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**COMAND - A FORTRAN PROGRAM FOR
SIMPLIFIED COMPOSITE ANALYSIS AND
DESIGN**

Garret N. Vanderplaats

**Ames Research Center
Moffett Field, Calif. 94035**

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16. Abstract A FORTRAN program is presented for preliminary analysis and design of multilayered composite panels subjected to inplane loads. All plies are of the same material. The composite is assumed symmetric about the midplane, but need not be balanced. Failure criterion include limit ply strains and lower bounds on composite inplane stiffnesses. Multiple load conditions are considered.			
The required input data is defined and examples are provided to aid the user in making the program operational. Average panel design times are two seconds on an IBM 360/67 computer. Results are compared with published literature. A complete FORTRAN listing of program COMAND is provided. In addition, the optimization program NMIN is required for design.			
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Garret N. Vanderplaats

Ames Research Center

INTRODUCTION

Early evaluation of composite materials in aerospace structures requires an efficient means of structural sizing for a given application. It is seldom possible to provide simple stress limits as is customary when designing with conventional isotropic materials, since failure of composites is dependent not only on the properties and orientations of the individual plies, but on the nature of the loading as well. Furthermore, by taking advantage of the ply orthotropicity, the designer is free (within certain limits) to actually design the structural material through the proper choice of ply thicknesses and orientations.

COMAND is one of several programs being developed in the Advanced Vehicle Concepts Branch of Ames Research Center to provide a general and consistent approach to structural analysis and design. This program is for the analysis and design of a multilayered composite subject to inplane loads. The principal method of analysis and the failure criterion considered here are those used by Schmit and Farshi (Ref. 1). The optimization algorithm is the method of feasible directions using program CONMIN, which is described in Reference 2. COMAND is intended to provide first level design information for membrane structural behavior. Another program under development includes more general analysis, loading conditions, and failure criterion.*

*Program COMPOS by J. Mullen, Advanced Vehicle Concepts Branch, Ames Research Center.

The analysis and design capabilities and the basic assumptions of the program are presented in Section I. Section II describes the required input to the program and several examples of the results are presented in Section III. Possible future efforts in composite analysis and design are identified in Section IV. The principle equations used in the analysis are presented in Appendix A. Appendix B is a complete program listing.

SECTION I

ASSUMPTIONS AND RESTRICTIONS

Program COMAND can be used to analyze a given composite panel in which the ply thicknesses are prescribed, or to design the ply thicknesses to satisfy strain and stiffness limitations. Ply orientation angles are prescribed, and are not design variables. Typical loading conditions and ply orientations are shown in Figures 1 and 2, respectively.

The composite analysis and design is based on the following assumptions and restrictions.

1. The panel is subjected to in-plane loads N_x , N_y and N_{xy} only. Bending and out-of-plane shear loads are not considered. Multiple loading conditions are considered and up to 10 independent loading conditions are allowed.
2. The composite is said to fail when the longitudinal, transverse or shear strain in any single ply exceeds a specified limit in the longitudinal, transverse or shear direction, respectively.
3. The composite is said to fail if the stiffness in the structural X , Y or XY direction is less than a specified lower limit.

4. The individual ply thicknesses are designed to give minimum total panel thickness. Ply thicknesses are treated as continuous variables and several plies may be required to be of equal thickness.
5. All plies are of the same material with the same elastic properties and strain limitations. Ply elastic properties (and therefore, those of the composite) are assumed to be the same in tension and compression.
6. Ply properties are required as program input. Micromechanics analysis is not performed in the program.
7. The composite is assumed to be symmetric about the midplane so that no bending-membrane coupling exists.
8. The composite need not be balanced. That is, a ply with +45 degrees fiber orientation need not be balanced with another ply of -45 degrees orientation. Up to 18 different ply orientations are permitted, allowing for design of composites with ply angles at 10 degree intervals. Ply fiber orientation angles are prescribed and are not design variables.
9. Temperature effects and temperature loading are not considered, except that the material properties and strain limits must be consistent with the design temperature.

SECTION II

PROGRAM INPUT

All program input is listed here. The variables and their definitions are presented first, followed by data organization. No units are provided

for the variables. It is required that all units be consistent. That is (for example), if loads are in newtons and thicknesses in meters, moduli must be given in newtons per square meter, strains in meters/meter and stiffness in newtons/meter.

Variables:

- TITLE(15) Anything may be given as a title.
- NCALC Calculation control. If NCALC=0, total composite thickness (weight) is minimized. If NCALC.NE.0. the given composite is analyzed only.
- NPLY Number of plies. Up to 18 plies are allowed.
- NDV Number of design variables. This is the number of ply thicknesses which are allowed to change independently in the optimization process or the number of different thicknesses prescribed for analysis. 1.LE.NDV.LE.NPLY
- NLC Number of loading conditions. Up to 5 loading conditions are allowed.
- IPRINT Print control for the optimization program, CONMIN. IPRINT = 0 gives no print during the optimization. IPRINT = 1 to IPRINT = 4 provide increasing degrees of output during optimization. IPRINT = 2 is usually desirable.
- LNK(NPLY) Design variable linking. LNK(I) gives variable number (ply thickness) associated with the ITH ply. For example, in a four ply problem (NPLY = 4), $\text{LNK}^T = (1, 2, 2, 3)$ will impose the requirement that plies 2 and 3 are of the same thickness. In this case NDV = 3.

X(NDV)	Initial thickness of the design variables (IE. $X^T = .05, .03, .04$). If NCALC.NE.0., the composite is analyzed for ply thicknesses defined in X and linked according to LNK. If J = LNK(I), the thickness of the ITH ply is stored in X(J).
VLB(NDV)	Lower bounds on the design variables. VLB(I).CE.0, I = 1,NDV. It is usually desirable to set at least one VLB(I) = 1.0E-10 if lower bounds of zero are desired, in order to prevent the optimization program from attempting to analyze a panel of zero thickness. If NCALC.NE.0. VLB(I) = 0, I = 1, NDV may be input.
THN(NPLY)	Ply orientations in degrees, referenced to the structural X-axis. THN(I) = Ply orientation of the ITH ply.
EL	Ply longitudinal modulus.
ET	Ply transverse modulus.
GLT	Ply shear modulus.
PRLT	Ply major Poisson's ratio (ply transverse Poisson's ratio, PRTL, is calculated internally).
EPLC	Ply longitudinal compressive strain limit (negative number).
EPLT	Ply longitudinal tensile strain limit (positive number).
EPTT	Ply transverse tensile strain limit (positive number).
GMLT	Ply maximum shear strain limit (positive number).
A11L	Lower bound on composite stiffness in the structural X-DIRECTION.
A22L	Lower bound on composite stiffness in the structural Y-DIRECTION.
A66L	Lower bound on composite shear stiffness.
PN(3, NLC)	Loads, column I corresponds to loading condition I, I = 1, NLC. Row J corresponds to load NX, NY and NXY for J = 1, 2 and 3, respectively of load condition I.

Data Organization:

<u>No. of Cards</u>	<u>Information</u>	<u>Format</u>
1	Title - Anything may be given here	15A4
1	NCALC, NPLY, NDV, NLC, IPRINT	515
1	LNK(I), I=1,NPLY	1515
1-3	X(I), I=1,NDV	8F10.2
1-3	VLB(I), I=1,NDV (Blank card(s) if NCALC.NE.0)	8F10.2
1-3	THN(I), I=1,NPLY	8F10.2
1	EL, ET, GLT, FRLT	4F10.2
1	EPLC, EPLT, EPTC, EPTT, GMLT, ALLL, A22L, A66L	8F10.2
NLC	PN(J,I), J=1,3 (One card per loading condition)	3F10.2
	Begin with next set of data. Program terminates if 2 blank cards are read here.	

This information is duplicated in Table 1, along with a data form for convenient reference.

SECTION III

EXAMPLES

Several examples are presented here to aid the user in making the program operational and to provide some insight into design using composite materials. All examples are for a high strength graphite-epoxy composite.

Typical ply unidirectional properties are listed in Table 2 for a fiber volume fraction of 0.6. The table is reproduced directly from Reference 3. Note that the ultimate strain limits are not specified for longitudinal and transverse strain or for shear. However, reasonable values are readily

obtained by analyzing a single ply of unit thickness, subject to a set of loads which are equal to the ultimate stresses. For example, given a longitudinal load of 180,000 lb/in. the resulting longitudinal strain will be ultimate strain. Therefore, a single ply composite is analyzed for the following load conditions:

<u>Load Condition</u>	<u>NX</u>	<u>NY</u>	<u>NXY</u>
1	180000.	0.	0.
3	0.	-30000.	0.
2	0.	8000.	0.
4	0.	0.	12000.

Note that a negative NX load is not imposed because the ultimate longitudinal compressive stress is the same in magnitude as the tensile stress. Therefore, the ultimate strains are also equal in magnitude (but opposite in sign).

The program input variables are now:

TITLE: Determination of strains - G/E composite.
 NCALC = 1 Analysis
 NPLY = 1 One ply.
 NDV = 1 One thickness.
 NLC = 4 Four load conditions.
 IPRINT = 0 Not used for analysis.
 LNK(1) = 1 Ply thickness = X(1).
 X(1) = 1.0 Composite thickness.
 VLB(1) = 0. Not used for analysis.
 THN(1) = 0. Zero degree ply orientation.

EL = 21,000,000 Longitudinal modulus.

ET = 1,700,000 Transverse modulus

GLT = 650,000 Shear modulus.

PRLT = 0.21 Major Poisson's ratio.

EPLT = EPLC = EPTT = EPTC = GMLT = 0 - Strain limits set to zero since they are not known.

A11L = A22L = A66L = 0 Not meaningful here

PN(I,J) - Loads, given above.

The input data is listed in Table 3 with the corresponding output in Figure 3.

The ultimate strains are now the actual ply strains in the direction of the applied load for the corresponding loading condition. For example, since load condition 1 is the ultimate longitudinal stress, the longitudinal strain, EPL, under this load condition is also ultimate. That is:

$$EPLT = 0.00857 \text{ (table 2 gives 0.00870)}$$

Similarly,

$$EPLC = -0.00857$$

$$EPTC = -0.0176$$

$$EPTT = 0.00471 \text{ (table 2 gives 0.00475)}$$

$$GMLT = 0.0185$$

These are now the limit strains to be used in design.

Example 1 - Quasi-isotropic composite

In order to draw a comparison between graphite epoxy composites and the familiar aluminum materials, a simple case is first considered in which plies are oriented at 15 degree intervals (NPLY = 12) and subject to a single

unidirectional load, $N_x = 20,000 \text{ lb/in.}$ ($N_y=N_{xy}=0$). All plies are required to be of the same thickness so that $NDV=1$ and $LNK(I)=1$, $I,NPLY$. The total thickness is minimized. No minimum stiffness limits are imposed, so that $A_{11}L=A_{22}L=A_{66}L=0$. Lower bounds on the thicknesses are arbitrarily set to 0.00001 in. Initial ply thickness is prescribed as 0.05 in. The input data is listed in Table 4, where the print control for the optimization program, CONMIN, is taken as $IPRINT = 2$. The program output is listed in Figure 4. The optimum composite thickness is 0.525 inches. The design is constrained by the transverse strain limit in the 90 degree direction (ply number 12). The average stress in the structural X-direction (direction of load) in the composite is 38,000 PSI. Note that this is significantly less than the ultimate stress of 60,000 PSI for a typical aluminum alloy. However, the density of the composite is $0.056 \text{ lb/in.}^{**3}$ as compared to $0.101 \text{ lb/in.}^{**3}$ for aluminum. Therefore, the relative weight of graphite epoxy as compared to aluminum for this example is $0.056*60000/(0.101*38000) = 0.875$ giving a 12.5 percent weight savings.

Note that even though the 90 degree ply has failed, some additional load may be carried before all plies fail. Therefore, the failure stress predicted here may be considered analogous to the limit stress, with the ultimate stress being (usually) somewhat higher.

Example 2 - (0, +45, 90) composite design

Due to practical considerations, it is improbable that many different ply orientations will be used in most structures. In this example, the composite is required to be balanced so that the thicknesses of the +45 and -45 degree plies are the same. Then there are three independent design

variables ($NDV = 3$) and the ply thickness linking vector becomes $LNK^T = (1, 2, 2, 3)$. The ply orientation vector is $THN^T = (0., 45., -45., 90.)$. A minimum stiffness of 500,000. lb/in. is required in the structural X-direction. The composite is required to support the following four independent loading conditions:

<u>Load Condition</u>	<u>NX</u>	<u>NY</u>	<u>NXY</u>
1	20000.	0.	0.
2	15000.	-15000.	5000.
3	-15000.	10000.	10000.
4	0.	0.	20000.

The input data is listed in Table 5 and the corresponding output in Fig. 5. The print control for CONMIN is set to IPRINT = 0 in this example and in example 3 for brevity. The optimum composite thickness is 0.578 inches. The active constraints are transverse strain limits and are identified by safety factors of unity in Fig. 5 (3 constraints are active).

Example 3 - (0. ± 30 , ± 60 , 90) composite design.

This composite is designed subject to the same constraints and loading conditions as example 2. the only difference is the number of plies and their orientations. The composite is again required to be balanced. In this case, $NDV = 4$, $NPLY = 6$, $LNK^T = (1, 2, 2, 3, 3, 4)$, and $THN^T = 0., 30., -30., 60., -60., 90.)$. The input data and output are listed in Table 6 and Fig. 6, respectively. The optimum composite thickness is 0.532 inches and there are six active strain limit constraints as seen from Fig. 6. Note that although the number of plies and their orientations are different from example 2, the total composite thickness is reduced by less than ten percent.

An additional exercise of interest is to eliminate plies which comprise a small percentage of the total thickness, and solve the optimization problem again. For example, a composite made up of ± 30 and ± 60 degree ply orientations results in an optimum thickness of 0.526 inches. It is instructive to design the 12 ply composite of example 1 subject to this same set of loads, but allowing for different ply thicknesses (require that the composite be balanced for consistency with examples 2 and 3). The resulting thickness is 0.588 inches. Solution of this case is left as an exercise.

Example 4 - Limit stress vs. ply thickness distribution

In order to assess the applicability of this program to preliminary composite design, results obtained using COMAND are compared here with design curves for a $(0, \pm 45, 90)$ composite subjected to uniaxial tension, compression and shear loading (applied separately). Figures 7-10 are reproduced from Reference 3. A composite with various relative ply thicknesses was analyzed under these separate loading conditions. No stiffness constraints were imposed and the lowest factor of safety was found for all strain failure criterion. The calculated stress was then multiplied by this factor to give the failure (limit) stress. The results are plotted on Figures 7-10 for 25 and 50 percent zero degree plies. Figure 10 compares the extensional modulus, E_x .

The results indicate reasonable comparison for compressive stress, shear stress and extensional modulus. However, considerable discrepancy is found in comparing tensile stress limits. This is because the composite is constrained by transverse strain limits on the 90 degree plies. In Reference 3, one or more plies are allowed to fail without assuming composite failure.

When a single ply fails, this ply is assumed to carry no load. The composite is said to fail only when all plies fail individually. This again demonstrates the difference between the limit stress calculated here and the ultimate stress presented in Reference 3. The difference in results between these two assumptions is usually reduced when multiple sets of combined loadings (practical design situations) are considered.

SECTION IV DISCUSSION

A short program has been presented by which first estimates are readily obtained for design requirements of composite structures. The program is easily used and requires minimal execution time. Because the failure criterion are extremely load dependent, some judgement is necessary in choosing permissible ply orientations, so that the existence of a given ply orientation does not prevent attainment of an optimum design. This problem is much less prevalent under multiple loading conditions. However, it does suggest that development of an optimization algorithm capable of completely eliminating plies may be fruitful.

For the results to be meaningful, it is important that this program be applied only to structures satisfying (at least approximately) the restrictions imposed in Section I. Of particular importance are the restrictions of inplane loading and composite symmetry about the midplane.

Recognizing the complexities of composite analysis and design as well as the benefits to be gained through the use of these materials, future development work in this area appears warranted.**

**Several of the topics identified here are currently being included in the COMPOS program by J. Mullen at ARC.

These efforts should include more complex loading such as bending, out of plane shear, and temperature loads on nonsymmetric composites. This necessarily requires the inclusion of more sophisticated analysis techniques and failure criterion. Panel buckling under various force and displacement boundary conditions is also an area of interest because, with increased composite strengths, stiffness requirements become increasingly important, since the probability of failure in this mode is increased with reduced plate thicknesses. Additionally, analysis and design of composites made up of plies of differing elastic properties is a needed and straight forward extension. This will provide the capability of selective reinforcement of conventional isotropic materials as well as use of various combinations of advanced materials. Finally, these capabilities should be incorporated into a general finite element analysis and design program for application to large scale structures of practical interest.

APPENDIX A

COMPOSITE ANALYSIS AND DESIGN EQUATIONS

Analysis Equations

The equations used for analysis and design are presented here. These equations are consistent with the assumptions listed in Section I. Equation numbers beginning with the letter A are consistent with Reference 1.

The analysis is based on the ply materials properties E_L , E_T , G_{LT} , v_{LT} and v_{TL} , ply thicknesses, t_i , and orientations, θ_i .

The force deformation equations for the k th load condition are;

$$\{N\}_k = [A] \{\epsilon\}_k \quad [A1]$$

where

$$\{N\}_k = \begin{Bmatrix} N_{xk} \\ N_{yk} \\ N_{xyk} \end{Bmatrix} \quad \{\epsilon\}_k = \begin{Bmatrix} \epsilon_{xk} \\ \epsilon_{yk} \\ \gamma_{xyk} \end{Bmatrix} = \begin{Bmatrix} \frac{\partial u_k}{\partial x} \\ \frac{\partial v_k}{\partial y} \\ \frac{\partial v_k}{\partial x} + \frac{\partial u_k}{\partial y} \end{Bmatrix}$$

$\{N\}_k$ is the vector of applied in-plane loads referenced to the structural x-axis and $\{\epsilon\}_k$ is the corresponding strain state. u and v are the displacements in the coordinate x and y directions, respectively.

$$A_{rs} = \sum_{i=1}^{N_{PLY}} (C'_{rs})_i t_i \quad r,s = 1,2,6 \quad [A2]$$

where t_i is the thickness of the plies oriented at angle θ_i with respect to the structural x-axis. Coefficients $(C'_{rs})_i$ are defined in terms of θ_i and

and the ply elastic constants as

$$\begin{aligned} (c'_{11})_i &= (c_{11})_i \ell_i^4 + 2(c_{12})_i \ell_i^2 m_i^2 \\ &\quad + (c_{22})_i m_i^4 + 4(c_{66})_i m_i^2 \ell_i^2 \end{aligned} \quad [A3]$$

$$\begin{aligned} (c'_{12})_i &= (c_{11})_i \ell_i^2 m_i^2 + (c_{12})_i (\ell_i^4 + m_i^4) \\ &\quad + (c_{22})_i \ell_i^2 m_i^2 - 4(c_{66})_i \ell_i^2 m_i^2 \end{aligned} \quad [A4]$$

$$\begin{aligned} (c'_{16})_i &= (c_{11})_i \ell_i^3 m_i + (c_{12})_i (m_i^3 \ell_i - \ell_i^3 m_i) \\ &\quad - (c_{22})_i m_i^3 \ell_i + 2(c_{66})_i (m_i^3 \ell_i - m_i \ell_i^3) \end{aligned} \quad [A5]$$

$$\begin{aligned} (c'_{22})_i &= (c_{11})_i m_i^4 + 2(c_{12})_i m_i^2 \ell_i^2 \\ &\quad + (c_{22})_i \ell_i^4 + 4(c_{66})_i m_i^2 \ell_i^2 \end{aligned} \quad [A6]$$

$$\begin{aligned} (c'_{26})_i &= (c_{11})_i m_i^3 \ell_i + (c_{12})_i (\ell_i^3 m_i - m_i^3 \ell_i) \\ &\quad - (c_{22})_i m_i \ell_i^3 + 2(c_{66})_i (m_i \ell_i^3 - m_i^3 \ell_i) \end{aligned} \quad [A7]$$

$$\begin{aligned} (c'_{66})_i &= (c_{11})_i m_i^2 \ell_i^2 - 2(c_{12})_i m_i^2 \ell_i^2 \\ &\quad + (c_{22})_i m_i^2 \ell_i^2 + (c_{66})_i (\ell_i^2 - m_i^2)^2 \end{aligned} \quad [A8]$$

where

$$\ell_i = \cos \theta_i \quad m_i = \sin \theta_i \quad [A9]$$

$$(c_{11})_i = \frac{E_{Li}}{(1-\nu_{LTi}\nu_{TLi})} \quad [A10]$$

$$(c_{12})_i = \frac{\nu_{TLi} E_{Li}}{(1-\nu_{LTi}\nu_{TLi})} = -\frac{\nu_{LTi} E_{Ti}}{(1-\nu_{LTi}\nu_{TLi})} \quad [A11]$$

$$(c_{22})_i = \frac{E_{Ti}}{(1-\nu_{LTi}\nu_{TLi})} \quad [A12]$$

$$(c_{66})_i = G_{LTi} \quad [A13]$$

Note that the subscript i is not required on equations [A10]-[A13] since the elastic properties are assumed the same for all plies. The subscript is retained here for consistency.

Given the loads $\{N\}_k$, the membrane strains are obtained from equation [A1] as

$$\{\epsilon\}_k = [A]^{-1} \{N\}_k$$

Finally the strains in the i th ply (k th load condition) are determined from

$$\begin{aligned} \epsilon_{lik} &= \ell_i^2 \epsilon_{xk} + m_i^2 \epsilon_{yk} + m_i \ell_i \gamma_{xyk} \\ \epsilon_{zik} &= m_i^2 \epsilon_{xk} + \ell_i^2 \epsilon_{yk} - m_i \ell_i \gamma_{xyk} \\ \gamma_{12ik} &= -2m_i \ell_i \epsilon_{xk} + 2m_i \ell_i \epsilon_{yk} + (\ell_i^2 - m_i^2) \gamma_{xyk} \end{aligned} \quad [A14]$$

If the stresses in the i th ply are required, these may be obtained from the orthotropic elastic stress-strain relationships to be

$$\sigma_{1ik} = (c_{11})_i \epsilon_{1ik} + (c_{12})_i \epsilon_{2ik}$$

$$\sigma_{2ik} = (c_{12})_i \epsilon_{1ik} + (c_{22})_i \epsilon_{2ik}$$

[15]

$$\tau_{12ik} = (c_{66})_i \gamma_{12ik}$$

Design Equations

The design objective is to minimize the total composite thickness (and therefore weight);

$$\text{Minimize } W = \sum_{i=1}^{\text{NPLY}} t_i$$

Constraints on the design include limit ply strains and lower bounds on stiffness.

The limit strains imposed on the individual plies are expressed as constraint functions as follows:

$$G_{1ik} = \frac{\epsilon_{1ik}}{EPLC} - 1. \leq 0 \quad i = 1, \text{NPLY}, k = 1, \text{NLC}$$

$$G_{2ik} = \frac{\epsilon_{2ik}}{EPLT} - 1. \leq 0 \quad i = 1, \text{NPLY}, k = 1, \text{NLC}$$

$$G_{3ik} = \frac{\epsilon_{2ik}}{EPTC} - 1. \leq 0 \quad i = 1, \text{NPLY}, k = 1, \text{NLC}$$

$$G_{4ik} = \frac{\epsilon_{2ik}}{EPTT} - 1. \leq 0 \quad i = 1, \text{NPLY}, k = 1, \text{NLC}$$

$$G_{5ik} = \left| \frac{\gamma_{12ik}}{GMLT} \right| - 1. \leq 0 \quad i = 1, \text{NPLY}, k = 1, \text{NLC}$$

where subscript i denotes ply number and subscript k denotes load condition.

Lower bounds on stiffness are expressed as constraint functions;

$$\bar{G}_1 = 1. - A(1,1)/A11L \leq 0.$$

$$\bar{G}_2 = 1. - A(2,2)/A22L \leq 0.$$

$$\bar{G}_3 = 1. - A(3,3)/A66L \leq 0.$$

Constraints on strains are nonlinear functions of the design variables, t_i . The values of these constraints are stored in vector G , (five values per ply, one ply after another) for each load condition in sequence.

Constraints \bar{G}_1 , \bar{G}_2 and \bar{G}_3 on stiffness are linear functions of the design variables. The values of these constraints are stored after constraints on strains in vector G .

There are $5*NPLY*NLC$ nonlinear constraints and three linear constraints on the optimization problem. Program "CONMIN" defines a nonlinear constraint as "active" if its value is greater than or equal to a specified value CT (a small negative number). Linear constraints are "active" if their value equals or exceeds a value of CTL. If a given constraint is active the analytic gradient of this constraint with respect to the independent design variables, t_i , must be supplied. This information is obtained by direct differentiation of the constraint functions and is readily calculated using the equations of analysis.

APPENDIX B

PROGRAM LISTING

A complete FORTRAN listing of program "COMAND" is given here.

In addition, program "CONMIN" is required and this program is described in reference 2. The general program organization is shown in block diagram form in figure 11.

COMPOSITE ANALYSIS AND DESIGN PROGRAM - COMAND

JULY, 1974

PROGRAM COMAND - A FORTRAN PROGRAM FOR COMPOSITE ANALYSIS AND DESIGN.
 COMMON X(20),DF(201),G(500),ISCI(500),IC(201),A(20,20),S(20),G1(500),
 *G2(500),C(20),HSI(40),B(20,20),VLB(20),VUD(20),SCAL(20)
 COMMON VCNMNL,IPRINT,NDV,ITMAX,NCON,NSIDE,ICNDIR,NSCAL,NFDG,FDCH,
 FDCHN,CT,CTIN,CTL,CILMIN,THETA,PHI,HAC,DELFUN,LINDB
 2J,LTRN,IER,INFO
 COMMON FCMPDOS,NPLY,EL,ET,GLT,PRLT,PPLC,EPLT,EPTE,EPTE,GMLT,
 1NLC,A11,A22L,A66L,TN118),THN(181),CP(3,3,181),PN(3,3)+AA(3,3),BB(3
 2,3),EF(3),DEP(3),LNK(18)
 DIMENSION TITLE(15)
 EXTERNAL COM3
 PROGRAM FOR MULTILAYERED COMPOSITE PANEL OPTIMIZATION,
 BY G. N. VANDERPLAATS SEPT., 1973.
 NASA-AMES RESEARCH CENTER, MCFETT FIELD, CALIF.
 REQUIRED DIMENSIONS: TH(NPLY),THN(NPLY),CP(3,3,NPLY),PN(3,NLC),
 LNK(NPLY). OTHERS REMAIN AS HOW DIMENSIONED
 STORAGE REQUIREMENTS (DECIMAL WORDS, COC):
 PROGRAM -
 CCOMMAND = 2000
 COMMON = 6000
 ARRAYS = 3000 FOR PROGRAM AS DIMENSIONED IN REF. 1.
 REF. 1 - VANDERPLAATS, G. N., SCOMAND - A FORTRAN PROGRAM FOR
 SIMPLIFIED COMPOSITE ANALYSIS AND DESIGN, NASA TM X-64, 1974,
 AUG. 1975.
 REF. 2 - SCHMIT, L. A., AND FARSHID, B. I. SUPTIMUM LAMINATE DESIGN
 FOR STRENGTH AND STIFFNESS. INT. J. FOR NUMERICAL METHODS
 IN ENGINEERING, VOL. 7, NO. 4, PP. 519-536, 1973.
 EQUATION NUMBERS LISTED IN THIS PROGRAM ARE FROM THE ABOVE
 REFERENCE.
 REF. 3 - COMAN - A FORTRAN PROGRAM FOR CONSTRAINED FUNCTION
 MINIMIZATION. USERS MANUAL, BY G. N. VANDERPLAATS,
 NASA TM X-62, 292, AUGUST, 1973.
 THIS PROGRAM USES COMAN VERSION II, DATED JULY, 1975.
 ASSUMPTIONS:
 BOUNDARY CONDITIONS ARE PRESCRIBED LOADS NX, NY AND NX.
 ALL PLYS HAVE SAME MATERIAL PROPERTIES AND FAILURE STRAINS.
 FAILURE CRITERION ARE MAX PLY LONGITUDINAL, TRANSVERSE AND SHEAR
 STRAINS, AND STIFFNESS LIMITS ON A11, A22 AND A66.
 WHEN ANY ONE PLY FAILS, THIS IS DEFINED AS COMPOSITE FAILURE.
 MEMBRANE LOADS ONLY - MULTIPLE LOADING CONDITIONS ARE
 CONSIDERED.
 SYMMETRY ABOUT MIDPLANE IS ASSUMED.
 COMPOSITE NEED NOT BE BALANCED.
 NCALC = CALCULATION CONTROL
 OF DC OPTIMIZATION
 NO. OF DC ANALYSIS ONLY
 NPLY = NUMBER OF PLYS. SYMMETRY ASSUMED.
 PROGRAM TERMINATED IF NPLY=0.

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C NLC = NUMBER OF LOAD CONDITIONS.
 C NDV = NUMBER OF DESIGN VARIABLES OR INDEPENDENT PLY THICKNESSES
 FOR ANALYSIS.
 C IPRINT = PRINT CONTROL FOR COMMAN.
 10. READ (5,140) TITLE
 READ (5,200) NCALC,NPLY,NDV,NLC,IPRINT
 IF (NPLY.EQ.0) STOP
 C DESIGN VARIABLE LINKING. LNK(I) = DESIGN VARIABLE
 ASSOCIATED WITH ITH PLY.
 READ (5,200) (LNK(I),I=1,NPLY)
 C INITIAL THICKNESS.
 READ (5,210) (X(I),I=1,NDV)
 C TOTAL INITIAL COMPOSITE THICKNESS.
 OBJ=0.
 DO 20 I=1,NPLY
 J=LNK(I)
 OBj=OBj+X(I)
 20 TN118=1(J)
 C LOWER BOUNDS ON DESIGN VARIABLES.
 READ (5,210) (VLB(I),I=1,NDV)
 C PLY ORIENTATION IN DEGREES.
 READ (5,210) (THN(I),I=1,NPLY)
 C PLY MATERIAL PROPERTIES.
 READ (5,210) EL,ET,GLT,PARL
 PRIL=PR1*ET*EL
 C STRAIN AND STIFFNESS LIMITS.
 READ (5,210) (PLC,PLT,EPTE,EPTE,GMLT,A11L,A22L,A66L
 C LOADS FOR EACH LOAD CONDITION.
 DO 30 I=1,NLC
 C LOADS - NX, NY AND NX FOR THIS LOAD CONDITION.
 30 READ (5,210) (PN(J,I),J=1,3)
 C NCON = NUMBER OF CONSTRAINTS.
 NCON=3+NPLY*NLC
 DO 40 I=1,NCON
 40 ISCI(I)=0
 NI=NCON+1
 ISCI(NI)=1
 ISCI(NI+1)=1
 ISCI(NI+2)=1
 IF (A11L.ET.1.0E-10) NCON=NCON+1
 IF (A22L.GT.1.0E-10) NCON=NCON+1
 IF (A66L.GT.1.0E-10) NCON=NCON+1
 C PRINT INPUT INFORMATION.
 IF (NCALC.EQ.0) WRITE(6,460)
 IF (NCALC.EQ.1) WRITE(6,470)
 WRITE (6,220)
 WRITE (6,150) TITLE
 WRITE (6,230) NPLY,NLC
 WRITE (6,240) EL,ET,GLT,PREL,PRTL
 WRITE (6,250)

COMPOSITE ANALYSIS AND DESIGN PROGRAM - COHARD

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50 DO 50 I=1,NPLY
      WRITE (6,270) I,IN(I),THN(I),LNK(I)
      GMHTI=GLHT
      WRITE (6,260) EPLC,EPLT,EPIC,EPIT,GLHTI,GLHT
      WRITE (6,290) A11L,A22L,A66L
      WRITE (6,300)
      DO 60 J=1,NLC
      WRITE (6,310) I,IPN(J,I),J=1,3
      C INITIALIZE COMBINING PARAMETERS TO DEFAULT VALUES.
      ITMAX=30
      NSIDE=1
      ECNDIN=0
      NSCAL=0
      NFUG=0
      FOCHE=C.
      FDCHM=C.
      CT=C.
      CTMIN=C.
      CTL=0.
      CILPH=C.
      THETA=C.
      PHI=C.
      DelFUN=0.
      DABFUN=0.
      LINUBJ=1
      ITRM=0
      C CONVERT PLY ANGLES TO RADIANS.
      DO 70 I=1,NPLY
      THN(I)=THN(I)*3.1415926
      C UPPER BOUNDS ON DESIGN VARIABLES ARBITRARILY SET = 100.
      70 VUB(I)=100.
      C PLY STIFFNESS COEFFICIENTS.
      CALL CMPI (NPLY,THN,FL,ET,GLT,PMLT,RTL,CPI)
      KN1=2G
      KN2=5C
      KN3=2D
      KN4=2C
      AN5=6G
      IF (INCALC.EQ.0) CALL COMIN (CJMP3,08J,A,DF,G,ESC,IC,A,S,G1,G2,C,M
      *S1,d,VLB,VLB,S2AL,NN1,NN2,NN3,NN4,NN5)
      C PRINT ANALYSIS RESULTS.
      WRITE (6,320)
      WRITE (6,320) TITLE
      WRITE (6,330)
      PP=100./UBJ
      C PLY THICKNESS AND PERCENT OF TOTAL THICKNESS.
      DO 80 I=1,NPLY
      J=LNK(I)
      TH(I)=X(I)
      PCT=PP*TH(I)

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80   1010  WRITE (6,260) I,IN(I),PCT
      1020  C TOTAL THICKNESS.
      1030  C WRITE (6,340) 003
      1040  C STIFFNESSES AND FLEXIBILITIES.
      1050  C CALL COMP2 (NPLY,TH,CP,AA+BB)
      1060  C PLY STRAINS AND COMPOSITE STRESSES FOR ALL LOAD CONDITIONS.
      1070  C WRITE (6,350)
      1080  C DO 100 I=1,NLC
      1090  C     WRITE (6,360) I
      1100  C     COMPOSITE STRAINS.
      1110  C     EP(1)=B01(1,1)*PN(1,1)+B01(2,1)*PN(2,1)+B01(3,1)*PN(3,1)
      1120  C     EP(2)=B02(2,1)*PN(1,1)+B02(2,2)*PN(2,1)+B02(2,3)*PN(3,1)
      1130  C     EP(3)=B03(3,1)*PN(1,1)+B03(3,2)*PN(2,1)+B03(3,3)*PN(3,1)
      1140  C     PLY STRAINS AND SAFETY FACTORS.
      1150  C     DJ 90 J=1,NPLY
      1160  C     THETA=THLT(J)
      1170  C     AL=COS(THLT(J))
      1180  C     AH=SIN(THLT(J))
      1190  C     AL2=AL+AL
      1200  C     AH2=AH+AH
      1210  C     STRAINS.
      1220  C     EP1=AL2*EP(1)+AH2*EP(2)+AL*AH*EP(3)
      1230  C     EP2=AH2*EP(1)+AL2*EP(2)-AL*AH*EP(3)
      1240  C     EP3=2.*AL*AH*(EP(2)-EP(1))+(AL2-AH2)*EP(3)
      1250  C     SET STRAINS TO MINIMUM ABSOLUTE VALUE OF 1.0E-20 TO PREVENT
      1260  C     CIVIDC BY ZERO.
      1270  C     IF (ABS(EP1).LT.1.0E-20) EP1=1.0E-20
      1280  C     IF (ABS(EP2).LT.1.0E-20) EP2=1.0E-20
      1290  C     IF (ABS(EP3).LT.1.0E-20) EP3=1.0E-20
      1300  C     SAFETY FACTOR.
      1310  SF1=EPLC/EP1
      1320  SF2=EPLC/EP2
      1330  SF3=GMHTI/EP3
      1340  IF (EP1.GT.0.) SF1=EP1/EP1
      1350  IF (EP2.GT.0.) SF2=EP2/EP2
      1360  IF (EP3.GT.0.) SF3=SF3
      1370  IF (SF1.GT.100.) SF1=100.
      1380  IF (SF2.GT.100.) SF2=100.
      1390  IF (SF3.GT.100.) SF3=100.
      1400  WRITE (6,370) J,EP1,SF1,EP2,SF2,EP3,SF3
      1410  C CONTINUE
      1420  C COMPOSITE STRAINS.
      1430  C     WRITE (6,380) I,EP(K),K=1,31
      1440  C CONTINUE
      1450  C COMPOSITE STRESSES.
      1460  C     WRITE (6,390)
      1470  C     DO 120 I=1,NLL
      1480  C       DO 110 J=1,3
      1490  C         G(I,J)=P(I,J)/CSJ
      1500  C     WRITE (6,400) I,(G(I,J),J=1,3)

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COMPOSITE ANALYSIS AND DESIGN PROGRAM - COMMAND

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120  CONTINUE
C   COMPOSITE STIFFNESSES.
      WRITE (6,160)
      SF=100.
      IF (A11L.GT.1.DE-10) SF=AA(1,13/A11)
      IF (SF.LT.160.) SF=100.
      WRITE (6,170) AA(1,1),A11L,SF
      SF=100.
      IF (A22L.GT.1.DE-10) SF=AA(2,2)/A22L
      IF (SF.LT.160.) SF=100.
      WRITE (6,180) AA(2,2),A22L,SF
      SF=100.
      IF (A66L.GT.1.DE-10) SF=AA(3,3)/A66L
      IF (SF.LT.160.) SF=100.
      WRITE (6,190) AA(3,3),A66L,SF
      WRITE (6,191)
      DJ 130 I=1,3
      DO 130 J=1,3
      88(I,J)=UBI*BUI(I,J)
      AA(1,J)=AA(1,J)+J/BJ
      C   COMPOSITE STRESS-STRAIN RELATIONSHIPS.
      WRITE (6,200) ((AA(I,J),J=1,3),I=1,3)
      WRITE (6,201)
      C   COMPOSITE STRAIN-STRESS RELATIONSHIPS.
      WRITE (6,210) ((BUI(I,J),J=1,3),I=1,3)
      C   COMPOSITE ELASTIC CONSTANTS.
      EX=1./BUI(1,1)
      EY=1./BUI(2,2)
      GXY=1./BUI(3,3)
      PRXY=-Bd(1,2)/B(1,1)
      PRYX=-B(1,1)/B(2,2)
      WRITE (6,220) EX,EY,GXY,PRXY,PRYX
      GJ TC 10
      C
      140  FORMAT (15A4)
      150  FORMAT (1/14X,5HTITLE/14X,15A4)
      160  FORMAT (//2X,3D,1HCOMPOSITE MEMBRANE STIFFNESSES/27X,0HACTUAL,7X,0H
      1RECIPLU/27X,5HV4LUe,9X,0HVALUc,0X,4HS,F,1
      170  FORMAT (14X,3HA11,L13.5,1X,L13.5,3X,F7.2)
      180  FORMAT (14X,3HA22,L13.5,2X,L13.5,3X,F7.2)
      190  FORMAT (14X,3HA66,L13.5,1X,L13.5,3X,F7.2)
      200  FORMAT (1L15)
      210  FORMAT (5F14.2)
      220  FORMAT (//1X,2HDF/30X,2HHSYMMETRIC COMPOSITE PANEL)
      230  FORMAT (//27X,25IND. OF PLYS      ,19/,27X,25IND. OF LOAD
      1 1 CONDITIONS ,15I1
      240  FORMAT (//25X,35HPLY PROPERTIES - ALL PLYS IDENTICAL/26X,22H
      1UDINAL MODULUS =,L12.5/26X,22HTRANSVERSE MODULUS =,E12.5/26X,22H
      2SHAK MODULUS =,E12.5/26X,22HPOISSONES RATIO, L-T =,E12.5/2
      3EX,22HPOISSONES RATIO, T-L =,E12.5)
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COMPOSITE ANALYSIS AND DESIGN PROGRAM - COMMAND

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260  FORMAT (//14X,31HPLY THICKNESSES, 0H1. TATIONS, ,27HANU DESIGN VARI
      1ABLE NUMBERS/2G,47HPLY NO.  THICKNESS     THETA    DES. VAR. NO
      *.)
      260  FJRMAL (2IX,19.3X,E13.,,F10.2)
      270  FORMAL (15X,19.3X,L13.5,3X,F7.2,5X,15)
      280  FORMAT (//33X,17HPLY STRAIN LIMITS/14X,23HLONGITUDINAL STRAIN,GE.,
      1L13.5,9H,ANL,LE,,E13.5/14X,23H TRANSVERSE STRAIN,GE.,E13.5,9H,A
      2HOLE, ,E13.5/14X,23H      SHEAR STRAIN,GE.,E13.5,9H,ANL,LE,,E13.
      35)
      290  FORMAT (//33X,16HSTIFFNESS LIMITS/33X,7HA11,GE.,E12.5/33X,7HA22,GE
      1,E12.5/33X,7HA65,GE.,E12.5)
      300  FORMAT (//46X,5HLOADS/19X,1DHLOAD COND.,LK,2HNX,IZX,P14Y,12X,3HNXY
      1)
      310  FORMAT (15X,16X,6X,E12.5,2X,E12.5,1)
      320  FORMAT (1H120x,3DDESIGN,ANU/DK ANALYSIS RESULTS)
      330  FORMAT (//25X,15HPLY INFORMATION/25X,32HPLY NO.  THICKNESS
      1PERCENT)
      340  FORMAT (35X,16X,-----,3X,1UM,-----,/23X,11HTHICKNESS ,E12.
      15X,4X,CHICC,C1)
      350  FORMAT (//37X,11HPLY STRAINS/33X,2DH5,F,  = SAFETY FACTOR/33X,26H
      1EPL = LONGITUDINAL STRAIN/33X,24HEPT = TRANSVERSE STRAIN/33X,19H
      2EPL = SHEAR STRAIN)
      360  FORMAT (//3CX,16HLOAD COND.,L5/5X,7HPLY NO.,0X,3HEPL,0X,4HS,F,0X,
      13HEPL,0X,4HS,F,0X,3X,4HEPL,7X,4HS,F)
      370  FORMAT (15X,15,X,12.5,2X,F7.3,2X,E12.5,2X,F7.3,2X,E12.5,2X,F7.3)
      380  FORMAT (15X,47HCOMPOSITE STRAINS REFERENCED TO STRUCTURAL AXIS/5X,
      16HEPL = ,E12.5,3X,0HEFY = ,E12.5,3X,7-EFY = ,E12.5)
      390  FORMAT (//23X,3D,1HMEMBRANE STRESSES IN COMPOSITE/4DX,10HLOAD COND.,
      15X,7HSIGMA-X,0X,7HSIGMA-Y,0X,0HTAU-X,Y)
      400  FORMAT (15X,15,X,X,13.5)
      410  FORMAT (//20A,4HCOEFFICIENTS OF STRESS-STRAIN RELATIONSHIPS/28X,26
      1HRELATIG STRUCTURAL AXES)
      420  FORMAT (10X,6HC011 = ,E12.5,4X,0HC12 = ,E12.5,4X,
      1/32X,6H022 = ,E12.5,4X,0H023 = ,E12.5/20X,4HSYMMETRIC,25X,6HC66 =
      2X,12.5)
      430  FORMAT (//20A,4HCOEFFICIENTS OF STRESS-STRAIN RELATIONSHIPS/28X,26
      1HRELATIG STRUCTURAL AXES)
      440  FORMAT (10X,CH011 = ,E12.5,4X,CHQ12 = ,E12.5,4X,0H012 = ,E12.5,4X,
      1/32X,6H022 = ,E12.5,4X,0H023 = ,E12.5/20X,4HSYMMETRIC,25X,6H066 =
      2X,12.5)
      450  FORMAT (//28X,27HCOMPOSITE ELASTIC CONSTANTS/11X,5HEX = ,E12.5,5X,
      15HEY = ,E12.5,5X,CHQ12 = ,E12.5,5X,7HNXYK = ,E1
      *2,5)
      460  FORMAT (1H1,3DX,0HDESIGN)
      470  FORMATE(1H1,37X,0HANALYSIS)
      END

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COMPOSITE ANALYSIS AND DESIGN PROGRAM - COMAND - COMPI JULY, 1974

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SUBROUTINE COMPI (INPLY, THN, EL, ET, GLT, PRLT, PRTL, CP)
  DIMENSION CP(3,3,18), THN(18)
C ROUTINE TO CALCULATE PLY STIFFNESS COEFFICIENTS - ALL PLYS THE SAME
C ELASTIC PROPERTIES.
C BY G. N. VANDENPLAATS          SEPT., 1973.
C NASA-AMES RESEARCH CENTER, NOFFETT FIELD, CALIF.
C MATERIAL ELASTIC PROPERTIES.
C PRI=1./((1.-PRLT)*PRTL)
C EQUATION A10
C C11=EL*PK1
C EQUATION A11
C C12=PK1*EL*PR1
C EQUATION A12
C C22=ET*PR1
C EQUATION A13
C C66=GLT
C DO FOR ALL PLYS.
DO 10 I=1,APLY
  THETA=THN(I)
C EQUATION A9
  AL=COS(THETA)
  AM=SIN(THETA)
  AL2=AL*AL
  AL3=AL*AL2
  AL4=AL2*AL2
  AM2=AM*AM
  AM3=AM*AM2
  AM4=AM2*AM2
C EQUATION A3
  CP(1,1,1)=C11*AL4+2.*C12*AL2*AM2+C22*AM4+4.*C66*AL2*AM2
C EQUATION A4
  CP(1,2,1)=C11*AL2*AL2+C12*(AL4+AM4)+C22*AL2*AM2-4.*C66*AL2*AM2
C EQUATION A5
  CP(1,3,1)=C11*AL3*AM+C12*(AL*AM3-AL3*AM)-C22*AL*AM3+2.*C66*(AL*AM3
  1-AM*AL3)
C EQUATION A6
  CP(1,2,2)=C11*AM4+2.*C12*AL2*AM2+C22*AL4+4.*C66*AL2*AM2
C EQUATION A7
  CP(1,2,3)=C11*AL*AM3+C12*(AL3*AM-AL*AM3)-C22*AL3*AM+2.*C66*(AL3*AM
  1-AL*AM3)
C EQUATION A8
  CP(1,3,2)=C11*AL2*AM2+2.*C12*AL2*AM2+C22*AL2*AM2+C66*(AL4-2.*AL2*AM
  1*AM*AM)
C IMPOSE SYMMETRY ON CP.
  CP(1,2,1,1)=CP(1,2,1)
  CP(1,3,1,1)=CP(1,3,1)
  CP(1,3,2,1)=CP(1,2,3,1)
  10  CONINUE
  RETURN
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COMPOSITE ANALYSIS AND DESIGN PROGRAM - LE-MAND - COMPG3      JULY, 1974

SUBROUTINE CLMP3 (INFO,OBJ,X,DF,G,IC,N1,N2,N3)          10
COMMON /CMN1/ IPRINT,NDIV,ITMAX,NCOM,NHSIDE,ICAOIR,NSCAL,NFBG,FOCH,
1FOCH,CT,CIKIN,CTL,CTLMIN,THETA1,PHI,NAC,DELFLV4,DAUFUN,LINO   20
2BL,LTMA,LTCP,IMFDG                                     30
DIMENSION KIN1),DF(N1),GIN2),IC(N1),X(N1,N1)           40
EXTERNAL ROUTINE FOR COMPUTING FOR COMPOSITE PANEL DESIGN,
BY G. N. VANDERPLAATS                                     50
NASA-AMES RESEARCH CENTER, MCKEETON FIELD, CALIF.        60
SEPT., 1973.                                              70
THIS IS A BUFFER BETWEEN CMNNH AND COMPG.                 80
CALL CLMP4 (INFO,JHJ,NDV,CT,NAC,K,DF,G,A,IC,N1,N2,N3)    90
RETURN                                                 100
END                                                 110

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C CAMPUS.TE ANALYSIS AND DESIGN PROGRAM - COMMAND - COMP4        JULY, 1974
C
C SUBROUTINE COMP4 (INFO,OBJ,NUV,CF,CTL,NAC,X,DF,G,A,IC,NN1,NN
C 2,NN3)
C
C COMMON /CGMPUS/ NPLY,EL,ET,GLT,PRTL,PTRL,EPLO,EPLO,EPLO,EPLO,EP
C GLT,INCL,A11L,A22L,A66L,TH(11),TH(16),CP(3,3,10),PN(3,3,5),AA(3,3,3),BB(3
C 2,3),EP(3,3),DIP(3,3),LNK(118)
C
C DIMENSION IMP(3), X(118), DF(118), CN(118), IC(118), A(118,118)
C
C ROUTINE TO CALCULATE FUNCTION VALUE, CONSTRAINT VALUES AND
C GRADIENT OF FUNCTION AND ACTIVE CONSTRAINTS FOR COMPOSITE
C ANALYSIS AND DESIGN PROGRAM - COMMAND.
C
C BY G. W. VANDERPLAATS          SEPT., 1973.
C NASA-AMES RESEARCH CENTER, MOUNTAIN VIEW, CALIF.
C
C IF (INFO,GT,2) GO TO 20
C
C OBJECTIVE
C
C   UD=0.
C   DO 10 J=1,NFLY
C     LNK(J)=J
C     T(E1)=J
C   10 C9J=6J+1
C   IF (INFO,LE,2) RETURN
C   CONTINUE
C
C GRADIENT OF OBJECTIVE
C   DO 30 I=1,NEV
C   DF(I)=C
C   DO 40 E=1,NPLY
C     J=LNK(E)
C   40 DF(E)=DF(J)+1.
C   IF (INFO,GE,3) RETURN
C
C CONTINUE
C
C CONSTRAINTS AND GRADIENT OF ACTIVE CONSTRAINTS.
C
C CTL1=C
C
C IF (INFO,LE,4) NAC=0
C
C STIFFNESS AND FLEXIBILITIES.
C CALL CGMP2 (NPLY,TH,CP,AA+38)
C
C DO 170 J=1,NLC
C
C INVERSE OF EQUATION A1.
C
C EP(1)=B(1,1)*PN(1,1)+B(1,2)*PN(2,1)+B(1,3)*PN(3,1)
C EP(2)=B(2,1)*PN(1,1)+B(2,2)*PN(2,1)+B(2,3)*PN(3,1)
C EP(3)=B(3,1)*PN(1,1)+B(3,2)*PN(2,1)+B(3,3)*PN(3,1)
C
C DO 170 J=1,NFLY
C   THE1A=TH(1,J)
C   AL=CGS1(THE1A)
C   AM=SIN(THE1A)
C   AL2=AL*AL
C   AM2=AM*AM
C
C EQUATION A14
C
C EP1=AL2*EP(1)+AM2*EP(2)+AL*AM*EP(3)
C EP2=AM2*EP(1)+AL2*EP(2)-AL*AM*EP(1)
C EP3=2.*AL*AM*EP(2)-EP(1)+(AL2-AM2)*EP(3)
C
C IC(1)=C1G1+1

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COMPOSITE ANALYSIS AND DESIGN PROGRAM - COMMAND - COMP4

JULY, 1974

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N1=NCTOT
C LONGITUDINAL STRAIN CONSTRAINT - COMPRESSION.
G(NCTOT)=EP1/EPLC-1.
NCTOT=NCTOT+1
C LONGITUDINAL STRAIN CONSTRAINT - TENSION.
G(NCTOT)=EP1/EPLT-1.
NCTOT=NCTOT+1
C TRANSVERSE STRAIN CONSTRAINT - COMPRESSION.
G(NCTOT)=EP2/EPTC-1.
NCTOT=NCTOT+1
C TRANSVERSE STRAIN CONSTRAINT - TENSION.
G(NCTOT)=EP2/EPTT-1.
NCTOT=NCTOT+1
C SHEAR STRAIN CONSTRAINT.
G(NCTOT)=ABS(EP3)/GMLT-1.
IF (INFO<LT.4) GO TO 160
MAC=MAC
DO 60 K=N1,NCTOT
IF (G(K).LT.CT) MAC=MAC+1
60 CUNTINUE
IF (MAC.LG.NAC) GO TO 160
N2=NAC+1
DO 70 II=N2,MAC
DO 70 JJ=1,NGV
70 A(IJ,JJ)=C.
MAC=NAC
N2=N1
DO 150 KK=1,NPLY
K=LNK(K)
C GRADIENT OF STRAINS - EQUATION 37.
DO 60 K1=1,3
TMP(K1)=U.
60 DO K2=1,3
TMP(K1)=TMP(K1)+CP(K1,K2,KK)*EP(K2)
60 DO K1=1,3
DEP(K1)=L.
60 DO K2=1,3
DEP(K1)=DEP(K1)-98(K1,K2)*TMP(K2)
DEP1=AL2*DEF(1)+AM2*DEF(2)+AL*AM*DEF(3)
DEP2=AM2*EP(1)+AL2*EP(2)-AL*AM*DEF(3)
DEP3=2.*A.*AM*(DEF(2)-DEF(1))+(AL2-AM2)*DEF(3)
NAC=NAC
N1=N2
IF (G(N1).LT.CT) GO TO 160
C GRADIENT OF ACTIVE LONGITUDINAL COMPRESSIVE STRAIN CONSTRAINT.
NAC=NAC+1
IF (NAC.EQ.NN3) RETURN
A(NAC,K)=A(NAC,K)+DEP1/EPLC
IC(NAC)=N1
100 N1=N1+1

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COMPCSITE ANALYSIS AND DESIGN PROGRAM - COMMAND - COMP4

JULY, 1974

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IF (G(N1).LT.CT) GO TO 110
C GRADIENT OF ACTIVE LONGITUDINAL TENSILE STRAIN CONSTRAINT.
NAC=NAC+1
IF (NAC.EQ.NN3) RETURN
A(NAC,K)=A(NAC,K)+DEP1/EPLT
IC(NAC)=N1
N1=N1+1
IF (G(N1).LT.CT) GO TO 120
C GRADIENT OF ACTIVE TRANSVERSE COMPRESSIVE STRAIN CONSTRAINT.
NAC=NAC+1
IF (NAC.EQ.NN3) RETURN
A(NAC,K)=A(NAC,K)+DEP2/EPTC
IC(NAC)=N1
N1=N1+1
IF (G(N1).LT.CT) GO TO 130
C GRADIENT OF ACTIVE TRANSVERSE TENSILE STRAIN CONSTRAINT.
NAC=NAC+1
IF (NAC.EQ.NN3) RETURN
A(NAC,K)=A(NAC,K)+DEP2/EPTT
IC(NAC)=N1
N1=N1+1
IF (G(N1).LT.CT) GO TO 140
C GRADIENT OF ACTIVE SHEAR STRAIN CONSTRAINT.
NAC=NAC+1
IF (NAC.EQ.NN3) RETURN
SIGN=1.
IF (EP3.LT.0.) SIGN=-1.
A(NAC,K)=A(NAC,K)+SIGN*DEP3/GMLT
IC(NAC)=N1
130 CONTINUE
140 CONTINUE
150 CONTINUE
160 CONTINUE
170 CONTINUE
C CONSTRAINTS ON STIFFNESS.
N1=NCTOT
IF (A111.LT.1.0E-10) GO TO 180
C CONSTRAINT ON A11.
NCTOT=NCTOT+1
G(NCTOT)=1.-AA(1,1)/A11
180 IF (A221.LT.1.0E-10) GO TO 190
C CONSTRAINT ON A22.
NCTOT=NCTOT+1
G(NCTOT)=1.-AA(2,2)/A22
190 IF (A112.LT.1.0E-10) GO TO 200
C CONSTRAINT ON A66.
NCTOT=NCTOT+1
G(NCTOT)=1.-AA(3,3)/A66
200 IF (INFO.LT.4.OR.N1.EC.NCTOT) RETURN
IF (A111.LT.1.0E-10) GO TO 230
N1=N1+1

```

```

1010
1020
1030
1040
1050
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1070
1080
1090
1100
1110
1120
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1140
1150
1160
1170
1180
1190
1200
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1390
1400
1410
1420
1430
1440
1450
1460
1470
1480
1490
1500

```

COMPOSITE ANALYSIS AND DESIGN PROGRAM - COMMAND - COMPA4

JULY, 1974

```

NL=NC1OT
C LONGITUDINAL STRAIN CONSTRAINT - COMPRESSION.
G1NC1OT=EP1/EPLC-1.
NCTOT=NCTOT+1
C LONGITUDINAL STRAIN CONSTRAINT - TENSION.
GENC1OT=EP1/EPLT-1.
NCTOT=NCTOT+1
C TRANSVERSE STRAIN CONSTRAINT - COMPRESSION.
GENC1OT=EP2/EPTC-1.
ACTOT=ACTOT+1
C TRANSVERSE STRAIN CONSTRAINT - TENSION.
GENC1OT=EP2/EPTT-1.
NCTOT=NCTOT+1
C SHEAR STRAIN CONSTRAINT.
GENC1OT=A65(EP31/GMLT-1.
IF (INFO.LT.4) GO TO 160
MAC=MAC
DO 60 K=N1,NCTOT
IF (G1K).GE.CT1 MAC=MAC+1
60 CUNTILE
IF (MAC).LE.AAC1 GO TO 160
A2=NAC+1
DO 70 I1=N2,MAC
DO 70 J1=1,NGV
70 A1II(JJ)=C.
MAC=MAC
N2=N1
DO 1DC KK=1,NPLY
K=LH4(KK)
C GRADIENT OF STRAINS - EQUATION 37.
DO 80 K1=1,3
TMP(K1)=0.
DO 80 K2=1,3
80 TMP(K2)=TMP(K1)+CP(K1,K2,KK)*EP(K2)
DO 90 K1=1,3
DEP(K1)=L
DO 90 K2=1,3
90 DEP(K1)=DEP(K1)-98(K1,K2)*TMP(K2)
DEP1=AL2*DEP(11)+AL2*DEP(21)+AL*AH*DEP(3)
DEP2=AH*EP(11)+AL2*EP(21)-AL*AH*DEP(3)
DEP3=2.*AH*(DEP(21)-DEP(11))+AL2*AH*DEP(3)
MAC=MAC
N1=N2
IF (G1N1.LT.C1) GO TO 100
C GRADIENT OF ACTIVE LONGITUDINAL COMPRESSIVE STRAIN CONSTRAINT.
MAC=MAC+1
IF (MAC.EC.NH3) RETURN
A1(NAC,K)=A1(NAC,K)+DEP1/EPLC
IC(NAC)=N1
100 N1=N1+1

```

COMPOSITE ANALYSIS AND DESIGN PROGRAM - COMMAND - COMPA4

JULY, 1974

```

IF (G1N1.LT.C1) GO TO 110
GRADIENT OF ACTIVE LONGITUDINAL TENSILE STRAIN CONSTRAINT.
NAC=NAC+1
IF (MAC.LD.NH3) RETURN
A1(NAC,K)=A1(NAC,K)+DEP1/EPLT
IC(NAC)=N1
110 N1=N1+1
IF (G1N1.LT.C1) GO TO 120
GRADIENT OF ACTIVE TRANSVERSE COMPRESSIVE STRAIN CONSTRAINT.
NAC=NAC+1
IF (MAC.LC.NH3) RETURN
A1(NAC,K)=A1(NAC,K)+DEP2/EPTC
IC(NAC)=N1
120 N1=N1+1
IF (G1N1.LT.C1) GO TO 130
GRADIENT OF ACTIVE TRANSVERSE TENSILE STRAIN CONSTRAINT.
NAC=NAC+1
IF (MAC.LD.NH3) RETURN
A1(NAC,K)=A1(NAC,K)+DEP2/EPTT
IC(NAC)=N1
130 N1=N1+1
IF (G1N1.LT.C1) GO TO 140
GRADIENT OF ACTIVE SHEAR STRAIN CONSTRAINT.
NAC=NAC+1
IF (MAC.LU.NH3) RETURN
SIGN1=
IF (EP3.LT.0.) SIGN=-1.
A1(NAC,K)=A1(NAC,K)+SIGN*DEP3/GMLT
IC(NAC)=N1
140 CONTINUE
150 CONTINUE
160 CONTINUE
170 CONTINUE
C CONSTRAINS ON STIFFNESS.
N1=NCTOT
IF (K1IL,L1,1,3E-10) GO TO 180
C CONSTRAINT ON A11.
NCTOT=NCTOT+1
G1NC1OT=1.-AA11,1/A11L
180 IF (A22L,L1,1,3E-10) GO TO 190
C CONSTRAINT ON A22.
NCTOT=NCTOT+1
G1NC1OT=1.-AA(2,2)/A22L
190 IF (A2L,L1,1,3E-10) GO TO 200
C CONSTRAINT ON A66.
NCTOT=NCTOT+1
G1NC1OT=1.-AA13,3/A66L
200 IF (INFO.LT.4.OR.N1.LC.NCTOT) RETURN
IF (A11L,L1,1,3E-10) GO TO 230
N1=N1+1

```

25

COMPOSITE ANALYSIS AND DESIGN PROGRAM - COMMAND - CUMP4

JULY, 1974

```

C     IF (G(N1).LT.CTL) GO TO 230
      GRADIENT OF ACTIVE CONSTRAINT ON A11.
      NAC=NAC+1
      IF (NAC.EQ.NN3) RETURN
      IC(NAC)=N1
      DO 210 K=1,NDV
      A(NAC,K)=C.
      DO 220 KK=1,NPLY .
      K=LNK(KK)
      A(NAC,K)=A(NAC,K)-CP(1,1,KK)/A11
      230 IF (A22L.LT.1.0E-10) GO TO 260
      N1=N1+1
      IF (G(N1).LT.CTL) GO TO 260
      GRADIENT OF ACTIVE CONSTRAINT ON A22.
      NAC=NAC+1
      IF (NAC.EQ.NN3) RETURN
      IC(NAC)=N1
      DO 240 K=1,NDV
      A(NAC,K)=C.
      DO 250 KK=1,NPLY .
      K=LNK(KK)
      A(NAC,K)=A(NAC,K)-CP(2,2,KK)/A22L
      260 IF (A22L.LT.1.0E-10) RETURN
      N1=N1+1
      IF (G(N1).LT.CTL) GO TO 290
      GRADIENT OF ACTIVE CONSTRAINT ON A32.
      NAC=NAC+1
      IF (NAC.EQ.NN3) RETURN
      IC(NAC)=N1
      DO 270 K=1,NDV
      A(NAC,K)=C.
      DO 280 KK=1,NPLY .
      K=LNK(KK)
      A(NAC,K)=A(NAC,K)-LP(3,3,KK)/A32L
      290 CONTINUE
      RETURN
      END

```

References

1. Schmit, L.A., Jr., and Farshi, B.: Optimum Laminate Design for Strength and stiffness. Int. J. For Numerical Methods in Engineering, Vol. 7, No. 4, pp. 519-536, 1973.
2. Vanderplaats, Garret, N.: CONMIN - A FORTRAN Program for Constrained Function Minimization - User's Manual, NASA TM X-62,282, Aug. 1973.
3. Advanced Composites Design Guide, Volume I - Design, Wright-Patterson Air Force Base, Ohio, January 1973.

COMAND DATA ORGANIZATION:

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Block	Number of Cards	INFORMATION	FORMAT
A	1	Title - Anything may be given here	15A4
B	1	NCALC, NPLY, NDV, NLC, IPRINT	515
C	1	LNK(I), I=1, NPLY	1215
D	1-3	X(I), I=1, NDV	8F10.2
E	1-3	VLB(I), I=1, NDV (Blank card(s) if NCALC.NE.0)	8F10.2
F	1-3	THN(I), I=1, NPLY	8F10.2
G	1	EL, ET, GLT, PRLT	4F10.2
H	1	EPLC, EPLT, EPTC, EPTT, GMLT, A11L, A22L, A66L	8F10.2
I	NLC	PN(J, I), J=1, 3 (One card per loading condition)	3F10.2
		Begin with next set of data - Program terminates if 2 blank cards are read here.	

TABLE 1 - DATA ORGANIZATION

DATA SHEET

COMPOSITE ANALYSIS AND DESIGN PROGRAM - COMAND

TABLE 1 - DATA ORGANIZATION - CONCLUDED

JANUARY 1973

TABLE 1.2.1-III. KEY UNIDIRECTIONAL PROPERTIES

HIGH-STRENGTH GRAPHITE/EPOXY -[0] $V_f = 0.60$

				RT	350°F
Design strengths*	Longitudinal tensile ultimate	Ksi	F_L^{tu}	180.0	180.0
	Transverse tensile ultimate	Ksi	F_T^{tu}	8.0	4.0
	Longitudinal compression ultimate	Ksi	F_L^{cu}	180.0	70.0
	Transverse compression ultimate	Ksi	F_T^{cu}	30.0	12.0
	In-plane shear ultimate	Ksi	F_{LT}^{su}	12.0	6.8
	Interlaminar shear ultimate	Ksi	F_{isu}	13.0	8.0
	Ultimate longitudinal strain	$\mu\text{in.}/\text{in.}$	ϵ_L^{tu}	8,700.0	9,650.0
	Ultimate transverse strain	$\mu\text{in.}/\text{in.}$	ϵ_T^{tu}	4,750.0	4,100.0
Elastic properties [typical]	Longitudinal tension modulus	Msi	E_L^t	21.0	18.7
	Transverse tension modulus	Msi	E_T^t	1.7	0.87
	Longitudinal compression modulus	Msi	E_L^c	21.0	18.7
	Transverse compression modulus	Msi	E_T^c	1.7	0.87
	In-plane shear modulus	Msi	G_{LT}	0.65	0.32
	Longitudinal Poisson's ratio		ν_{LT}	0.21	0.21
	Transverse Poisson's ratio		ν_{TL}	0.017	0.010
Physical constants [typical]	Density	lb/in.^3	ρ	0.056	0.056
	Longitudinal coefficient of thermal expansion	$\mu\text{in.}/\text{in.}/{}^\circ\text{F}$	α_L	-0.21	-0.005
	Transverse coefficient of thermal expansion	$\mu\text{in.}/\text{in.}/{}^\circ\text{F}$	α_T	16.0	21.8

References: 1.2-15, -19, -21

*Typical Design Allowable, reference section 1.2.0

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DATA SHEET

COMPOSITE ANALYSIS AND DESIGN PROGRAM - COMAND

Col Block \	1	5	11	21	31	41	51	61	71
A	DETERMINATION OF LIMIT STRAINS - G/E COMPOSITE								
B	1	1	1	4	0				
C	1								
D	1.0								
E	0.								
F	0.								
G	21000000.	17000000.	650000.	.21					
H	0.	0.	0.	0.	0.	0.	0.	0.	
I	180000.	0.	0.						
	0.	-30000.	0.						
	0.	8000.	0.						
	0.	0.	12000.						

TABLE 3 - DETERMINATION OF LIMIT STRAINS - G/E COMPOSITE

DATA SHEET

COMPOSITE ANALYSIS AND DESIGN PROGRAM - COMAND

TABLE 4 - QUASI-ISOTROPIC COMPOSITE UNDER UNIAXIAL LOAD - EXAMPLE 1

DATA SHEET

COMPOSITE ANALYSIS AND DESIGN PROGRAM - COMAND

Col Block \	1	5	11	21	31	41	51	61	71
A	(0, 45, -45, 90) GRAPHITE EPOXY COMPOSITE - EXAMPLE 2								
B	0	4	3	4	0				
C	1	2	2	3					
D	.1		.1		.1				
E	.00001		.00001		.00001				
F	0.		45.		-45.		90.		
G	21000000.	17000000.	650000.		.21				
H	-.00857	.00857	-.0176	.00471	.0184	500000.	0.	0.	
I	20000.	0.	0.						
	15000.	-15000.	5000.						
	-15000.	10000.	10000.						
	0.	0.	20000.						

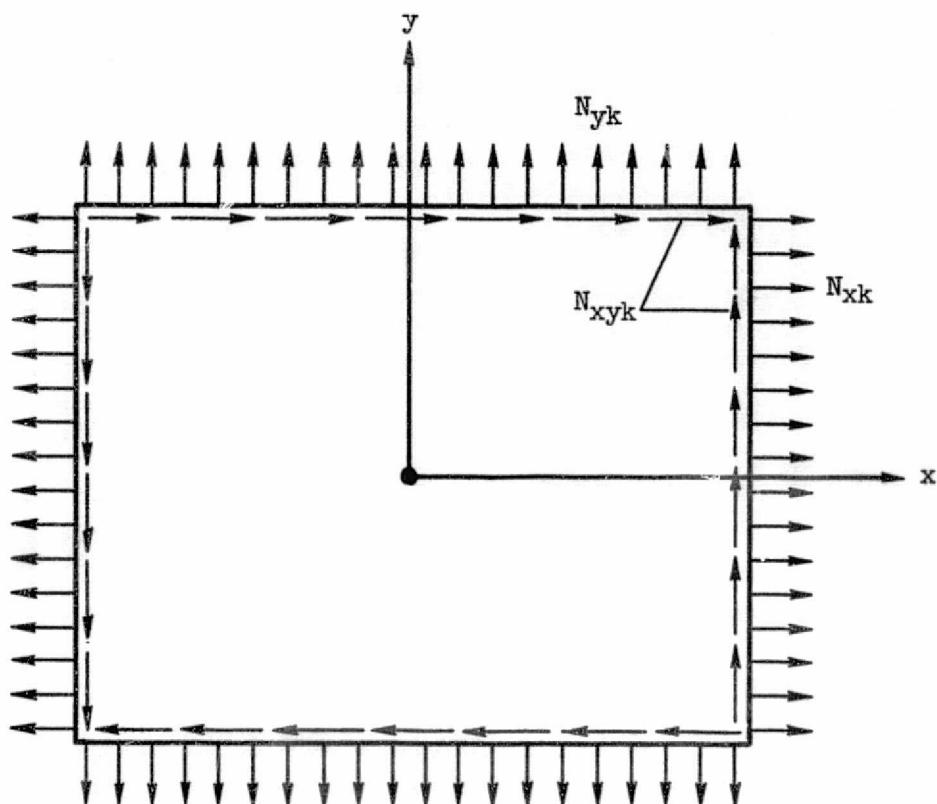
TABLE 5 - (0, ±45, 90) GRAPHITE EPOXY COMPOSITE - EXAMPLE 2

DATA SHEET

COMPOSITE ANALYSIS AND DESIGN PROGRAM - COMAND

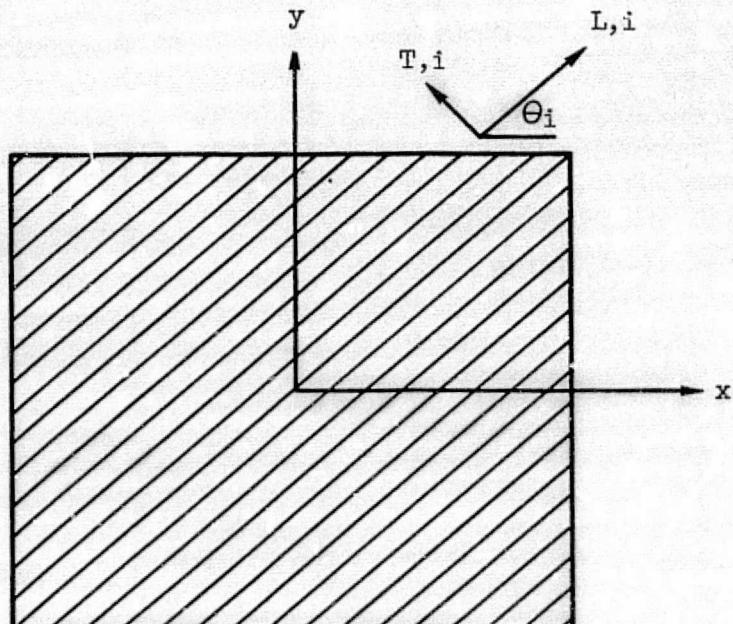
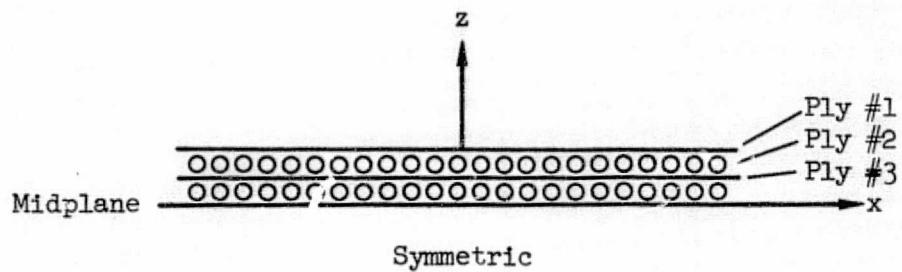
Col Block \	1	5	11	21	31	41	51	61	71
A	(0, 30, -30, 60, -60, 90) GRAPHITE EPOXY COMPOSITE - EXAMPLE 3								
B	0	6	4	4	0				
C	1	2	2	3	3	4			
D	.1		.1		.1				
E	.00001	.00001	.00001	.00001					
F	0.	30.	-30.	60.	-60.	90.			
G	21000000.	17000000.	650000.	.21					
H	-.00857	.00857	-.0176	.00471	.0184	500000.	0.	0.	
I	20000.	0.	0.						
	15000.	-15000.	5000.						
	-15000.	10000.	10000.						
	0.	0.	20000.						

TABLE 6 - (6, ±30, ±60, 90) GRAPHITE EPOXY COMPOSITE - EXAMPLE 3



Inplane loads N_x , N_y , N_{xy}
Load condition k.

Figure 1.- Typical composite loading.

Ply orientation, θ_i 

Symmetric composite layup

Figure 2.- Typical ply orientation.

ANALYSIS

DESIGN AND/OR ANALYSIS RESULTS

OF

SYMMETRIC COMPOSITE PANEL

TITLE
DETERMINATION OF LIMIT STRAINS - G/E COMPOSITENO. OF PLYS = 1
NO. OF LOAD CONDITIONS = 4

PLY PROPERTIES = ALL PLYS IDENTICAL
 LONGITUDINAL MODULUS = .21000E+06
 TRANSVERSE MODULUS = .17000E+07
 SHEAR MODULUS = .65000E+05
 POISSON'S RATIO, L-T = .21000E+00
 POISSON'S R-T, T-L = .17000E-01

PLY THICKNESSES, ORIENTATIONS, AND DESIGN VARIABLE NUMBERS
 PLY NO. THICKNESS THETA DEF. VAR. NO.
 1 .10000E+01 0.00 1

PLY STRAIN LIMITS
 LONGITUDINAL STRAIN, LGE = 0. AND, LE = 0.
 TRANSVERSE STRAIN, LGE = 0. AND, LE = 0.
 SHEAR STRAIN, LGE = 0. AND, LE = 0.

STIFFNESS LIMITS
 411, GE = 0.
 422, GE = 0.
 446, GE = 0.
 LOAD COND. LOADS
 1 .18000E+05 NY NY
 2 0. -30000E+05 0.
 3 0. 8000E+04 0.
 4 0. 0. 12000E+05

TITLE
DETERMINATION OF LIMIT STRAINS - G/E COMPOSITE

PLY NO.	THICKNESS	PERCENT
1	.10000E+01	100.00
	THICKNESS = .10000E+01	100.00

PLY STRAINS
 SF = SAFETY FACTOR
 EPL = LONGITUDINAL STRAIN
 EPT = TRANSVERSE STRAIN
 EP LT = SHEAR STRAIN

LOAD COND. 1
 PLY NO. EPL S,F. EPT S,F. EPL S,F.
 1 .85714E-03 0.000 .18000E-03 0.000 .10000E-19 0.000

COMPOSITE STRAINS REFERENCED TO STRUCTURAL AXIS
 EPX = .85714E-03 EPY = .18A00E-03 EPXY = 0.

LOAD COND. 2
 PLY NO. EPL S,F. EPT S,F. EPL S,F.
 1 .30000E-03 0.000 .17647E-01 0.000 .10000E-19 0.000

COMPOSITE STRAINS REFERENCED TO STRUCTURAL AXIS
 EPX = .30000E-03 EPY = .17A47E-01 EPXY = 0.

LOAD COND. 3
 PLY NO. EPL S,F. EPT S,F. EPL S,F.
 1 .80000E-04 0.000 .47059E-02 0.000 .10000E-19 0.000

COMPOSITE STRAINS REFERENCED TO STRUCTURAL AXIS
 EPX = .80000E-04 EPY = .47A59E-02 EPXY = 0.

LOAD COND. 4
 PLY NO. EPL S,F. EPT S,F. EPL S,F.
 1 .10000E-19 0.000 .10000E-19 0.000 .18462E-01 0.000

COMPOSITE STRAINS REFERENCED TO STRUCTURAL AXIS
 EPX = 0. EPY = 0. EPXY = .18462E-01

MEMBRANE STRESSES IN COMPOSITE
 LOAD COND. SIGMAX SIGMAY TAU=XY
 1 .18000E+05 0. 0.
 2 0. -.30000E+05 0.
 3 0. .80000E+04 0.
 4 0. 0. .12000E+05

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Figure 3.- Determination of limit strains - G/E composite.

PLY PROPERTIES: MECHANICAL STIFFNESSES
 ACTUAL REQUIRED
 VALUE VALUE S.F.
 C11 = .21075E+08 0. 100.00
 C22 = .17061E+07 0. 100.00
 S11 = .65000E+08 0. 100.00

COEFFICIENTS OF STRESS-STRAIN RELATIONSHIPS
 RELATED TO STRUCTURAL AXES
 C11 = .21075E+08 C12 = .35428E+06 C16 = 0.
 C22 = .17061E+07 C26 = 0.
 S11 = .65000E+08 C66 = .65000E+08

COEFFICIENTS OF STRAIN-STRESS RELATIONSHIPS
 RELATED TO STRUCTURAL AXES
 D11 = .076149E+07 D12 = .10000E+07 D16 = 0.
 D22 = .58824E+06 D26 = 0.
 SYMMETRIC D66 = .15385E+05

COMPOSITE ELASTIC CONSTANTS
 Fx = .21000E+09 Sy = .17000E+07 Gxy = .65000E+08
 Gxy = .21000E+09 Gyx = .17000E+01

Figure 3.- Concluded.

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DESIGN

OF

SYMMETRIC COMPOSITE PANEL

TITLE
QUASI-ISOTROPIC COMPOSITE UNDER UNIAXIAL LOAD - EXAMPLE 1

NO. OF PLYS = 12
NO. OF LOAD CONDITIONS = 1

PLY PROPERTIES = ALL PLYS IDENTICAL
LONGITUDINAL MODULUS = .21000E+08
TRANSVERSE MODULUS = .17000E+07
SHEAR MODULUS = .65000E+06
POISSON'S RATIO, L-T = .21000E+00
POISSON'S RATIO, T-L = .17000E-01

PLY THICKNESSES, ORIENTATIONS, AND DESIGN VARIABLE NUMBERS

PLY NO.	THICKNESS	THETA	DES. VAR. NO.
1	.50000E-01	0.00	1
2	.50000E-01	15.00	1
3	.50000E-01	-15.00	1
4	.50000E-01	30.00	1
5	.50000E-01	-30.00	1
6	.50000E-01	45.00	1
7	.50000E-01	-45.00	1
8	.50000E-01	60.00	1
9	.50000E-01	-60.00	1
10	.50000E-01	75.00	1
11	.50000E-01	-75.00	1
12	.50000E-01	90.00	1

PLY STRAIN LIMITS
LONGITUDINAL STRAIN,LE, = .85700E+02 AND,LE, = .85700E+02
TRANSVERSE STRAIN,LE, = .17600E+01 AND,LE, = .47100E+02
SHEAR STRAIN,LE, = .18400E+01 AND,LE, = .18400E+01

STIFFNESS LIMITS
411,LT, 0.
422,LT, 0.
466,LT, 0.

LOADS

LOAD CNDN.	UX	UY	UXX
1	.20000E+05	0.	0.

Figure 4.- Quasi-isotropic G/E composite under uniaxial load - Example 1.

```

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*          C O U N T N
*          F O R T R A N P R O G R A M F O R
*          C O N S T R A I N E D F U N C T I O N M I N I M I Z A T I O N
*          N A S A / J A M E S R E S E A R C H F E N T E R , H O F F E T T F I E L D , C A L I F .
*          V E R S I O N 1.1      J U L Y , 1 9 7 5
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

```

CONSTRAINED FUNCTION MINIMIZATION

CONTROL PARAMETERS

IPRINT	NOV	ITMAX	NCON	NSIDE	ICNDIR	NSCAL	NFDG
2	1	30	60	1	2	0	0

LINORJ ITRN

1 3

CT	PTMIN	RTL	R/LMIN
.+10000F+00	.+40000F-02	.+10000E+01	.+10000E-02

THETA	BHI	DEFUN	DABFUN
.+10000F+01	.+50000E+01	.+10000F-03	.+60000E-03

FDFM	FUPH
.+10000F+01	.+10000E-01

LOWER BOUNDS ON DECISION VARIABLES (VLR)

1) .+10000F-04

UPPER BOUNDS ON DECISION VARIABLES (VUR)

1) .+10000E+05

ALL CONSTRAINTS ARE NONNEGATIVE

INITIAL FUNCTION INFORMATION

OBJ = .+600000F+00

DECISION VARIABLES (X=VECTOR)

1) .+50000E+01

CONSTRAINT VALUES (G=VECTOR)

1) .+14809F+01	.+51908E+00	.+92703E+00	.+12727E+01	.+10000E+01	.+14187E+01
7) .+56134E+00	.+94760F+00	.+11958E+01	.+85310E+00	.+14387E+01	.+56134E+00
13) .+6476nF+00	.+11958E+01	.+A5310E+00	.+13232E+01	.+67678E+00	.+10038E+01
19) .+98575E+00	.+74557E+00	.+13232E+01	.+67678E+00	.+10038E+01	.+98575E+00
25) .+74557E+00	.+11655E+01	.+A3447E+00	.+10806E+01	.+69882E+00	.+70621E+00
31) .+11655E+01	.+A3447E+00	.+10806E+01	.+69882E+00	.+70621E+00	.+10076E+01
37) .+99217E+00	.+11574F+01	.+41188E+00	.+74557E+00	.+10078E+01	.+99217E+00
43) .+11574F+01	.+41188F+00	.+74557E+00	.+89239E+00	.+11076E+01	.+12136E+01
49) .+20180F+00	.+85310F+00	.+89239F+00	.+11076E+01	.+12136E+01	.+20184E+00
55) .+85310F+00	.+85310F+00	.+11499E+01	.+12342E+01	.+12495E+00	.+10000E+01

ITER # 1 OBJ = .+525aaf100

DECISION VARIABLES (X=VECTOR)

1) .+3753E+01

CONSTRAINT VALUES (G=VECTOR)

1) .+15496E+01	.+45042E+00	.+91661E+00	.+13116E+01	.+10000E+01	.+15013E+01
7) .+49870E+00	.+94012E+00	.+12238E+01	.+83213E+00	.+15013E+01	.+49870E+00
13) .+94012E+00	.+12238E+01	.+83213E+00	.+13694E+01	.+63063E+00	.+10044E+01
19) .+98572E+00	.+70924E+00	.+13694E+01	.+83036E+00	.+10044E+01	.+98372E+00
25) .+70924E+00	.+11892E+01	.+81084E+00	.+10921E+01	.+65582E+00	.+66426E+00
31) .+11892E+01	.+81084E+00	.+10921E+01	.+65582E+00	.+66426E+00	.+10089E+01
37) .+99105E+00	.+11799E+01	.+32791E+00	.+70924E+00	.+10089E+01	.+99105E+00
43) .+11799E+01	.+32791E+00	.+70924E+00	.+87703E+00	.+11230E+01	.+12441E+01
49) .+8775E+01	.+83213E+00	.+87703E+00	.+11230E+01	.+12441E+01	.+8775E+01
55) .+83213E+00	.+82874E+00	.+11713E+01	.+12676E+01	.+14203E+04	.+10000E+01

ITER # 2 OBJ = .+525a04E100 NO CHANGE IN OBJ

DECISION VARIABLES (X=VECTOR)

1) .+3753F+01

CONSTRAINT VALUES (G=VECTOR)

1) .+15496E+01	.+45042E+00	.+91661E+00	.+13116E+01	.+10000E+01	.+15013E+01
7) .+49870E+00	.+94012E+00	.+12238E+01	.+83213E+00	.+15013E+01	.+49870E+00
13) .+94012E+00	.+12238E+01	.+83213E+00	.+13694E+01	.+63063E+00	.+10044E+01
19) .+98572E+00	.+70924E+00	.+13694E+01	.+83036E+00	.+10044E+01	.+98372E+00
25) .+70924E+00	.+11892E+01	.+81084E+00	.+10921E+01	.+65582E+00	.+66426E+00
31) .+11892E+01	.+81084E+00	.+10921E+01	.+65582E+00	.+66426E+00	.+10089E+01
37) .+99105E+00	.+11799E+01	.+32791E+00	.+70924E+00	.+10089E+01	.+99105E+00
43) .+11799E+01	.+32791E+00	.+70924E+00	.+87703E+00	.+11230E+01	.+12441E+01
49) .+8775E+01	.+83213E+00	.+87703E+00	.+11230E+01	.+12441E+01	.+8775E+01
55) .+83213E+00	.+82874E+00	.+11713E+01	.+12676E+01	.+14203E+04	.+10000E+01

ITER # 3 OBJ = .+525a04E100 NO CHANGE IN OBJ

DECISION VARIABLES (X=VECTOR)

1) .+3753E+01

CONSTRAINT VALUES (G=VECTOR)

1) .+15496E+01	.+45042E+00	.+91661E+00	.+13116E+01	.+10000E+01	.+15013E+01
7) .+49870E+00	.+94012E+00	.+12238E+01	.+83213E+00	.+15013E+01	.+49870E+00
13) .+94012E+00	.+12238E+01	.+83213E+00	.+13694E+01	.+63063E+00	.+10044E+01
19) .+98572E+00	.+70924E+00	.+13694E+01	.+83036E+00	.+10044E+01	.+98372E+00
25) .+70924E+00	.+11892E+01	.+81084E+00	.+10921E+01	.+65582E+00	.+66426E+00
31) .+11892E+01	.+81084E+00	.+10921E+01	.+65582E+00	.+66426E+00	.+10089E+01
37) .+99105E+00	.+11799E+01	.+32791E+00	.+70924E+00	.+10089E+01	.+99105E+00
43) .+11799E+01	.+32791E+00	.+70924E+00	.+87703E+00	.+11230E+01	.+12441E+01
49) .+8775E+01	.+83213E+00	.+87703E+00	.+11230E+01	.+12441E+01	.+8775E+01
55) .+83213E+00	.+82874E+00	.+11713E+01	.+12676E+01	.+14203E+04	.+10000E+01

Figure 4.- Continued.

ITER # 0 OBJ # .52504F100 NO CHANGE IN OBJ

DECISION VARIABLES (X=VECTOR)

1) .03753E+01

CONSTRAINT VALUES (G=VECTOR)

1)	-.15496E+01	-.45042E+00	-.91661E+00	-.15110E+01	-.14000E+01	-.15013E+01
7)	-.49870E+00	-.94012E+00	-.12238E+01	-.81213E+00	-.15013E+01	-.49870E+00
13)	-.94012E+00	-.12238E+01	-.81213E+00	-.15013E+01	-.63063E+00	-.10044E+01
19)	-.96372E+00	-.70924E+00	-.13694E+01	-.63063E+00	-.10044E+01	-.98372E+00
25)	-.70924E+00	-.11892E+01	-.81084E+00	-.10921E+01	-.65582E+00	-.66426E+00
31)	-.11892E+01	-.81084E+00	-.10921E+01	-.65582E+00	-.10089E+01	-.10089E+01
37)	-.99105E+00	-.11799E+01	-.32791E+00	-.70924E+00	-.10089E+01	-.99105E+00
43)	-.11799E+01	-.32791E+00	-.70924E+00	-.87703E+00	-.11230E+01	-.12541E+01
49)	-.87875E+01	-.83213E+00	-.87703E+00	-.11230E+01	-.12441E+01	-.87875E+01
55)	-.83213E+00	-.82874E+00	-.11713E+01	-.12678E+01	-.14203E+04	-.10000E+01

FINAL OPTIMIZATION INFORMATION

OBJ # .525036E+00

DECISION VARIABLES (X=VECTOR)

1) .03753E+01

CONSTRAINT VALUES (G=VECTOR)

1)	-.15496E+01	-.45042E+00	-.91661E+00	-.13116E+01	-.10000E+01	-.15013E+01
7)	-.49870E+00	-.94012E+00	-.12238E+01	-.81213E+00	-.15013E+01	-.49870E+00
13)	-.94012E+00	-.12238E+01	-.81213E+00	-.15013E+01	-.63063E+00	-.10044E+01
19)	-.98372E+00	-.70924E+00	-.13694E+01	-.63063E+00	-.10044E+01	-.98372E+00
25)	-.70924E+00	-.11892E+01	-.81084E+00	-.10921E+01	-.65582E+00	-.66426E+00
31)	-.11892E+01	-.81084E+00	-.10921E+01	-.65582E+00	-.10089E+01	-.10089E+01
37)	-.99105E+00	-.11799E+01	-.32791E+00	-.70924E+00	-.10089E+01	-.99105E+00
43)	-.11799E+01	-.32791E+00	-.70924E+00	-.87703E+00	-.11230E+01	-.12441E+01
49)	-.87875E+01	-.83213E+00	-.87703E+00	-.11230E+01	-.12441E+01	-.87875E+01
55)	-.83213E+00	-.82874E+00	-.11713E+01	-.12678E+01	-.14203E+04	-.10000E+01

THERE ARE 1 ACTIVE CONSTRAINTS

CONSTRAINT NUMBERS ARE

59

THERE ARE 0 VIOLATED CONSTRAINTS

THERE ARE 0 ACTIVE SIDE CONSTRAINTS

TERMINATION CRITERION

ABS(1-OBJ(I-1)/OBJ(I)) LESS THAN DELFUN FOR 5 ITERATIONS
ABS(OBJ(I)-OBJ(I-1)) LESS THAN DABFUN FOR 5 ITERATIONS

NUMBER OF ITERATIONS = 4

OBJECTIVE FUNCTION WAS EVALUATED 5 TIMES

CONSTRAINT FUNCTIONS WERE EVALUATED 5 TIMES

GRADIENT OF OBJECTIVE WAS CALCULATED 2 TIMES

GRADIENTS OF CONSTRAINTS WERE CALCULATED 2 TIMES

Figure 4.- Continued.

DESIGN AND/OR ANALYSIS RESULTS

TITLE
QUASI-ANISOTROPIC COMPOSITE UNDER UNIAXIAL LOAD - EXAMPLE 1

PLY INFORMATION		
PLY NO.	THICKNESS	PERCENT
1	.03753E-01	8.33
2	.03744E-01	8.33
3	.03753E-01	8.33
4	.03753E-01	8.33
5	.03753E-01	8.33
6	.03753E-01	8.33
7	.03753E-01	8.33
8	.03753E-01	8.33
9	.03753E-01	8.33
10	.03753E-01	8.33
11	.03753E-01	8.33
12	.03753E-01	8.33

THICKNESS = .62500E+00 100.00

PLY STRAINS
 S_{FL} = SAFETY FACTOR
 EPL = LONGITUDINAL STRAIN
 FPT = TRANSVERSE STRAIN
 $FOLT$ = SHEAR STRAIN

PLY NO.	EPL	S.F.	FPT	S.F.	EPL	S.F.
1	.47099E-02	1.820	.14577E-02	11.991	.74777E-10	100.000
2	.42961E-02	1.995	.10539E-02	16.700	.10888E-02	5.957
3	.42961E-02	1.995	.10539E-02	16.700	.10888E-02	5.957
4	.51655E-02	2.707	.76849E-04	61.412	.53500E-02	3.439
5	.51655E-02	2.707	.76849E-04	61.413	.53500E-02	3.439
6	.16211E-02	5.287	.16211E-02	2.905	.61777E-02	2.978
7	.16211E-02	5.287	.16211E-02	2.905	.61777E-02	2.978
8	.76694E-04	100.000	.31655E-02	1.488	.53500E-02	3.439
9	.76694E-04	100.000	.31655E-02	1.488	.53500E-02	3.439
10	.105539E-02	8.132	.42961E-02	1.096	.10888E-02	5.957
11	.105539E-02	8.132	.42961E-02	1.096	.10888E-02	5.957
12	.14677E-02	5.819	.47799E-02	1.000	.12648E-08	100.000

COMPOSITE STRAINS REFERENCED TO STRUCTURAL AXIS
 $\text{EPX} = .47099E-02 \quad \text{EPY} = .14577E-02 \quad \text{FPXY} = .74777E-10$

MEMBRANE STRESSES IN COMPOSITE
LOAD Cond. SIGMAX SIGMAY TAU_{XY}
1 38000E+05 0. 0.

COMPOSITE MEMBRANE STIFFNESSES

ACTUAL	REFGIREN
VALUE	VALUE
A11 = .47030E+07	0.
A22 = .47031E+07	0.
A66 = .16187E+07	0.

COEFFICIENTS OF STRESS-STRAIN RELATIONSHIPS
RELATED TO STRUCTURAL AXES

C11 = .89576E+07	C12 = .27914E+07	C16 = .38574E+03
C22 = .89576E+07	C26 = .15584E+00	C66 = .30831E+07

COEFFICIENTS OF STRAIN-STRESS RELATIONSHIPS
RELATED TO STRUCTURAL AXES

G11 = .12384E-04	G12 = .38530E-07	G16 = .19830E-14
G22 = .12384E-04	G26 = .62547E-14	G66 = .32435E-08

COMPOSITE ELASTIC CONSTANTS
 $E_X = .80877E+07 \quad F_Y = .80877E+07 \quad G_{XY} = .50831E+07$
 $N_{UXY} = .31162E+00 \quad N_{UYX} = .31162E+00$

Figure 4.- Concluded.

DESIGN

OF

SYMMETRIC COMPOSITE PANEL

TITLE
 $0, +45, -45, 90$ GRAPHITE EPOXY COMPOSITE - EXAMPLE 2

NO. OF PLYS = 4
NO. OF LOAD CONDITIONS = 4

PLY PROPERTIES - ALL PLYS IDENTICAL
LONGITUDINAL MODULUS = .21000E+08
TRANSVERSE MODULUS = .17000E+07
SHEAR MODULUS = .65000E+06
POISSON'S RATIO, L=T = .21000E+00
POISSON'S RATIO, T=L = .17000E+01

PLY THICKNESSES, ORIENTATIONS, AND DESIGN VARIABLE NUMBERS
PLY NO. THICKNESS THETA DES. VAR. NO.
1 .10000E+00 0.00 1
2 .10000E+00 45.00 2
3 .10000E+00 -45.00 2
4 .10000E+00 90.00 3

PLY STRAIN LIMITS
LONGITUDINAL STRAIN,RE = .85700E-02 ,AND,LE = .85700E-02
TRANSVERSE STRAIN,RE = .17600E-01 ,AND,LE = .47100E-02
SHEAR STRAIN,RE = .18000E-01 ,AND,LE = .18400E-01

STIFFNESS LIMITS
A11,CE = .50000E+06
A22,CE = 0.
A66,CE = 0.
LOADS
LOAD Cond. NX NY ZY
1 .20000E+05 0. 0.
2 .15000E+05 -.15000E+05 .50000E+04
3 .15000E+05 .15000E+05 .10000E+05
4 0. 0. .20000E+05

Figure 5.- (0, ± 45 , 90) Graphite epoxy composite - Example 2.

DESIGN AND/OR ANALYSIS RESULTS

TITLE
0°, 45°, -45°, 90° GRAPHITE EPOXY COMPOSITE - EXAMPLE 2

PLY INFORMATION

PLY NO.	THICKNESS	PENSITY
1	.15936E+00	27.56
2	.10149E+00	31.16
3	.10149E+00	31.16
4	.48507E+01	10.12
THICKNESS =		100.00

PLY STRAINS
 ϵ_{F} = SAFETY FACTOR
 ϵ_{PL} = LONGITUDINAL STRAIN
 ϵ_{PT} = TRANSVERSE STRAIN
 ϵ_{SPL} = SHEAR STRAIN

PLY NO.	LOAD COND.	$S_x F_s$	ϵ_{PT}	$S_y F_s$	ϵ_{PL}	$S_z F_s$
1	.41561E+02	.2,082	.21131E+02	.0,329	.10912E+04	100,000
2	.10215E+02	.0,390	.10215E+02	.0,611	.02692E+02	2,935
3	.10215E+02	.0,390	.10215E+02	.0,611	.02692E+02	2,935
4	.21131E+02	.0,056	.41561E+02	.1,153	.15167E+00	100,000

COMPOSITE STRAINS REFERENCED TO STRUCTURAL AXIS
 $\epsilon_{\text{Fx}} = .41561E+02$ $\epsilon_{\text{Fy}} = -.21131E+02$ $\epsilon_{\text{Fxy}} = .10912E+04$

PLY NO.	LOAD COND.	$S_x F_s$	ϵ_{PT}	$S_y F_s$	ϵ_{PL}	$S_z F_s$
1	.47014E+02	1,823	.62811E+02	2,802	.23485E+02	7,835
2	.35646E+03	22,280	.19638E+02	0,962	.10983E+01	1,075
3	.19638E+02	0,364	.35646E+03	12,245	.10983E+01	1,075
4	.62811E+02	1,824	.47014E+02	1,002	.23485E+02	7,835

COMPOSITE STRAINS REFERENCED TO STRUCTURAL AXIS
 $\epsilon_{\text{Fx}} = .47014E+02$ $\epsilon_{\text{Fy}} = -.62811E+02$ $\epsilon_{\text{Fxy}} = .23485E+02$

PLY NO.	LOAD COND.	$S_x F_s$	ϵ_{PT}	$S_y F_s$	ϵ_{PL}	$S_z F_s$
1	.41730E+02	2,053	.47157E+02	0,900	.46970E+02	3,917
2	.26105E+02	3,272	.20777E+02	0,672	.08893E+02	4,070
3	.20777E+02	3,175	.26105E+02	1,708	.08893E+02	4,070
4	.47157E+02	1,917	.41730E+02	4,217	.46970E+02	3,917

COMPOSITE STRAINS REFERENCED TO STRUCTURAL AXIS
 $\epsilon_{\text{Fx}} = .41730E+02$ $\epsilon_{\text{Fy}} = .47157E+02$ $\epsilon_{\text{Fxy}} = .46970E+02$

PLY NO.	LOAD COND.	$S_x F_s$	ϵ_{PT}	$S_y F_s$	ϵ_{PL}	$S_z F_s$
1	.10912E+09	100,000	.12206E+09	100,000	.43939E+02	1,959
2	.46970E+02	1,825	.46970E+02	0,747	.47357E+09	100,000
3	.46970E+02	1,825	.46970E+02	1,003	.13359E+08	100,000
4	.58270E+09	100,000	.79564E+09	100,000	.43939E+02	1,959

COMPOSITE STRAINS REFERENCED TO STRUCTURAL AXIS
 $\epsilon_{\text{Fx}} = .10912E+09$ $\epsilon_{\text{Fy}} = .32206E+09$ $\epsilon_{\text{Fxy}} = .43939E+02$

MEMBRANE STRESSES IN COMPOSITE

LOAD COND.	$\sigma_{\text{Mx}=y}$	$\sigma_{\text{My}=y}$	$\tau_{\text{xy}=xy}$
1	.34503E+05	0,	0,
2	.25905E+05	.25905E+05	.86482E+08
3	.25905E+05	.17296E+05	.17296E+05
4	0,	0,	.34593E+05

COMPOSITE MEMBRANE STIFFNESSES

ACTUAL VALUE	REQUIRED VALUE	S_{F}
A11 .58090E+07	.50000E+06	11.62
A22 .34558E+07	0,	100,00
A66 .21290E+07	0,	100,00

COEFFICIENTS OF STRESS-STRAIN RELATIONSHIPS

RELATED TO STRUCTURAL AXES

C11 = .10n48E+08	C12 = .33908E+07	C16 = .46600E+03
C22 = .65689E+07	C26 = .18925E+00	C66 = .36825E+07

SYMMETRIC

COEFFICIENTS OF STRAIN-STRESS RELATIONSHIPS

RELATED TO STRUCTURAL AXES

Q11 = .12n14E+06	Q12 = .61088E+07	Q16 = .31545E+14
------------------	------------------	------------------

SYMMETRIC

COMPOSITE ELASTIC CONSTANTS

$E_x = .83235E+07$	$E_y = .55246E+07$	$G_{xy} = .36825E+07$
--------------------	--------------------	-----------------------

$\nu_{xy} = .50n45E+00$ $\nu_{yyx} = .33747E+00$

Figure 5.- Concluded.

DESIGN

DESIGN AND/OR ANALYSIS RESULTS

TITLE
0, 30, -30, 60, -60, 90 GRAPHITE EPOXY COMPOSITE - EX. 3

SYMMETRIC COMPOSITE PANEL

TITLE
0, 30, -30, 60, -60, 90 GRAPHITE EPOXY COMPOSITE - EX. 3

NO. OF PLYS = 6
NO. OF LOAD CONDITIONS = 4

PLY PROPERTIES - ALL PLYS IDENTICAL
LONGITUDINAL MODULUS = 21000E+08
TRANSVERSE MODULUS = 17000E+07
SHEAR MODULUS = 65000E+06
POISSON'S RATIO, L-T = 0.2000E+00
POISSON'S RATIO, T-L = 0.17000E+01

PLY THICKNESSES, THICKNESS, AND DESIGN VARIABLE NUMBERS
PLY NO. THICKNESS THETA DTS, VAE, NO.
1 .1000E+00 0.00 1
2 .1000E+00 30.00 2
3 .1000E+00 -30.00 2
4 .1000E+00 60.00 3
5 .1000E+00 -60.00 3
6 .1000E+00 90.00 4

PLY STRAIN LIMITS
LONGITUDINAL STRAIN, SF = .85700E-02 AND, LE = .85700E+02
TRANSVERSE STRAIN, SF = .17400E-01 AND, LE = .47100E+02
SHEAR STRAIN, SF = .18400E-01 AND, LE = .18400E+01

STIFFNESS LIMITS
SF, LE = .5000E+06
SF, SF = 0.
SF, LE = 0.

LOADS

LOAD COND.	X	Y	Z
1	.2000E+05	0.	0.
2	.1500E+05	.1500E+05	.5000E+04
3	.1500E+05	.1000E+05	.1000E+05
4	0.	0.	.2000E+05

PLY INFORMATION

PLY NO.	THICKNESS	PERCENT
1	.1136E+00	21.35
2	.91215E-01	17.13
3	.91215E-01	17.13
4	.1132E+00	21.28
5	.1132E+00	21.28
6	.97205E-02	1.81

THICKNESS = .63239E+00 100.00

PLY STRAINS

S_F = SAFETY FACTOR
EPL = LONGITUDINAL STRAIN
EPT = TRANSVERSE STRAIN
EPLT = SHEAR STRAIN

PLY NO.	EPL	S _F	EPT	S _F	EPLT	S _F
1	.45339E+02	1.977	.19309E-02	9.115	.19195E+10	100.000
2	.27677E+02	3.094	.38648E+03	48.242	.54255E+02	3.391
3	.27677E+02	3.094	.38648E+03	48.242	.54255E+02	3.391
4	.35648E+03	23.500	.27677E+02	1.702	.54255E+02	3.391
5	.35648E+03	23.500	.27677E+02	1.702	.54255E+02	3.391
6	.19350E+02	0.438	.43339E+02	1.047	.12260E+08	100.000

COMPOSITE STRAINS REFERENCED TO STRUCTURAL AXIS
EPX = .45339E+02 EPY = .19309E+02 EPZ = .19195E+10

PLY NO.	EPL	S _F	EPT	S _F	EPLT	S _F
1	.46986E+02	1.824	.60633E+02	2.903	.27193E+02	5.766
2	.31856E+02	2.690	.45503E+02	3.868	.79404E+02	2.311
3	.83061E+03	10.318	.21953E+02	8.017	.10680E+01	1.723
4	.21953E+02	3.904	.83062E+03	5.670	.10680E+01	1.723
5	.45553E+02	1.585	.51856E+02	1.079	.79404E+02	2.311
6	.60633E+02	1.413	.46886E+02	1.002	.27193E+02	5.766

COMPOSITE STRAINS REFERENCED TO STRUCTURAL AXIS
EPX = .46986E+02 EPY = .60633E+02 EPZ = .27193E+02

PLY NO.	EPL	S _F	EPT	S _F	EPLT	S _F
1	.42159E+02	2.033	.45240E+02	1.001	.54386E+02	5.383
2	.32433E+03	26.423	.15298E+04	100.000	.10289E+01	1.788
3	.43857E+02	1.950	.46947E+02	1.003	.48504E+02	3.794
4	.46947E+02	1.824	.41857E+02	8.013	.48504E+02	3.794
5	.15297E+04	100.000	.32433E+03	14.522	.10289E+01	1.788
6	.85249E+02	1.894	.42159E+02	1.175	.54386E+02	5.383

Figure 6.- (0, ±30, ±60, 90) Graphite epoxy composite - Example 3.

COMPOSITE STRAINS REFERENCED TO STRUCTURAL AXIS
 $F_{Px} = +1.02150F=02$ $E_{Py} = -1.45209F=02$ $F_{PyX} = +1.44366E=02$

PLANE NO.	LOAD COMB. # 4				$S_x F_x$
	F_{Px}	$S_y F_x$	F_{Py}	$S_y F_x$	
1	+1.19195F=10	100,000	+60804E=10	100,000	+10877E=01
2	+07100F=02	1,820	+47100E=02	3,717	+54366E=02
3	+07100F=02	1,820	+47100E=02	1,000	+54366E=02
4	+07100F=02	1,820	+47100F=02	3,717	+54367E=02
5	+07100F=02	1,820	+47100F=02	1,000	+54367E=02
6	+98674F=09	100,000	+10294F=08	100,000	+10877E=01

COMPOSITE STRAINS REFERENCED TO STRUCTURAL AXIS
 $F_{Px} = +1.19195F=10$ $E_{Py} = -1.6484E=10$ $F_{PyX} = +1.0877E=01$

LOAD COMB.	MEMBRANE STRESSES IN COMPOSITE		
	$SIGMA_{xxy}$	$SIGMA_{yyx}$	TAU_{xy}
1	+3747E+05	0	0
2	+2R175E+05	+28175E+05	+93917E+04
3	+2R175E+05	+1R7A3E+05	+1R783E+05
4	0	0	+375b7E+05

COMPOSITE MEMBRANE STIFFNESSES

ACTUAL	REQUIRED	
	V_{1111F}	V_{1111F}
A11	+53648F+07	+50000F+00
A22	+37784E+07	0
A44	+1R5A7E+07	0
		100,00

COEFFICIENTS OF STRESS-STRAIN RELATIONSHIPS

RELATED TO STRUCTURAL AXES

C11 = +10077E+04	C12 = +31620E+07	C16 = +84078E+04
	C22 = +70971E+07	C26 = +34145E+01
SYMMETRIC		
		C66 = +34537E+07

COEFFICIENTS OF STRAIN-STRESS RELATIONSHIPS

RELATED TO STRUCTURAL AXES

C11 = +11537E+06	C12 = +41594E+07	C16 = +51096E+15
	C22 = +16380E+06	C26 = +1R207E+14
SYMMETRIC		
		C66 = +28955E+06

COMPOSITE ELASTIC CONSTANTS					
F_x	E_y	G_{xy}	E_z	G_{yz}	G_{xz}
+86681E+07	+61094E+07	+54557E+07			
+04653E+00	+31378E+00				

Figure 6.- Concluded.

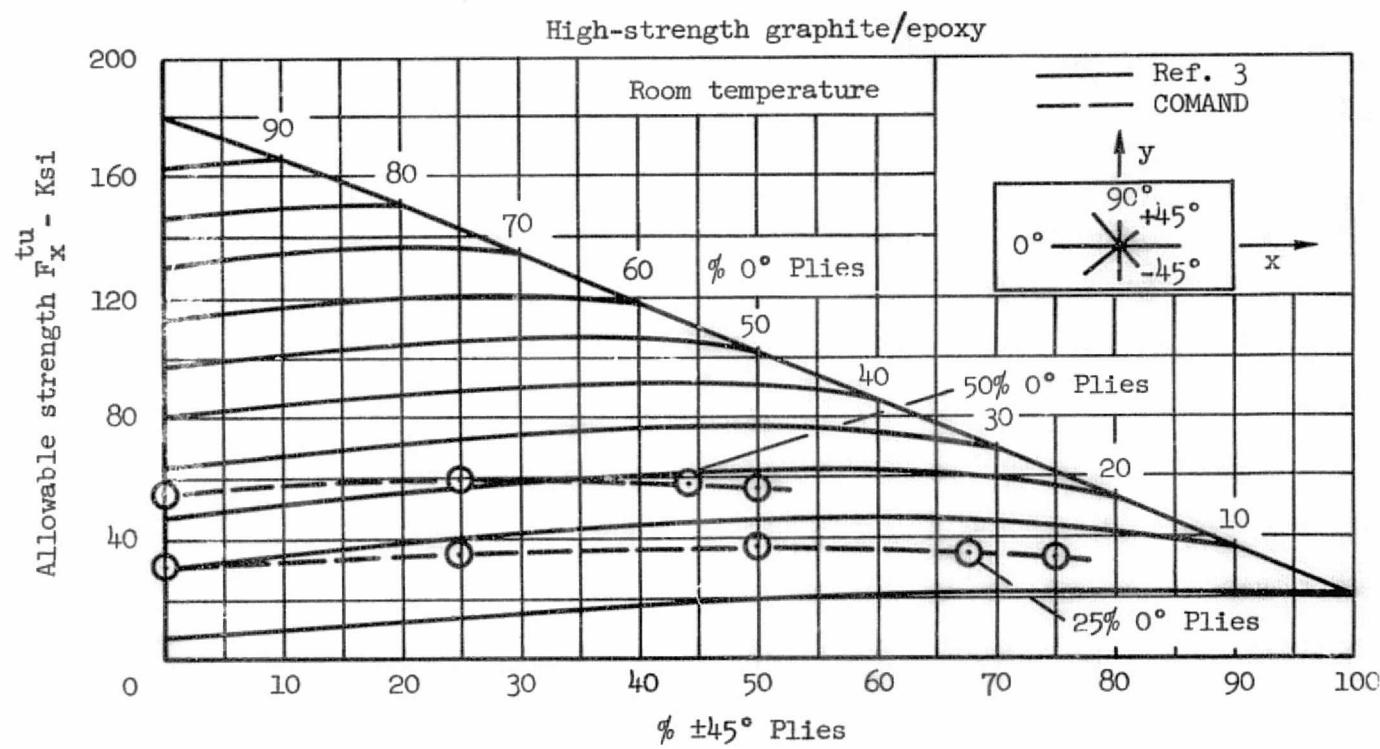


Figure 7.- Ultimate tensile strength F_x^tu high-strength graphite/epoxy - $[0_i/\pm 45_j/90_k]^x$ family.

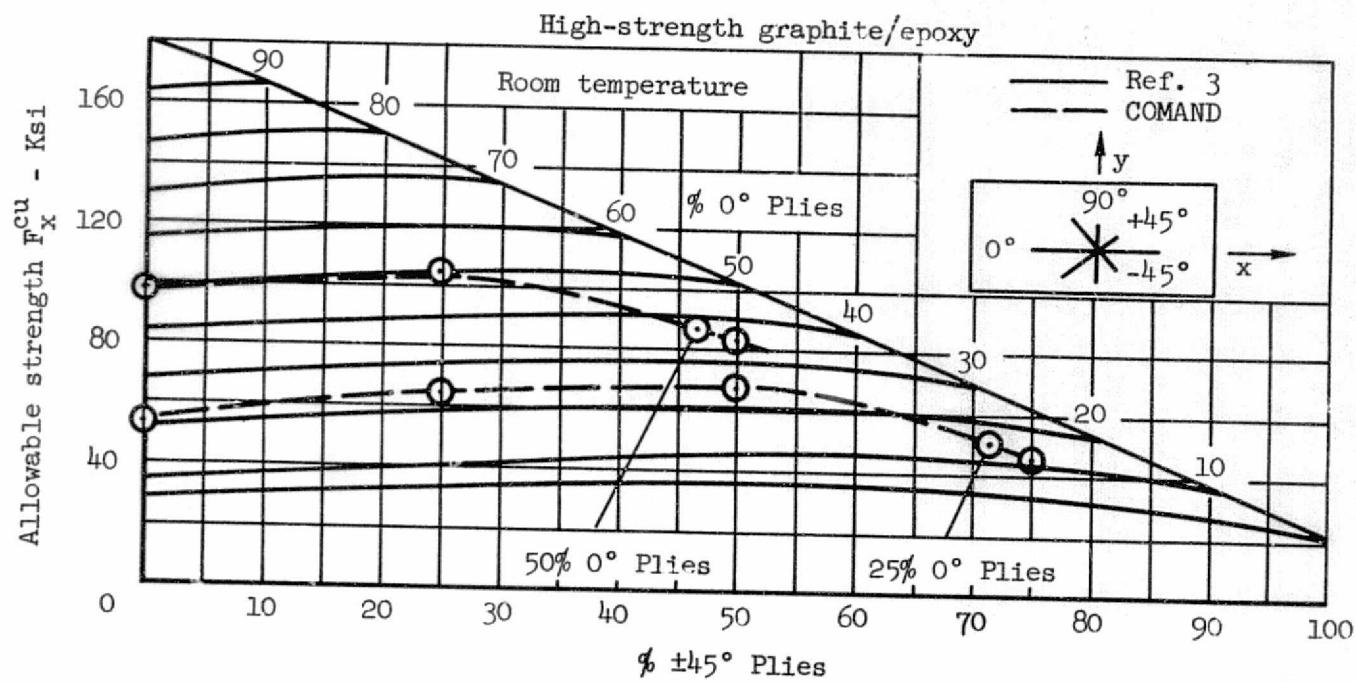


Figure 8.- Ultimate compressive strength F_x^{cu} high-strength graphite/epoxy - $[0_i/\pm 45_j/90_k]$ family.

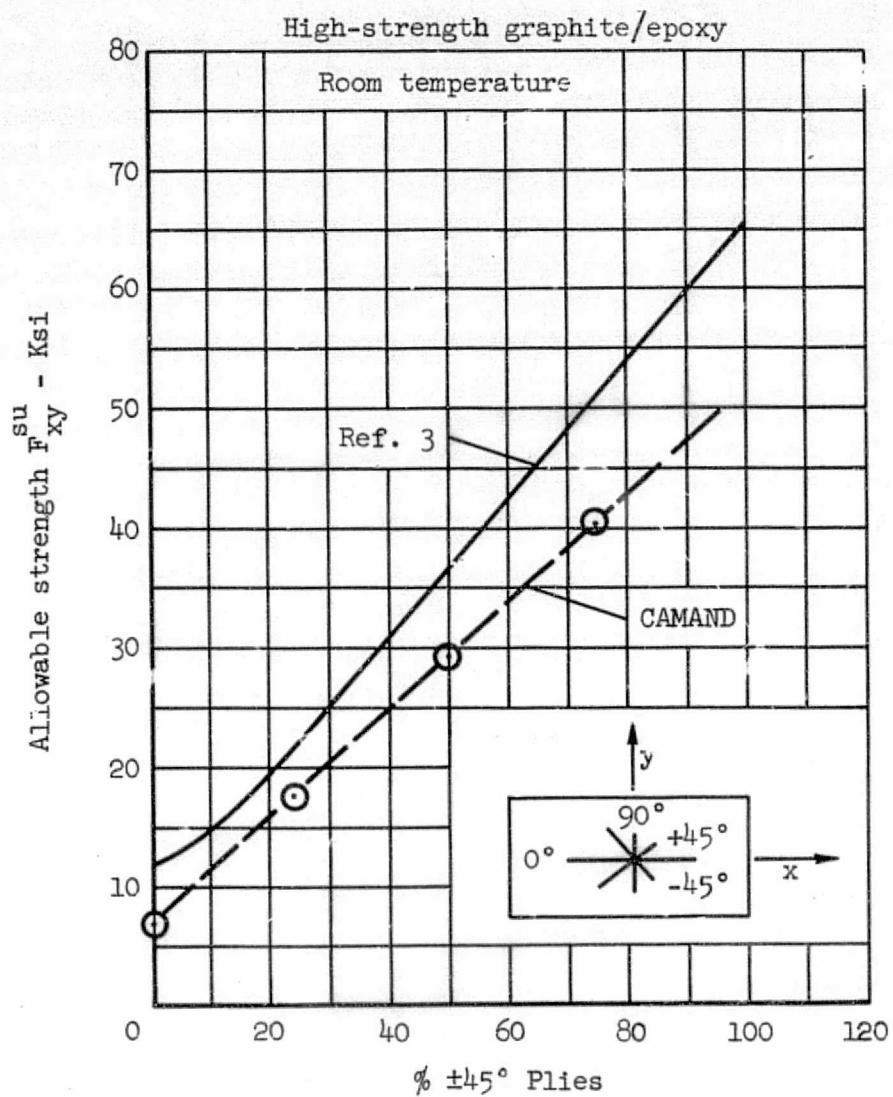


Figure 9.- Ultimate shear strength F_{xy}^{su} high-strength graphite/epoxy - $[0_i/\pm 45_j/90_k]$ family.

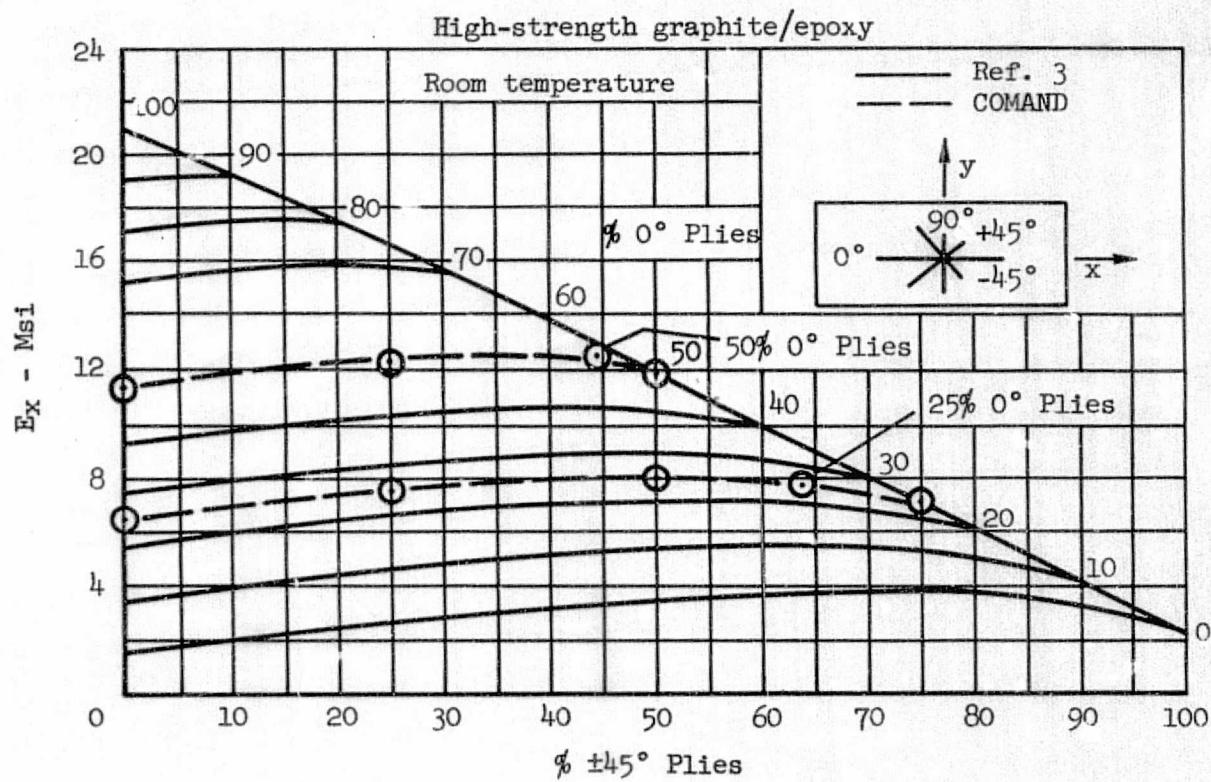


Figure 10.- Extensional modulus E_x high-strength graphite/epoxy - $[0_1/\pm 45_j/90_k]$ family.

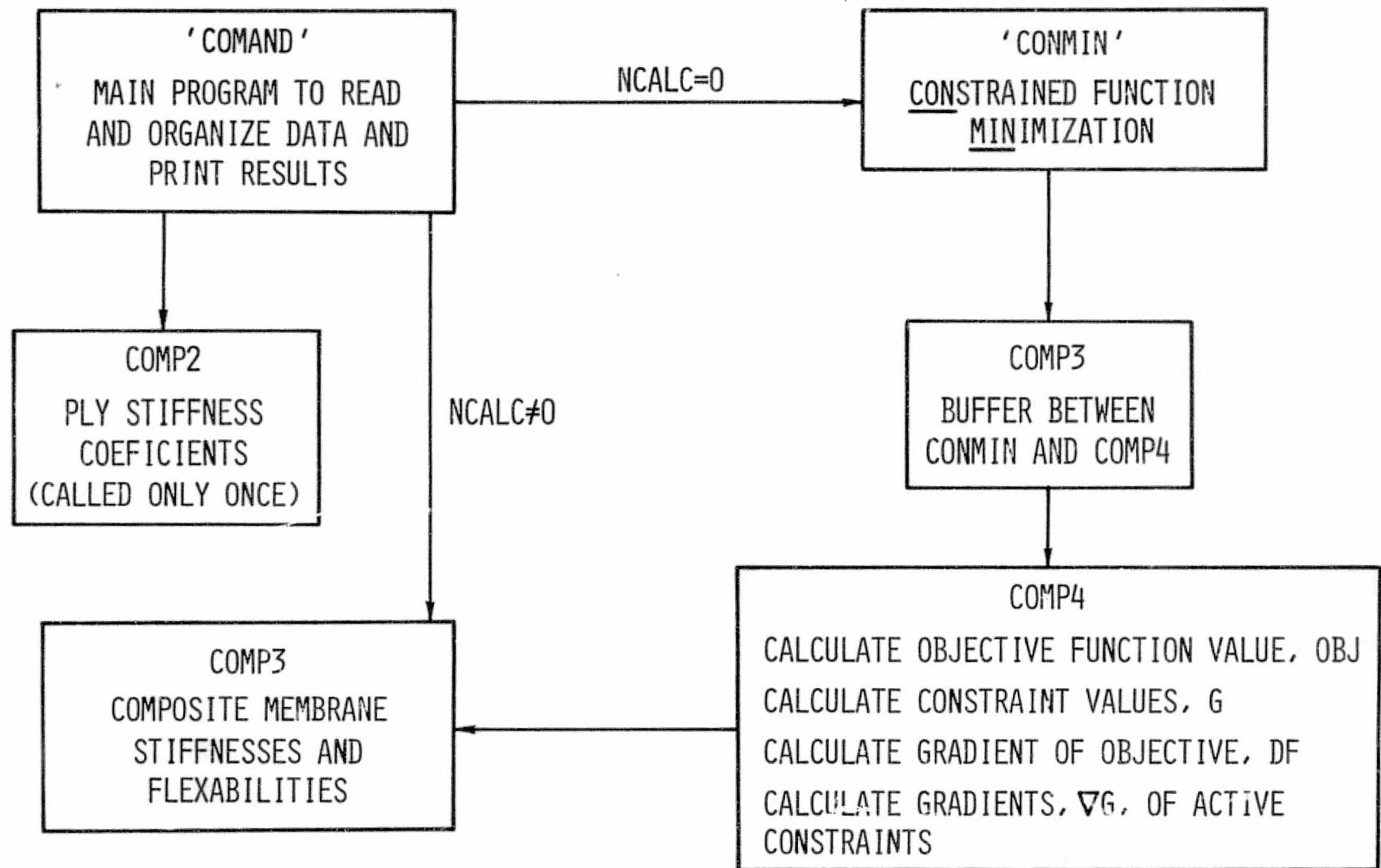


FIGURE 11.- 'COMAND' BLOCK DIAGRAM.