Interactive Laminate Postprocessing of NASTRAN Structural Analyses

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Abstract

The analysis of laminated composite structures requires significant ply stress and strain data recovery to determine margins-of-safety. If obtained in batch mode for a large number of plies even a modest structural model will produce boxes of printout. An interactive laminate postprocessing feature in PATRAN was used to recover ply data for an aircraft access door cutout analysis in which several PCOMP directives were used to model increases in laminate thickness around the cutout. Both ply stresses and strains were recovered and the stresses are the same as those (fiber dominated) recovered by NASTRAN. The interlaminar shears differ only in the off-axis or angle plies where a known problem exists. The paper also presents margins-of-safety for ply failure analyses based on the Tsai-Wu criteria in graphical format. These enhanced postprocessing features increase significantly the utility of NASTRAN for laminated composite structural design.

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Introduction

Engineers responsible for finite element analyses have long been aware of the burden associated with both pre and postprocessing model data. To evaluate and describe efficiently the stress mechanics of even moderate size three-dimensional problems, it is necessary to have advanced graphics capabilities, such as the PATRAN system. The burden of this information processing is compounded when the engineer is working on composite structures. A laminated composite structure will typically involve a series of lamina or plies, arranged in a stacking sequence, with each ply having a different material angle and, sometimes, different thicknesses and material properties as well. Since laminates of 50 to 100 plies are not unusual, it is easy to see that an analysis of a laminated structure, when compared to the analysis of an isotropic material, can quickly lead to significant data transfer and reduction tasks. This paper introduces a new feature of a PATRAN system module, P/COMPOSITE, which is designed to facilitate data handling for composite analysis with external applications codes. The interface to the NASTRAN program was developed first due to the wide use of NASTRAN in composite analysis of laminated structures.

Laminated Composite Analysis With NASTRAN

Laminated composites are made by forming individual lamina or plies to a structural shape. The individual ply is typically a material with several phases present. The main load carrying material (the fiber) is supported in a binder material (the matrix) which serves as a load transfer medium. The fibers are arranged in parallel rows, creating preferred directional properties. The individual lamina are stacked at specific angles to obtain a laminate which has the desired stiffness or strength properties. An exploded view of a cross-ply laminated plate is illustrated in Figure 1. The laminate is normal to the z-axis of the indicated coordinate system and the angles appended to the individual lamina denote the orientation of the ply material axes.

Classical lamination theory [1] is used to compute the properties of the laminate from the properties defined for the individual lamina and the material angle of each lamina. The properties of the lamina are defined on the PCOMP card [2] (the material properties are defined by reference to material property cards, usually MAT8). The material frame for each lamina is given by an angle (the ply orientation angle) relative to the material frame for the element, defined on the element card. The PCOMP card will also specify the failure theory to be used, and will control printing of the stresses and failure indices in the individual plies. The stresses associated with a plane stress state (which is the state assumed by classical lamination theory) are recovered at the mid-point of each ply. Shear stresses associated with the through thickness coordinate (τ_{xz} and τ_{yz} in the coordinate system of Figure 1), known as interlaminar shears, are estimated by a technique based on equilibrium considerations. These stresses are recovered at ply boundaries. The stress normal to the thickness coordinate (the interlaminar normal) is assumed zero. It should be noted that NASTRAN recovers ply interlaminar shear in laminate not ply material coordinates. This can be confusing and in PATRAN all ply stresses are recovered in ply material coordinates. Sorting operations are available to facilitate inspection of the printout.

P/COMPOSITE Module Enhancements

P/COMPOSITE is a new PATRAN system module [3] for the design and analysis of general composite structures. It is intended to be used in conjunction with the modeling features of PATRAN and thus uses the PATRAN neutral file system to transfer information to and from the module, as well as between the various functions of the module. Upon entering the system and specifying the finite element model neutral file, the user is asked to supply additional information specific to composite structural analysis (e.g., 3D material orientation and nonlinear material properties if required). This information can be used to complete a three-dimensional analysis by PATCHES, the finite element code internal to P/COMPOSITE. Often the more accurate three-dimensional analysis can be relaxed in favor of a more economical analysis using two-dimensional elements, at least in regions away from geometric discontinuities and free edges where evaluation of interlaminar normal stresses is required. The two-dimensional analysis will quite often be made using NASTRAN rather than PATCHES although special elements are available in PATCHES for laminates. When such an analysis is complete and element results are obtained, the P/COMPOSITE module can again be entered during a PATRAN session for postprocessing tasks specific to composites.

Given the finite element strain results from NASTRAN or PATCHES, the ply stresses and strains can be found by tensor transforms using geometric and material angle information, and the stress-strain properties. In this way it is possible to use P/COMPOSITE with a great deal of control and flexibility over the ply data recovery process. For example, it is possible to recover all ply strain information as well as the ply stress information currently output by NASTRAN. Ply stresses and strains can be recovered at the top, bottom or mid-fiber of any ply. Summary tables for the overall model, as well as summary tables for each laminate type are also output in the batch report. It is also possible to redefine the stacking arrangement and/or material properties and recover ply values using the same element resultants to perform a type of sensitivity analysis. This feature is used later in the paper to estimate the effect of a ply misalignment defect.

The same flexibility is seen in laminated composite failure analysis. In addition to the Tsai-Wu failure model (which includes as subsets almost all other quadratic criteria), the more commonly used maximum stress and maximum strain criteria are also available. The failure index, as defined by NASTRAN, is output for all criteria, and P/COMPOSITE also outputs a "margin-of-safety" which is used by PDA for composite design studies. To envision the margin-of-safety for a Tsai-Wu failure analysis, consider stress space as divided into allowable and non-allowable regions by an ellipsoid. Next imagine a ray from the origin through the current stress state point. If the loading increases proportionally, the stress state will scale linearly to intersect the failure surface which is an ellipsoid. The margin-of-safety is the ratio of the distance along the ray to the current stress point, to the distance along the ray to the intersection of the failure surface. Failure indices in contrast are a nonlinear function of load increases which makes predicting the critical load difficult.

Stress and strain information for the plies are passed to PATRAN and can be plotted. The margins-of-safety also can be plotted to depict regions where design changes may be required. The composite analyst will usually run a failure analysis first to find critical geometrical regions and critical plies and then go back to recover detailed stress/strain data based on this information. The P/COMPOSITE module facilitates this procedure by allowing interactive control of the recovery process and automatic results file creation for PATRAN processing. A schematic of the process is depicted in Figure 2.

Benchmark Analysis

A NASTRAN model was analyzed by PDA for British Aerospace PLC to test the capabilities of P/COMPOSITE for postprocessing of composite structures. Figure 3 shows their model of the cutout for an access door modeled using 716 QUAD4 elements and 9 PCOMP directives. Laminate 1, located directly around the cutout, is expected to experience the most distress and thus has 52 plies in the laminate. Farther away from the cutout the stress can be expected to decrease and here the design uses fewer plies in the design uses fewer plies in the laminate. There are only 24 plies at the edges of the model away from the cutout. The concept of tailoring the laminate to match the expected stress illustrates both the flexibility of composites in design as well as the increase in complexity of composite failure analysis.

The NASTRAN Case Control input requested output of all ply information to facilitate comparison and even this relatively modest structural model produced nearly a box of output. The element strains were output using a DMAP alter and then used in the P/COMPOSITE model to generate a PATRAN compatible file containing the margins-of-safety using the Tsai-Wu criterion. A schematic of the interactive session is shown in Figure 4. Also in this file were the critical ply numbers (i.e., a value indicating which ply in the laminate had the lowest margin-of-safety) as well as the failure type (i.e., a value indicating whether the in-plane or interlaminar stress state in the critical ply was closest to the failure envelope). Margins-of-safety contours are shown in Figure 5. To view the ply stresses directly, P/COMPOSITE was again entered during the interactive session and ply recovery was completed in under 3 minutes wall clock time. A schematic of this interactive session is shown in Figure 6. A ply stress file for ply 1 of all laminates was then generated and Figure 7 shows a contour plot of the fiber stress while Figure 8 shows the in-plane shear. Note that when generating these plots, each laminate region was plotted separately to prevent averaging of the stress results at laminate boundaries. This is accomplished easily within PATRAN by plotting those elements with the same property identifier, which corresponds to a PCOMP number in the NASTRAN bulk data file.

Consider now a situation that happens all too often in practice. Long after the initial analysis of the ideal structure, the actual structure is found to have a misaligned ply. The analyst is asked what effect this defect will have on critical ply stresses. A good estimate can be had by postprocessing the original laminate strains with the actual ply orientation. To illustrate this process, ply stresses were revaluated for a 10^{o} change from 45^{o} to 55^{o} in ply orientation. These results, Figure 9, show a 30% increase in fiber compressive stress and a 36% decrease in fiber tensile stress. Note that this sensitivity analysis does not require another finite element analysis.

SUMMARY

The P/COMPOSITE module of the PATRAN system is designed to integrate the design and analysis process for composite structures. A new feature of P/COMPOSITE imports laminate results from external finite element programs into an expanded PATRAN neutral file. This feature has been completed for use with MSC/NASTRAN, allowing interactive directives for ply stress/strain recovery and failure analysis postprocessing . Since the module requires only element strains (the module reconstructs all material and element geometry transforms required for further ply processing), it is possible to avoid batch postprocessing of ply results. The module also augments NASTRAN laminate capabilities by including ply strains (as well as stresses), increasing the choices for failure criterion, and allowing alternative ply property data for sensitivity analyses. All files produced by the module are directly available to the PATRAN system for image processing.

Acknowledgements

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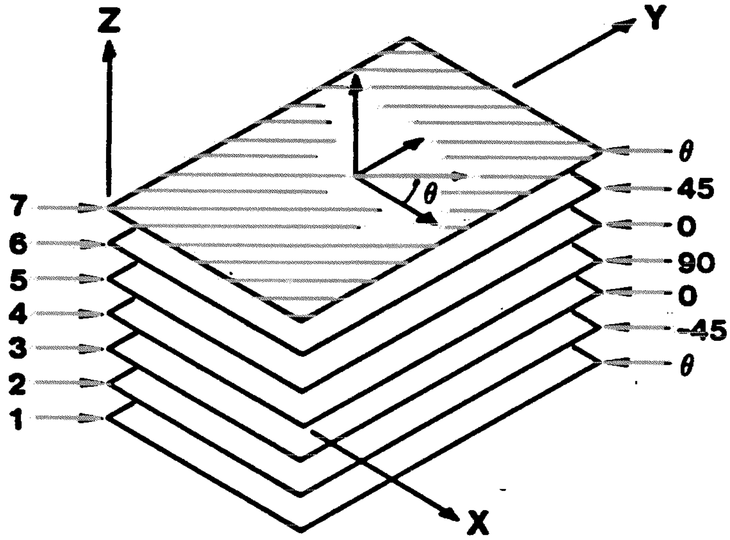
References:

1. Halpin, J. C., Primer on Composite Materials: Analysis, Technomic Publishing, Lancaster, PA, Revised 1984.

2. MSC/NASTRAN Handbook for Linear Static Analysis, The MacNeal Schwendler Corp., 1981, Los Angeles, CA.

3. Stanton, E. L., Hart, J. K. and T. E. Kipp, PATRAN II Composite Module Primer, Volume 1 Analysis, PDA Engineering, Costa Mesa, CA, 1986.

■ LAMINATE PLY STRUCTURE CONVENTIONS: PATRAN, NASTRAN



INCREASING Z-SEQUENCE: $[\theta/-45/0/90/0/45/\theta]_T$

Figure 1. Laminate Nomenclature for Ply Sequence and Orientation

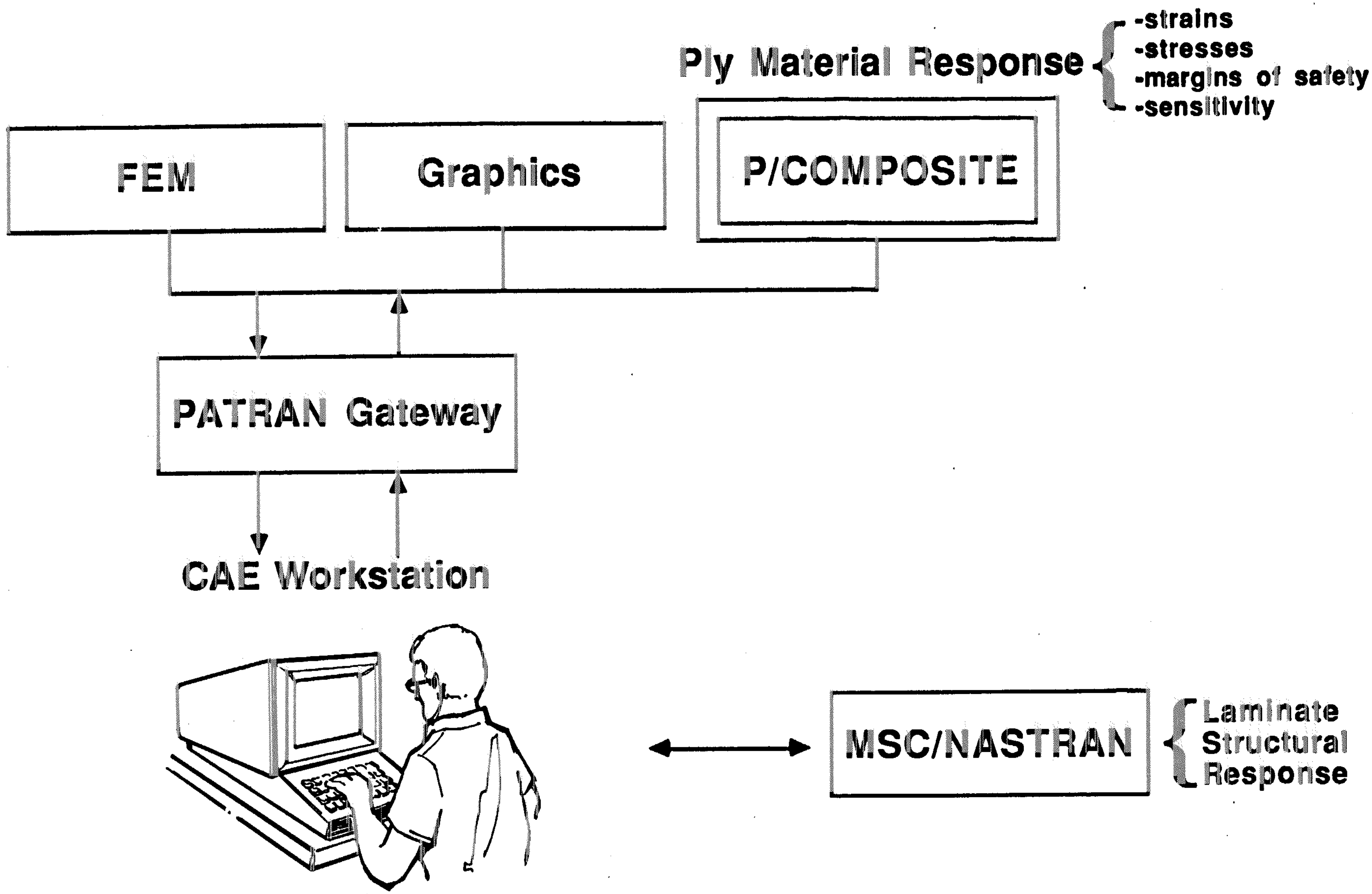


Figure 2. Schematic of Laminate Post-Processing Using P/COMPOSITE

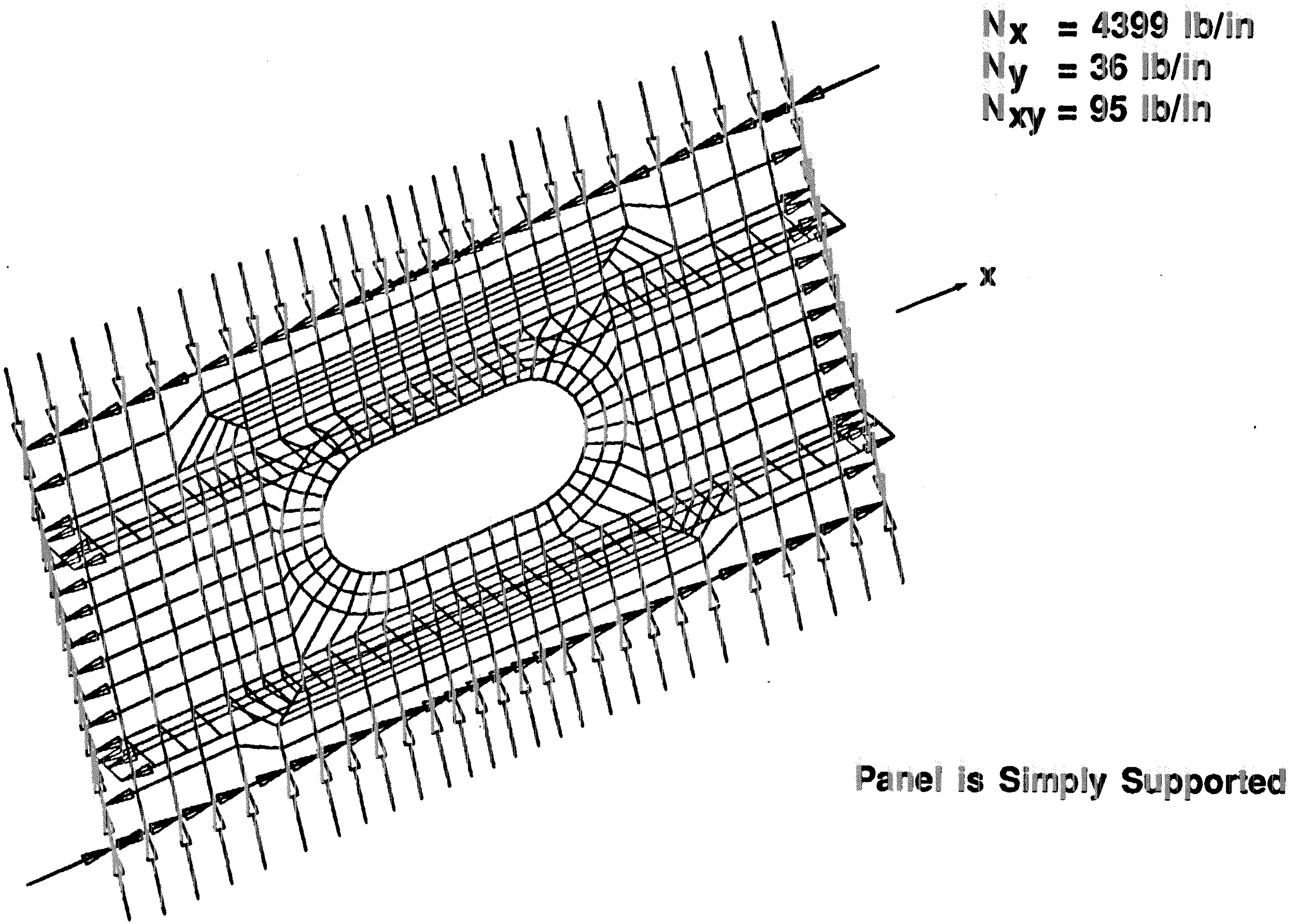
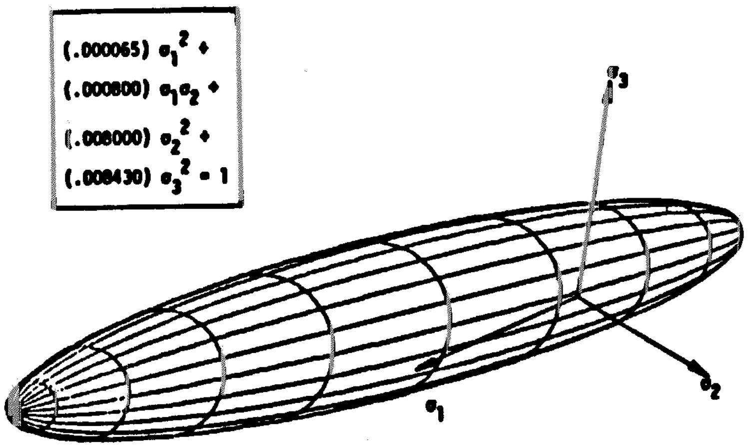


Figure 3. Model of the Access Door Cutout Analysis

P/COMPOSITE
NASTRAN POSTPROCESSING
FAILURE ANALYSIS



PATRAN Image Processing

3. POSTPROCESSING

4. FAILURE ANALYSIS

3. NASTRAN FEM Files

FILES DEFINE GEOMETRY, ELEMENTS, AND MATERIAL RELATIONS

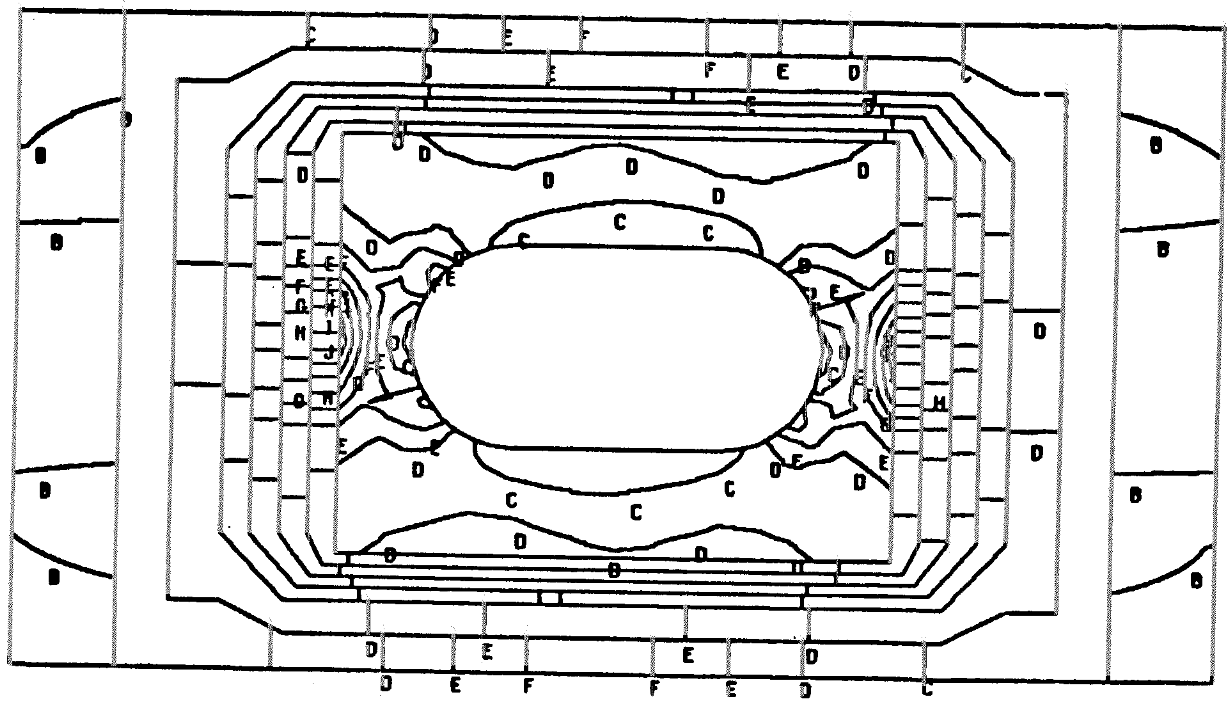
2. NASTRAN Results File

ε^{o}_{ij} κ_{ij} AND (OPTIONALLY) ELEMENT FORCES FOR INTERLAMINAR SHEARS

Select Finite Elements
Select Load Type
Select Laminate
Select Recovery Point { Middle / Top / Bottom / Extreme Fiber

Select Failure Criterion { Maximum Stress / Maximum Strain / Modified Tsai-Wu

Figure 4. Interactive Session for Failure Analysis

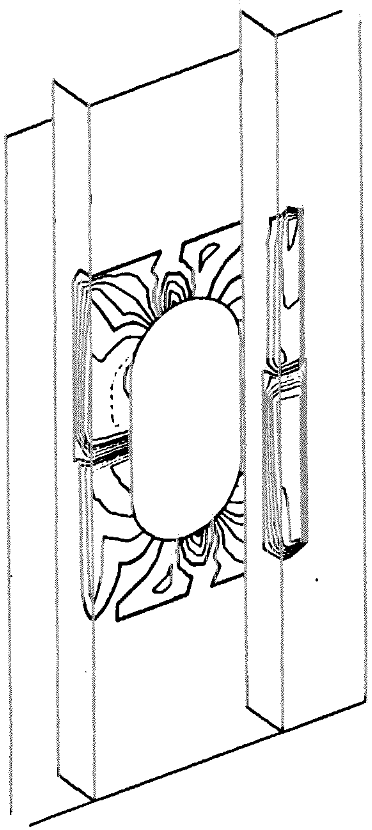


0 = A
.500 = B
1.00 = C
1.50 = D
2.00 = E
2.50 = F
3.00 = G
3.50 = H
4.00 = I
4.50 = J
5.00 = K

ACCESS DOOR CUTOUT ANALYSIS

Figure 5. Margin-of-Safety Contours

P/COMPOSITE
NASTRAN POSTPROCESSING
PLY RESULTS RECOVERY



PATRAN Image Processing

3. POSTPROCESSING

4. PLY RESULTS TRANSLATION

3. NASTRAN FEM Files

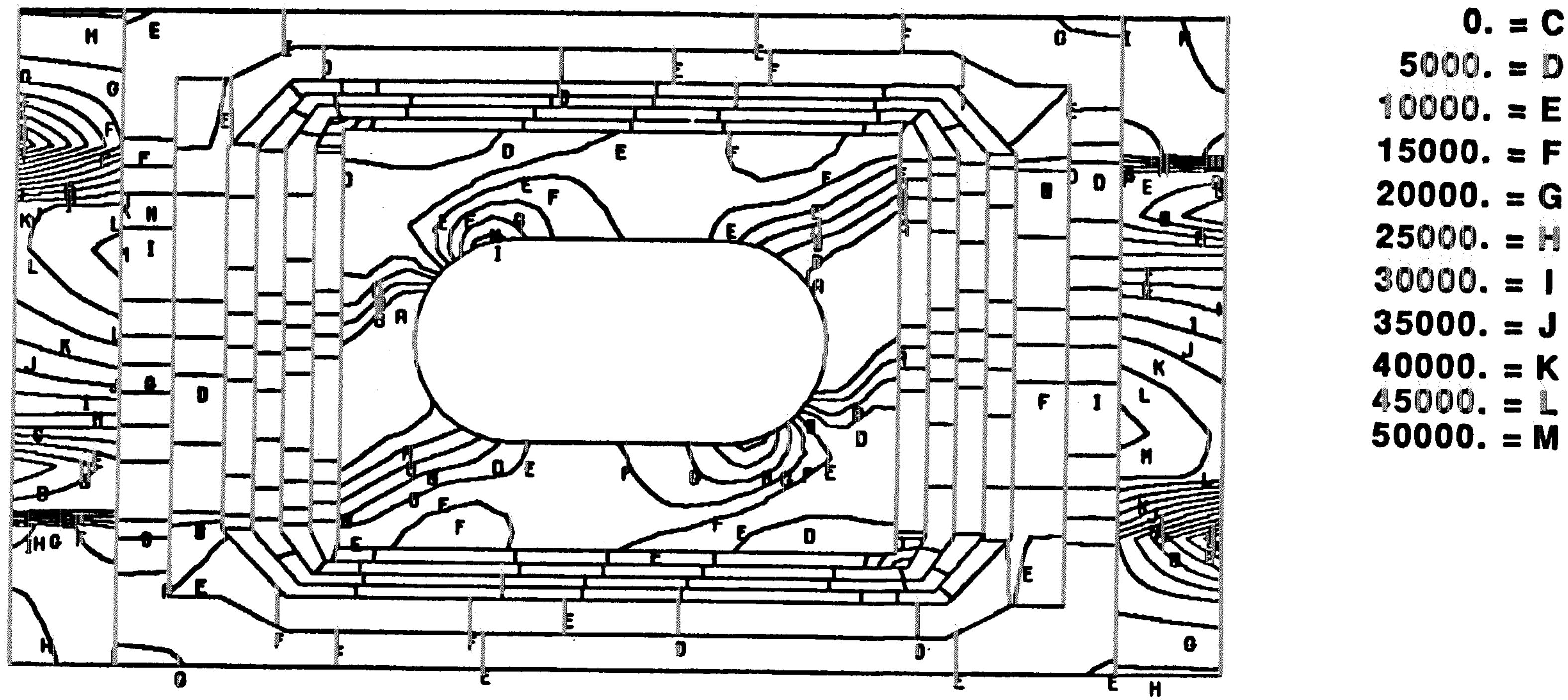
FILES DEFINE GEOMETRY, ELEMENTS, AND MATERIAL RELATIONS

2. NASTRAN Results File

ε^{o}_{ij}, κ_{ij} AND (OPTIONALLY) ELEMENT FORCES FOR INTERLAMINAR SHEARS

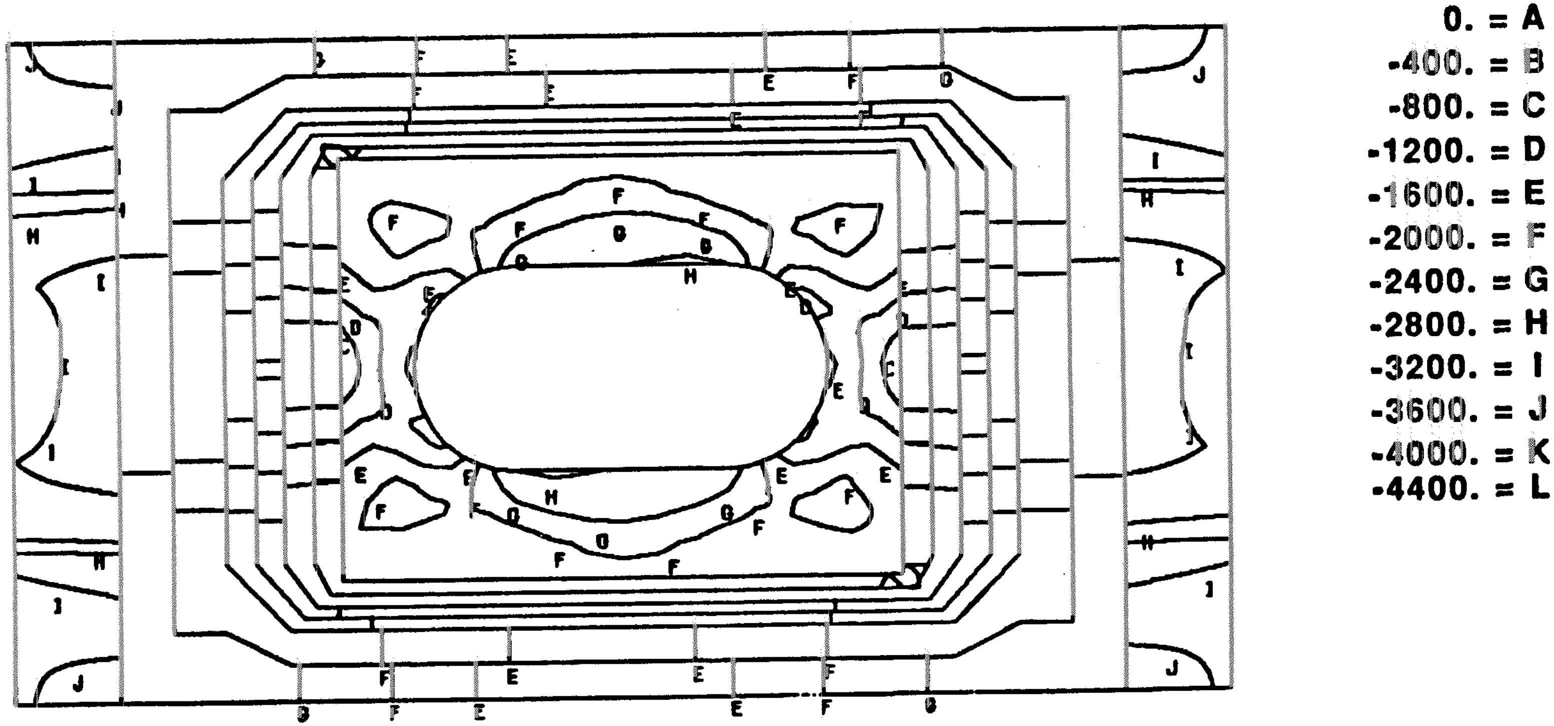
Select Finite Elements
Select Load Type
Select Laminate (PCOMP No.)
Select Ply No.
Select Recovery Point { Middle / Top / Bottom / Extreme Fiber }

Figure 6. Interactive Session for Ply Stress/Strain Recovery



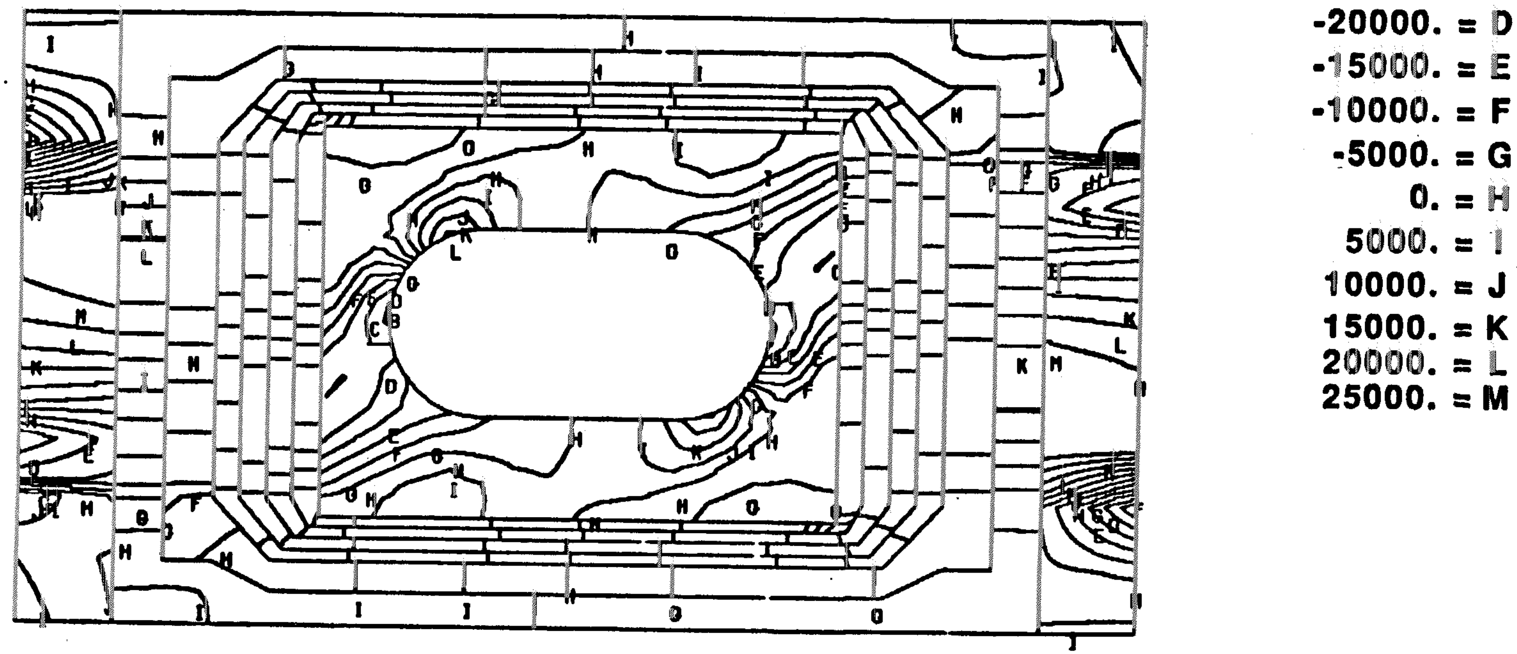
ACCESS DOOR CUTOUT ANALYSIS

Figure 7. Fiber Stress in Ply 1 (45°) of All Laminates



ACCESS DOOR CUTOUT ANALYSIS

Figure 8. Shear Stress in Ply 1 (45o) of All Laminates



ACCESS DOOR CUTOUT SENSITIVITY ANALYSIS

Figure 9. Fiber Stress in Ply 1 (55°) of All Laminates