4/90_5/\pm 45_5 \parallel 0_6/\pm 45_5/0_4 \parallel 0_4/\mp 45_5/0_6 \parallel \mp 45_5/90_5/\mp 45_4/0_6)$ . The instability of these delaminations was analyzed simultaneously. For comparison, the critical buckling load of the entire

component without the presence of delaminations was computed by removing the \*DELAMINATION statement from the input file. The model input, job log, and abbreviated output files are shown subsequently, together with the resulting mode shape plots.

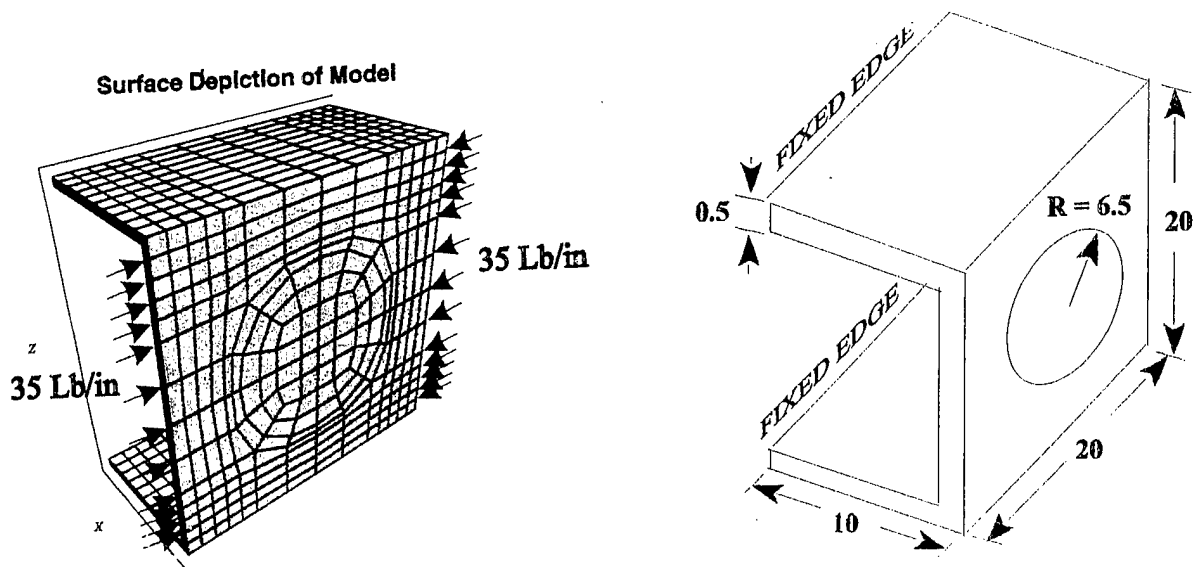


Figure 30. Model used for linear buckling analysis.

### 7.2.1 Input Data File for a Linear Buckling Problem

```
*HEADING
  STABILITY ANALYSIS OF A DELAMINATED COMPOSITE CASING
*SOLUTION, METH = LBA
  6,15
**ECHO
**PREPASS
*NODE PRINT
  D,M
*MEMORY ALLOCATION
  BAND
*GRAPHICS, format = mathematica
  2, 2, 1.0
**
**  NODE DEFINITIONS
**
*NODE
**
** TOP HORIZONTAL COMPONENT, LEFT
**
  1  0.0  -0.1000005E+02  10.0
  2  0.0  -0.9009584E+01  10.0
  3  0.0  -0.8019119E+01  10.0
```

```

.
.
**
** TOP HORIZONTAL COMPONENT, RIGHT
**
151 10.0 -0.1000005E+02 10.0
152 10.0 -0.9009584E+01 10.0
153 10.0 -0.8019119E+01 10.0
.
.

```

```

** BOTTOM HORIZONTAL COMPONENT, LEFT
**
1501 0.0 -0.1000005E+02 -10.0
1502 0.0 -0.9009584E+01 -10.0
1503 0.0 -0.8019119E+01 -10.0
.
.

```

```

**
** BOTTOM HORIZONTAL COMPONENT, RIGHT
**
1651 10.0 -0.1000005E+02 -10.0
1652 10.0 -0.9009584E+01 -10.0
1653 10.0 -0.8019119E+01 -10.0
.
.

```

```

**
** DEFINE NODE SETS FOR FILL OPERATION
**
*NSET, NSID = 10
 1, 2, 3, 4, 5, 6, 7, 8, 9, 10
11, 12, 13, 14, 15
*NSET, NSID = 20
151, 152, 153, 154, 155, 156, 157, 158, 159, 160
161, 162, 163, 164, 165
*NSET, NSID = 30
301, 302, 303, 304, 305, 306, 307, 308, 309, 310
311, 312, 313, 314, 315
.
.
.
*nset, nsid = 620
7098, 7113, 7128, 7143, 7158, 7166, 7174, 7182, 7190, 7198
7206, 7214, 7229, 7244, 7259
*nset, nsid = 630
8098, 8113, 8128, 8143, 8158, 8166, 8174, 8182, 8190, 8198
8206, 8214, 8229, 8244, 8259
*nset, nsid = 640
9098, 9113, 9128, 9143, 9158, 9166, 9174, 9182, 9190, 9198
9206, 9214, 9229, 9244, 9259
**

```

\*\* EQUIVALENCE NODES TO JOIN SEPARATE MODEL DOMAINS

\*\*

\*EQUIVALENCE

500, 20  
510, 40  
520, 60  
530, 80  
540, 100  
600, 120  
610, 140  
620, 160  
630, 180  
640, 200

\*\*

\*\* GENERATE NODE PLANES

\*\*

\*NFILL

10, 20, 9, 15  
30, 40, 9, 15  
50, 60, 9, 15  
70, 80, 9, 15  
90, 100, 9, 15  
110, 120, 9, 15  
130, 140, 9, 15  
150, 160, 9, 15  
170, 180, 9, 15  
190, 200, 9, 15

\*\*

\*\* NODES, ELEMENTS, AND NODE SETS FOR DELAMINATED VERTICAL  
\*\* COMPONENT OBTAINED FROM THE FOLLOWING \*MODEL GENERATION  
\*\* STATEMENT:

\*\*

\*\*

\*MODEL GENERATION

\*\*

4,5,10.0,10.0,5,5,5,5

\*\*

1.5,1,1,1,1,1,1

\*\*

0.0, 0.0, 1.0

\*\*

0.0, 1.0, 0.0

\*\*

1.0, 0.0, 0.0

\*\*

1.0,10.0

\*\*

1,6,250,5000,5000

\*\*

1.0,9.875

\*\*

2,6,255,6000,6000

\*\*

1.0,9.750

\*\*

3,6,260,7000,7000

\*\*

1.0,9.625

\*\*

4,6,265,8000,8000

\*\*

1.0,9.50

\*\*

5,6,270,9000,9000

\*\*

\*NODE

5001	0.1000000E+02	0.0000000E+00	0.0000000E+00
5002	0.1000000E+02	0.1333340E+01	0.0000000E+00
5003	0.1000000E+02	0.1333340E+01	0.1333340E+01
5004	0.1000000E+02	0.0000000E+00	0.1333340E+01

```

5005  0.1000000E+02  -0.1333340E+01  0.1333340E+01
.
.
.
9268  0.9500000E+01  0.1000005E+02  0.4894511E+01
9269  0.9500000E+01  0.1000005E+02  0.6038188E+01
9270  0.9500000E+01  0.1000005E+02  0.7028653E+01
9271  0.9500000E+01  0.1000005E+02  0.8019119E+01
9272  0.9500000E+01  0.1000005E+02  0.9009584E+01
9273  0.9500000E+01  0.1000005E+02  0.1000005E+02

```

```

**
** NODE SETS TO DEFINE DELAMINATION PLANES
**

```

```

*NSSET, NSID = 255
 6001  6002  6003  6004  6005  6006  6007  6008
 6009  6010  6011  6012  6013  6014  6015  6016
 6017  6018  6019  6020  6021  6022  6023  6024
 6025  6026  6027  6028  6029  6030  6031  6032
 6033  6034  6035  6036  6037  6038  6039  6040
 6041
*NSSET, NSID = 260
 7001  7002  7003  7004  7005  7006  7007  7008
 7009  7010  7011  7012  7013  7014  7015  7016
 7017  7018  7019  7020  7021  7022  7023  7024
 7025  7026  7027  7028  7029  7030  7031  7032
 7033  7034  7035  7036  7037  7038  7039  7040
 7041
*NSSET, NSID = 265
 8001  8002  8003  8004  8005  8006  8007  8008
 8009  8010  8011  8012  8013  8014  8015  8016
 8017  8018  8019  8020  8021  8022  8023  8024
 8025  8026  8027  8028  8029  8030  8031  8032
 8033  8034  8035  8036  8037  8038  8039  8040
 8041

```

```

**
** DEFINE GENERATOR ELEMENTS
**

```

```

** top horizontal component
**
*ELEMENT, LAYUP = 1
 1, 301, 316, 317, 302, 1, 16, 17, 2
*ELEMENT, LAYUP = 2
 300, 601, 616, 617, 602, 301, 316, 317, 302
*ELEMENT, LAYUP = 3
 600, 901, 916, 917, 902, 601, 616, 617, 602
*ELEMENT, LAYUP = 4
 900, 1201, 1216, 1217, 1202, 901, 916, 917, 902
**
** bottom horizontal component
**
*ELEMENT, LAYUP = 1
1200, 1801, 1816, 1817, 1802, 1501, 1516, 1517, 1502
*ELEMENT, LAYUP = 2
1500, 2101, 2116, 2117, 2102, 1801, 1816, 1817, 1802

```

```

*ELEMENT, LAYUP = 3
1800, 2401, 2416, 2417, 2402, 2101, 2116, 2117, 2102
*ELEMENT, LAYUP = 4
2100, 2701, 2716, 2717, 2702, 2401, 2416, 2417, 2402
**
** ELEMENT GENERATION
**
*ELGEN, ELID = 10
  1, 10,15,1, 14,1,10,,,
 300, 10,15,1, 14,1,10,,,
 600, 10,15,1, 14,1,10,,,
 900, 10,15,1, 14,1,10,,,
1200, 10,15,1, 14,1,10,,,
1500, 10,15,1, 14,1,10,,,
1800, 10,15,1, 14,1,10,,,
2100, 10,15,1, 14,1,10,,,
**
** ELEMENTS IN VERTICAL COMPONENT FROM PRIOR *MODEL GENERATION RUN
**
*ELEMENT, LAYUP = 5, ORIENTATION = 1
 5001   6001   6004   6003   6002   5001   5004   5003   5002
 5002   6006   6005   6004   6001   5006   5005   5004   5001
 5003   6007   6006   6001   6008   5007   5006   5001   5008
 5004   6008   6001   6002   6009   5008   5001   5002   5009
 5005   6002   6003   6011   6010   5002   5003   5011   5010
      .
      .
      .
 8239   9252   9253   9268   9267   8252   8253   8268   8267
 8240   9253   9254   9269   9268   8253   8254   8269   8268
 8241   9254   9255   9270   9269   8254   8255   8270   8269
 8242   9255   9256   9271   9270   8255   8256   8271   8270
 8243   9256   9257   9272   9271   8256   8257   8272   8271
 8244   9257   9258   9273   9272   8257   8258   8273   8272
**
** RELAX TOLERANCE OF DEFORMED GEOMETRY CHECKS
**
*DEFORMED GEOMETRY
20.0
**
** LAMINATE DESCRIPTION
**
*LAYER, LAYUP = 1
  1, 0.0416, 90.0
  1, 0.0208, 45.0
  1, 0.0208, -45.0
*LAYER, LAYUP = 2
  1, 0.0208, 45.0
  1, 0.0208, -45.0
  1, 0.1456,  0.0
*LAYER, LAYUP = 3
  1, 0.1456,  0.0
  1, 0.0208, -45.0
  1, 0.0208, 45.0

```

```

*LAYER, LAYUP = 4
  1, 0.0208, -45.0
  1, 0.0208, 45.0
  1, 0.0416, 90.0
**
*LAYER, LAYUP = 5
  1, 0.0312, 0.0
  1, 0.0208, 45.0
  1, 0.0208, -45.0
  1, 0.0260, 90.0
  1, 0.0260, 45.0
  1, 0.0260, -45.0
*LAYER, LAYUP = 6
  1, 0.0312, 0.0
  1, 0.0260, 45.0
  1, 0.0260, -45.0
  1, 0.0208, 0.0
*LAYER, LAYUP = 7
  1, 0.0208, 0.0
  1, 0.0260, -45.0
  1, 0.0260, 45.0
  1, 0.0312, 0.0
*LAYER, LAYUP = 8
  1, 0.0260, -45.0
  1, 0.0260, 45.0
  1, 0.0260, 90.0
  1, 0.0208, -45.0
  1, 0.0208, 45.0
  1, 0.0312, 0.0
**
** MATERIAL DEFINITION
**
*MATERIAL, MATID = 1
  2.48E6,2.48E6,0.71E6,0.3E6,0.3E6,0.99E6
  0.28,0.28,0.243
*FAILURE CRITERIA, FCID = 1
  MAX-STRESS
  21.2E3, 47.8E3, 21.2E3, 47.8E3, 21.2E3, 21.0E3
  1.65E3, 1.65E3, 7.0E3
*DAMAGE LAW, DLID = 1
  NULL
**
** ESTABLISH LOCAL COORDINATE SYSTEM
**
*ORIENTATION
  1, 0.0, 1.0, 0.0, 0.0, 0.0, 1.0
**
*BOUNDARY2
  10, 1, 1
  30, 1, 1
  50, 1, 1
  70, 1, 1
  90, 1, 1
*BOUNDARY2

```

110, 1, 3  
130, 1, 3  
150, 1, 3  
170, 1, 3  
190, 1, 3

\*\*

\*CLOAD

136, 3, -50.0  
137, 3, -100.0  
138, 3, -100.0  
139, 3, -100.0  
140, 3, -100.0  
141, 3, -100.0  
142, 3, -100.0  
143, 3, -100.0  
144, 3, -100.0  
145, 3, -100.0  
146, 3, -100.0  
147, 3, -100.0  
148, 3, -100.0  
149, 3, -100.0  
150, 3, -50.0  
151, 3, -50.0  
152, 3, -100.0  
153, 3, -100.0  
154, 3, -100.0  
155, 3, -100.0  
156, 3, -100.0  
157, 3, -100.0  
158, 3, -100.0  
159, 3, -100.0  
160, 3, -100.0  
161, 3, -100.0  
162, 3, -100.0  
163, 3, -100.0  
164, 3, -100.0  
165, 3, -50.0

\*ENDDTA

## 7.2.2 Solution Timing Summary for Linear Buckling Analysis

```

@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
@@
@@          U.S. ARMY RESEARCH LABORATORY          @@
@@
@@                   R E S T R A N                   @@
@@
@@ RESIDUAL STRENGTH ANALYSIS OF IMPACT              @@
@@           DAMAGED COMPOSITE LAMINATES              @@
@@
@@                   VERSION 1.0                      @@
@@
@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@

```

M O D E L S I Z E P A R A M E T E R S

NUMBER OF ELEMENTS = 2096  
NUMBER OF NODES = 2865  
DEGREES OF FREEDOM = 8595  
SYSTEM BANDWIDTH = 1005

TOTAL RAM MEMORY AVAILABLE = 14500000 WORDS

TOTAL RAM MEMORY REQUIRED = 9232360 WORDS

\*\*\*\*\*  
\*\* \*\*  
\*\* TIMING SUMMARY OF PROGRAM EXECUTION \*\*  
\*\* \*\*  
\*\*\*\*\*

RESTRAN PREFACE OPERATIONS: 24.5313 SECONDS

@@  
@@@ @@@  
@@@ BEGINNING LINEAR BUCKLING ANALYSIS @@@  
@@@ @@@  
@@

ELASTIC STIFFNESS ASSEMBLY TIME: 42.2373 SECONDS

BOUNDARY CONSTRAINT PROCESSING TIME: 11.7441 SECONDS

LINEAR SOLUTION TIME: 2 MINUTES 33.4424 SECONDS

STRESS RECOVERY TIME: 37.7783 SECONDS

DIFFERENTIAL STIFFNESS ASSEMBLY TIME: 14.0586 SECONDS

BOUNDARY CONSTRAINT PROCESSING TIME: 11.5098 SECONDS

BOUNDARY CONSTRAINT PROCESSING TIME: 11.9873 SECONDS

EIGENVALUE EXTRACTION TIME: 1 HOURS 53 MINUTES 45.6260 SECONDS

GRAPHICAL OUTPUT GENERATION TIME: 12.9336 SECONDS

TOTAL JOB EXECUTION TIME: 1 HOURS 58 MINUTES 44.2803 SECONDS

7.2.3 Linear Buckling Solution Output File

```

@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
@@                               @@
@@   U.S. ARMY RESEARCH LABORATORY   @@
@@                               @@
@@           R E S T R A N           @@
@@                               @@
@@ RESIDUAL STRENGTH ANALYSIS OF IMPACT @@
@@   DAMAGED COMPOSITE LAMINATES   @@
@@                               @@
@@           VERSION 1.0           @@
@@                               @@
@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@

```

\*\*\* MESSAGE: ELEMENT NODE ORDER IS BEING CONVERTED TO RESTRAN FORMAT

```

#####
###                               ###
### M O D E L   D E F I N I T I O N ###
###                               ###
#####

```

J O B H E A D I N G :  
-----

MODEL OF A COMPOSITE CASING

S O L U T I O N C O N T R O L :  
-----

S O L U T I O N A L G O R I T H M :

LINEAR BUCKLING ANALYSIS

M E M O R Y A L L O C A T I O N :

BANDWIDTH STORAGE MODE

\* BANDWIDTH MINIMIZATION WILL BE PERFORMED

P R O G R A M O P T I O N S :  
-----

\* EXTENDED JOB EXECUTION STATISTICS WILL BE PRINTED

R E Q U E S T E D P R I N T O P T I O N S :  
-----

\* PRINT DISPLACEMENTS AFTER CONVERGENCE AT THE iTH LOAD INCREMENT

\* PRINT BUCKLING MODE SHAPE CORRESPONDING TO THE LOWEST BUCKLING  
LOAD MULTIPLIER AT THE ITH ITERATION

G R A P H I C S:

- @ GRAPHICAL OUTPUT IN MATHEMATICA FORMAT WILL BE GENERATED
- @ BOTH UNDEFORMED AND DEFORMED GEOMETRY IS REQUESTED  
DEFORMATION/MODE MAGNIFICATION FACTOR = 0.1000E+01
- @ RESTRAN GRAPHICS CONTAINED IN FILE: restran.grf

N O D E D E F I N I T I O N S:

NODE ID	X	Y	Z
1	0.000E+00	-.100E+02	0.100E+02
2	0.000E+00	-.901E+01	0.100E+02
3	0.000E+00	-.802E+01	0.100E+02
4	0.000E+00	-.703E+01	0.100E+02
5	0.000E+00	-.604E+01	0.100E+02
		.	
		.	
		.	
9268	0.950E+01	0.100E+02	0.489E+01
9269	0.950E+01	0.100E+02	0.604E+01
9270	0.950E+01	0.100E+02	0.703E+01
9271	0.950E+01	0.100E+02	0.802E+01
9272	0.950E+01	0.100E+02	0.901E+01

S P E C I F I E D N O D E S E T S:

SET ID 10:									
1	2	3	4	5	6	7	8	9	10
11	12	13	14	15					
		.							
		.							
		.							
SET ID 265:									
8001	8002	8003	8004	8005	8006	8007	8008	8009	8010
8011	8012	8013	8014	8015	8016	8017	8018	8019	8020

8021	8022	8023	8024	8025	8026	8027	8028	8029	8030
8031	8032	8033	8034	8035	8036	8037	8038	8039	8040
8041									

E L E M E N T D E F I N I T I O N S:

---

ELEMENT	N1	N2	N3	N4	N5	N6	N7	N8
1	301	316	317	302	1	16	17	2
2	316	331	332	317	16	31	32	17
3	331	346	347	332	31	46	47	32
4	346	361	362	347	46	61	62	47
5	361	376	377	362	61	76	77	62
8240	9253	9268	9269	9254	8253	8268	8269	8254
8241	9254	9269	9270	9255	8254	8269	8270	8255
8242	9255	9270	9271	9256	8255	8270	8271	8256
8243	9256	9271	9272	9257	8256	8271	8272	8257
8244	9257	9272	1365	1364	8257	8272	1065	1064

E L E M E N T S E T S:

---

ELEMENT SET ID 10:

2	3	4	5	6	7	8	9	10	11
12	13	14	15	16	17	18	19	20	21
22	23	24	25	26	27	28	29	30	31
2218	2219	2220	2221	2222	2223	2224	2225	2226	2227
2228	2229	2230	2231	2232	2233	2234	2235	2236	2237
2238	2239								

M A T E R I A L P R O P E R T Y D A T A:

---

MATERIAL ID 1

E1 = 0.248E+07 G23 = 0.300E+06 MU23 = 0.28000  
 E2 = 0.248E+07 G13 = 0.300E+06 MU13 = 0.28000  
 E3 = 0.710E+06 G12 = 0.990E+06 MU12 = 0.24300

ASSOCIATED FAILURE LAW:

MAXIMUM STRESS CRITERION

XT = 0.212E+05 XC = 0.478E+05 YT = 0.212E+05

YC = 0.478E+05 ZT = 0.212E+05 ZC = 0.210E+05  
R = 0.165E+04 S = 0.165E+04 T = 0.700E+04

ASSOCIATED DAMAGE LAW:

NULL POST-FAILURE PROPERTIES

MATERIAL ID 2

E1 = 0.100E+06 G23 = 0.385E+05 MU23 = 0.30000  
E2 = 0.100E+06 G13 = 0.385E+05 MU13 = 0.30000  
E3 = 0.100E+06 G12 = 0.385E+05 MU12 = 0.30000

ASSOCIATED FAILURE LAW:

MAXIMUM STRESS CRITERION

XT = 0.212E+05 XC = 0.478E+05 YT = 0.212E+05  
YC = 0.478E+05 ZT = 0.212E+05 ZC = 0.210E+05  
R = 0.165E+04 S = 0.165E+04 T = 0.700E+04

ASSOCIATED DAMAGE LAW:

NULL POST-FAILURE PROPERTIES

M A T E R I A L L A Y E R D E F I N I T I O N S

LAYUP ID = 1  
NUMBER OF PLYS = 3

MATERIAL ID	PLY THICKNESS	ORIENTATION
1	0.04160	90.00000
1	0.02080	45.00000
1	0.02080	-45.00000

LAYUP ID = 88  
NUMBER OF PLYS = 6

MATERIAL ID	PLY THICKNESS	ORIENTATION
2	0.02600	-45.00000
2	0.02600	45.00000
2	0.02600	90.00000
2	0.02080	-45.00000
2	0.02080	45.00000
2	0.03120	0.00000

M A T E R I A L C O O R D I N A T E S Y S T E M S

---

ID	V11	V12	V13	V21	V22	V23
1	0.000E+00	0.100E+01	0.000E+00	0.000E+00	0.000E+00	0.100E+01

B O U N D A R Y C O N D I T I O N S :

---

SINGLE POINT CONSTRAINTS:

NODE	DOF1	TO	DOF2
1	1		3
2	1		3
3	1		3
4	1		3
5	1		3
.			
.			
.			
2711	1		3
2712	1		3
2713	1		3
2714	1		3
2715	1		3

APPLIED CONCENTRATED FORCES:

NODE	DIRECTION	MAGNITUDE
1651	2	0.500E+01
5099	2	0.100E+02
5100	2	0.100E+02
5101	2	0.100E+02
.		
.		
.		
9269	2	-.100E+02
9270	2	-.100E+02
9271	2	-.100E+02
9272	2	-.100E+02
1365	2	-.500E+01

FORCE/MOMENT RESULTANTS AT ORIGIN:

|R| = 0.000E+00    |M| = 0.000E+00

Rx = 0.000E+00    Ry = 0.000E+00    Rz = 0.000E+00

Mx = 0.000E+00 My = 0.000E+00 Mz = 0.000E+00

Xo = 0.000E+00 Yo = 0.000E+00 Zo = 0.000E+00

\*\*\* END OF MODEL DEFINITION \*\*\*

MODEL SIZE PARAMETERS

NUMBER OF ELEMENTS = 2096  
NUMBER OF NODES = 2865  
DEGREES OF FREEDOM = 8595  
SYSTEM BANDWIDTH = 1005

#####  
## ##  
## LINEAR BUCKLING ANALYSIS ##  
## ##  
#####

CONVERGED EIGENVALUES:

NUMBER	LAMBDA
1	0.1782068E+03
2	0.1763134E+03
3	0.8268226E+02
4	0.7179661E+02

BUCKLING MODE SHAPE  
(SCALE = 0.718E+02)

NODE	U	V	W
1	0.00000E+00	0.00000E+00	0.00000E+00
2	0.00000E+00	0.00000E+00	0.00000E+00
3	0.00000E+00	0.00000E+00	0.00000E+00
4	0.00000E+00	0.00000E+00	0.00000E+00
5	0.00000E+00	0.00000E+00	0.00000E+00
		.	
		.	
		.	
9268	0.67520E+00	0.41156E-01	-.27246E-01
9269	0.52133E+00	0.32320E-01	-.31375E-01
9270	0.37198E+00	0.22749E-01	-.33309E-01
9271	0.21898E+00	0.12126E-01	-.31172E-01
9272	0.83349E-01	0.21711E-02	-.25241E-01

#####  
@@ ##  
@@ BUCKLING ANALYSIS COMPLETED @@  
@@ ##  
#####

A graphical depiction of the deformed shape is shown in Figure 31.

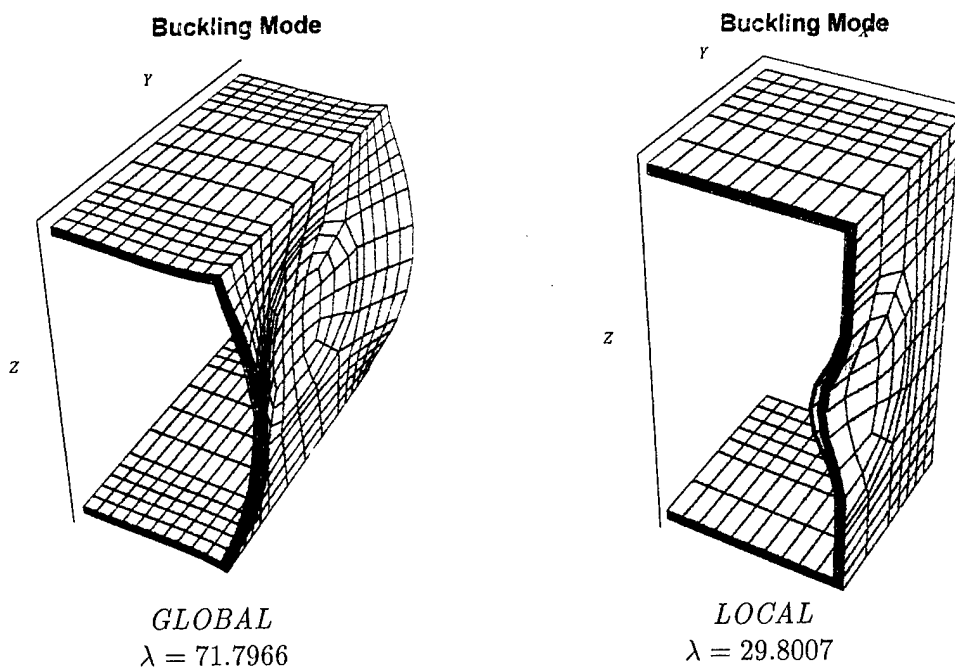


Figure 31. Global and local buckling mode shapes.

The presence of the delaminations at the specified ply interfaces is thus shown to reduce the critical buckling load by 66%.

### 7.3 Residual Strength Analysis

To illustrate the execution of a residual strength analysis, a model of an elastically supported laminated composite face plate is analyzed. Due to the lack of data of sufficient resolution regarding the spatial distribution of specific internal damage modes and subsequent experimental determination of residual strength, a specific state of internal damage is assumed for the following example.

The geometry and applied loading is shown in Figure 32. Material properties were selected as S2-Glass/3501 Epoxy tape with a nominal ply thickness of 0.0052 in. The material elastic properties are given by

$$\begin{array}{lll}
 E_1 & = & 7.150E6 \quad E_2 & = & 2.13E6 \quad E_3 & = & 2.13E6 \\
 G_{23} & = & 0.71E6 \quad G_{13} & = & 0.98E6 \quad G_{12} & = & 0.98E6 \\
 \nu_{23} & = & 0.499 \quad \nu_{13} & = & 0.306 \quad \nu_{12} & = & 0.296
 \end{array}$$

with strengths given by

$$\begin{array}{lll}
 X_{Ten} & = & 2.43E5 \quad X_{Comp} & = & 1.77E5 \quad Y_{Ten} & = & 7.0E3 \\
 Y_{Comp} & = & 3.06E4 \quad Z_{Ten} & = & 7.03E3 \quad Z_{Comp} & = & 3.5E4 \\
 R & = & 1.7E4 \quad S & = & 1.57E4 \quad T & = & 1.57E4
 \end{array}$$

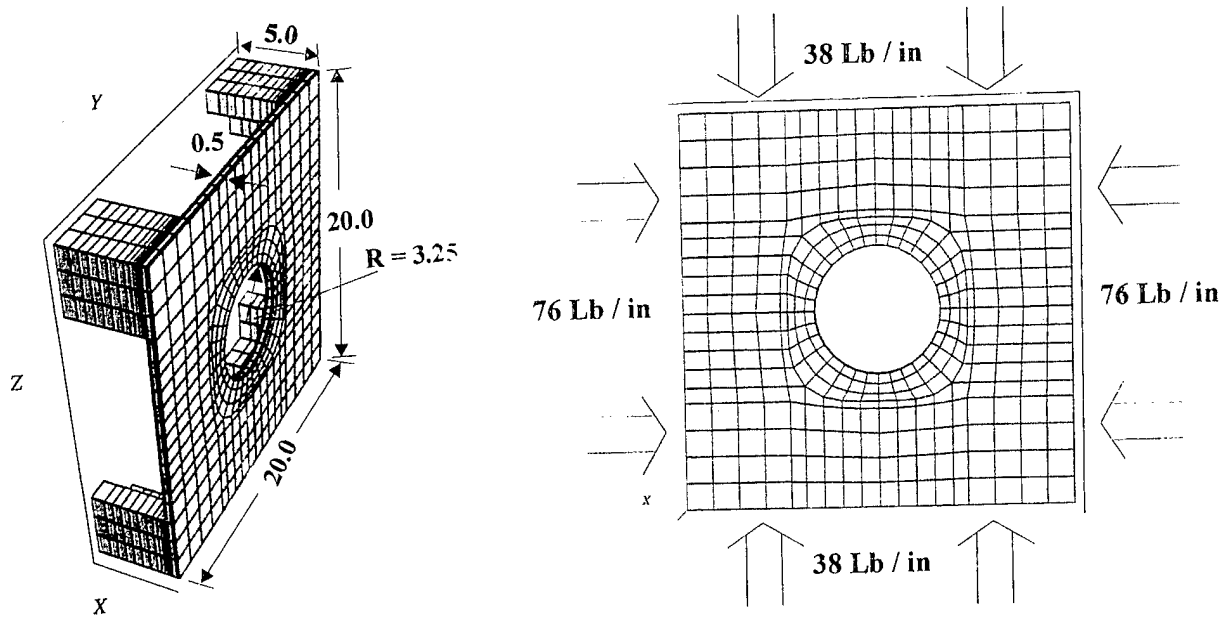


Figure 32. Geometry and loading of an elastically supported composite plate.

The face plate is composed of 96 plies and is assumed to have been subjected to a normal impact leading to an inner circular region where all properties are effectively zero and the region is modeled as an open hole. The laminate was divided into three layers, where 'l' indicates a layer interface. The layup is given by  $[\pm 45/0_6 | \pm 45_5/90_6 \pm 45_5/0_6 \pm 45_2/0_8 / \mp 45_2/0_6 \mp 45_5/90_6 / \mp 45_5 | 0_6 / \mp 45]$ . A residual strength analysis is performed which is selected to evaluate material failure with nonlinear material properties. Secant moduli were computed for the inplane Young's moduli as

$$E'_i = E_i \left( 1.0 - 0.75 \left| \frac{\sigma_{ii}}{\alpha_i} \right| \right), \quad (20)$$

and for shear moduli as

$$G'_{ij} = G_{ij} \left( 1.0 - 0.5 \left| \frac{\tau_{ij}}{\beta_i} \right| \right), \quad (21)$$

where  $\alpha$  and  $\beta$  are taken as material strengths given by

$$\begin{aligned} \alpha_1 &= 2.43E5 & \alpha_2 &= 7.0E3 & \alpha_3 &= 7.03E3 \\ \beta_1 &= 1.7E4 & \beta_2 &= 1.57E4 & \beta_3 &= 1.57E4 \end{aligned}$$

The maximum reduction in Young's moduli was limited to 25% of the initial values and 50% for the shear moduli. For this example, the maximum stress failure criteria is used with a nonspecific damage law that assigns zero modulus to plies experiencing failure without regard to failure mode. Abbreviated input and output files are shown, followed by a graphical presentation of the progression of failure.

### 7.3.1 Input Data File for a Residual Strength Problem

```
*HEADING
MODEL OF AN ELASTICALLY SUPPORTED COMPOSITE PLATE WITH AN OPEN HOLE
**
** [45/-45/0_6|(45/-45)_5/90_6/(45/-45)_5/0_6/(45/-45)_2/0_8/
** (-45/45)_2/0_6/(-45/45)_5/90_6/(-45/45)_5|0_6/-45/45]
**
**          LAYUP TAPE THICKNESS = 0.0052''
**
*SOLUTION, METH = MTL
  6,15,1.05
**ECHO
**PREPASS
**NODE PRINT
**  D,M
**PLY FAILURE PRINT
*NONLINEAR MATERIAL
  10, 0.01, 2.0
3
  2.43E5, 1.77E5
  7.0E3, 3.06E4
  7.0E3, 3.5E4
  1.7E4, 1.57E4, 1.57E4
*parameter lapfail
*parameter directory = current
*MEMORY ALLOCATION
  BAND
*GRAPHICS, format = mathematica
  2, 2, 1.0
**
**  NODE DEFINITIONS
**
**
**
**
** elastic supports
**
  1   5.0      -10.0      10.0
  2   5.8      -10.0      10.0
  3   6.3      -10.0      10.0
  4   6.8      -10.0      10.0
  5   7.3      -10.0      10.0
  .
  .
4708  8.7      -8.6396     -5.9189
4709  8.9875   -8.6396     -5.9189
4710  9.1875   -8.6396     -5.9189
4711  9.3375   -8.6396     -5.9189
4712  9.4375   -8.6396     -5.9189
4713  9.5      -8.6396     -5.9189
**
**          NODES, ELEMENTS, AND NODE SETS FOR DELAMINATED VERTICAL
**          COMPONENT OBTAINED FROM THE FOLLOWING *MODEL GENERATION
```

```

**      STATEMENT:
**
**          *MODEL GENERATION
**          8,4,10.0,10.0,4,4,4,4
**          2.0,1,1,1,0,1
**          0.0, 0.0, 1.0
**          0.0, 1.0, 0.0
**          1.0, 0.0, 0.0
**          1.0,10.0
**          1,5,250,5000,5000
**          0.95,9.875
**          2,6,255,7000,7000
**          0.85,9.625
**          3,7,265,11000,11000
**          0.8,9.50
**          4,8,270,13000,13000
**
** *NODE
5114  0.1000000E+02  0.3250000E+01  0.0000000E+00
5115  0.1000000E+02  0.3198816E+01  0.5745243E+00
5116  0.1000000E+02  0.3040097E+01  0.1149049E+01
5117  0.1000000E+02  0.2755322E+01  0.1723573E+01
5118  0.1000000E+02  0.2298097E+01  0.2298097E+01
.
.
.
13517  0.9500000E+01  0.1000000E+02  0.4558612E+01
13518  0.9500000E+01  0.1000000E+02  0.5918959E+01
13519  0.9500000E+01  0.1000000E+02  0.7279306E+01
13520  0.9500000E+01  0.1000000E+02  0.8639653E+01
13521  0.9500000E+01  0.1000000E+02  0.1000000E+02
**
**      DEFINE GENERATOR ELEMENTS
**
** *ELEMENT, LAYUP = 4, ELSET = 300
**
** top front elastic support
**
1, 401, 402, 902, 901, 1, 2, 102, 101
101, 501, 502, 802, 801, 401, 402, 902, 901
201, 601, 602, 702, 701, 501, 502, 802, 801
301, 901, 902, 1002, 1001, 101, 102, 202, 201
401, 1001, 1002, 1102, 1101, 201, 202, 302, 301
**
** top back elastic support
**
501, 1601, 1602, 1702, 1701, 1201, 1202, 1302, 1301
601, 1701, 1702, 1802, 1801, 1301, 1302, 1402, 1401
701, 1801, 1802, 1902, 1901, 1401, 1402, 1502, 1501
801, 2001, 2002, 2102, 2101, 1801, 1802, 1902, 1901
901, 2201, 2202, 2302, 2301, 2001, 2002, 2102, 2101
**
** bottom front elastic support
**

```

1001, 3601, 3602, 3702, 3701, 4001, 4002, 4102, 4101  
1101, 4001, 4002, 4102, 4101, 4401, 4402, 4502, 4501  
1201, 4401, 4402, 4502, 4501, 4601, 4602, 4702, 4701  
1301, 3701, 3702, 3802, 3801, 4101, 4102, 4202, 4201  
1401, 3801, 3802, 3902, 3901, 4201, 4202, 4302, 4301

\*\*

\*\* bottom back elastic support

\*\*

1501, 2401, 2402, 2502, 2501, 2801, 2802, 2902, 2901  
1601, 2501, 2502, 2602, 2601, 2901, 2902, 3002, 3001  
1701, 2601, 2602, 2702, 2701, 3001, 3002, 3102, 3101  
1801, 3001, 3002, 3102, 3101, 3201, 3202, 3302, 3301  
1901, 3201, 3202, 3302, 3301, 3401, 3402, 3502, 3501

\*\*

\*\* ELEMENT GENERATION FOR ELASTIC SUPPORTS

\*\*

\*ELGEN, ELID = 300

1, 12,1,1,,,,,

101, 12,1,1,,,,,

.

.

1801, 12,1,1,,,,,

1901, 12,1,1,,,,,

\*\*

\*\* CREATE NODE SETS FOR EQUIVALENCING

\*\*

\*NSET, NSID = 10

13, 113, 213, 313, 413, 913, 1013, 1113

513, 813, 613, 713

\*NSET, NSID = 20

13300, 13319, 13338, 13357, 13299, 13318, 13337, 13356

13298, 13317, 13297, 13316

.

.

\*NSET, NSID = 70

3413, 3513, 3213, 3313, 2813, 2913, 3013, 3113

2413, 2513, 2613, 2713

\*NSET, NSID = 80

13487, 13506, 13486, 13505, 13447, 13466, 13485, 13504

13446, 13465, 13484, 13503

\*\*

\*\* EQUIVALENCE NODE SETS

\*\*

\*EQUIVALENCE

10, 20

30, 40

50, 60

70, 80

\*\*

\*\* ELEMENTS IN VERTICAL COMPONENT FROM PRIOR \*MODEL GENERATION RUN

\*\*

\*ELEMENT, LAYUP = 1 ORIENTATION = 1

5129	7114	7115	7147	7146	5114	5115	5147	5146
5130	7115	7116	7148	7147	5115	5116	5148	5147
5131	7116	7117	7149	7148	5116	5117	5149	5148

5482	7499	7500	7519	7518	5499	5500	5519	5518
5483	7500	7501	7520	7519	5500	5501	5520	5519
5484	7501	7502	7521	7520	5501	5502	5521	5520

\*ELEMENT, LAYUP = 2 ORIENTATION = 1

7129	11114	11115	11147	11146	7114	7115	7147	7146
7130	11115	11116	11148	11147	7115	7116	7148	7147
7131	11116	11117	11149	11148	7116	7117	7149	7148

7482	11499	11500	11519	11518	7499	7500	7519	7518
7483	11500	11501	11520	11519	7500	7501	7520	7519
7484	11501	11502	11521	11520	7501	7502	7521	7520

\*ELEMENT, LAYUP = 3 ORIENTATION = 1

11129	13114	13115	13147	13146	11114	11115	11147	11146
11130	13115	13116	13148	13147	11115	11116	11148	11147
11131	13116	13117	13149	13148	11116	11117	11149	11148

11482	13499	13500	13519	13518	11499	11500	11519	11518
11483	13500	13501	13520	13519	11500	11501	11520	11519
11484	13501	13502	13521	13520	11501	11502	11521	11520

```

**
** EXCLUDE ELEMENTS IN ELASTIC SUPPORTS
**
*EXCLUDE ELEMENT
300
**
** RELAX TOLERANCE OF DEFORMED GEOMETRY CHECKS
**
*DEFORMED GEOMETRY
20.0
**
** LAMINATE DESCRIPTION
**
*LAYER, LAYUP = 1
1, 0.0052, 45.0
1, 0.0052, -45.0
1, 0.0312, 0.0
*LAYER, LAYUP = 2
1, 0.0260, 45.0
1, 0.0260, -45.0
1, 0.0312, 90.0
1, 0.0260, 45.0
1, 0.0260, -45.0
1, 0.0312, 0.0
1, 0.0104, -45.0

```

```

1, 0.0104, 45.0
1, 0.0416, 0.0
1, 0.0104, -45.0
1, 0.0104, 45.0
1, 0.0312, 0.0
1, 0.0260, -45.0
1, 0.0260, 45.0
1, 0.0312, 90.0
1, 0.0260, -45.0
1, 0.0260, 45.0
*LAYER, LAYUP=3
1, 0.0312, 0.0
1, 0.0052, -45.0
1, 0.0052, 45.0
*LAYER, LAYUP = 4
2, 1.0, 0.0
**
** MATERIAL DEFINITIONS
**
** COMPOSITE PLY PROPERTIES (S2-GLASS/3501 EPOXY)
**
*MATERIAL, MATID = 1
7.150E6, 2.13E6, 2.13E6, 0.98E6, 0.71E6, 0.98E6
0.306, 0.499, 0.296
*FAILURE CRITERIA, FCID = 1
MAX-STRESS
2.43E5, 1.77E5, 7.0E3, 3.06E4, 7.0E3, 3.5E4
1.7E4, 1.57E4, 1.57E4
*DAMAGE LAW, DLID = 1
NULL
**
** METALLIC PROPERTIES
**
*MATERIAL, MATID = 2
1.0E8, 1.0E8, 1.0E8, 0.3846E8, 0.3846E8, 0.3846E8
0.3, 0.3, 0.3
*FAILURE CRITERIA, FCID = 2
MAX-STRESS
5.3E4, 2.2E5, 5.3E4, 2.2E5, 5.3E4, 2.2E6
4.8E4, 4.8E4, 4.8E4
*DAMAGE LAW, DLID = 2
NULL
**
** ESTABLISH LOCAL COORDINATE SYSTEM
**
*ORIENTATION
1, 0.0, 1.0, 0.0, 0.0, 0.0, 1.0
**
** NODE SET DEFINITION FOR BOUNDARY CONSTRAINT INPUT
**
*NSET, NSID = 100
1, 101, 201, 301, 401, 501, 601, 701, 801
901, 1001, 1101
*NSET, NSID = 110

```

```

1201, 1301, 1401, 1501, 1601, 1701, 1801, 1901, 2001
2101, 2201, 2301
*NSET, NSID = 120
2401, 2501, 2601, 2701, 2801, 2901, 3001, 3101, 3201
3301, 3401, 3501
*NSET, NSID = 130
3601, 3701, 3801, 3901, 4001, 4101, 4201, 4301, 4401
4501, 4601, 4701
*BOUNDARY2
100, 1, 3
110, 1, 3
120, 1, 3
130, 1, 3
**
** biaxial y-z plane loading
**
*CLOAD
5300, 3, -.1000000E+02
5319, 3, -.1000000E+02
5338, 3, -.1000000E+02
.
.
.
13519, 2, -.2000000E+02
13520, 2, -.2000000E+02
13521, 2, -.2000000E+02
*ENDDATA

```

### 7.3.2 Output Data File for a Residual Strength Problem

```

@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
@@
@@          U.S. ARMY RESEARCH LABORATORY          @@
@@
@@              R E S T R A N              @@
@@
@@ RESIDUAL STRENGTH ANALYSIS OF IMPACT @@
@@   DAMAGED COMPOSITE LAMINATES   @@
@@
@@              VERSION 1.0              @@
@@
@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@

```

\*\*\* MESSAGE: ELEMENT NODE ORDER IS BEING CONVERTED TO RESTRAN FORMAT

\*\*\* WARNING: MATERIAL ID 1 HAS A MIXED MODE FAILURE CRITERIA  
ASSOCIATED WITH A SINGLE MODE DAMAGE LAW (NULL).  
NULL ACCEPTED

\*\*\* WARNING: MATERIAL ID 2 HAS A MIXED MODE FAILURE CRITERIA  
ASSOCIATED WITH A SINGLE MODE DAMAGE LAW (NULL).  
NULL ACCEPTED

```
#####  
###                               ###  
### M O D E L   D E F I N I T I O N ###  
###                               ###  
#####
```

J O B H E A D I N G :  
-----

M O D E L O F A N E L A S T I C A L L Y S U P P O R T E D C O M P O S I T E P L A T E

S O L U T I O N C O N T R O L :  
-----

S O L U T I O N A L G O R I T H M :

R E S I D U A L S T R E N G T H A N A L Y S I S : M A T E R I A L F A I L U R E O N L Y

I T E R A T I O N P A R A M E T E R S :

M A X I M U M N U M B E R O F G L O B A L A N A L Y S I S C Y C L E S = 6  
N U M B E R O F I T E R A T I O N S T O C O N V E R G E M A T E R I A L F A I L U R E = 15

M E M O R Y A L L O C A T I O N :

B A N D W I D T H S T O R A G E M O D E

\* B A N D W I D T H M I N I M I Z A T I O N W I L L B E P E R F O R M E D

M A T E R I A L B E H A V I O R :

N O N L I N E A R E L A S T I C

L O C A L N O N L I N E A R S O L U T I O N P A R A M E T E R S :

M A X I M U M N U M B E R O F I T E R A T I O N S = 10  
M A T E R I A L C O N V E R G E N C E T O L E R A N C E = 0.100E-01  
B U C K L I N G C O N V E R G E N C E T O L E R A N C E = 0.200E+01

P R O G R A M O P T I O N S :  
-----

- \* E L E M E N T S A S S O C I A T E D W I T H L O A D A P P L I C A T I O N P O I N T S  
A R E E X C L U D E D F R O M E X H I B I T I N G F A I L U R E
- \* E X T E N D E D J O B E X E C U T I O N S T A T I S T I C S W I L L B E P R I N T E D
- \* T H E F O L L O W I N G E L E M E N T S E T S A R E E X C L U D E D F R O M F A I L U R E P R E D I C T I O N

300

REQUESTED PRINT OPTIONS:

\* PRINT ELEMENT PLY FAILURE STATISTICS

GRAPHICS:

- @ GRAPHICAL OUTPUT IN MATHEMATICA FORMAT WILL BE GENERATED
- @ BOTH UNDEFORMED AND DEFORMED GEOMETRY IS REQUESTED  
DEFORMATION/MODE MAGNIFICATION FACTOR = 0.1000E+01
- @ RESTRAN GRAPHICS CONTAINED IN FILE: restran.grf

NODE DEFINITIONS:

NODE ID	X	Y	Z
1	0.500E+01	-.100E+02	0.100E+02
2	0.580E+01	-.100E+02	0.100E+02
3	0.630E+01	-.100E+02	0.100E+02
4	0.680E+01	-.100E+02	0.100E+02
5	0.730E+01	-.100E+02	0.100E+02
	.	.	.
13517	0.950E+01	0.100E+02	0.456E+01
13518	0.950E+01	0.100E+02	0.592E+01
13519	0.950E+01	0.100E+02	0.728E+01
13520	0.950E+01	0.100E+02	0.864E+01
13521	0.950E+01	0.100E+02	0.100E+02

SPECIFIED NODE SETS:

SET ID 10:	
13 113 213 313 413 913 1013 1113 513 813	613 713
SET ID 20:	
13300 13319 13338 13357 13299 13318 13337 13356 13298 13317	13297 13316

ELEMENT DEFINITIONS:

ELEMENT	N1	N2	N3	N4	N5	N6	N7	N8
---------	----	----	----	----	----	----	----	----

1	401	402	902	901	1	2	102	101
2	402	403	903	902	2	3	103	102
3	403	404	904	903	3	4	104	103
4	404	405	905	904	4	5	105	104
5	405	406	906	905	5	6	106	105

11480	13497	13516	13517	13498	11497	11516	11517	11498
11481	13498	13517	13518	13499	11498	11517	11518	11499
11482	13499	13518	13519	13500	11499	11518	11519	11500
11483	13500	13519	13520	13501	11500	11519	11520	11501
11484	13501	13520	13521	13502	11501	11520	11521	11502

E L E M E N T S E T S:

-----  
ELEMENT SET ID 300:

1 101 201 301 ... 1909 1910 1911 1912

M A T E R I A L P R O P E R T Y D A T A:

-----  
MATERIAL ID 1

E1 = 0.715E+07 G23 = 0.980E+06 MU23 = 0.30600  
E2 = 0.213E+07 G13 = 0.710E+06 MU13 = 0.49900  
E3 = 0.213E+07 G12 = 0.980E+06 MU12 = 0.29600

ASSOCIATED FAILURE LAW:

HOFFMAN CRITERION (3-D MIXED MODE)

ASSOCIATED DAMAGE LAW:

NULL POST-FAILURE PROPERTIES

MATERIAL ID 2

E1 = 0.100E+09 G23 = 0.385E+08 MU23 = 0.30000  
E2 = 0.100E+09 G13 = 0.385E+08 MU13 = 0.30000  
E3 = 0.100E+09 G12 = 0.385E+08 MU12 = 0.30000

ASSOCIATED FAILURE LAW:

MAXIMUM STRESS CRITERION

XT = 0.530E+05 XC = 0.220E+06 YT = 0.530E+05  
YC = 0.220E+06 ZT = 0.530E+05 ZC = 0.220E+07  
R = 0.480E+05 S = 0.480E+05 T = 0.480E+05

ASSOCIATED DAMAGE LAW:

NULL POST-FAILURE PROPERTIES

M A T E R I A L L A Y E R D E F I N I T I O N S

---

LAYUP ID = 1  
 NUMBER OF PLYS = 3

MATERIAL ID	PLY THICKNESS	ORIENTATION
1	0.00520	45.00000
1	0.00520	-45.00000
1	0.03120	0.00000

LAYUP ID = 2  
 NUMBER OF PLYS = 17

MATERIAL ID	PLY THICKNESS	ORIENTATION
1	0.02600	45.00000
1	0.02600	-45.00000
1	0.03120	90.00000
1	0.02600	45.00000
1	0.02600	-45.00000
1	0.03120	0.00000
1	0.01040	-45.00000
1	0.01040	45.00000
1	0.04160	0.00000
1	0.01040	-45.00000
1	0.01040	45.00000
1	0.03120	0.00000
1	0.02600	-45.00000
1	0.02600	45.00000
1	0.03120	90.00000
1	0.02600	0.00000
1	0.02600	45.00000

LAYUP ID = 3  
 NUMBER OF PLYS = 3

MATERIAL ID	PLY THICKNESS	ORIENTATION
1	0.03120	0.00000
1	0.00520	0.00000
1	0.00520	45.00000

LAYUP ID = 4  
 NUMBER OF PLYS = 1

MATERIAL ID	PLY THICKNESS	ORIENTATION
2	1.00000	0.00000

M A T E R I A L C O O R D I N A T E S Y S T E M S

---

ID	V11	V12	V13	V21	V22	V23
1	0.000E+00	0.100E+01	0.000E+00	0.000E+00	0.000E+00	0.100E+01

B O U N D A R Y C O N D I T I O N S :

---

SINGLE POINT CONSTRAINTS:

NODE	DOF1 TO DOF2
1	1 1
101	1 1
201	1 1
301	1 1
.	.
.	.
.	.
4401	1 3
4501	1 3
4601	1 3
4701	1 3

APPLIED CONCENTRATED FORCES:

NODE	DIRECTION	MAGNITUDE
5300	3	-.100E+02
5319	3	-.100E+02
5338	3	-.100E+02
.	.	.
.	.	.
.	.	.
13519	2	-.200E+02
13520	2	-.200E+02
13521	2	-.200E+02

FORCE/MOMENT RESULTANTS AT ORIGIN:

|R| = 0.000E+00      |M| = 0.000E+00

Rx = 0.000E+00    Ry = 0.000E+00    Rz = 0.000E+00

Mx = 0.000E+00    My = 0.000E+00    Mz = 0.000E+00

Xo = 0.000E+00    Yo = 0.000E+00    Zo = 0.000E+00

\*\*\* E N D O F M O D E L D E F I N I T I O N \*\*\*

M O D E L S I Z E P A R A M E T E R S

NUMBER OF ELEMENTS = 1308  
NUMBER OF NODES = 2208  
DEGREES OF FREEDOM = 6624  
SYSTEM BANDWIDTH = 2574

#####  
## ##  
## B E G I N F A I L U R E A N A L Y S I S ##  
## ##  
#####

#####  
@@ ##  
@@ PRIMARY ANALYSIS CYCLE. PASS NUMBER 1 @@  
@@ ##  
#####

#####  
### ###  
### NONLINEAR SOLUTION PROCEDURE ###  
### ###  
#####

<< GLOBAL ANALYSIS CYCLE: 1 ITERATION: 1 >>  
\* MATERIAL FAILURE LOAD CONVERGENCE FACTOR: 0.177E+03  
<< GLOBAL ANALYSIS CYCLE: 1 ITERATION: 2 >>  
\* MATERIAL FAILURE LOAD CONVERGENCE FACTOR: 0.196E+00  
<< GLOBAL ANALYSIS CYCLE: 1 ITERATION: 3 >>  
\* MATERIAL FAILURE LOAD CONVERGENCE FACTOR: 0.267E-01  
<< GLOBAL ANALYSIS CYCLE: 1 ITERATION: 4 >>  
\* MATERIAL FAILURE LOAD CONVERGENCE FACTOR: 0.212E-01  
<< GLOBAL ANALYSIS CYCLE: 1 ITERATION: 5 >>  
\* MATERIAL FAILURE LOAD CONVERGENCE FACTOR: 0.657E-02

\*\*\*\*\*  
\*\*\* NONLINEAR MATERIAL LOADS HAVE CONVERGED \*\*\*  
\*\*\* IN 5 ITERATIONS. \*\*\*  
\*\*\*\*\*

\*\*\*\*\*  
\*\* \*\*  
\*\* ALGORITHMIC PATH FOR MINIMUM LOAD INCREMENT \*\*  
\*\* TO NEXT FAILURE: MATERIAL DEGRADATION \*\*  
\*\* \*\*

```

**          MATERIAL          BUCKLING          **
**          -----          -----          **
** SCALE:    0.151E+03      EXCLUDED          **
**                                                  **
*****

```

```

*****
*
* MATERIAL FAILURE ANALYSIS *
*
* ITERATION NO.  SCALE FACTOR *
* -----          ----- *
*          1          0.151E+03 *
*
*
*****

```

\* NUMBER OF ELEMENTS DEGRADED = 3

```

*****
*
* MATERIAL FAILURE ANALYSIS *
*
* ITERATION NO.  SCALE FACTOR *
* -----          ----- *
*          2          0.151E+03 *
*
*
*****

```

\* NUMBER OF ELEMENTS DEGRADED = 14

```

*****
*
* MATERIAL FAILURE ANALYSIS *
*
* ITERATION NO.  SCALE FACTOR *
* -----          ----- *
*          3          0.151E+03 *
*
*
*****

```

\* NUMBER OF ELEMENTS DEGRADED = 7

```

*****
*
* MATERIAL FAILURE ANALYSIS *
*
* ITERATION NO.  SCALE FACTOR *
* -----          ----- *
*          4          0.151E+03 *
*
*
*****

```

\* NUMBER OF ELEMENTS DEGRADED = 6

```

*****
*
* MATERIAL FAILURE ANALYSIS *
*
* ITERATION NO. SCALE FACTOR *
* ----- *
* 5 0.151E+03 *
*
*****

```

\* NUMBER OF ELEMENTS DEGRADED = 10

```

*****
*
* MATERIAL FAILURE ANALYSIS *
*
* ITERATION NO. SCALE FACTOR *
* ----- *
* 6 0.151E+03 *
*
*****

```

\* NUMBER OF ELEMENTS DEGRADED = 20

```

*****
*
* MATERIAL FAILURE ANALYSIS *
*
* ITERATION NO. SCALE FACTOR *
* ----- *
* 7 0.151E+03 *
*
*****

```

\* NUMBER OF ELEMENTS DEGRADED = 54

```

*****
*
* MATERIAL FAILURE ANALYSIS *
*
* ITERATION NO. SCALE FACTOR *
* ----- *
* 8 0.151E+03 *
*
*****

```

\* NUMBER OF ELEMENTS DEGRADED = 140

```

*****
*
* MATERIAL FAILURE ANALYSIS *
*
* ITERATION NO. SCALE FACTOR *
* ----- *

```

```

*          9          0.151E+03  *
*                                     *
*****

```

```
* NUMBER OF ELEMENTS DEGRADED =      188
```

```
* ELEMENT FAILURE HAS ALTERED MODEL STABILITY SUCH
  THAT RIGID BODY MODES HAVE BEEN DETECTED.
```

```
TOTAL FAILURE IS ASSUMED.
```

```
ELEMENT PLY FAILURE STATUS AT CYCLE NO      1
```

ELEMENT ID	PLY FAILURE MODES:			%TOTAL
	%FIBER	%MATRIX	%BUCKLING	
5129	0	0	0	100
5130	0	0	0	100
5131	0	0	0	33
5132	0	0	0	33
11461	0	0	0	100
11462	0	0	0	100
11463	0	0	0	100
11464	0	0	0	33

```

#####
##                                     ##
## ANALYSIS PREDICTS CATASTROPHIC FAILURE OF ##
## THE MODEL AT AN ULTIMATE LOAD GIVEN BY: ##
##                                     ##
## P(ULT) = (0.15140E+03) * P(INITIAL) ##
##                                     ##
#####

```

```

@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
@@                                     @@
@@ F A I L U R E   A N A L Y S I S   C O M P L E T E D @@
@@                                     @@
@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@

```

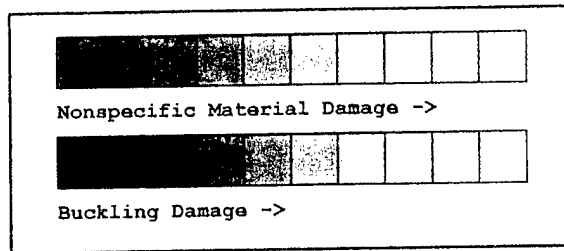
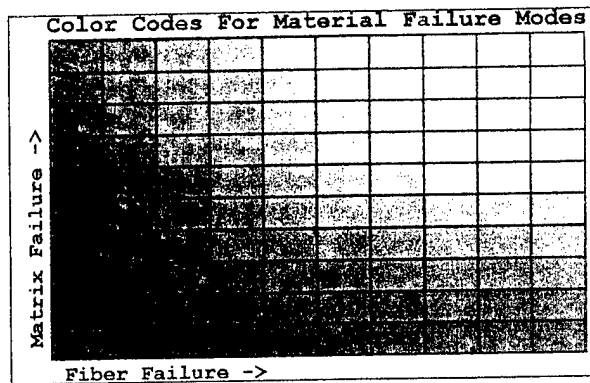
### 7.3.3 Graphical Output Using MATHEMATICA

The initial graphics generated by MATHEMATICA show the color codes used to display various element failure modes. In the specific demonstration problem analyzed, complete element failure is indicated by a wireframe depiction; because no specific failure modes were predicted using the maximum stress criterion, material failure is shown using the general material failure color coding scheme.



### GRAPHICAL DEPICTION OF FAILURE MODES

Fiber and matrix damage are shown using a bichromatic color code. Nonspecific material failure is indicated using a monochrome scheme. Buckling failure is shown in grayscale. Complete failure is indicated by a wireframe depiction.



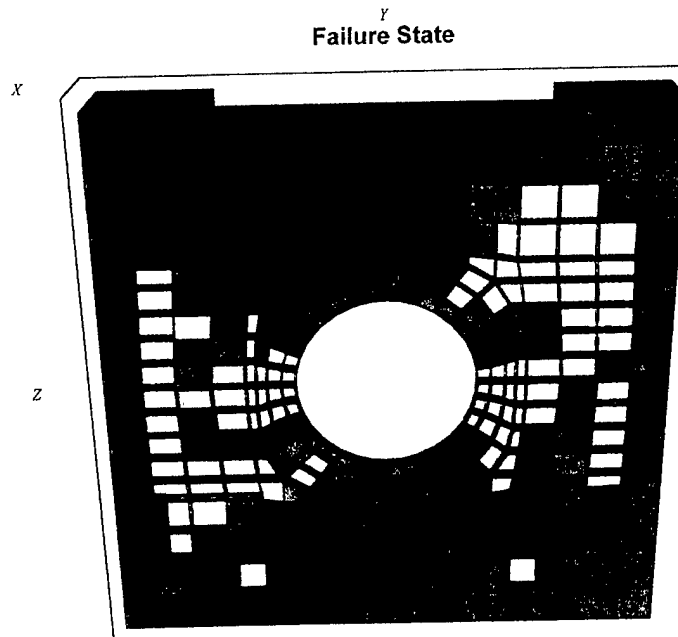
Equilibrium between external and internal forces was converged in six iterations. With the material-only failure option set, in each element all plies were analyzed using the maximum stress criterion to determine the scale factor to be applied to the external loads to cause failure in a specific ply. The lowest factor was selected, multiplied by the acceleration factor (which in this sample run was selected as 1.05 or 5% above the minimum ply failure load), and then applied to the external loads. During the first analysis cycle, the initial failure of three plies was sufficient to cause a sequence of load redistribution and subsequent additional failures that led to a cascade process resulting in ultimate total failure as listed in Table 3.

Table 3. Cascade failure in residual strength analysis.

Iteration	Element Failures
1	3
2	14
3	7
4	6
5	10
6	20
7	54
8	140
9	188

This was automatically determined by the presence of fragmentation which caused the global stiffness matrix to become singular, which terminated execution. The final failure state is shown below. Mediating element failures are shown to have progressed to the outer boundary. Failure in the line of elements comprising the outer boundary have been precluded using the LAPFAIL parameter, which prevents elements to which applied external loads have been applied from exhibiting failure.

ANALYSIS CYCLE     1  
 Material Failure at Scale = 0.151E+03



The final residual strength prediction yields the ultimate load carrying capability as a multiple of the initial biaxial loads equal to 151.4. Because a 5% acceleration was used, the resolution of the residual strength measure  $R$  falls within the bounds  $144.19 \leq R \leq 151.4$ .

## 8 Conclusion

The RESTRAN computer program is a finite element based design tool for the analysis of residual strength in composite structures with arbitrary three-dimensional geometry, loading, support conditions, and material properties. The unique feature of RESTRAN is the combined algorithmic accounting of both material and structural failure modes. Material failure modes are predicted using a robust suite of failure criteria and damage laws. Structural failure due to sublaminar buckling of multiple delaminations is performed, allowing for an arbitrary number of assumed delaminations. User-defined subroutine interfaces are provided to permit user modification and enhancement of basic analysis procedures. A progressive failure analysis is performed until ultimate structural failure is simulated, yielding an estimate of the residual strength. Thus, the RESTRAN program constitutes a robust design/research tool which can provide an accurate assessment of remaining strength in composite structures containing impact damage.

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## 9 References

1. Wolfram, S. *MATHEMATICA: A System for Doing Mathematics by Computer*, Second Edition, New York, Addison Wesley, 1993.
2. Amtec Engineering, Inc., *TECPLOT, Version 7*, Bellevue, Washington, 1996.
3. Saether, E., "RESTRAN: *RE*sidual *ST*rength *AN*alysis. Vol. I: Theoretical Manual" ARL-TR- , U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, 2001.
4. Hibbitt, Karlsson, and Sorensen, Inc. *ABAQUS User's Manual, Version 5.2*, Pawtucket, RI, 1992.
5. MSC Software Corp., *MSC-NASTRAN, Quick Reference Guide*, Costa Mesa, CA 2001.
6. PDA Engineering, PATRAN Division, *PATRAN Plus User Manual, Release 2.5*, Costa Mesa, CA, 1990.

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**Appendix A:**

**Sample User-Defined Subroutine to Compute Nonlinear Material Properties**

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```

SUBROUTINE USERNL ( STRESS,STRAIN,SXX,SY,SZZ,TYZ,TZX,TTY,EXX,
1          EYY,EZZ,GYZ,GZX,GXY,THKN,ATHK,TLM,THETA,
2          PNLRM,FE1,FE2,FE3,FG31,FG23,FG12,FV31,
3          FV23,FV12,NORD )
C
C *****
C **                **
C **  USER-DEFINED ROUTINE TO COMPUTE SECANT **
C **  MODULI IN NONLINEAR MATERIAL ANALYSIS **
C **                **
C *****
C
C      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
C
C      DIMENSION STRESS(27,6),STRAIN(27,6),PNLRM(25)
C
C      @@@ THREE DIFFERENT USER-DEFINED NONLINEARITIES ARE CONTAINED @@@
C      @@@ IN THIS SUBROUTINE. THE FIRST SPECIFIES A PIECE-WISE LINEAR @@@
C      @@@ LINEAR STRESS-STRAIN RELATIONSHIP, THE SECOND DEFINES @@@
C      @@@ UNEQUAL MODULI IN TENSION AND COMPRESSION. THE THIRD CASE @@@
C      @@@ YIELDS MODULI THAT ARE A CONTINUOUS FUNCTION OF STRESSES @@@
C      @@@ UP TO SET LEVEL. THESE CASES ARE SELECTED THROUGH SETTING @@@
C      @@@ THE FIRST ELEMENT OF THE PNLRM ARRAY WHICH CONTAINS, IN @@@
C      @@@ SEQUENCE, THE PARAMETERS, Pn, SPECIFIED IN THE *NONLINEAR @@@
C      @@@ MATERIAL INPUT STATEMENT. @@@
C
C      IF ( INT(PNLRM(1)) .EQ. 1 ) THEN
C
C      @@@ USER-DEFINED PIECE-WISE LINEAR STRESS-STRAIN LAW @@@
C      @@@ @@@ @@@
C      @@@ PNLRM(2,3,4) : CONTAINS YIELD STRESS VALUES @@@
C      @@@ PNLRM(5,6,7) : CONTAINS MODULI REDUCTION FACTOR @@@
C
C      @@@ COMPUTE VON MISES STRESS @@@
C
C      VMSS = SQRT(( (SXX-SY)**2 + (SY-SZZ)**2 + (SZZ-SXX)**2)/2.0)
C
C      @@@ DETERMINE WHICH LINEAR SECTION OF THE @@@
C      @@@ STRESS/STRAIN CURVE WE ARE IN @@@
C
C      IF ( VMSS .LT. PNLRM(1) ) THEN
C
C      @@@ INITIAL MODULI @@@
C
C      FAC = 1
C
C      ELSE IF ( VMSS .GE. PNLRM(1) .AND. VMSS .LT. PNLRM(2) ) THEN
C
C      @@@ SECOND LINEAR SEGMENT @@@
C
C      FAC = PNLRM(4)
C
C      ELSE IF ( VMSS .GE. PNLRM(2) .AND. VMSS .LT. PNLRM(3) ) THEN

```

```

C      @@@ THIRD LINEAR SEGMENT @@@
C
C      FAC = PNLRM(5)
C
C      ELSE IF ( VMSS .GE. PNLRM(3) ) THEN
C
C      @@@ FINAL LINEAR SEGMENT @@@
C
C      FAC = PNLRM(5)
C
C      END IF
C
C      @@@ ASSIGN MODULI REDUCTION FACTORS @@@
C
C      FE1 = FAC
C      FE2 = FAC
C      FE3 = FAC
C      FG31 = FAC
C      FG23 = FAC
C      FG12 = FAC
C
C      ELSE IF ( INT(PNRLM(1)) .EQ. 2 ) THEN
C
C      @@@      UNEQUAL TENSION AND COMPRESSION MODULI      @@@
C      @@@      @@@      @@@
C      @@@ PNRLM(2-7)  CONTAIN MULTIPLIERS TO YIELD TENSION MODULI @@@
C      @@@      VALUES FOR Exx,Eyy,Ezz,Gzx,Gyz,Gxy      @@@
C      @@@ PNRLM(8-15) CONTAIN MULTIPLIERS TO YIELD COMPRESSION @@@
C      @@@      MODULI VALUES FOR Exx,Eyy,Ezz,Gzx,Gyz,Gxy @@@
C
C      IF ( SXX .GT. 0.000 ) THEN
C          FE1 = PNRLM(2)
C      ELSE
C          FE1 = PNRLM(8)
C      END IF
C      IF ( SYX .GT. 0.000 ) THEN
C          FE2 = PNRLM(3)
C      ELSE
C          FE2 = PNRLM(9)
C      END IF
C      IF ( SZZ .GT. 0.000 ) THEN
C          FE3 = PNRLM(4)
C      ELSE
C          FE3 = PNRLM(10)
C      END IF
C      IF ( TYZ .GT. 0.000 ) THEN
C          FG31 = PNRLM(5)
C      ELSE
C          FG31 = PNRLM(11)
C      END IF
C      IF ( TZX .GT. 0.000 ) THEN
C          FG23 = PNRLM(6)
C      ELSE
C          FG32 = PNRLM(12)

```

```

END IF
IF ( TXY .GT. 0.000 ) THEN
  FG12 = PNRLM(7)
ELSE
  FG12 = PNRLM(13)
END IF

C
ELSE IF ( INT(PNLRM(1)) .EQ. 3 ) THEN
C
C   @@@ USER-DEFINED NONLINEAR STRESS-STRAIN LAW   @@@
C   @@@                                           @@@
C   @@@ PNLRM(2-11) : CONTAINS ULTIMATE STRENGTHS @@@
C   @@@           SXX-TEN, SXX-COMP,           @@@
C   @@@           SYX-TEN, SYX-COMP,           @@@
C   @@@           SZZ-TEN, SZZ-COMP,           @@@
C   @@@           R, S, T                       @@@
C
C   @@@ REDUCTION LAW: FACi = 1.0 - BETA*(Si/STRENGTHi) @@@
C
  BETA1 = 0.75
  BETA2 = 0.50
  IF ( SXX .GE. 0.0 ) THEN
    FE1 = 1.0 - BETA1*ABS(SXX/PNLRM(2))
  ELSE
    FE1 = 1.0 - BETA1*ABS(SXX/PNLRM(3))
  END IF

C
  IF ( SYX .GE. 0.0 ) THEN
    FE2 = 1.0 - BETA1*ABS(SYX/PNLRM(4))
  ELSE
    FE2 = 1.0 - BETA1*ABS(SYX/PNLRM(5))
  END IF

C
  IF ( SZZ .GE. 0.0 ) THEN
    FE3 = 1.0 - BETA1*ABS(SZZ/PNLRM(6))
  ELSE
    FE3 = 1.0 - BETA1*ABS(SZZ/PNLRM(7))
  END IF

C
  FG31 = 1.0 - BETA2*ABS(TYZ/PNLRM(8))
  FG23 = 1.0 - BETA2*ABS(TZX/PNLRM(9))
  FG12 = 1.0 - BETA2*ABS(TXY/PNLRM(10))

C
C   @@@ LIMIT MODULI REDUCTION TO FACTOR OBTAINED TO 25% @@@
C   @@@ FOR YOUNG'S MODULI AND 50% FOR SHEAR MODULI   @@@
C
  IF ( FE1 .LT. 0.75 ) FE1 = 0.75
  IF ( FE2 .LT. 0.75 ) FE2 = 0.75
  IF ( FE3 .LT. 0.75 ) FE3 = 0.75
  IF ( FG31 .LT. 0.50 ) FG31 = 0.50
  IF ( FG23 .LT. 0.50 ) FG23 = 0.50
  IF ( FG12 .LT. 0.50 ) FG12 = 0.50

C
END IF

```

C  
C @@@ END EXAMPLE @@@  
C  
    RETURN  
    END

**Appendix B:**

**Sample User-Defined Subroutine to Compute Material Failure**

INTENTIONALLY LEFT BLANK.

```

SUBROUTINE USERFC ( SGPTS,EGPTS,STRESS,STRAIN,PTHK,THETA,IPLY,
1          NELID,PARAM,E1,E2,E3,G12,G23,G31,V12,V23,
2          V13,EM,EF,NORD,NSTAT,NFSTAT,NACCS )
C
C *****
C **                                     **
C ** USER-DEFINED FAILURE CRITERION TO COMPUTE **
C ** MATERIAL FAILURE UNDER APPLIED LOAD **
C **                                     **
C *****
C
C IMPLICIT DOUBLE PRECISION(A-H,O-Z)
C
C DIMENSION SGPTS(27,6),EGPTS(27,6),STRESS(6),STRAIN(6)
C DIMENSION PARAM(15)
C
C ### BEGIN EXAMPLE ###
C
C <<< VALUE IN PARAM(1) IS USED TO SELECT THE >>>
C <<< FAILURE CRITERION TO BE APPLIED. OTHER >>>
C <<< VALUES STORED IN PARAM ARRAY AS NEEDED. >>>
C
C     NFLAG = INT(PARAM(1))
C
C     IF ( NFLAG .EQ. 1 ) THEN
C
C     <<< FAILURE CRITERIA AND DAMAGE LAWS AS PRESENTED IN: >>>
C     <<< FU-KUO CHANG AND KUO-YEN CHANG, "A PROGRESSIVE DAMAGE >>>
C     <<< MODEL FOR LAMINATED COMPOSITES CONTAINING STRESS >>>
C     <<< CONCENTRATION," J. COMP. MAT, PP. 834-855, 1987. >>>
C
C     S1 = STRESS(1)
C     S2 = STRESS(2)
C     S12 = STRESS(6)
C
C     <<< NONLINEAR SHEAR STRESS-STRAIN FACTOR ALPHA >>>
C
C     ALPHA = PARAM(2)
C
C     <<< ULTIMATE STRENGTH MEASURES >>>
C
C     XT = PARAM(3)
C     YT = PARAM(4)
C     SC = PARAM(5)
C
C     EM = SQRT( (S2/YT)**2 + (S12**2/(2*G12)+3*ALPHA*S12**4/4)/
1          (SC**2 / (2*G12)+3*ALPHA* SC**4/4) )
C
C     <<< FIBER-MATRIX SHEARING AND FIBER BREAKAGE >>>
C
C     EF = SQRT( (S1/XT)**2 + (S12**2/(2*G12)+3*ALPHA*S12**4/4)/
1          (SC**2 / (2*G12)+3*ALPHA* SC**4/4) )
C
C     ET = MAX(EM,EF)

```

```

      EF = 1.0/ET
      EM = EF
C
      NFSTAT = NSTAT
      NACCS = 0
C
C <<< EMPLOY PROPERTY DEGRADATION LAWS >>>
C
      IF ( EM .GT. 1.0 ) THEN
C
C <<< MATRIX CRACKING >>>
C
      V12 = 0.0
      V23 = 0.0
      V13 = 0.0
      E2 = 0.0
      E3 = 0.0
      G23 = 0.0
C
      IF ( NSTAT .EQ. 0 ) THEN
        NFSTAT = 2
      ELSE
        NFSTAT = 3
      END IF
      NACCS = 1
C
      END IF
C
      IF ( EF .GT. 1.0 ) THEN
C
C <<< FIBER BREAKAGE/FIBER-MATRIX SHEARING DAMAGE CALCULATED >>>
C <<< USING A MICROMECHANICAL FIBER BUNDLE FAILURE APPROACH >>>
C
      A = PTHK
      A0 = PARAM(6)
      BETA = PARAM(7)
C
C <<< DAMAGE IS ASSUMED TO FOLLOW A WEIBUL DISTRIBUTION >>>
C
      E1 = E1* EXP(-(A/A0)**BETA)
      G12 = G12*EXP(-(A/A0)**BETA)
      G31 = G31*EXP(-(A/A0)**BETA)
C
      IF ( NSTAT .EQ. 0 ) THEN
        NFSTAT = 2
      ELSE
        NFSTAT = 3
      END IF
      NACCS = 1
C
      END IF
C
      END IF
C

```

C \*\*\* END EXAMPLE \*\*\*

C

RETURN  
END

INTENTIONALLY LEFT BLANK.

**Appendix C:**

**Sample User-Defined Subroutine to Assign Initial Material Damage**

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```

SUBROUTINE USERID (PTHK,THETA,E1,E2,E3,G13,G23,G12,V13,V23,
1          V12,P1,P2,P3,P4,P5,P6,P7,P8,P9,NELID,
2          IPLY,NSTAT )
C
C *****
C **                               **
C **   USER-DEFINED SUBROUTINE TO ASSIGN   **
C **   INITIAL ELEMENT MATERIAL DAMAGE.     **
C **                               **
C *****
C
C   IMPLICIT DOUBLE PRECISION(A-H,O-Z)
C
C       *** EXAMPLE ROUTINE ***
C
C   @@@ USER DEFINITION FOR THE INITIAL PROPERTIES OF   @@@
C   @@@ Kth PLY IN ELEMENT WITH ID LABEL NELID:         @@@
C
C   @@@ SELECTION OF INITIAL DAMAGE IS BASED ON ELEMENT @@@
C   @@@ ID SERIES AND SPECIALIZED MATERIAL PROPERTY    @@@
C   @@@ DEGRADATION RELATIONS USING INPUT PARAMETERS   @@@
C   @@@ P1 -> P9                                       @@@
C
C       IF ( NELID .GE. 2000 .AND. NELID .LT. 3000 ) THEN
C
C   @@@ PARTIAL FAILURE I. TRANSVERSE MODULI REDUCTION @@@
C
C       E2 = P1*E2
C       G12 = P1*G12
C       G23 = P2*G23
C
C       NSTAT = 2
C
C       ELSE IF ( NELID .GE. 3000 .AND. NELID .LT. 4000 ) THEN
C
C   @@@ PARTIAL FAILURE II. TRANSVERSE INPLANE AND NORMAL @@@
C   @@@ MODULI REDUCTION @@@
C
C       E2 = P3*E2
C       E3 = P5*E3
C       G12 = P3*G12
C       G23 = P4*G23
C       G13 = P6*G13
C
C       NSTAT = 2
C
C       ELSE IF ( NELID .GE. 4000 .AND. NELID .LT. 5000 ) THEN
C
C   @@@ PARTIAL FAILURE III. TRANSVERSE INPLANE AND   @@@
C   @@@ NORMAL MODULI REDUCTION @@@
C
C       E2 = P3*E2
C       E3 = P5*E3
C       G12 = P3*G12

```

```

      G23 = P4*G23
      G13 = P6*G13
C
      NSTAT = 2
C
      ELSE IF ( NELID .GE. 5000 .AND. NELID .LT. 7000 ) THEN
C
C     @@@ TOTAL FAILURE. REDUCE ALL MATERIAL PROPERTIES      @@@
C     @@@ TO ZERO                                           @@@
C
      E1 = 0.0
      E2 = 0.0
      E3 = 0.0
      G13 = 0.0
      G23 = 0.0
      G12 = 0.0
      V13 = 0.0
      V23 = 0.0
      V12 = 0.0
C
      NSTAT = 3
C
      END IF
C
      *** END EXAMPLE ***
C
      RETURN
      END

```

**Appendix D:**

**Sample User-Defined Subroutine to Interpret Buckling Modes**

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```

SUBROUTINE USERB1 ( EMODE,NELEM,NDSET,NXSET,NSETI,NDID,EIGV,
1          NUMNOD,NBPRC,LCNSL,ITERB,NUMEXC, NELNUM,
2          NACC,NSURF,NINC,MDX0,MDX1,MAXB,MDX3 )
C
C *****
C **          **
C **    USER-DEFINED SUBROUTINE TO EVALUATE    **
C **    BUCKLING FAILURE MODE                  **
C **          **
C *****
C
C      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
C
C      DIMENSION EMODE(MDX0,MAXB),NELEM(MDX3,12),NDSET(MDX1)
C      DIMENSION NXSET(MDX1)
C
C      ### BEGIN EXAMPLE ###
C
C @@@ DESCRIPTION: FOR DELAMINATION NODE SETS 10 AND 20, ELEMENT @@@
C @@@ PAIRS HAVE BEEN IDENTIFIED ON EITHER DELAMINATION FACE WHICH @@@
C @@@ WILL INDICATE BUCKLING IF THEY SHOW THE SAME SIGN OF @@@
C @@@ RELATIVE MOTION AND IF THE RELATIVE DEFORMATION IS GREATER @@@
C @@@ THAN 0.4. THIS IS BASED ON THE FACT THAT THE MODE SHAPE IS @@@
C @@@ NORMALIZED AND THAT A PARTICIPATION OF THE SELECTED ELEMENTS @@@
C @@@ GREATER THAN 40% OF THE MAXIMUM DEFLECTION IS TAKEN AS A @@@
C @@@ SIGNIFICANT PARTICIPATION IN THE MODE. THE SIGNS OF THE @@@
C @@@ DISPLACEMENTS INDICATING AN OPENING OR CLOSING MODE ARE @@@
C @@@ ARBITRARY SINCE THE MAGNITUDE OF THE MODE SHAPE IS @@@
C @@@ INDETERMINATE. @@@
C
C      NACCS = 0
C
C      IF ( NDID .EQ. 10 ) THEN
C
C @@@ DELAMINATION ID 10 IS BEING PROCESSED. BUCKLING WILL BE @@@
C @@@ BASED ON THE MAGNITUDE OF RELATIVE DISPLACEMENT BETWEEN @@@
C @@@ OPPOSING ELEMENTS 2050 AND 3050 WHICH ARE LOCATED ABOVE @@@
C @@@ AND BELOW THE DELONANE. @@@
C
C @@@ OBTAIN THE FOLLOWING DISPLACEMENTS: @@@
C @@@     NODE 1 IN ELEMENT 2050 @@@
C @@@     NODE 5 IN ELEMENT 3050 @@@
C
C @@@ LOCATE ELEMENTS IN ARRAREEQ. 2050 ) NL2050 = I
C @@@     IF ( NELEM(I,1) .EQ. 3050 ) NL3050 = I
C @@@     END DO
C
C @@@ CONVERT INTERNAL NODE NUMBERS IN NELEM ARRAY TO @@@
C @@@ INPUT NODE NUMBERS @@@
C
C @@@     NODE1 = NSETI(NELEM(NL2050,2))
C @@@     NODE5 = NSETI(NELEM(NL3050,6))
C
C @@@ LOCATE NODE MODAL DEFLECTIONS IN EMODE ARRAY. TEST @@@

```

```

C   @@@ ON INPUT NODE NUMBER AND GENERATED COINCIDENT NODE @@@
C   @@@ NUMBER STORED IN SAME RECORD @@@
C
      NPNT1 = 0
      NPNT5 = 0
      DO I = 1, NUMNOD
        IF ( NODE1 .EQ. INT(EMODE(I,1)) .OR.
1         NODE1 .EQ. INT(EMODE(I,5)) ) NPNT1 = I
        IF ( NODE5 .EQ. INT(EMODE(I,1)) .OR.
1         NODE5 .EQ. INT(EMODE(I,5)) ) NPNT5 = I
      END DO
C
C   @@@ OBTAIN W-COMPONENT FOR COMPARISON @@@
C
      IF ( NODE1 .EQ. INT(EMODE(NPNT1,1)) ) W1 = EMODE(NPNT1,4)
      IF ( NODE1 .EQ. INT(EMODE(NPNT1,5)) ) W1 = EMODE(NPNT1,8)
      IF ( NODE5 .EQ. INT(EMODE(NPNT5,1)) ) W5 = EMODE(NPNT5,4)
      IF ( NODE5 .EQ. INT(EMODE(NPNT5,5)) ) W5 = EMODE(NPNT5,8)
C
      IF ( ABS(W1-W5) .GT. 0.40 ) THEN
C
C   @@@ LOCAL BUCKLING IS DETERMINED @@@
C
      NACC = 1
      NSURF = 1
C
      ELSE
C
      NACC = 0
C
      END IF
C
      END IF
C
      RETURN
      END

```

**Appendix E:**

**Sample User-Defined Subroutine to Assign Material Degradation Due to Buckling**

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```

SUBROUTINE USERB2 ( NELEM,NODSET,NDELM,NDID,NELFL,ELFAC,NFAIL,
1          NUMELF,NSURF,MDX1,MDX2,MDX3,MDX4 )
C
C *****
C **                               **
C **   USER-DEFINED SUBROUTINE TO DETERMINE   **
C **   ELEMENTS FAILED DUE TO BUCKLING AND   **
C **   ASSIGNED REDUCED MATERIAL PROPERTIES   **
C **                               **
C *****
C
C   IMPLICIT DOUBLE PRECISION(A-H,O-Z)
C
C   DIMENSION NELEM(MDX3,12),NODSET(MDX2)
C   DIMENSION NELFL(MDX1),ELFAC(MDX1),NDELM(MDX4)
C
C   NUMELF   = 0
C   NELFL(1) = 0
C   ELFAC(1) = 0.0
C
C   ### BEGIN EXAMPLE ###
C
C   @@@ ASSIGN DIFFERENT LEVELS OF MATERIAL FAILURE DUE @@@
C   @@@ BUCKLING DEPENDING ON THE DELAMINATION LOCATION @@@
C   @@@ WHICH IS SIGNIFIED BY THE DELAMINATION ID @@@
C
C   IF ( NDID .EQ. 10 ) THEN
C
C   @@@ PARTIAL FAILURE @@@
C
C   @@@ REDUCE MODULI BY 50% IN ELEMENTS 5000 THRU 5500. @@@
C   @@@ NUMBER OF FAILED ELEMENTS RETURNED IN NUMELF @@@
C
C     NUMELF = 501
C     DO I = 1, 501
C       NELFL(I) = 4999+I
C       ELFAC(1) = 0.50
C     END DO
C
C   END IF
C
C   RETURN
C   END

```

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**Appendix F:**  
**Sample Generated MATHEMATICA Input File**

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```

(*)
      @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@
      @@                               @@
      @@  MATHEMATICA INPUT FILE    @@
      @@                               @@
      @@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@@

*)
      fcode = {
{RGBColor[ 1.0, 1.0, 1.0],Rectangle[{ 0.0,0.0},{10.0, 6.0}]},
{RGBColor[ 0.0, 0.5, 1.0],Rectangle[{ 0.0,3.0},{10.0, 4.0}]},
  Text["RESTRAN GRAPHICAL RESULTS",{5.0,3.5]}
      }
      Show[Graphics[ fcode ] ]

      model1 = {
{RGBColor[ 1.0, 1.0, 1.0],Rectangle[{ 0.0,0.5},{10.0, 5.0}]},
{Text[FontForm["ANALYSIS CYCLE      1 ",
{"Courier-Bold",8}],{5.0,4.0},{0,-1}]},
{Text[FontForm["Linear Buckling Analysis",
{"Courier-Bold",8}],{5.0,3.5}]},
  Line[{{0.0,2.75},{10.0,2.75},{10.0,4.5},{0.0,4.5},{0.0,2.75}}]
      }
      Show[Graphics[model1,
      Frame -> False ] ]

(*)
      @@@ UNDEFORMED MODEL GEOMETRY @@@
      @@@ SHOWING MATERIAL FAILURE @@@

*)
      ppnts1 = {{ 0.0000, 0.0000, 0.9000},{ 2.0000, 0.0000, 0.9000},
      { 2.0000, 0.0000, 1.0000},{ 0.0000, 0.0000, 1.0000}}
      ppnts2 = {{ 0.0000, 0.0000, 0.9000},{ 0.0000, 0.0000, 1.0000},
      { 0.0000, 1.0000, 1.0000},{ 0.0000, 1.0000, 0.9000}}
      ppnts3 = {{ 0.0000, 0.0000, 0.9000},{ 0.0000, 1.0000, 0.9000},
      { 2.0000, 1.0000, 0.9000},{ 2.0000, 0.0000, 0.9000}}
      ppnts4 = {{ 0.0000, 0.0000, 1.0000},{ 2.0000, 0.0000, 1.0000},
      { 2.0000, 1.0000, 1.0000},{ 0.0000, 1.0000, 1.0000}}
      .
      .
      .
      model2 = {
{FaceForm[RGBColor[.00,.00,.99],RGBColor[.00,.00,.99]],Polygon[ppnts1]},
{FaceForm[RGBColor[.00,.00,.99],RGBColor[.00,.00,.99]],Polygon[ppnts2]},
{FaceForm[RGBColor[.00,.00,.99],RGBColor[.00,.00,.99]],Polygon[ppnts3]},
      .
      .
      .
      }

      Show[ Graphics3D[model2,
      Boxed -> False,
      Axes -> True,
      Ticks -> None,
      Lighting -> False,
      RenderAll -> True,

```

```

ViewPoint -> {1.3,-2.4,2.0},
ViewVertical -> {0,0,1},
DefaultFont -> {"Times-Italic",6},
PlotLabel -> FontForm["Initial Geometry",
                    {"Helvetica-Bold",9}],
AxesLabel -> {"X","Y","Z"} ] ]

ClearAll[ppnts1,ppnts2,ppnts3,ppnts4,ppnts5]
(*
    @@@ DEFORMED MODEL GEOMETRY @@@

    THE FOLLOWING AMPLITUDE FACTOR, GAMMAi, CAN BE
    CHANGED TO GIVE THE DESIRED DEFORMED SHAPE
*)
    gamma1      =      -1.5000

tpnts1 = {0.0000,0.0000,0.9000} + gamma1{0.0000,0.0000,-1.0000}
tpnts2 = {2.0000,0.0000,0.9000} + gamma1{0.0188,0.0000,-0.6335}
tpnts3 = {2.0000,0.0000,1.0000} + gamma1{-0.0182,0.0000,-0.6335}
tpnts4 = {0.0000,0.0000,1.0000} + gamma1{0.0000,0.0000,-1.0000}
ppnts223 = {tpnts1      ,tpnts2      ,tpnts3      ,tpnts4      }
(*
    @@@ DEFORMED MODEL GEOMETRY @@@
*)
    model3      =      {
Polygon[ppnts223 ],Polygon[ppnts224 ],Polygon[ppnts225 ],
Polygon[ppnts226 ],Polygon[ppnts227 ],Polygon[ppnts228 ],
.
.
.
    }

Show[ Graphics3D[model3,
    Boxed -> False,
    Axes -> True,
    Ticks -> None,
    Lighting -> True,
    RenderAll -> True,
    ViewPoint -> {1.3,-2.4,2.0},
    ViewVertical -> {0,0,1},
    DefaultFont -> {"Times-Italic",6},
    PlotLabel ->
    FontForm["Buckling Mode",
            {"Helvetica-Bold",9}],
    AxesLabel -> {"X","Y","Z"} ] ]

ClearAll[tpnts1 ,tpnts2 ,tpnts3 ,tpnts4 ,tpnts5 ]
ClearAll[tpnts6 ,tpnts7 ,tpnts8 ,tpnts9 ,tpnts10 ]

```

## Appendix G

### Sample User-Defined Subroutine to Output Model Data for Graphical Display

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```

C
C @@@ DETERMINE COORDINATES OF ELEMENT NODES FOR A @@@
C @@@ PLOT OF UNDEFORMED GEOMETRY @@@
C
      DO I = 1, NELNUM
C
      NELID = NELEM(I,1)
      DO J = 1, 9
        M = NELEM(I,J+1)
C
C @@@ SEARCH COORDINATE ARRAY FOR ELEMENT NODE @@@
C
      DO K = 1, NUMNOD
        IF ( M .EQ. INT(COORDS(K,1)) ) THEN
          N = K
          GO TO 100
        END IF
      END DO
100    CONTINUE
C
C @@@ COORDINATES OF NODE M IN ELEMENT I ARE: @@@
C
      CX = COORDS(N,2)
      CY = COORDS(N,3)
      CZ = COORDS(N,4)
C
      END DO
C
      END DO
C
C @@@ EXTRACT DISPLACEMENTS AT NODES TO ADD TO NODE @@@
C @@@ COORDINATES FOR A PLOT OF DEFORMED GEOMETRY @@@
C
      DO I = 1, NELNUM
C
      DO K = 1, 8
        N = NELEM(I,K+1)
        DO IC = 1, NUMNOD
          IF ( N .EQ. INT(COORDS(IC,1)) ) THEN
            NL = IC
            GO TO 200
          END IF
        END DO
200    CONTINUE
C
C @@@ COORDINATES FOR THE K+1 NODE IN ELEMENT I DETERMINED @@@
C
      CX = COORDS(NL,2)
      CY = COORDS(NL,3)
      CZ = COORDS(NL,4)
C
C @@@ DISPLACEMENTS AT THE CURRENT NODE ARE OBTAINED AS @@@
C
      DX = U(3*N-2)

```

```

        DY = U(3*N-1)
        DZ = U(3*N )
C
C   @@@ THE LOCATION OF THE DISPLACED NODE IS GIVEN BY @@@
C
        DNX = CX + DX
        DNY = CY + DY
        DNZ = CZ + DZ
C
C   @@@ THESE COORDINATES ARE THEN USED TO DEVELOP THE @@@
C   @@@ THE GEOMETRY IN A USER-DEFINED FORMAT TO PLOT @@@
C   @@@ THE DEFORMED GEOMETRY OF THE MODEL @@@
C
        END DO
C
        END DO
C
        RETURN
        END

```

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4	COMMANDER US ARMY ARDEC AMSTA AR CC G PAYNE J GEHBAUER C BAULIEU H OPAT PICATINNY ARSENAL NJ 07806-5000	1	COMMANDER US ARMY ARDEC AMSTA ASF PICATINNY ARSENAL NJ 07806-5000

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13. ABSTRACT (Maximum 200 words) <p>A general predictive methodology for determining residual strength in impact damaged composite laminates has been developed and incorporated into a computer code designated RESTRAN (RESidual STrength ANalysis). RESTRAN is a finite element based design tool that can analyze composite structures with arbitrary three-dimensional (3-D) geometry, loading and support conditions, material properties, and initial material and delamination damage. Material failure modes are predicted using a robust suite of failure criteria and damage laws. Structural failure due to sequential sublaminates buckling of delaminated layers is also accounted for. A progressive failure analysis is performed until ultimate structural failure is predicted, thereby yielding an estimate of the residual strength. This report contains a user's manual for the RESTRAN program with complete descriptions of input statements and program output. Several examples are shown to illustrate the use of the RESTRAN computer code.</p>				
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