NASA Technical Memorandum 105882

/N-24
127127
p. 116

Thermostructural Tailoring of Fiber Composite Structures

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October 1992

(NASA-TM-105882) THERMOSTRUCTURAL TAILORING OF FIBER COMPOSITE STRUCTURES (NASA) 116 p

N93-12078

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SYMBOLS	
[A]	membrane stiffness coefficients
A	area
[B]	membrane-bending coupling coefficients
[D]	bending coefficients
D	diffusivity
[E]	elastic constants in the strain-stress law
E	elastic modulus
{F}	nodal forces vector
G	shear modulus
I	moment of inertia
[K]	structural stiffness matrix
K	conductivity
{M}	bending forces
[M]	mass matrix
M	bending load
{N}	membrane forces
N	axial load
[R]	transformation matrix
S	limit strength
T	temperature

SYMBOLS

h_ℓ , z	distance from mid-plane to mid-surface of ply
h	convection coefficient
k	partial volumes
q	heat flux
t, t_c	thickness
$\{u\}$	nodal degrees of freedom
α	thermal coefficient of linear expansion
β	moisture expansion coefficient
ϵ	strain
κ	curvature
λ	weight ratios
ν	Poisson's ratio
ρ	density
σ	stress

Subscripts:

a	analysis degrees of freedom
c	composite
f	fiber
ℓ	ply
m	matrix
o	omitted degrees of freedom
v	voids
x, y, z	coordinate reference axes of the composite
1, 2, 3	material axes

ABSTRACT

A significant area of interest in design of complex structures involves the study of multidisciplined problems. The coordination of several different intricate areas of study to obtain a particular design of a structure is a new and pressing area of research.

In the past, each discipline would perform its task consecutively using the appropriate inputs from the other disciplines. This process usually required several time-consuming iterations to obtain a satisfactory design. The alternative pursued here is combining various participating disciplines and specified design requirements into a formal structural computer code. The main focus of this research is to develop a multidisciplines structural tailoring method for select composite structures and to demonstrate its application to specific areas.

The development of an integrated computer program involves the coupling of three independent computer programs using an executive module. This module will be the foundation for integrating a structural optimizer, a composites analyzer and a thermal analyzer.

With the completion of the executive module, the first step was taken toward the evolution of multidiscipline software in the field of composite mechanics. Through the use of an array of cases involving a variety of objective functions/constraints and thermal-mechanical load conditions, it became evident that simple composite structures can be designed to a combined loads environment.

CHAPTER I

INTRODUCTION

A major area of interest to date involves the study of multidisciplinary problems. Multidiscipline is defined here as the coupling of technical disciplines such as structural analysis, composite mechanics, structural optimization, and heat transfer. It can be further described as the coordination of several different intricate areas of study to obtain a design of a particular structure which will concurrently satisfy these fields of interest. The study of fiber composite structures is the particular problem of concern here and will involve the four complex areas of study described above. The ability to have these disciplines interact with each other simultaneously on a specific structural design problem is a new and urgently needed area of research.

In the past, each discipline would tailor its research to the particular interested field of study. If information from other related areas were needed, the task of collating the input from the relating field of study involved several time-consuming iterations to complete the task at hand. With the development of multidisciplinary structural tailoring methods into a formal structural computer code, a new tool for design of composite structures is within the grasp of the design engineer.

Though this research is limited to composite structures and a few of its related disciplines of study, it must be stated that there are potentially no limitations to the software development of integrated multidisciplinary research.

CHAPTER II

RESEARCH OBJECTIVE AND APPROACH

The main focus of this research is to develop a multidisciplinary structural tailoring method for select composite structures and to demonstrate its applications to specific cases.

The underlying objective will be to develop an integrated computer program that will couple together three independent computer programs using an executive module. The software packages used have been developed at, or for, the Lewis Research Center in the recent past. The executive module developed here for the purposes of this research will be the foundation for integrating the three codes: STAEBL/GENCOM, ICAN and the thermal analyzer section of CSTEM. This integrated computer program will complement the conventional approach which presently requires substantial professional and computer time to obtain acceptable designs.

The computer code will be subsequently used for the thermostructural tailoring of select composite structures. An array of cases which involves a variety of objective functions/constraints and thermal-mechanical loading conditions has been selected.

The array of cases includes four types of material systems, each with a fiber volume ratio of 0.60. The material systems are:

1) AS/IMHS

2) HMSF/IMHS

3) HMSF/IMHS//SGLA/IMHS (intraply system)

4) HMSF/IMHS and SGLA/IMHS (interply system)

Definitions:

AS: Graphite fiber

HMSF: High modulus surface treated fiber

SGLA: S-glass fiber

IMHS: Intermediate modulus high strength matrix

Intraply: 20% of each ply in layup will have the second system integrated within it

Interply: 20% of plies in layup will be second system

The optimizer within STAEBL/GENCOM uses design variables, decision variables and constraints to obtain optimal designs of these composite material systems.

Design variables are perturbed at each iteration to give the optimizer a direction and magnitude of change toward a design which is considered to be optimal. Ply angles, ply thicknesses and composite thickness are design variables in these cases.

Decision variables are used by the optimizer in STAEBL/GENCOM as the object to be optimized, this is commonly known as the objective function. The bending modulus of the composite, composite weight and composite displacements are typical decision variables.

The constraints are needed to define a feasible region in which the final design must satisfy. Modified distortion energy failure criteria of each material property will be used as the main constraints in the cases of concern. Another important constraint to be considered will be deflections of the structure.

The type of thermal loads applied will be a temperature gradient along the length, across the width and through the thickness. The thermal analyzer is used to perform this task. Each gradient will be applied separately and in combination to each material system mentioned.

The orchestration and coordination of input variables as well as variables passed between the codes will be explained further in the following chapters. Also, information on validation cases with predictable results will be collated and discussed. Finally, the demonstration cases involving the mentioned material systems will be run with the appropriate loading conditions. The results from these cases will be compared and analyzed.

CHAPTER III

THEORY AND DESCRIPTION

3.1 ICAN

This section of the analyses will be used as the composites analyzer. This branch is necessary for analyzing the composite structure prescribed by the user in the initial design as well as all subsequent designs of the structure determined internally by the code. The composite structure is more precisely defined as a multilayered structure composed of unidirectional fiber-reinforced composite plies or layers. ICAN (Integrated Composites Analyzer) was predominantly designed to analyze the hygrothermomechanical response/properties of these multilayered composites. The types of layers recognized by the program are: 1) a standard composite system that consists entirely of a primary composite system made of one type of fiber and matrix, 2) an intraply hybrid composite system that is made up of a primary and a secondary composite system arranged in a prescribed manner "within" a ply, and finally, 3) an interply hybrid composite system consisting of different material systems (fiber and matrix) within the composite structure.

By definition, a multilayered fiber reinforced composite structure is not homogeneous in the microscopic or macroscopic level, thus the advantage to using ICAN comes to light. By employing the theories of composite micromechanics and laminate theory, this composites analyzer can portray the essentially heterogeneous composite structure as a synthetic homogeneous structure. The discussion of these theories involved in the analysis of a composite structure is expounded on in greater detail in the following sections.

3.1.1 Composite Mechanics

The equations used in ICAN that related the ply properties to the constituent (fiber and matrix) properties of the ply or lamina were derived through the use of composite micromechanics. This branch of composite mechanics was formally structured and based on certain assumptions pertaining to geometry of the structures and the fundamentals of solid mechanics. In the derivation of the equations, the main assumptions made were: 1) the ply resists in-plane loads as depicted schematically in figure 3-1, and 2) the ply and its constituents behave linearly elastic to the point of fracture as shown in figure 3-2. These equations for the material properties of a unidirectional fiber-reinforced lamina that were based on the constituent properties of the ply were proposed in simple form by Chamis (Ref. 1).

Figure 3-1 shows the coordinate axis system used in the definition of the different material properties of the lamina. Note that the predicted equations will represent values for the equivalent homogeneous ply that is assumed to be transversely isotropic in the 2-3 plane.

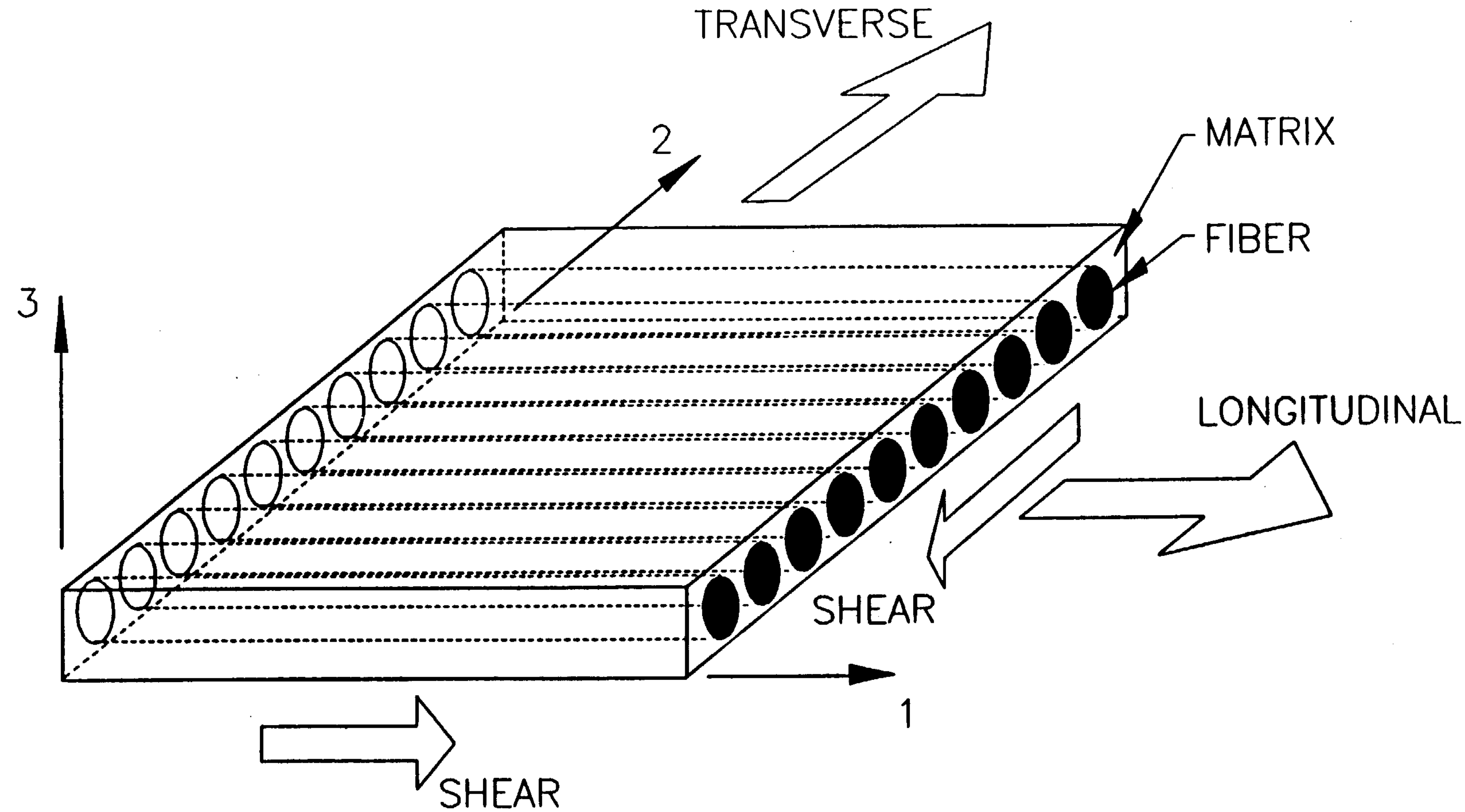


Figure 3.1 : Typical Fiber Composite Geometry

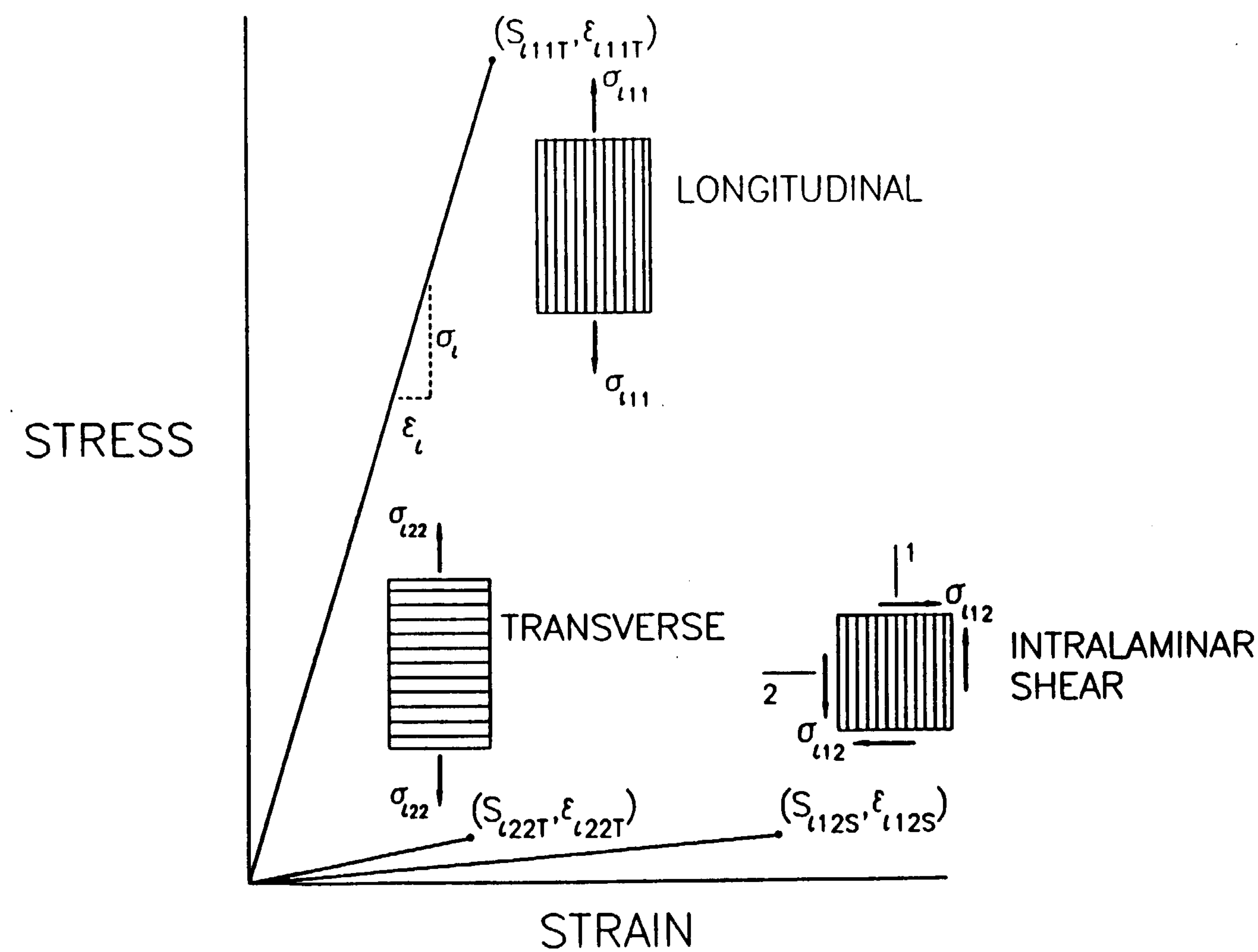


Figure 3.2: Stress–Strain Behavior of Unidirectional Fiber Composite

Micromechanistic geometric relationships are described in figure 3-3. Represented in these and all future equations: k denotes constituent volume fractions, ρ and λ denote density and weight ratios respectively, the subscripts f, m, and ℓ denote the affiliation with the fiber, matrix and ply respectively. The composite micromechanics equations for predicting mechanical, thermal and hygral properties are shown in figures 3-4, 5 and 6 respectively. Also included in this study are the composite micromechanics equations for strength, and environmental effects of moisture and temperature on the material properties (Ref. 2).

Another aspect of composite micromechanics important to this study is the stress failure criteria (Ref. 3). The importance is brought to light by the observation that a combined stress state will limit the strength of a ply much more than a simpler uniaxial load condition. One of the failure criteria output by ICAN is the modified distortion energy (MDEIE) shown in figure 3-7. The optimizer within STAEBL will determine the stress constraint that represents the maximum value for each ply that will most effect the design in an adverse way. It can be observed from figure 3-7 that the MDEIE stress failure criteria determines failure on a minimum value, not the maximum needed by the optimizer. Therefore, the following equation will be adapted from figure 3-7 and will be the representation value used within the optimizer for establishing the stress constraints of the composites.

$$F = 1.0 - MDEIE$$

The optimizer determines the minimum value for "F" from each ply of the composite, then comparing that value to 1.0, the decision if a ply has failed is made. If "F" is less than 1.0 there is no failure, if "F" is equal to 1.0, the ply is on the verge of failing, and if "F" is greater than 1.0, the ply has failed.

3.1.2 Laminate Theory

Laminate theory is the aspect of composite mechanics which will relate the individual lamina and its properties to the overall composite structure and its properties. In this discussion, the terms composite, laminate and composite structure will be used interchangeably, as will be the labels ply, lamina and layer.

The stress-strain relations for a unidirectionally reinforced lamina are contiguous to an orthotropic material under a plane stress state, or more simply stated, $\sigma_{33} = \sigma_{23} = \sigma_{31} = 0$. The derived stress-strain relations of the generalized orthotropic ply are defined with respect to the principal material axis of the ply, this relation then has to be transferred to the global structure coordinate axis of the composite.

If each ply or lamina of the laminated composite structure is considered to be a thin plate, then according to Kirchoff's hypothesis for plates, the lamina is assumed to be in a plane stress state. Also, for the linear case of a deformed plate, the strains of each ply are related to the extension and curvature of the mid-surface (Ref. 4). The

PARTIAL VOLUMES : $k_f + k_m + k_v = 1$

PLY DENSITY : $\rho_\ell = k_f \rho_f + k_m \rho_m$

RESIN VOLUME RATIO : $$k_m = \frac{(1 - k_v)}{\left[1 + \left[\rho_m / \rho_f\right]\left[1/\lambda_m - 1\right]\right]}$$

FIBER VOLUME RATIO : $$k_f = \frac{(1 - k_v)}{\left[1 + \left[\rho_f / \rho_m\right]\left[1/\lambda_f - 1\right]\right]}$$

WEIGHT RATIOS : $\lambda_f + \lambda_m = 1$

Figure 3.3: Composite Micromechanics: Geometric Relationships

LONGITUDINAL MODULUS : $E_{\ell 11} = k_f E_{f11} + k_m E_m$

TRANSVERSE MODULUS : $E_{\ell 22} = \dfrac{E_m}{1 - \sqrt{k_f}\,(1 - E_m / E_{f22})} = E_{\ell 33}$

SHEAR MODULUS : $G_{\ell 12} = \dfrac{G_m}{1 - \sqrt{k_f}\,(1 - G_m / G_{f22})} = G_{\ell 13}$

SHEAR MODULUS : $G_{\ell 23} = \dfrac{G_m}{1 - k_f\,(1 - G_m / G_{f23})}$

POISSON'S RATIO : $\nu_{\ell 12} = k_f \nu_{f12} + k_m \nu_m = \nu_{\ell 23}$

POISSON'S RATIO : $\nu_{\ell 23} = \dfrac{E_{\ell 22}}{2G_{\ell 23}} - 1$

Figure 3.4: Composite Micromechanics : Mechanical Properties

LONGITUDINAL CONDUCTIVITY : $K_{\ell 11} = k_f K_{f11} + k_m K_m$

TRANSVERSE CONDUCTIVITY : $K_{\ell 22} = (1 - \sqrt{k_f})K_m + \dfrac{K_m \sqrt{k_f}}{1 - \sqrt{k_f}\,(1 - K_m / K_{f22})} = K_{\ell 33}$

LONGITUDINAL THERMAL EXPANSION COEFFICIENT : $\alpha_{\ell 11} = \dfrac{k_f \alpha_{f11} E_{f11} + k_m \alpha_m E_m}{E_{\ell 11}}$

TRANSVERSE THERMAL EXPANSION COEFFICIENT : $\alpha_{\ell 22} = \alpha_{f22}\sqrt{k_f} + (1 - \sqrt{k_f})(1 + k_f \nu_m \dfrac{E_{f11}}{E_{\ell 11}})\alpha_m = \alpha_{\ell 33}$

Figure 3.5: Composite Micromechanics : Thermal Properties

LONGITUDINAL DIFFUSIVITY :	$D_{\ell 11} = (1 - k_f)D_m$
TRANSVERSE DIFFUSIVITY :	$D_{\ell 22} = (1 - \sqrt{k_f})D_m = D_{\ell 33}$
LONGITUDINAL MOISTURE EXPANSION COEFFICIENT :	$\beta_{\ell 11} = \beta_m(1 - k_f)E_m \,/\, E_{\ell 11}$
TRANSVERSE MOISTURE EXPANSION COEFFICIENT :	$\beta_{\ell 22} = \beta_m(1 - \sqrt{k_f})\left[1 + \frac{\sqrt{k_f}(1 - \sqrt{k_f})E_m}{\sqrt{k_f}E_{\ell 22} + (1 - \sqrt{k_f})E_m}\right] = \beta_{\ell 33}$
MOISTURE EXPANSION COEFFS. FOR INCOMPRESSIBLE MATRIX :	$\begin{cases} \beta_{\ell 11} = 0.0 \\ \beta_{\ell 22} = \beta_m \rho_\ell \,/\, 2\rho_m - \beta_{\ell 33} \end{cases}$

Figure 3.6: Composite Micromechanics : Hygral Properties

$$MDEIE = 1 - \left[\left[\frac{\sigma_{\ell 1 1 \alpha}}{S_{\ell 1 1 \alpha}} \right]^2 + \left[\frac{\sigma_{\ell 2 2 \beta}}{S_{\ell 1 1 \beta}} \right]^2 - K_{\ell 1 2 \beta} \frac{\sigma_{\ell 1 1 \alpha}}{S_{\ell 1 1 \alpha}} \frac{\sigma_{\ell 2 2}}{S_{\ell 2 2}} + \left[\frac{\sigma_{\ell 1 2 S}}{S_{\ell 1 2 S}} \right]^2 \right]_i$$

When .... $MDEIE > 0$: no failure ; $MDEIE = 0$: incipient failure ; $MDEIE < 0$: failure

The parameters for α and β are specified as follows:

$$\alpha = \begin{cases} T & \sigma_{\ell 1 1} \geq 0 \\ C & \sigma_{\ell 1 1} < 0 \end{cases} \quad \text{AND} \quad \beta = \begin{cases} T & \sigma_{\ell 2 2} \geq 0 \\ C & \sigma_{\ell 2 2} < 0 \end{cases}$$

$$S_{\ell 1 1 \alpha} = \begin{cases} S_{\ell 1 1 T} & \alpha = T \\ \min(S_{\ell 1 1 C}, S_{\ell 1 1 CD}) & \alpha = C \end{cases} \quad \text{AND} \quad S_{\ell 2 2 \alpha} = \begin{cases} S_{\ell 2 2 T} & \beta = T \\ S_{\ell 2 2 C} & \beta = C \end{cases}$$

Also :

$$K_{\ell 1 2 \alpha \beta} = K'_{\ell 1 2 \alpha \beta} \frac{(1 + 4\nu_{\ell 1 2} - \nu_{\ell 1 3}) E_{\ell 2 2} + (1 - \nu_{\ell 2 3}) E_{\ell 1 1}}{\left[E_{\ell 1 1} E_{\ell 2 2} (2 + \nu_{\ell 1 2} + \nu_{\ell 1 3})(2 + \nu_{\ell 2 1} + \nu_{\ell 2 3}) \right]^{\frac{1}{2}}}$$

$K'_{\ell 1 2 \alpha \beta} = 1.0$ .... unless a theory/experiment correlation factor is needed.

Figure 3. 7 : Modified Distortion Energy (MDEIE) Failure Criteria

relationship between the individual ply strains and that of the composite is shown in figure 3.8 where z_k is the perpendicular distance from the laminate mid-plane to the mid-surface of the k^{th} ply. Even though the strain variation is linear, the stress variation through the thickness of the composite might not be since the stress-strain relation can be different for each ply.

It can be seen from figure 3.8 that the resultant stresses and moments acting on the composite can be derived. This is done by integrating the individual ply stresses over the thickness of the laminate (Ref. 4).

This brief review of laminate theory, or better stated, classical laminated plate theory, should be understood to be a superficial study of this intricate field. For a more integral study of the important elements that comprise laminate theory, the ICAN User's Manual (Ref. 5) cites many references.

In summary, figure 3-9 will state the important equations for laminate theory. These equations will include the hygral and thermal relations as well as the mechanical relations.

3.2 Thermal Analyzer

The thermal analyzer used here was developed using the fundamentals of heat transfer (Ref. 6). Heat transfer falls in the general classification of a transport phenomenon. Also included in this broad classification are the areas of mass transfer, momentum transfer or

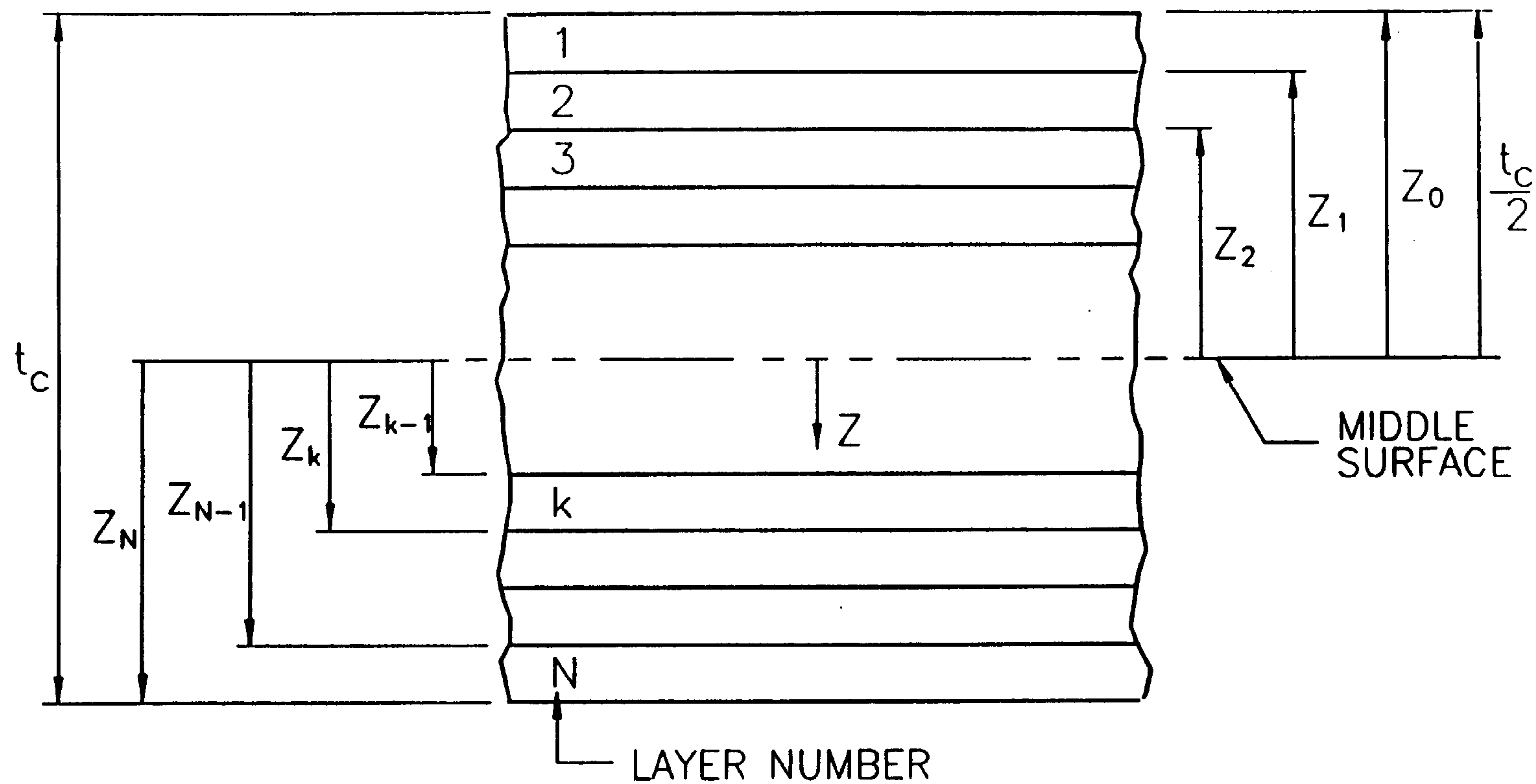


Figure 3.8 : N – Layered Laminate Geometry

PLY CONSTITUTIVE RELATIONSHIP :

$$\{\epsilon\}_\ell = [E]_\ell^{-1}\,\{\sigma\}_\ell + \Delta T_\ell\,\{\alpha\}_\ell$$

PLY STRAIN :

$$\{\epsilon\}_\ell = [R_\epsilon]_\ell \left\langle \{\epsilon^0\}_c - Z_\ell^0\,\{\kappa\}_c \right\rangle$$

PLY STRESS :

$$\{\sigma\}_\ell = [E]_\ell \left\langle \{\epsilon\}_\ell - \Delta T_\ell\,\{\alpha\}_\ell \right\rangle$$

LAMINATE CONSTITUTIVE RELATIONSHIP :

$$\left\{\begin{array}{c} N \\ \hline M \end{array}\right\}_c = \left[\begin{array}{c|c} A & B \\ \hline B^T & D \end{array}\right]_c \left\{\begin{array}{c} \epsilon^0 \\ \hline \kappa \end{array}\right\}_c - \left\{\begin{array}{c} N_T \\ \hline M_T \end{array}\right\}_c$$

LAM. THERMAL FORCES/MOMENTS :

$$\{N_T,\ M_T\}_c = \sum_{\ell=1}^{n} [R_\epsilon]_\ell^T [E]_\ell \{\alpha\}_\ell \Delta T_\ell \left\langle (h_\ell - h_{\ell-1}),\ \tfrac{1}{2}(h_\ell^2 - h_{\ell-1}^2) \right\rangle$$

LAMINATE STIFFNESS :

$$[A,\ B,\ D]_c = \sum_{\ell=1}^{n} [R_\epsilon]_\ell^T [E]_\ell [R_\epsilon]_\ell \left\langle (h_\ell - h_{\ell-1}),\ \tfrac{1}{2}(h_\ell^2 - h_{\ell-1}^2),\ \tfrac{1}{3}(h_\ell^3 - h_{\ell-1}^3) \right\rangle$$

Figure 3.9 : Summary of Governing Equations of Laminate Theory

fluid friction and electrical conduction. The rate equation of all these unique transfer systems is very similar in that the flux is proportional to a potential difference. The flux is defined as the quantity transferred per area per time; and the potential difference, in the case of heat transfer by conduction and convection, is the temperature difference. From this, the definition of heat transfer is described as the transmission of energy from one region to another primarily as a result of temperature difference.

Generally, heat transfer is split into three different modes which are referred to as conduction, convection and radiation. Of the three modes mentioned, convection is the only one that does not comply with the definition described above since mass transport is also involved, but "heat transfer by convection" is a widely accepted term.

The thermal analyzer code has the ability to analyze each of the mentioned modes of heat transfer: conduction, heat transfer by convection and radiation. This code was adopted for use in this research due to its flexibility. Some of the features incorporated within the code involve types of heat transfer analysis (linear steady-state, nonlinear steady-state, linear transient and nonlinear transient), material types (isotropic and orthotropic), element types (8, 16 and 20 nodes) and units (metric or English). Additional details about what components were used and why will be explained in much greater detail in the next chapter.

3.2.1 Conduction

Conduction is the process by which heat is transferred from a region of higher temperature to a region of lower temperature within a medium. That particular medium can be described as a solid, liquid or gas. Also, heat transferred between different media in direct physical contact where there is no heat transfer by mass movement can be considered conduction. The energy is transmitted by direct intermolecular collision without any appreciable displacement of the molecules.

The internal energy of a system is the energy possessed by an element of matter due to the velocity and relative position of the molecules. This energy is directly proportional to temperature of the element according to kinetic theory. From this it is deduced that the greater the temperature and thus, the internal energy, the more rapidly the molecules are vibrating. If there is a difference in temperature between two adjacent regions, the molecules of greater energy will lose part of their energy to the molecules of lower energy. In fluids, this energy loss is by elastic collision while in metals the loss comes in the form of diffusion of electrons.

Thermal conduction can be expressed by the following relationship:

$$\frac{q}{A} = -k \ \nabla T$$

q = heat flux

k = thermal conductivity

∇ = vector gradient operation

A = area

This theory was proposed by J. B. Fourier in 1822 and is a generalization of the experimental work done by J. B. Biot in 1804 and 1816.

3.2.2 Convection

Heat transfer by convection is the method of energy transport by the combined action of conduction, energy storage and mixing motion. Heat transfer between a solid surface and a fluid can best be described using convection, since this method of energy transfer involves mixing and diffusion as well as conduction. To facilitate in understanding this intricate mode of energy transfer, examine the situation of heat transfer to a fluid flowing inside a pipe. Three different flow regions are present for a fast flowing fluid. The laminar sublayer adjacent to the pipe wall uses heat transfer by thermal conduction. The transition region outside the laminar sublayer has eddy mixing as well as thermal conduction. Finally, toward the center of the pipe, eddy mixing is the prevailing method of energy transfer.

When modeling heat transfer by convection, several steps must be considered. Assuming a surface has a temperature greater than the surrounding fluid, the first step is the energy transfer to the fluid particles in direct contact with the surface. This results in increased temperature of these fluid particles. These more active fluid particles then will move toward and mix with the lower temperature fluid particles. This fluid movement has a two fold effect; more lower temperature particles can now be in contact with the surface of higher temperature, and the more energetic fluid will transfer some of its energy to other fluid particles. This transfer is a result of mass motion. At this time it can be pointed out that due to this resulting mass motion, this mode of transfer does not strictly depend on a temperature difference and, as stated before, does not conform to the strict definition of heat transfer. The overall heat transfer effect is in the direction of the temperature gradient and therefore is loosely classified as a type of heat transfer. The class of heat transfer by convection is dependent upon the manner of motivation. The one described above is considered free convection. The mixing motion is due to density differences caused by a temperature gradient. Another cause of mixing motion is due to an external effect. An example of this could be from the use of a pump or blower; this form of convection is called forced convection.

In 1701, Sir Isaac Newton successfully analyzed this intricate and unique field of convection. He proposed the general Newton Rate Equation:

$$q = hA\,(T_w - T_\infty)$$

q = heat flux

h = convection coefficient

T_w = surface temperature

T_∞ = fluid temperature

A = area

Convection coefficient, h, was a consideration of fluid motion, fluid conductivity and the role of turbulent eddies.

3.2.3 Radiation

The final method of heat transfer is by radiation. This occurs when a high temperature body transfers energy to a low temperature body when the two are separated in space. Radiant heat transfer acts from the internal energy at a source first being changed to electromagnetic energy. This energy is then transmitted to a receiving material and changed into internal energy in that material. Unlike conduction and convection, radiation is not dependent upon a material to act as a medium to convey the energy between the two regions, actually thermal radiation is impeded by the presence of any intermediate material. Radiant heat emitted by a body is in the form of finite groups of energy called quanta. These quanta have motions in space similar to light propagation and therefore can be described in wave theory.

The expression that describes thermal radiation heat transfer has the form:

$$\frac{q}{A} = \sigma \; T^4$$

q = heat flux

T = temperature (absolute)

σ = constant

A = area

In 1879, Stefan obtained this expression from empirical data of Timdall, and then Boltzmann, in 1884, used classic thermodynamics to derive it. The expression is more commonly known as the Stefan-Boltzmann Law.

3.2.4 Finite Element Formulation

As stated previously, this module can analyze linear steady-state, nonlinear steady-state, linear transient and nonlinear transient conditions. The details disclosed next should give insight to the finite element formulation used in the thermal analyzer code (Ref. 9). The use of three-dimensional isoparametric solid elements will allow the temperature, T, within the element to be defined at time, t, in terms of nodal temperatures.

$$T(x, y, z, t) = \Sigma\, H_i(x, y, z)\, T_i(t)$$

where H_i is the shape function and T_i is the temperature at node, i.

The general three-dimensional heat transfer condition in a body assumes the material obeys Fourier's law of heat conduction. The expression for heat flow equilibrium in the interior of a body can follow:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) = -q_b \qquad (3\text{-}1)$$

where q_b is the rate of heat generated per unit volume, the thermal conductivities of the principal axes are denoted by k_x, k_y, k_z and T is the temperature of the body. On the surface of the body, the following conditions must be satisfied:

$$T \Big|_{S1} = T_e \tag{3-2}$$

$$k_n \left. \frac{\partial T}{\partial n} \right|_{S2} = q_s \tag{3-3}$$

where T_e is the environmental temperature and q_s is the heat flow input to the surface of the body. The details of these boundary conditions are expounded upon in the user's manual for the thermal analyzer (Ref. 9).

To solve the differential equation, 3-1, with the given boundary conditions, 3-2 and 3-3, a finite element scheme was developed. A variational formulation of the heat transfer problem was engaged. This formulation defined a function such that when stationarity of that function is invoked, the governing differential equations 3-1, 3-2 and 3-3 were obtained.

The user's manual (Ref. 9) outlines a general solution scheme for linear and non-linear, steady-state and transient problems. The development of incremental equilibrium equations for each problem was done using the modified Newton-Raphson iteration for heat flow equilibrium.

At each iteration, the stiffness matrix will remain constant while any change will be realized by the load vectors.

The cursory description of the finite element formulation outlined above should be deduced to be a review/summary. The details are delineated in the thermal analyzer user's manual (Ref. 9) and can be referenced if an in-depth study is required.

3.3 STAEBL:

Structural tailoring of engine blades/general composite structures (STAEBL/GENCOM) is an extension and modification of the program STAEBL (Ref. 7). Most of the modifications were carried out in order to apply the program to general composite structures. Since the overall program logic follows that of the original STAEBL program, this part of the module will be described first followed by the capabilities of the GENCOM version.

The STAEBL computer program was developed to perform engine fan and compressor blade optimizations through the use of realistic blade design constraints such as blade stresses, vibratory response, flutter and foreign object damage. The optimization is reached by tuning one to twenty design variables. Included are airfoil thickness at several locations, blade chord and certain blade internal configuration variables.

Three component parts are required to perform a blade optimization: an optimization algorithm, approximate analysis procedures for objective function and constraint evaluation and refined analysis procedures for design validation.

Control Program for Engineering Synthesis/Constrained Minimization (COPES/CONMIN) optimization package is used as the optimization algorithm in STAEBL. This is a proven tool for optimizations with a small to medium number of design variables. The optimization method using COPES/CONMIN will be discussed in greater detail in the next section.

The approximate analysis utilized is an efficient, coarse mesh, plate finite element procedure in STAEBL. How this approximate analysis was decided upon will be reviewed in greater detail in a later section of this chapter. This analysis can also provide blade frequencies, mode shapes, stresses under loads, flutter and foreign object damage, which are utilized to evaluate respective design requirements in the form of constraints.

A refined analysis should be applied to the optimal design to assure that all constraints are satisfied. This task is not performed by STAEBL automatically, but is the user's responsibility by incorporating an existing design/analysis system. If the first choice of optimal design is found to violate one or more of the constraint values, the allowable for the constraint values must be adjusted to take into consideration the difference between the approximate and refined analysis. During the development of STAEBL, a fully satisfactory design was found for all cases studied.

To use STAEBL, the coordinate description of an initial design must be known. From here the optimization system will adjust the design variables to try to establish an optimal design. In addition to geometry variables, there are additional construction variables available for composite blades, some of which are material thickness and ply angle orientation.

3.3.1 STAEBL/GENCOM

The GENCOM version of STAEBL (Ref. 7) had several additions and modifications in order to incorporate composite structural analysis and also allow the user certain options not in STAEBL. The user now can input a NASTRAN blade geometry description and a second option replaces calls to the external math library, IMSL, with calls to subroutines added to the source code.

Since composite blades can experience high temperatures and large temperature gradients, through-the-thickness as well as in-plane, a thermal stress analysis capability was added. The capacity to analyze thermal gradients will allow the composite properties to be temperature dependent. A similar adjunct involving moisture gradients was included in the new version of STAEBL.

The composite construction variables added to STAEBL involve simple composite blade preprocessing. Up to seven material systems can be analyzed with the thicknesses and fiber angles of each material system incorporated as design variables. The design thickness is built up from the outside toward the core with the thickness of each material system. Thickness of the core material system is adjusted to accommodate the balance of the design thickness.

3.3.2 COPES/CONMIN

As stated earlier, the COPES/CONMIN (Ref. 7) optimization package is used as the optimization algorithm of STAEBL. It was selected because of its versatility for structural optimization problems. It is applicable to both constrained and unconstrained minimization problems.

The engineering design problem involved in STAEBL/GENCOM is the determination of design variables which minimize a design quantity while satisfying a set of auxiliary conditions. This is generally a constrained minimization problem and is mathematically expressed as follows:

$$\text{minimize } f(\underline{x}) \tag{3-4}$$

where $f(\underline{x})$ is the scalar function to be minimized. This function, $f(\underline{x})$, is the objective function subjected to m number of auxiliary conditions known as the inequality constraints:

$$g_i(\underline{x}) < 0, \quad i = 1,\ldots,m \tag{3-5}$$

The vector of n number of design variables is represented by the quantity $\underline{x} = (x,\ldots,x_n)$. Each design variable, x_i, has imposed upon them, upper and lower bounds referred to as the side constraints. These side constraints can be represented in the form:

$$L_i < x_i < U_i, \quad i = 1,\ldots,n \tag{3-6}$$

A feasible region is the combination of all feasible points in a design space. Each feasible point is any choice of design variables, $\underline{x}$, which satisfy all the constraints, equations 3-5 and 6.

The feasible region is bounded by a constraint surface or a locus of points which satisfy the equation $g_i\ (\underline{x}) = 0$ for some i. On one side of the surface, $g_i(\underline{x}) < 0$, the constraint is satisfied, on the other side, $g_i(\underline{x}) > 0$, the constraint is violated. Any feasible points on the boundary, $g_i\ (\underline{x}) = 0$ are called bound points and that particular constraint is said to be active. Any points inside the feasible region are known as free points. If the objective function is at a minimum and the design point is in the feasible region, the solution to the problem presented in equations 3-4, 5 and 6 is known as an optimal feasible point. A feasible region is disjoint if it is made up of two or more distinct sets of feasible points. This could occur in any nonlinear minimization problem, that is, when $f(\underline{x})$ or any $g_i(x)$'s are nonlinear. In this instance, there can be multiple local minima and the global minimum is now the optimal feasible point. A structural optimization problem almost always finds a solution on the boundary of the feasible region. In fact, it is usually at the intersection of two or more constraint surfaces and therefore the solution will have two or more active constraints.

STAEBL uses the direct method, versus indirect method, to solve the constrained optimization program. In this method, the objective function and the constraints are evaluated independently and the constraints are treated as a limiting surface. Zoutendijk's method of feasible directions is an example of a direct method of solution and is incorporated in the exact analysis available for a solution technique.

3.3.3 Finite Element Analysis

STAEBL (Ref. 7) uses an approximate analysis procedure to establish an optimal design. This type of analysis is required to obtain, with reasonable accuracy, a design as quickly and as efficiently as possible. At this point, the acquired design is then evaluated using a more rigorous refined analysis for comparison with the approximate analysis. This comparison will allow the user to become aware if the optimal design is valid.

NASTRAN finite element analysis is used for the refined analysis, and a beam analysis procedure was initially used for the approximate analysis. It was found that to properly model complex blades, a plate finite element was required for the approximate analysis. It can be shown by using the same plate finite element analysis as NASTRAN, with a comparatively coarse mesh, satisfactory results were obtained with competitive run times to the original beam analysis procedure.

Therefore, for the approximate analysis procedure and using NASTRAN plate technology, a self-contained plate finite element analysis procedure was developed. NASTRAN technology was chosen for several reasons: 1) proven computational efficiency, 2) established successful correlations with test cases, 3) the convenience of the input and output, and importantly, 4) the compatibility with NASTRAN refined analysis procedures.

With the usage of a plate bending triangle, the approximate analysis in STAEBL preserves the similarity with NASTRAN. This isoparametric element of the QUAD4 family is very similar to the NASTRAN TRIA3 element. This TRIA3 element is a reduced integration triangular plate bending element with the following features: 1) recognition of thickness taper, 2) properly stacked triangular plate element meshes to simulate airfoil pretwist and camber, 3) composite material capabilities (using lamination theory), 4) element differential stiffness, and 5) lumped masses are employed, assuring a diagonal mass matrix, for storage efficiency.

Since the approximate plate finite element analysis procedure is derived from NASTRAN, it uses NASTRAN-format bulk data for its input and produces NASTRAN-format displacement and stress output. Duplicate pre- and postprocessing can be used for both the approximate and refined analysis; however, since all storage and processing of the approximate analysis take place in the core, the program will have limited capacity, but the allowable size can be shown to be sufficient for relative accuracy.

The finite element mesh and final Guyan reduction pattern is shown on a model in figure 3-10. With this comparatively coarse mesh in combination with the Guyan reduction, it reduces a 330 degree-of-freedom model down to 24 degrees-of-freedom. This Guyan reduction procedure (Ref. 8) has been shown to reduce the number of degrees-of-freedom with minimal loss of accuracy in a dynamic analysis. In STAEBL, the reduced or omitted degrees-of-freedom, u_o, and the remaining or analysis degrees-of-freedom, u_a, are related to static loads according to:

$$\begin{bmatrix} K_{aa} & K_{ao} \\ K_{oa} & K_{oo} \end{bmatrix} \begin{Bmatrix} u_a \\ u_o \end{Bmatrix} = \begin{Bmatrix} F_a \\ F_o \end{Bmatrix}$$

neglecting the forces F_o,

$$[u_o] = [G_{oa}] \quad [u_a]$$

where

$$[G_{oa}] = - [K_{oo}]^{-1} \quad [K_{oa}]$$

the reduced stiffness matrix thus becomes:

$$[K_{aa}] = [K_{aa}] + [K_{ao}] \ [G_{oa}]$$

The reduced mass matrix is determined by equating the kinetic energies before and after the reduction and becomes:

$$[M_{aa}] = [M_{aa}] + [M_{ao}] \ [G_{oa}] + [G_{oa}]^T \ (M_{oa} + M_{oo} \ G_{oa})$$

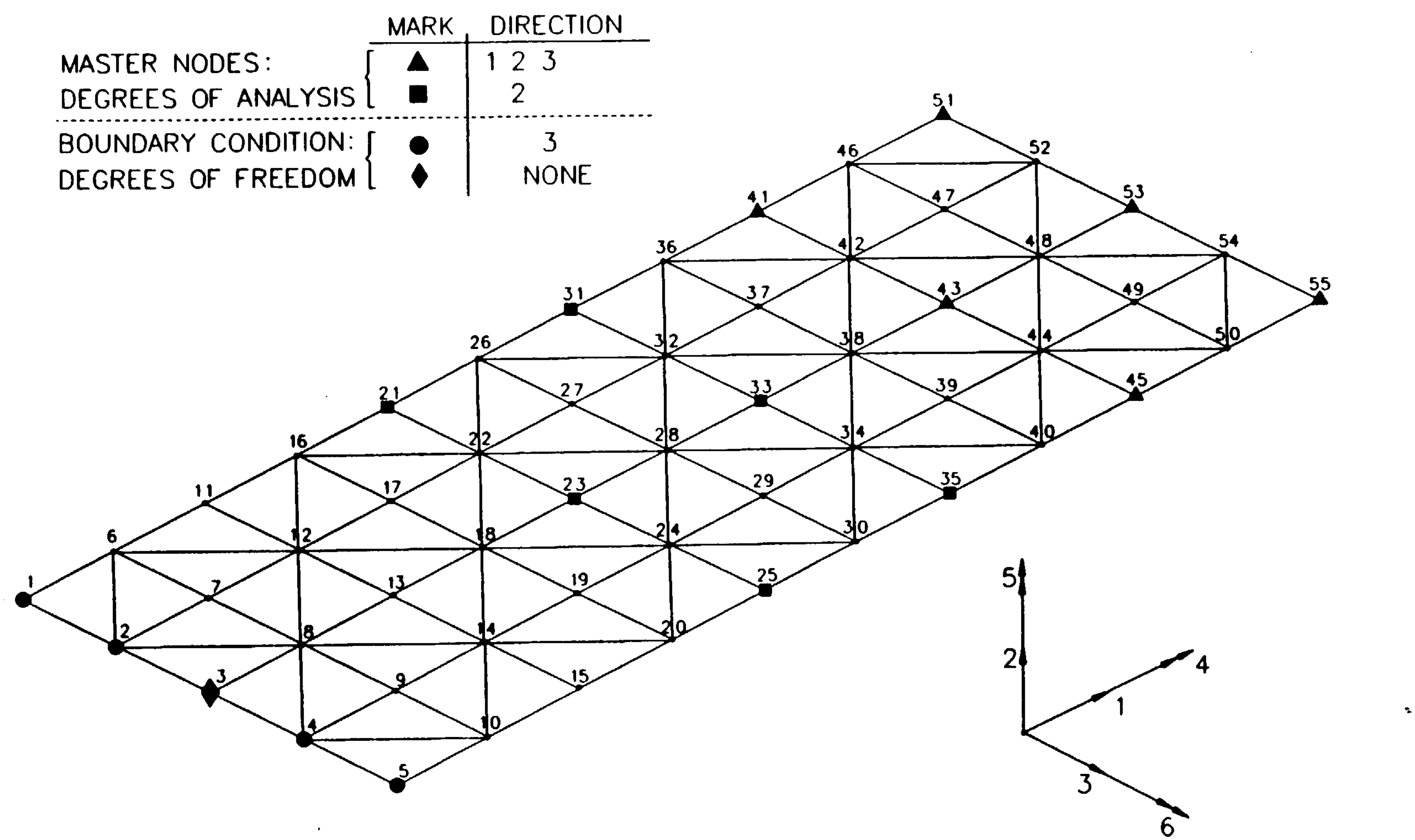


Figure 3. 10 : STAEBL Guyan Reduction Pattern & Boundary Conditions

After the stiffness and mass matrices have been reduced, they are, in general, symmetric but full, yet small in size, and the unsymmetric eigenvalue problem becomes:

$$-\omega^2 \left\{ u_a \right\} + [M_{aa}]^{-1} \cdot [K_{aa}] \left\{ u_a \right\} = \left\{ 0 \right\}$$

Both eigenvalues and eigenvectors are found for the reduced size problem.

CHAPTER IV

COMPUTER IMPLEMENTATION

4.1 General Framework

The essence of this section will be the discussion of each module of the program, how it was used, where it was used and why it was used. Also addressed herein will be any modifications or adaptations to each of the modules. As discussed earlier, the program consists of four parts: the executive module, ICAN, thermal analyzer and STAEBL/GENCOM. The theories and backgrounds of the last three modules were discussed in the previous chapter. This segment will examine closely the interaction that each module has with each other as well as its collaboration with the executive module.

Figure 4-1 displays the general framework and flow of the program. To start, all variables for an initial design are input, this initial design sets up the geometry and design criteria for ICAN, STAEBL/GENCOM and the thermal analyzer. Included are connectivities, boundary conditions and mechanical loads applied to the structure. As earlier specified, STAEBL/GENCOM will use NASTRAN-type formats and figure 4-2 shows the arrangement of nodes and plate elements used in this study. The thermal analyzer will use an 8-node brick element, figure 4-3 displays the geometry of the structure as viewed by this module.

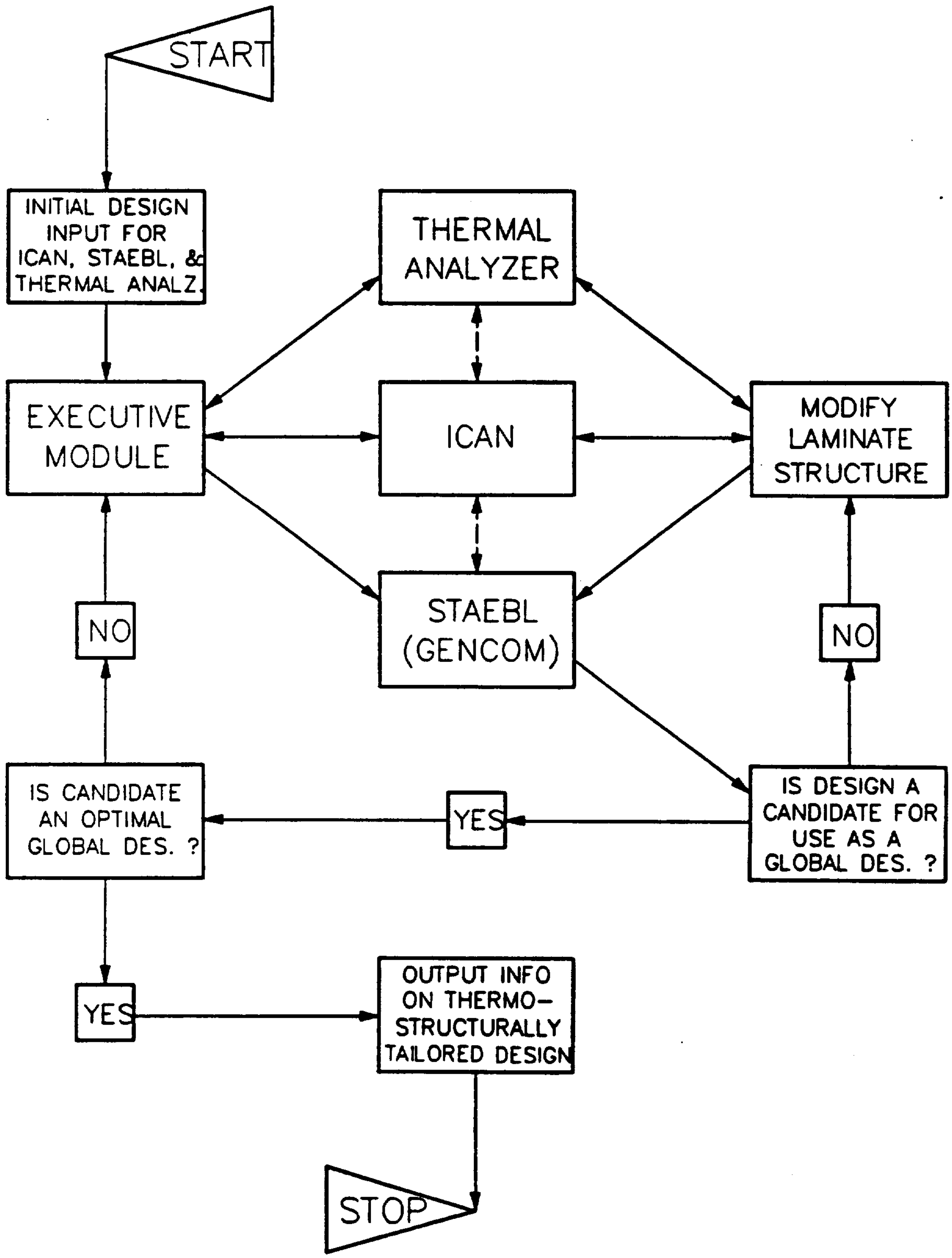


Figure 4. 1 : Flowchart

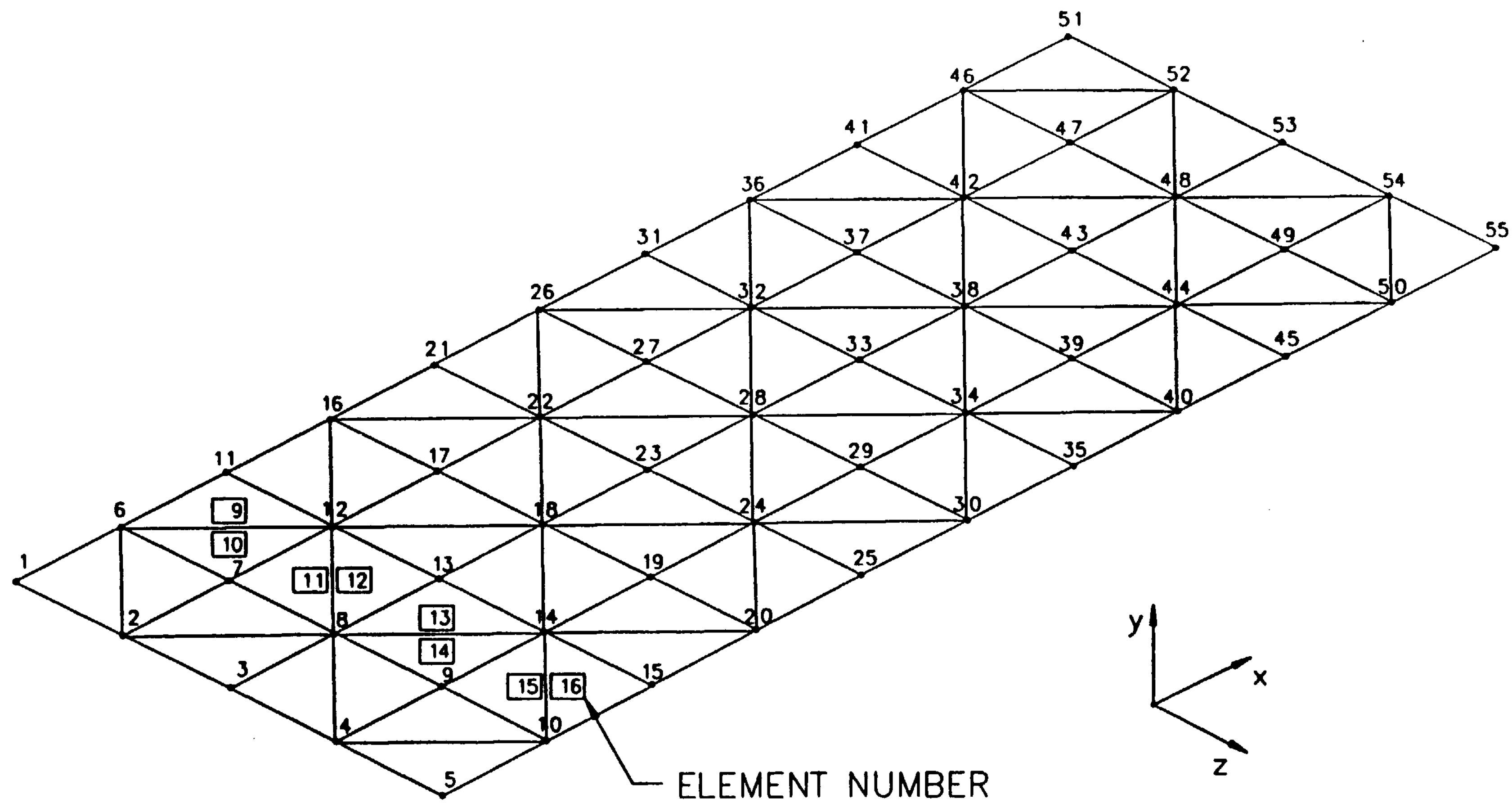


Figure 4.2 : STAEBL Finite Element Mesh

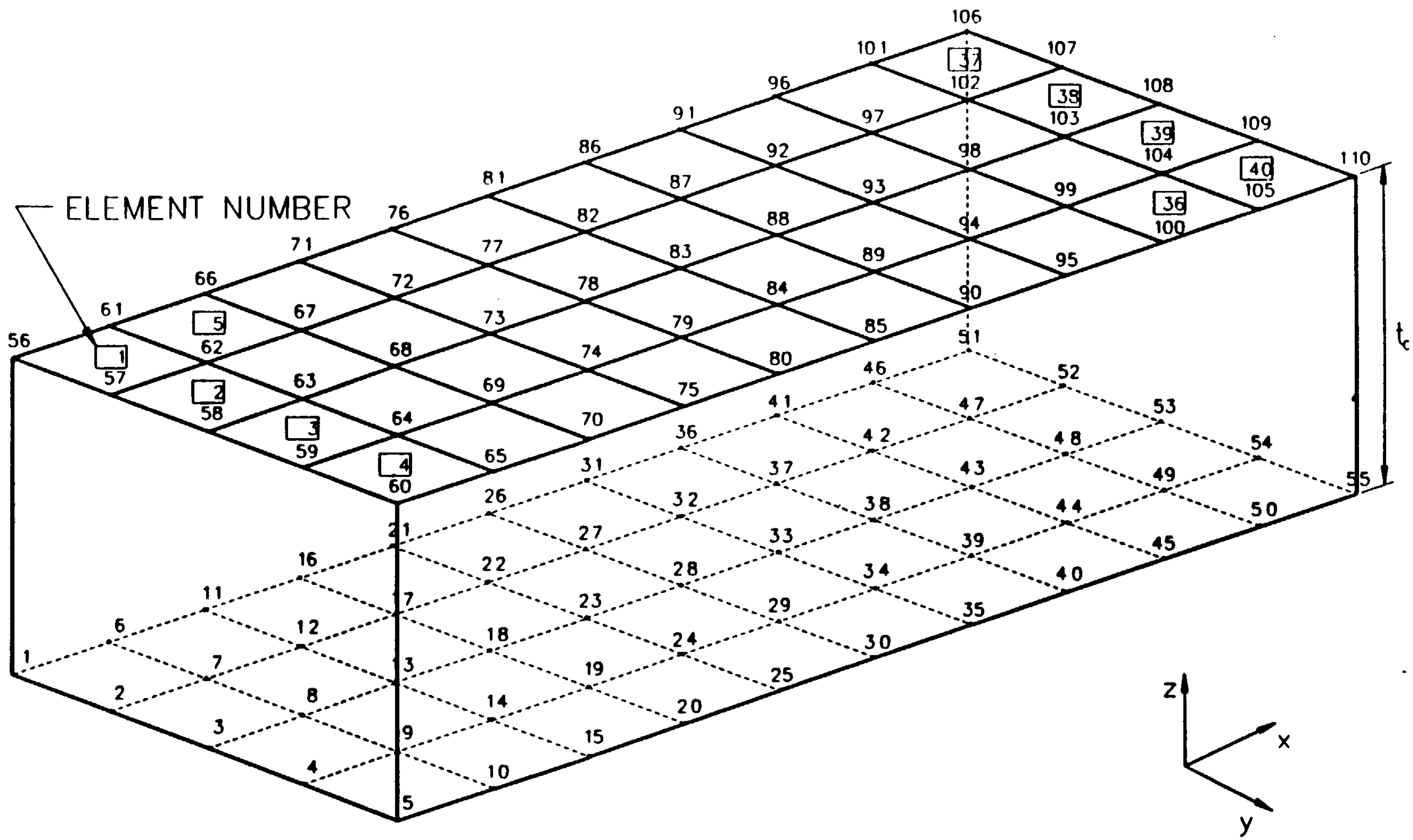


Figure 4.3 : Thermal Analyzer Finite Element Mesh

After the input variables are read, the next steps of the program involve ICAN and the thermal analyzer. ICAN is called to provide the thermal conductivities of the composite material at room temperature. These thermal conductivities are employed by the thermal analyzer to generate the temperature profile in the structure. This temperature profile is dependent upon the thermal loads applied to the structure. ICAN is now engaged to produce the element membrane and bending properties along with the failure criteria and thermal stresses. The location of this latest call to ICAN is dependent on the type of thermal load condition encountered. The call will be denoted with dashed lines on Figure 4.1 between ICAN and the other two modules. If a thermal gradient exists along the length or width of the structure, each plate element may have a different temperature gradient. In view of this fact, combined with the reality that many of the properties are temperature dependent, they must therefore be calculated for each element and so this final call to ICAN comes from STAEBL/GENCOM. If it is found that the temperature gradient through the thickness is the same for each element, then one call from the thermal analyzer is all that is needed to generate the properties for the entire structure.

The subsequent stage of the program involves the optimizer and finite element analysis of STAEBL/GENCOM. The optimizer will perturb each design variable from the assigned initial design, then the analysis outlined in the previous paragraph is applied to each of these designs. The finite element analysis uses the calculated properties to output the displacements for each node and the stresses for each element. These elemental stresses are converted to internal mechanical loads to be used in the final ICAN analysis for determining failure criteria. By comparing the output of each design, a gradient is established that will move the global design toward an optimum as determined by the assigned decision variable and constraints.

Once a global design is decided on, it is then compared to the previous global design. If there is no relative change in the design variables, the global design is said to be optimal and all pertinent information is output. If the design is determined not to be optimal, the process starts over and continues until an optimal global design is established.

4.2 ICAN

The only change in ICAN apparent to the user is the load cards. Originally there were three "PLOAD" cards for each loading condition. The first card contained entries for the membrane loads along with their orientation. The second card contained the bending resultants, and the last card, the transverse shear resultants and the transverse pressures. These cards no longer are needed considering the loads now are being generated from the stresses output in STAEBL/GENCOM. In place of the three "PLOAD" cards a single "ELOAD" card will be used and will have the format shown below.

1 8	9 16	17 24	25 32	33 40
MNEMONIC	NSTR	NEND	NINC	NANL
ELOAD	9	16	7	1

The card in this group starts with the mnemonic "ELOAD". Each entry in the card will be defined as follows:

NSTR: starting element number

NEND: ending element number

NINC: increment of element numbers between the NSTR and NEND

NANL: type of thermal gradient expected:

1: gradient through the thickness only

2: gradient along the length only

3: gradient along the width only

4: any gradient combination of 1, 2 or 3

Note that the element numbering system used here is the same used in STAEBL/GENCOM, see figure 4-1.

Outwardly, the use of the "ELOAD" card is a minor change, but in reality it has multiple effects. First, it informs ICAN which elemental mechanical loads to apply to its analyses since the stresses within each element may differ depending on the type of global load conditions applied. Secondly, the thermal analyzer uses the gradient information when assigning temperature output to each layer in each element. Finally, STAEBL/GENCOM utilizes the data in determining the pertinent failure criteria to be conveyed to the optimizer for possible constraint evaluations.

4.3 Thermal Analyzer

The sole change discernible in the thermal analyzer was the method by which the thermal properties are input. Initially, these properties were contained in the thermal analyzer input deck. They are now being generated in the ICAN module and passed to the thermal analyzer. This procedure is considered valid only because the composite analysis done by ICAN will render the essentially heterogeneous composite structure into a quasi-homogeneous structure where the thermal properties along the structural axes are known. The thermal analyzer uses these properties to evaluate the temperature profile within the structure due to the thermal loads applied. This temperature profile will be utilized by the other modules in the structural analysis procedure.

4.4 STAEBL/GENCOM

The modifications to STAEBL/GENCOM were much more extensive than the other two modules. All but two of the input files were either eliminated or hard coded into the module. At present, the needed input data includes any optimization information, geometry and connectivities of the initial design, along with the initial layup and design information.

The boundary conditions are needed as part of the STAEBL/GENCOM input file. For purposes of this research, nodes 1-5 (see figure 3-10) are restricted from movement in all directions except along the width. This will allow for thermal expansion of these nodes. The boundary conditions that involve the Guyan reduction pattern (see figure 3-10) are entered as ASET card information directly into the code.

The mechanical loads applied to the structure are input through the SAVX file. The loads are entered using English notation and will be applied in much the same manner as the boundary conditions. There will be 55 lines of input to this file, one for each node. Each line has six entries. The first three correspond to an extension load applied in the directions of the main axis, that being along the length, through the thickness, and along the width. Figure 4-2 shows the positive directions of each. The final three entries correspond to moment loads applied in the same direction as the extension loads. These mechanical loads combined with thermal and hygral loads are employed by the finite element within STAEBL/GENCOM to output the stresses (σ_{xx}, σ_{yy}, σ_{xy}) at the top and bottom of each element. Owing to the fact that this is a linear case study, a combined stress formula can be incorporated with this stress output to calculate the loads needed for the composites failure analysis.

The combined stress formula uses the coalition of stresses due to axial and bending loads. Therefore,

$$\sigma = \frac{N}{A} \pm \frac{M\,c}{I}$$

σ = top or bottom stress, i.e. σ^T and σ^B

N = axial loads (N_{cxx}, N_{cyy}, N_{cxy})

M = bending loads (M_{cxx}, M_{cyy}, M_{cxy})

A = area per unit length, i.e., thickness (t)

I = moment of inertia per unit length, i.e., $\frac{t^3}{12}$

c = distance to stresses, i.e. $\frac{t}{2}$ for top and bottom and so:

$$\sigma_c^T = \frac{N_c}{t} + \frac{6\ M_c}{t^2} \tag{4-1}$$

$$\sigma_c^B = \frac{N_c}{t} - \frac{6\ M_c}{t^2} \tag{4-2}$$

by adding equations 4-1 and 4-2:

$$\sigma_c^T + \sigma_c^B = \frac{2\ N_c}{t}$$

It follows that:

$$N_c = \frac{t}{2}\ (\sigma_c^T + \sigma_c^B) \tag{4-3}$$

by subtracting equations 4-1 and 4-2:

$$\sigma_c^T + \sigma_c^B = \frac{12\ M_c}{t^2}$$

it then can be shown that:

$$M_c = \frac{t^2}{12}\ (\sigma_c^T + \sigma_c^B) \tag{4-4}$$

Equations 4-3 and 4-4 are used for the calculation of N_{cxx}, N_{cyy}, N_{cxy} and M_{cxx}, M_{cyy}, M_{cxy} at each element. These membrane loads are transferred to the ICAN module for the composite analysis of any element in question. The elements in consideration have been defined on the "ELOAD" card located in the ICAN input deck.

Finally, in addition to the above changes, alterations were made to the global variable array. This array contains all the possible decision variables, design variables and constraints used by the optimizer in determining an optimal design. The new variables include the NASTRAN bending equivalent elastic coefficients (G11, G22, G12), maximum static nodal displacement in the directions of the main axes (x, y, z), overall composite thickness and the combined stress failure criteria of each composite material.

CHAPTER V

CASE STUDY APPLICATION

In the previous chapter, the general framework of the executive module was described. Also included was an explicit explanation of how each of the other modules were incorporated into the program. The next step will be the verification of the integrated program by applying a set of test cases. This chapter will characterize the design factors involved in this validation process. It will also define any involvement these design factors may have with the predescribed demonstration cases. It would be appropriate at this time to state that the test cases described here will only be a verification that the executive module has successfully integrated all the other modules involved in this research. It is assumed that the modules have been individually verified.

The typical cross-section of the composite structure involved with each test case, and later the demonstration cases, is shown with figure 5.1. This figure shows the properties of the cross-section that were used as design variables: composite thickness, material thickness and ply angle. This generic section may be adjusted considering the allowance of these design variables to change over a predetermined range. The range is dependent upon which property of the cross-section is being addressed. A maximum composite thickness of 0.625 inches was used for all cases studied. For the individual material systems, the maximum thickness was

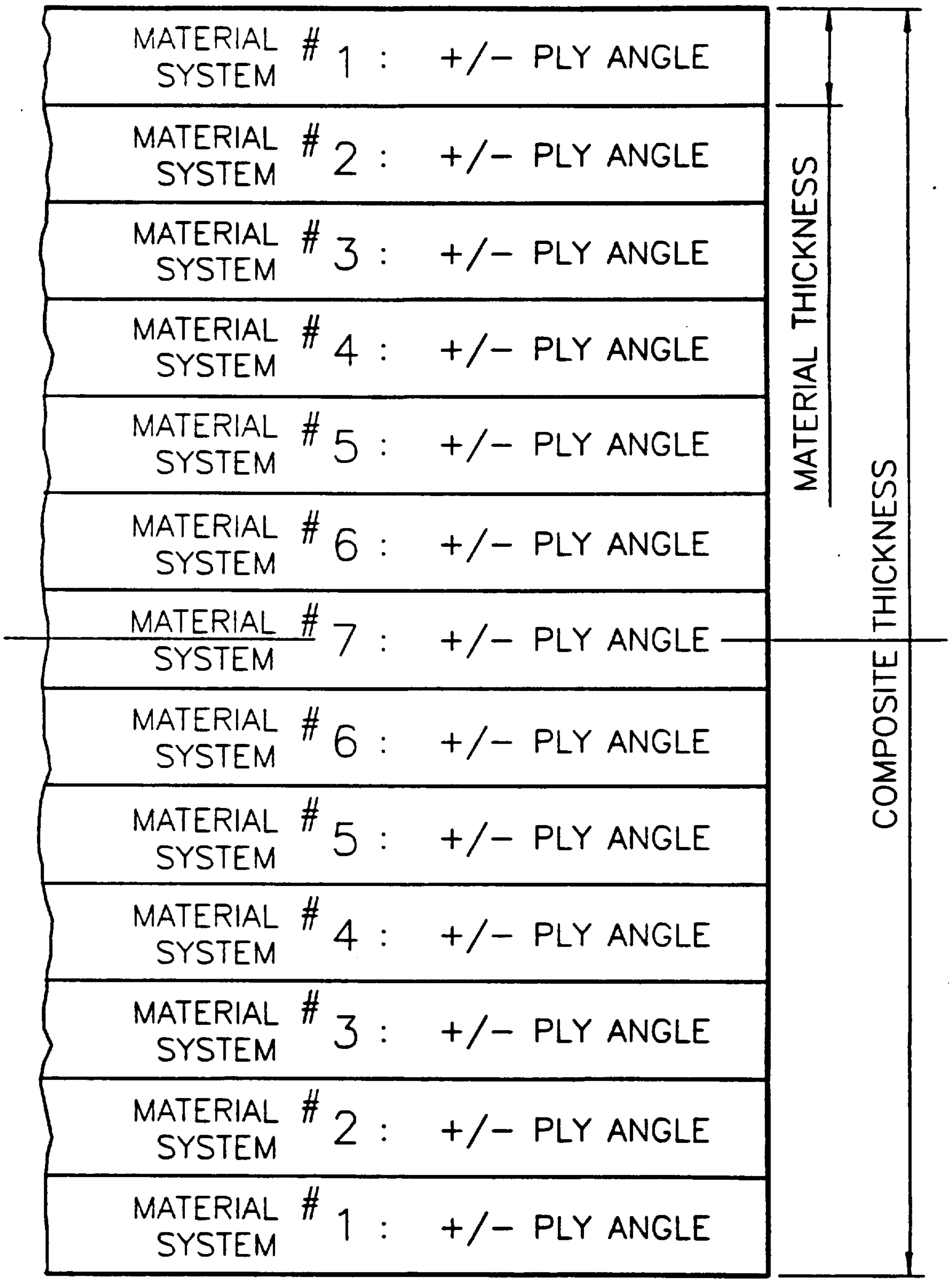


Figure 5.1 : Typical Composite Section

0.050 inches. Material system No. 7 was the only exception, a thickness of 0.025 inches was applied. The material systems are built up from individual plies, each 0.005 inches thick; the ply angles can vary from +90.0 degrees to -90.0 degrees. If a particular material system is not needed due to the relationship of the overall composite thickness to the combined thicknesses of the seven material systems, the material system number in question will be labeled "not used" in the tables referred to later in this chapter and the Appendix. This is done in order to present the results in a consistent format.

Several load conditions will be attached to this structure, and for each load condition an appropriate objective function is chosen. The objective function for the test cases, as well as the demonstration cases, will be a bending modulus that is considered to best model the equivalent of a NASTRAN-obtained bending modulus for the entire structure. The optimal value of the bending modulus in question will be the largest possible value.

The choice of design variable is dependent on the objective function used; a design variable that has a noticeable effect on the objective function is most desirable. The ply angle direction of each material system was the first choice of a design variable because of its strong effect on the bending modulus of a composite structure as well as the failure criteria of the individual plies. The ply angles of each material system will be measured off the 1-1 (x-x) axis for the validation cases as well as each demonstration case. When an attempt was made to facilitate a clear design, it was found that ply angle direction was not as effective as first thought in some of the demonstration cases. Material system thickness and the overall thickness of the composite were some of the acceptable substitutes used. For the purpose of program validation, the ply angle directions were determined to be suitable design variables. The use and results of the other design variables mentioned will be expounded upon in the section dedicated to the demonstration cases.

The final factor involved in controlling the design tailoring of a composite structure will be choosing the constraint variables. For the test cases, the combined stress failure criteria and maximum static deflection of the structure will be used. With regard to the demonstration cases, only the combined stress failure criteria was deemed relevant for design purposes. The stress failure criteria is based on the failure of an individual ply due to an applied stress. This translates into a failure of the entire structure.

5.1 Validation Cases

Tables 5.1 through 5.5 (pages 52 through 56) depict the form of each validation (test) case to be presented. This same descriptive format is used to document the demonstration cases. The top of each table shows the fiber/matrix system as well as the load conditions applied to the composite structure. The balance of each table will display the initial and final design values for the objective function, the design variables and the constraint variables.

TABLE 5.1 : TEST CASE # 1

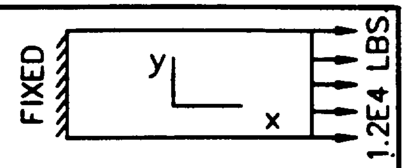
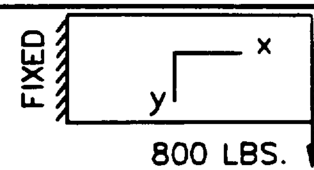
FIBER/MATRIX SYSTEM				LOAD CONDITION	
T300 / IMHS FVR: 0.62				TEMP. EACH NODE $T_u = 250.0^{\circ}F$	
OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)			170.0072	196.3611
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	0.0000
			2	30.0000	0.0820
			3	60.0000	5.9920
			4	90.0000	89.9130
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0172	0.0183
			2	0.0188	0.0183
			3	0.0221	0.0184
			4	0.0238	0.0257
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
	MAX. STATIC DEFLEC. IN 'X' DIREC. (IN.) 3.50E–4 ≤ Δ ≤ 5.50E–4			5.1486E–4	3.5000E–4

TABLE 5.2 : TEST CASE #2

FIBER/MATRIX SYSTEM	LOAD CONDITION	
T300 / IMHS FVR: 0.62	TEMP. EACH NODE $T_u = 250.0^\circ F$	

OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)			170.0072	194.4557
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	0.0000
			2	30.0000	0.0820
			3	60.0000	16.7150
			4	90.0000	89.8920
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 − MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0172	0.0146
			2	0.0188	0.0146
			3	0.0221	0.0199
			4	0.0238	0.0307
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
	MAX. STATIC DEFLEC. IN 'Y' DIREC. (IN.) $0.90E-2 \le \Delta \le 1.15E-2$			0.9747E−2	1.1500E−2

TABLE 5.3 : TEST CASE #3

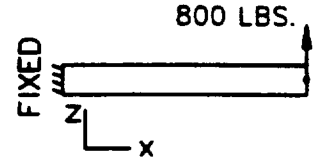
FIBER/MATRIX SYSTEM				LOAD CONDITION	
T300 / IMHS FVR: 0.62				TEMP. EACH NODE $T_u = 250.0^{0}F$	
OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)			170.0072	193.2950
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	0.0000
			2	30.0000	0.0820
			3	60.0000	21.0780
			4	90.0000	89.9390
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0172	0.0566
			2	0.0188	0.0357
			3	0.0221	0.0264
			4	0.0238	0.0371
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
	MAX. STATIC DEFLEC. IN 'Z' DIREC. (IN.) $2.50E-1 \leq \Delta \leq 3.00E-1$			2.8657E-1	2.4932E-1

TABLE 5.4 : TEST CASE #4

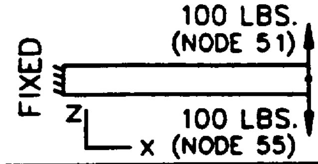
FIBER/MATRIX SYSTEM				LOAD CONDITION	
T300 / IMHS FVR: 0.62				TEMP. EACH NODE $T_u = 250.0^{\circ}$ F	
OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)			170.0072	180.4136
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	0.0000
			2	30.0000	15.7390
			3	60.0000	51.4950
			4	90.0000	90.0000
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0172	0.0170
			2	0.0188	0.0193
			3	0.0221	0.0252
			4	0.0238	0.0259
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
	MAX. STATIC DEFLEC. IN 'Z' DIREC. (IN.) $2.00E-2 \le \Delta \le 2.70E-2$			2.1826E−2	2.7027E−2

TABLE 5.5 : TEST CASE #5

<table>
<tr><td colspan="3">FIBER / MATRIX SYSTEM
T300 / IMHS
FVR: 0.62</td><td>LOAD CONDITION
TEMP. EACH NODE
$T_u = 250.0^\circ F$</td><td>NO MECHANICAL
LOADS APPLIED</td></tr>
<tr><td colspan="3">OPTIMIZATION VARIABLES</td><td>INITIAL DESIGN</td><td>FINAL DESIGN</td></tr>
<tr><td>OBJECTIVE FUNCTION</td><td colspan="2">NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)</td><td>170.0072</td><td>177.0385</td></tr>
<tr><td rowspan="7">DESIGN VARIABLES</td><td rowspan="7">PLY ANGLES (DEGREES)</td><td>MATERIAL SYSTEM # 1</td><td>0.0000</td><td>0.0000</td></tr>
<tr><td>2</td><td>30.0000</td><td>20.7020</td></tr>
<tr><td>3</td><td>60.0000</td><td>54.4550</td></tr>
<tr><td>4</td><td>90.0000</td><td>90.0000</td></tr>
<tr><td>5</td><td>NOT USED</td><td>NOT USED</td></tr>
<tr><td>6</td><td>NOT USED</td><td>NOT USED</td></tr>
<tr><td>7</td><td>NOT USED</td><td>NOT USED</td></tr>
<tr><td rowspan="8">CONSTRAINT VARIABLES</td><td rowspan="7">STRESS FAILURE CRITERIA
F = 1.0 – MDEIE
NO FAILURE : F < 1
INCIPIENT : F = 1
FAILURE : F > 1</td><td>MATERIAL SYSTEM # 1</td><td>0.0172</td><td>0.1641</td></tr>
<tr><td>2</td><td>0.0188</td><td>0.0175</td></tr>
<tr><td>3</td><td>0.0221</td><td>0.0221</td></tr>
<tr><td>4</td><td>0.0238</td><td>0.0250</td></tr>
<tr><td>5</td><td>NOT USED</td><td>NOT USED</td></tr>
<tr><td>6</td><td>NOT USED</td><td>NOT USED</td></tr>
<tr><td>7</td><td>NOT USED</td><td>NOT USED</td></tr>
<tr><td colspan="2">MAX. STATIC DEFLEC. IN 'X' DIREC. (IN.)
$0.30E-4 \leq \Delta \leq 1.50E-4$</td><td>0.3979E−4</td><td>0.3000E−4</td></tr>
</table>

A detailed inspection of the variable values in Table 5.1 (test case No. 1) will show the anticipated trend associated with the particular load condition shown. The fiber direction should align itself in the same direction as the bending modulus for a said bending modulus to be optimal. Therefore, if the modulus in question is "G11", the ply angle of each material system should tend toward zero degrees off the 1-1 axis. Closer examination of the ply angles shows that some stopped short of that zero degree target. The reason for this anomaly comes clear by scrutinizing the constraint variables. The stress failure criteria of each material system were well within the given limits, yet the limiting value of the maximum static deflection was reached and the design obtained was considered to be optimal.

Tables 5.2 and Table 5.3 (test cases No. 2 and No. 3 respectively), are very similar to the first validation case discussed above. The obvious differences are the load conditions and the direction of the maximum allowable deflections. Test case No. 2 has a uniform mechanical load applied in the y-direction, while test case No. 3 has a uniform load applied in the z-direction. In each case, the final design of the composite structure (as in test case No. 1) was determined by the maximum allowable deflection in the direction of the loads.

The final two validation cases, No. 4 and No. 5, shown in Tables 5.4 and 5.5, reassured this researcher that given a twisting load as well as a pure thermal load applied to the structure, the program will perform as expected. These two test cases revealed little when examined alone, but in concert with the other validation cases, they proved to be informative.

The initial design of all five validation cases was the same, but the final designs were determined by their individual load conditions and applied constraints. Since the same objective function is being optimized for each case, a comparison of the final design strength to ply angle directions can be made. It can be observed that the increase in the "G11" NASTRAN bending modulus of the composite structure is in direct proportion to how close the ply angles came to the 1-1 axis. Though this can be regarded as obvious to the trained eye, it is reassuring to see this basic trend come to light.

From the results of the test cases shown on Table 5.1 through 5.5, the modules contained in this program can be considered to have been successfully coupled. The depth of the validation outlined above was determined by the needs of the demonstration cases. The next chapter will expound on further recommendations for program expansion and increased validation testing.

5.2 Demonstration Cases

In Chapter 2, the fiber/matrix systems used for the demonstration cases were described in detail. This section will elaborate on the load conditions applied to each composite system chosen. The effects these different mechanical and thermal loads will have on the composite structure will determine the next step in establishing an optimal design for the aforementioned loading conditions.

Tables 5.6 through 5.35, found in the Appendix (pages 72 to 106), contain the details of each demonstration case and will be referred to periodically throughout the rest of the chapter. In the title of these tables, the demonstration case number also refers to the load condition number shown in figure 5.2; the letter adjacent to the load condition number refers to the following fiber/matrix systems:

A:	AS/IMHS	FVR = 0.60
B:	HMSF/IMHS	FVR = 0.60
C:	HMSF/IMHS//SGLA/IMHS	FVR = 0.60 (each)

For example, demonstration case "4C" will use load case "4" applied to fiber/matrix system "C". For quick reference, each table will contain the fiber/matrix system used as well as the load condition applied.

As mentioned above, figure 5.2 shows the load conditions applied to each composite structure. The details of the mechanical and thermal loads are conveyed in a concise manner in this figure. A steady-state temperature of 250°F will be used with all six mechanical loading conditions. This steady-state condition is needed to isolate the effects of the variety of applied mechanical loads on the structure. The balance of the loads shown in figure 5.2 will be the four thermal gradients applied to the structure. These thermal conditions were designed to segregate thermal gradients in the three directions of the main axes as well as a gradient applied simultaneously in the same three directions.

As stated in the previous section, the only constraints of concern for the demonstration cases are the stress failure criteria of each ply. This has been determined to be an adequate test as to the ability of the structure to withstand the load imposed upon it. If the ply stress failure criteria is less than 1.0, there is no ply failure, and therefore no failure of the structure. If the failure criteria is exactly 1.0, the ply is on the verge of failing, and when the stress failure criteria goes

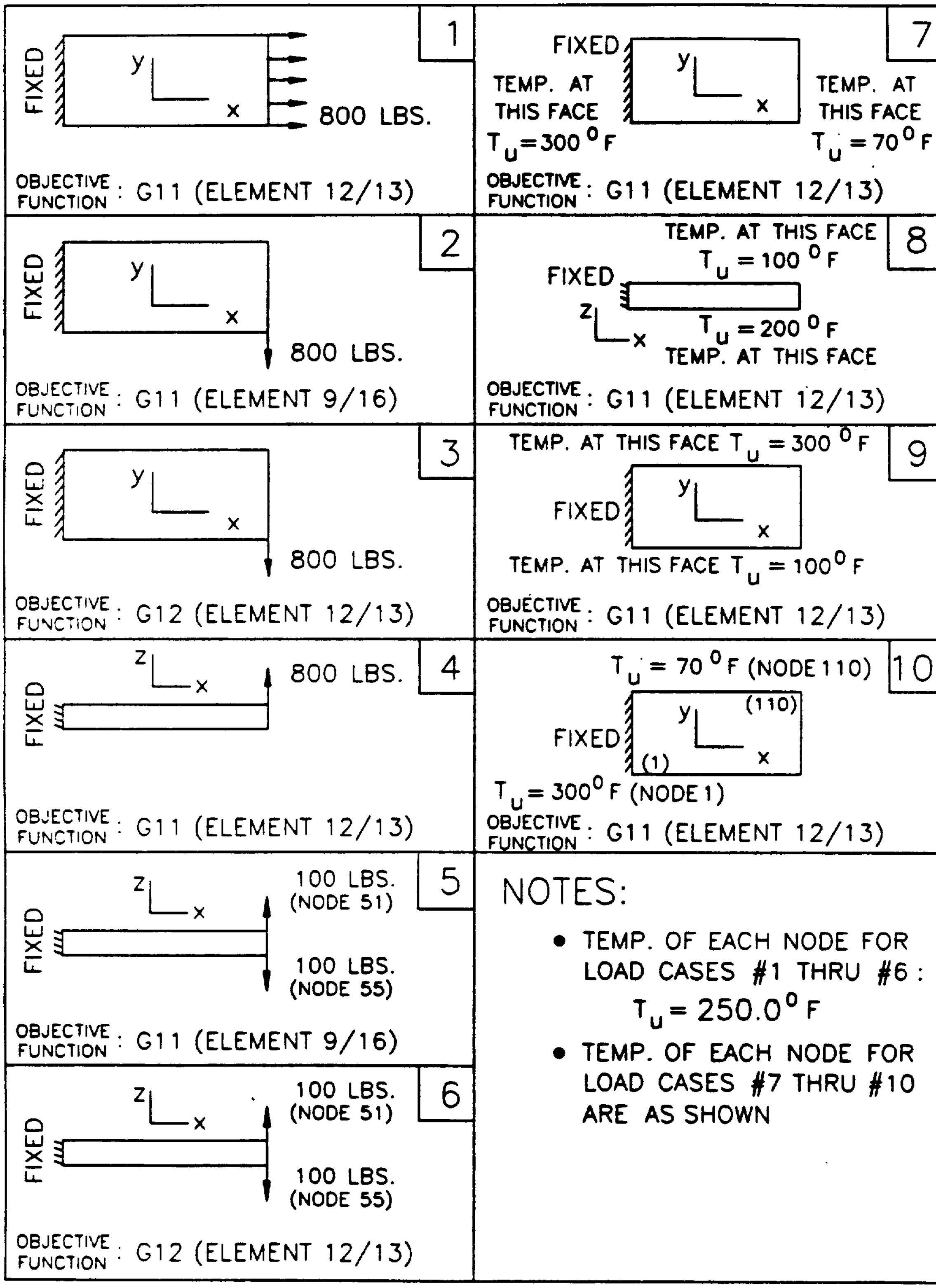


Figure 5.2: Load Conditions

above 1.0, the ply has failed. At the point where an individual ply has failed, the entire structure is considered to have failed.

The balance of this section will discuss some of the more interesting demonstration cases found on Tables 5.6 through 5.35. The ones chosen are considered to have problems that warrant discussion and the unique results are due to their particular combination of load condition, fiber/matrix system and optimization variables.

A detailed look at Table 5.10 reveals the failure of material system No. 4 within the HMSF/IHMS composite structure that has load condition No. 2 imposed on it. Examining the ply angle of said material system shows that it is well off an expected play angle to given an optimal "G11" NASTRAN bending modulus. A second case, Table 5.10.1, was run using the same composite system and load condition, but with different design variables. In this case, the thickness of each material system, rather than the ply angle, was allowed to vary.

Examining the results of this case shows that the optimal bending modulus was obtained by the proper distribution of the material system thicknesses to the system with the critical ply angle. Comparing the results of the two cases shown in Tables 5.10 and 5.10.1 confirms that the original bending modulus had reached an optimum value, within a very small percentage, the failure criteria however, had improved to a value well within the limits of failure. This demonstration case is proof of the sensitivity of the failure criteria to ply angle direction.

The demonstration case that will be addressed next is shown on Table 5.16. The HMSF/IMHS composite structure failed with the initial design having load condition No. 4 bearing on it. It was observed, using engineering judgement, that the structure failed due to inadequate overall composite thickness. This posed an interesting problem of finding the optimal thickness of the composite and still obtaining a maximum value for the "G11" bending modulus. Table 5.16.1 shows the results of how this particular problem was attempted to be solved. The objective function used is the summation of the bending modulus and the inverse of the composite thickness. Analysis of the results discloses an attempt by the program to vary the ply angles to increase the bending modulus, and at the same time, decrease the thickness to an optimal value. Before any effective change of the bending modulus could be made by changing the ply angle direction, the composite thickness was reduced to where the outermost plies were failing under the load. This is evident by the stress failure criteria of material system No. 1 increasing to a value above incipient failure and thus stopping the design.

Using the final design thickness from Table 5.16.1, a third run was made with the same load conditions. This case used the objective function and design variables of the original case shown on Table 5.16. The outcome of this endeavor is displayed in Table 5.16.2. It can be seen that using the new composite thickness, a final optimal design was achieved which kept the stress failure criteria well below the value needed to fail the structure.

The problem encountered using the HMSF/IMHS composite structure was repeated when the same load condition No. 4 was applied to the HMSF/IMHS/SGLA/IMHS intraply composite system. The same methodology as above was applied to this case top obtain a desired design that would not fail with the load bearing on it. The effect of using the problem solving techniques formulated with the previous case is shown in greater detail on Tables 5.17, 5.17.1 and 5.17.2. The aspects of the final design are much the same as those shown in the preceding problem, yet with one big difference; the optimal thickness for this fiber/matrix system is smaller.

5.3 Summary

Each load case was run with identical initial design variables and allowed to reach an optimal design dependent on the respective objective functions and constraints. The ply stress failure values were output for each case, and the maximum value is displayed in figure 5.3. The importance of this constraint variable follows from the fact that the failure of the entire structure hinges on its value. When addressing these results, the structural capacities inherent to each fiber/matrix system are revealed. This is evident from the effects of different load conditions on each composite system. The intrinsic capabilities of these composites can be shown to be directly attributed to the properties of the fibers used in the structure. This observation is based on the knowledge that the same matrix material and fiber volume ratio were used in each composite. Therefore, the differences encountered between the composite system are based strictly on the differences in fiber properties.

Further reinforcement of this statement can be found by a closer examination of figure 5.3. The HMSF/IMHS composite structure appears to perform poorly compared to the other fiber/matrix systems. The maximum stress failure value of the HMSF/IMHS system is greater than the other two systems, yet the NASTRAN bending modulus is the largest. This apparent

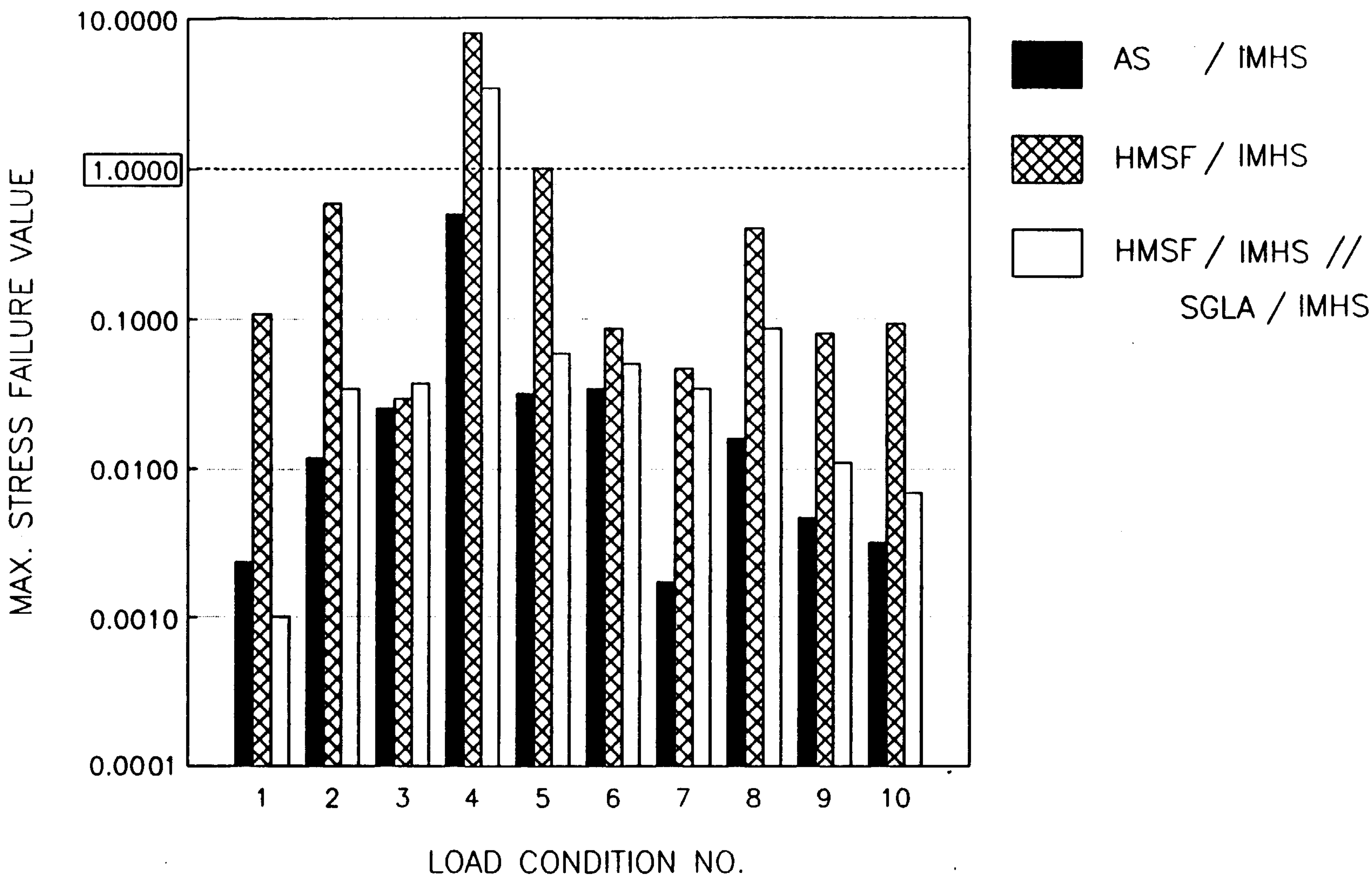


Figure 5.3 : Max. Stress Failure Value per Load Condition

lack of strength is traced to the fiber properties shown in figure 5.4. The strength of the "AS" and "SGLA" fibers is larger than the "HMSF", but the normal moduli is lower. Taking this into consideration, it is now understood why the overall composite strength was improved when the "SGLA" fiber was intermixed with the "HMSF" fiber.

Name : Symbol	Units	AS	SGLA	HMSF
Density : $_{f}$	lb/in^3	0.063	0.090	0.070
Longit. modulus : E_{f11}	10^6 psi	31.00	12.40	55.00
Transv. modulus : E_{f22}	10^6 psi	2.000	12.40	0.900
Long. shear mod. : G_{f12}	10^6 psi	2.000	5.170	1.100
Trans. shear mod. : G_{f23}	10^6 psi	1.000	5.170	0.700
Longitudinal Poisson's ratio : $_{f12}$	--	0.200	0.200	0.200
Transverse Poisson's ratio : $_{f23}$	--	0.250	0.200	0.250
Heat capacity : C_f	$\frac{Btu}{lb-{}^0F}$	0.200	0.170	0.200
Longitudinal heat conductivity : K_{f11}	$\frac{Btu}{hr-ft^2-{}^0F-in}$	580.0	21.00	580.0
Transverse heat conductivity : K_{f22}	$\frac{Btu}{hr-ft^2-{}^0F-in}$	58.00	21.00	58.00
Longit. thermal expansion coeff. : $_{f11}$	$10^{-6}\ \frac{in}{in-{}^0F}$	−55.0	2.800	−55.0
Transv. thermal expansion coeff. : $_{f22}$	$10^{-6}\ \frac{in}{in-{}^0F}$	5.600	2.800	5.600
Longitudinal tension strength : S_{ft}	ksi	350.0	600.0	250.0
Longitudinal compressive str. : S_{fc}	ksi	260.0	540.0	200.0

Figure 5.4 : Fiber Properties

CHAPTER VI

OBSERVATIONS, RECOMMENDATIONS AND SUMMARY

As researchers strive to improve their understanding of new and existing materials, the marriage of laboratory testing and computer software development was a necessity. From this union, many different disciplines of study were able to develop accurate and capable programs. As computer software development evolved, it was evident that a more "real life" loads environment could be duplicated without the major expense of repeated labor and hardware intensive laboratory test. I am not advocating abandoning the use of laboratory testing, but with the application of multidiscipline software, expensive testing processes can be reduced. This can be accomplished by generating a design from a verified multidiscipline program. This design will be tailored to a combined load condition derived from surroundings the structure is exposed to. The final step is to confirm the design by duplicating the environment in a test cell and testing a prototype of the structure.

This project could be considered to be a step toward the evolution of multidiscipline software in the field of composite mechanics. With the successful integration of programs involving composite mechanics, heat transfer, structural analysis and structural optimization, it becomes evident that a composite structure can be designed to a combined loads environment. This first step individually applied various thermal and mechanical loads to a composite structure. The computer code notably used ply angles, ply thickness and combined stress criteria to affect the design of the composite. The integrated program performed well in designing a composite upon which different isolated mechanical loads were imposed. The effects of combined mechanical load conditions were not detailed in this research. Combinations of the load cases used in this research are left to be run as a follow-on to this research. The evaluation of results from the combined mechanical load states will lead to a more complete study of the fiber/matrix systems used.

Elaborating on this statement, it is evident that the expansion of this research is necessary. As mentioned above, increasing the variety of demonstration cases is one suggestion. Incorporating different composite properties as design variables could greatly increase the number of design possibilities. The use of cost or weight constraints could be helpful since these are two important design drivers in the space program. Examining the other fields of study, such as the structural or thermal disciplines, would also expand the possibilities for more research. The structures area could include dynamic loading, not just the static loading investigated here. In the region of heat transfer, the thermal distortion of a structure could be taken into consideration. Fatigue life cycles of a composite structure can also be studied.

In all examples cited above, a full spectrum of validation testing will be needed. As each milestone is reached, verification testing should follow as a means of independent demonstration that true results were obtained.

To reinforce the conclusions, and since the main thrust of this research was the effects of composite materials in a multidiscipline environment, any further research should start here. Expansion of the optimization variables to include the fiber and matrix properties used in ICAN, and including the fiber volume ratio, could help if weight and/or cost versus strength became an issue.

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APPENDIX

TABLE 5.6 : DEMO. CASE # 1A

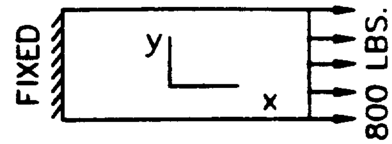
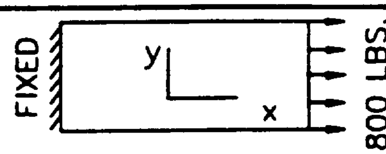
FIBER / MATRIX SYSTEM				LOAD CONDITION	
AS / IMHS FVR: 0.60				TEMP. EACH NODE $T_u = 250.0^{o}F$	
OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)			175.0035	188.0425
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	0.0000
			2	18.0000	– 0.1300
			3	36.0000	0.4320
			4	54.0000	46.2840
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0043	0.0023
			2	0.0113	0.0024
			3	0.0253	0.0026
			4	0.0375	0.0453
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED

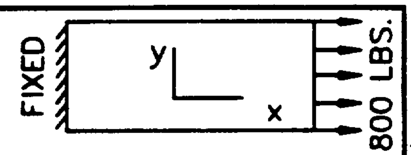
TABLE 5.7 : DEMO. CASE # 1B

FIBER / MATRIX SYSTEM	LOAD CONDITION
HMSF / IMHS FVR: 0.60	TEMP. EACH NODE $T_u = 250.0^0 F$ 

OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)			308.0044	331.8291
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	0.0000
			2	18.0000	−0.2684
			3	36.0000	0.3800
			4	54.0000	38.4180
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 − MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0035	0.0996
			2	0.0586	0.1055
			3	0.1371	0.1080
			4	0.1553	0.8154
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED

TABLE 5.8 : DEMO. CASE # 1C

FIBER/MATRIX SYSTEM		LOAD CONDITION
HMSF/IMHS // SGLA/IMHS		TEMP. EACH NODE
FVR: 0.60	FVR: 0.60	$T_u = 250.0^{\circ}F$
% PLY: 80	% PLY: 20	



OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)			260.7607	280.7705
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	0.0000
			2	18.0000	0.0610
			3	36.0000	0.5410
			4	54.0000	19.0430
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 − MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0049	0.0007
			2	0.0199	0.0007
			3	0.0448	0.0010
			4	0.0662	0.0395
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED

TABLE 5.9 : DEMO. CASE # 2A

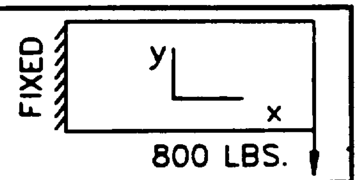
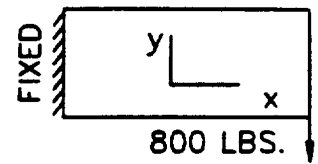
FIBER / MATRIX SYSTEM AS / IMHS FVR: 0.60				LOAD CONDITION TEMP. EACH NODE $T_u = 250.0^0 F$	
OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 9/16)			175.0035	188.0425
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	0.0000
			2	18.0000	– 0.1300
			3	36.0000	0.4320
			4	54.0000	46.2840
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0043	0.0103
			2	0.0113	0.0104
			3	0.0253	0.0107
			4	0.0375	0.0519
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED

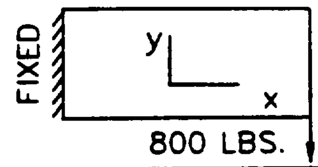
TABLE 5.10 : DEMO. CASE #2B

FIBER/MATRIX SYSTEM	LOAD CONDITION
HMSF / IMHS FVR: 0.60	TEMP. EACH NODE $T_u = 250.0^{o}F$



OPTIMIZATION VARIABLES			INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 9/16)		308.0044	331.6025
DESIGN VARIABLES	PLY ANGLES (DEGREES) — MATERIAL SYSTEM #	1	0.0000	0.0000
		2	18.0000	2.0560
		3	36.0000	0.9800
		4	54.0000	54.0000
		5	NOT USED	NOT USED
		6	NOT USED	NOT USED
		7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1 — MATERIAL SYSTEM #	1	0.0035	0.5153
		2	0.0586	0.5931
		3	0.1371	0.5510
		4	0.1553	1.3752
		5	NOT USED	NOT USED
		6	NOT USED	NOT USED
		7	NOT USED	NOT USED

TABLE 5.10.1 : DEMO. CASE #2B2

FIBER/MATRIX SYSTEM	LOAD CONDITION	
HMSF / IMHS FVR: 0.60	TEMP. EACH NODE $T_u = 250.0^{0}F$	

OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 9/16)			308.0044	331.8411
DESIGN VARIABLES	MATERIAL THICKNESS (INCHES @ PLY ANGLE)	MATERIAL SYSTEM #	1	0.0500 @ 00^{0}	0.1550 @ 00^{0}
			2	0.0500 @ 18^{0}	0.0000 @ 18^{0}
			3	0.0500 @ 36^{0}	0.0000 @ 36^{0}
			4	0.0050 @ 54^{0}	0.0000 @ 54^{0}
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 − MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0035	0.2000
			2	0.0586	----
			3	0.1371	----
			4	0.1553	----
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED

TABLE 5.11 : DEMO. CASE # 2C

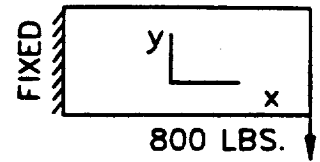
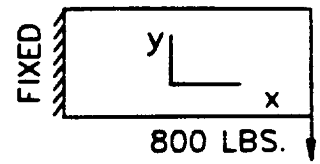
FIBER / MATRIX SYSTEM				LOAD CONDITION	
HMSF / IMHS // SGLA / IMHS FVR: 0.60 FVR: 0.60 % PLY: 80 % PLY: 20				TEMP. EACH NODE $T_u = 250.0^\circ F$	
OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 9/16)			260.7607	280.7705
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	0.0000
			2	18.0000	0.0610
			3	36.0000	0.5410
			4	54.0000	19.0430
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0049	0.0332
			2	0.0199	0.0332
			3	0.0448	0.0334
			4	0.0662	0.0347
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED

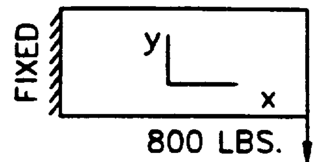
TABLE 5.12 : DEMO. CASE # 3A

FIBER / MATRIX SYSTEM	LOAD CONDITION
AS / IMHS FVR: 0.60	TEMP. EACH NODE $T_u = 250.0^{\circ}F$



OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G12 (ELEMENT 12/13)			8.2800	16.0392
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	0.0000
			2	18.0000	44.9737
			3	36.0000	46.1552
			4	54.0000	53.9851
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0043	0.0133
			2	0.0113	0.0249
			3	0.0253	0.0253
			4	0.0375	0.0209
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED

TABLE 5.13 : DEMO. CASE # 3B

FIBER/MATRIX SYSTEM	LOAD CONDITION	
HMSF / IMHS FVR: 0.60	TEMP. EACH NODE $T_u = 250.0^{\circ}F$	

OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G12 (ELEMENT 12/13)			12.2744	26.4908
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	0.0000
			2	18.0000	44.8047
			3	36.0000	45.9202
			4	54.0000	53.9840
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 − MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0035	0.0072
			2	0.0586	0.0288
			3	0.1371	0.0287
			4	0.1553	0.0256
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED

TABLE 5.14 : DEMO. CASE # 3C

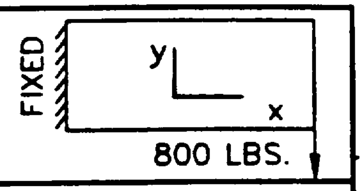
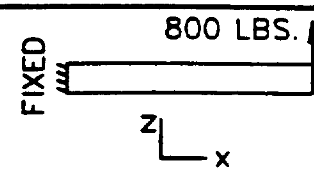
FIBER / MATRIX SYSTEM			LOAD CONDITION	
HMSF / IMHS // SGLA / IMHS FVR: 0.60 FVR: 0.60 % PLY: 80 % PLY: 20			TEMP. EACH NODE $T_u = 250.0^{\circ}F$	
OPTIMIZATION VARIABLES			INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G12 (ELEMENT 12/13)		10.7768	22.6956
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM # 1	0.0000	0.0000
		2	18.0000	45.0151
		3	36.0000	46.1603
		4	54.0000	53.9770
		5	NOT USED	NOT USED
		6	NOT USED	NOT USED
		7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM # 1	0.0049	0.0165
		2	0.0199	0.0356
		3	0.0448	0.0360
		4	0.0662	0.0283
		5	NOT USED	NOT USED
		6	NOT USED	NOT USED
		7	NOT USED	NOT USED

TABLE 5.15 : DEMO. CASE #4A

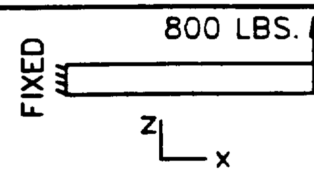
FIBER/MATRIX SYSTEM	LOAD CONDITION	
AS / IMHS FVR: 0.60	TEMP. EACH NODE $T_u = 250.0^\circ F$	

OPTIMIZATION VARIABLES			INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)		175.0035	188.0326
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM # 1	0.0000	0.0000
		2	18.0000	– 0.3961
		3	36.0000	1.1737
		4	54.0000	50.1540
		5	NOT USED	NOT USED
		6	NOT USED	NOT USED
		7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM # 1	0.0043	0.4846
		2	0.0113	0.2169
		3	0.0253	0.0568
		4	0.0375	0.0516
		5	NOT USED	NOT USED
		6	NOT USED	NOT USED
		7	NOT USED	NOT USED

TABLE 5.16 : DEMO. CASE #4B

FIBER/MATRIX SYSTEM
HMSF / IMHS
FVR: 0.60

LOAD CONDITION
TEMP. EACH NODE
$T_u = 250.0^{\circ} F$



OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)			308.0044	
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	
			2	18.0000	
			3	36.0000	
			4	54.0000	
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	8.0508	
			2	3.1547	
			3	0.6581	
			4	0.1687	
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED

TABLE 5.16.1 : DEMO. CASE #4B2

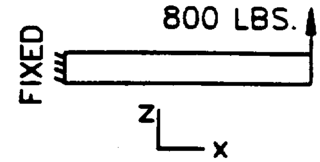
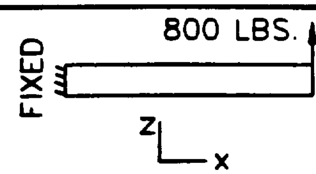
FIBER/MATRIX SYSTEM HMSF / IMHS FVR: 0.60			LOAD CONDITION TEMP. EACH NODE $T_u = 250.0^0 F$	
OPTIMIZATION VARIABLES			INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	BENDING MODULUS + INVERSE OF THICKNESS (G11 + 1.0 / t_c) (ELEMENT 12/13)		244.2977	261.7686
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM # 1	0.0000	0.0000
		2	18.0000	17.6872
		3	36.0000	35.0955
		4	54.0000	53.4269
		5	72.0000	71.9281
		6	90.0000	90.0000
		7	0.0000	----
	COMPOSITE THICKNESS (IN.)		0.6200	0.5484
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM # 1	0.0116	1.0015
		2	0.0117	0.5486
		3	0.0118	0.1978
		4	0.0120	0.0644
		5	0.0122	0.0254
		6	0.0122	0.0148
		7	0.0116	----

TABLE 5.16.2 : DEMO. CASE #4B3

FIBER/MATRIX SYSTEM	LOAD CONDITION	
HMSF / IMHS FVR: 0.60	TEMP. EACH NODE $T_u = 250.0^0 F$	

OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)			257.1384	331.5830
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	0.0000
			2	18.0000	0.1660
			3	36.0000	0.1628
			4	54.0000	0.4220
			5	72.0000	1.3700
			6	90.0000	95.0850
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0110	0.5163
			2	0.0113	0.3287
			3	0.0119	0.1836
			4	0.0125	0.0808
			5	0.0128	0.0208
			6	0.0130	0.0476
			7	NOT USED	NOT USED

TABLE 5.17 : DEMO. CASE #4C

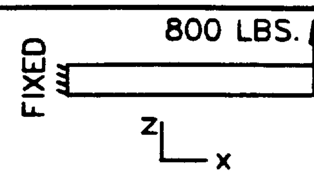
FIBER/MATRIX SYSTEM				LOAD CONDITION	
HMSF/IMHS // SGLA/IMHS FVR: 0.60 FVR: 0.60 % PLY: 80 % PLY: 20				TEMP. EACH NODE $T_u = 250.0^{\circ}F$	
OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)			260.7607	
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	
			2	18.0000	
			3	36.0000	
			4	54.0000	
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 − MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	3.4189	
			2	1.1535	
			3	0.1059	
			4	0.0678	
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED

TABLE 5.17.1 : DEMO. CASE #4C2

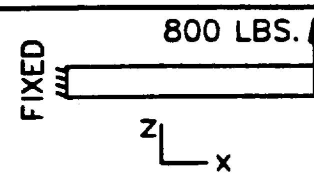
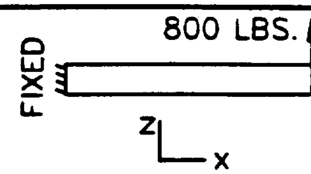
FIBER / MATRIX SYSTEM			LOAD CONDITION	
HMSF / IMHS // SGLA / IMHS FVR: 0.60 FVR: 0.60 % PLY: 80 % PLY: 20			TEMP. EACH NODE $T_u = 250.0^{\circ}F$	
OPTIMIZATION VARIABLES			INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	BENDING MODULUS + INVERSE OF THICKNESS $(G11 + 1.0 / t_c)$ (ELEMENT 12/13)		207.5044	247.7756
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM # 1	0.0000	0.0000
		2	18.0000	16.7065
		3	36.0000	32.6863
		4	54.0000	52.2459
		5	72.0000	71.8550
		6	90.0000	----
		7	0.0000	----
	COMPOSITE THICKNESS (IN.)		0.6200	0.4270
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM # 1	0.0262	0.9977
		2	0.0263	0.4356
		3	0.0266	0.0849
		4	0.0269	0.0439
		5	0.0271	0.0423
		6	0.0272	----
		7	0.0262	----

TABLE 5.17.2 : DEMO. CASE #4C3

FIBER / MATRIX SYSTEM	LOAD CONDITION	
HMSF / IMHS // SGLA / IMHS FVR: 0.60 FVR: 0.60 % PLY: 80 % PLY: 20	TEMP. EACH NODE $T_u = 250.0^{o}$ F	

OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)			240.9406	280.7046
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	0.0000
			2	18.0000	0.2610
			3	36.0000	– 0.4880
			4	54.0000	1.0140
			5	72.0000	71.6960
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0180	0.6513
			2	0.0216	0.3578
			3	0.0267	0.1514
			4	0.0328	0.0350
			5	0.0376	0.0980
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED

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TABLE 5.18 : DEMO. CASE # 5A

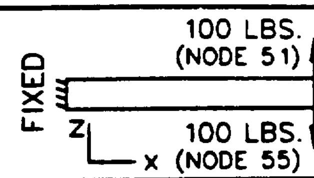
FIBER / MATRIX SYSTEM AS / IMHS FVR: 0.60				LOAD CONDITION TEMP. EACH NODE $T_u = 250.0^{\circ}F$	
OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 9/16)			175.0035	188.0326
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	0.0000
			2	18.0000	– 0.1300
			3	36.0000	0.4320
			4	54.0000	46.2840
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0043	0.0314
			2	0.0113	0.0182
			3	0.0253	0.0081
			4	0.0375	0.0466
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED

TABLE 5.19 : DEMO. CASE #5B

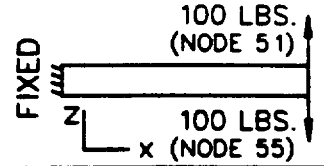
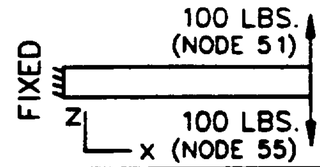
FIBER/MATRIX SYSTEM				LOAD CONDITION	
HMSF / IMHS FVR: 0.60				TEMP. EACH NODE $T_u = 250.0^0 F$	
OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 9/16)			308.0044	331.4558
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	0.0000
			2	18.0000	− 1.8559
			3	36.0000	4.7415
			4	54.0000	53.1936
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 − MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0035	1.0014
			2	0.0586	0.7041
			3	0.1371	0.4648
			4	0.1553	0.8008
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED

TABLE 5.20 : DEMO. CASE # 5C

FIBER / MATRIX SYSTEM		LOAD CONDITION
HMSF / IMHS // SGLA / IMHS		TEMP. EACH NODE
FVR: 0.60	FVR: 0.60	$T_u = 250.0^{\circ}F$
% PLY: 80	% PLY: 20	



OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 9/16)			260.7607	280.7705
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	0.0000
			2	18.0000	0.0610
			3	36.0000	0.5410
			4	54.0000	19.0430
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0049	0.0588
			2	0.0199	0.0289
			3	0.0448	0.0097
			4	0.0662	0.0416
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED

TABLE 5.21 : DEMO. CASE # 6A

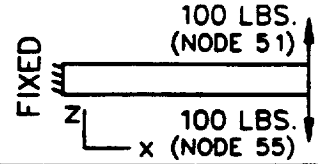
FIBER / MATRIX SYSTEM			LOAD CONDITION	
AS / IMHS FVR: 0.60			TEMP. EACH NODE $T_u = 250.0^{\circ}F$	
OPTIMIZATION VARIABLES			INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G12 (ELEMENT 12/13)		8.2800	16.0392
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM # 1	0.0000	0.0000
		2	18.0000	44.9737
		3	36.0000	46.1552
		4	54.0000	53.9851
		5	NOT USED	NOT USED
		6	NOT USED	NOT USED
		7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM # 1	0.0043	0.0276
		2	0.0113	0.0332
		3	0.0253	0.0270
		4	0.0375	0.0234
		5	NOT USED	NOT USED
		6	NOT USED	NOT USED
		7	NOT USED	NOT USED

TABLE 5.22 : DEMO. CASE # 6B

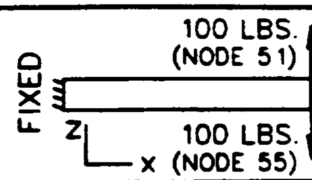
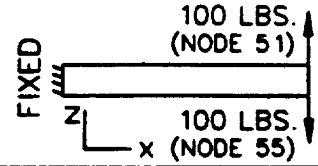
FIBER/MATRIX SYSTEM			LOAD CONDITION	
HMSF / IMHS FVR: 0.60			TEMP. EACH NODE $T_u = 250.0^\circ F$	
OPTIMIZATION VARIABLES			INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G12 (ELEMENT 12/13)		12.2744	26.4905
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM # 1	0.0000	0.0000
		2	18.0000	44.8097
		3	36.0000	45.9582
		4	54.0000	53.9830
		5	NOT USED	NOT USED
		6	NOT USED	NOT USED
		7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 − MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM # 1	0.0035	0.0901
		2	0.0586	0.0937
		3	0.1371	0.0515
		4	0.1553	0.0253
		5	NOT USED	NOT USED
		6	NOT USED	NOT USED
		7	NOT USED	NOT USED

TABLE 5.23 : DEMO. CASE # 6C

FIBER / MATRIX SYSTEM	LOAD CONDITION
HMSF / IMHS // SGLA / IMHS FVR: 0.60 FVR: 0.60 % PLY: 80 % PLY: 20	TEMP. EACH NODE $T_u = 250.0^o F$ 

OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G12 (ELEMENT 12/13)			10.7767	22.6956
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	0.0000
			2	18.0000	45.0151
			3	36.0000	46.1603
			4	54.0000	53.9770
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0049	0.0471
			2	0.0199	0.0519
			3	0.0448	0.0400
			4	0.0662	0.0324
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED

TABLE 5.24 : DEMO. CASE # 7A

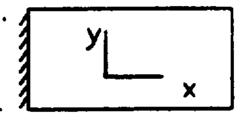
FIBER / MATRIX SYSTEM AS / IMHS FVR: 0.60			LOAD CONDITION TEMP. THIS FACE $300\ ^0F$	 FIXED TEMP. THIS FACE $70\ ^0F$
OPTIMIZATION VARIABLES			INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)		174.9219	187.9811
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM # 1	0.0000	0.0000
		2	18.0000	− 0.1956
		3	36.0000	− 0.4041
		4	54.0000	30.9430
		5	NOT USED	NOT USED
		6	NOT USED	NOT USED
		7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 − MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM # 1	0.0094	0.0015
		2	0.0237	0.0016
		3	0.0512	0.0018
		4	0.0749	0.0519
		5	NOT USED	NOT USED
		6	NOT USED	NOT USED
		7	NOT USED	NOT USED

TABLE 5.25 : DEMO. CASE # 7B

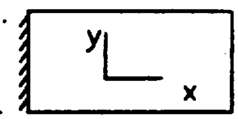
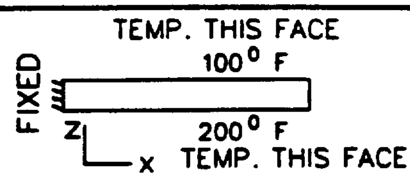
FIBER / MATRIX SYSTEM				LOAD CONDITION	
HMSF / IMHS FVR: 0.60				TEMP. THIS FACE 300 °F  FIXED; TEMP. THIS FACE 70 °F	
OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)			307.9368	329.0864
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	0.0000
			2	18.0000	– 0.5280
			3	36.0000	18.2170
			4	54.0000	54.0000
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0073	0.0399
			2	0.1149	0.0464
			3	0.2665	0.5062
			4	0.3015	1.0000
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED

TABLE 5.26 : DEMO. CASE # 7C

FIBER / MATRIX SYSTEM HMSF / IMHS // SGLA / IMHS FVR: 0.60 FVR: 0.60 % PLY: 80 % PLY: 20				LOAD CONDITION TEMP. THIS FACE 300 °F y, x, FIXED TEMP. THIS FACE 70 °F	
OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)			260.6892	280.7083
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	0.0000
			2	18.0000	– 0.1785
			3	36.0000	0.0160
			4	54.0000	54.0000
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0114	0.0328
			2	0.0447	0.0338
			3	0.0953	0.0329
			4	0.1387	0.2614
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED

TABLE 5.27 : DEMO. CASE # 8A

FIBER/MATRIX SYSTEM	LOAD CONDITION
AS / IMHS FVR: 0.60	

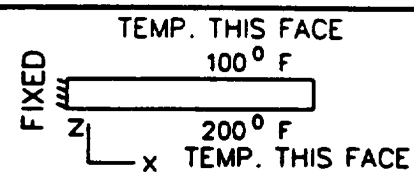
OPTIMIZATION VARIABLES			INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)		175.5846	188.4926
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM # 1	0.0000	0.0000
		2	18.0000	0.0290
		3	36.0000	− 1.0090
		4	54.0000	54.0000
		5	NOT USED	NOT USED
		6	NOT USED	NOT USED
		7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 − MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM # 1	0.0079	0.0163
		2	0.0044	0.0069
		3	0.0037	0.0015
		4	0.0048	0.0074
		5	NOT USED	NOT USED
		6	NOT USED	NOT USED
		7	NOT USED	NOT USED

TABLE 5.28 : DEMO. CASE # 8B

FIBER / MATRIX SYSTEM			LOAD CONDITION	
HMSF / IMHS FVR: 0.60			FIXED; TEMP. THIS FACE 100° F; 200° F TEMP. THIS FACE; Z, X	
OPTIMIZATION VARIABLES			INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)		308.4839	332.2351
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM # 1	0.0000	0.0000
		2	18.0000	– 0.0470
		3	36.0000	0.3720
		4	54.0000	32.3690
		5	NOT USED	NOT USED
		6	NOT USED	NOT USED
		7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM # 1	0.0537	0.3944
		2	0.0251	0.1826
		3	0.0361	0.0482
		4	0.0215	0.0972
		5	NOT USED	NOT USED
		6	NOT USED	NOT USED
		7	NOT USED	NOT USED

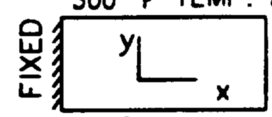
TABLE 5.29 : DEMO. CASE # 8C

FIBER / MATRIX SYSTEM		LOAD CONDITION
HMSF / IMHS // SGLA / IMHS		
FVR: 0.60	FVR: 0.60	
% PLY: 80	% PLY: 20	



OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)			261.2646	281.1792
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	0.0000
			2	18.0000	– 0.0194
			3	36.0000	0.5820
			4	54.0000	37.0820
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0176	0.0846
			2	0.0043	0.0388
			3	0.0070	0.0097
			4	0.0081	0.0141
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED

TABLE 5.30 : DEMO. CASE # 9A

FIBER / MATRIX SYSTEM	LOAD CONDITION
AS / IMHS FVR: 0.60	

OPTIMIZATION VARIABLES			INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)		175.5099	188.4361
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM # 1	0.0000	0.0000
		2	18.0000	– 0.0840
		3	36.0000	– 0.7670
		4	54.0000	51.0419
		5	NOT USED	NOT USED
		6	NOT USED	NOT USED
		7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM # 1	0.0076	0.0040
		2	0.0194	0.0040
		3	0.0423	0.0047
		4	0.0620	0.0850
		5	NOT USED	NOT USED
		6	NOT USED	NOT USED
		7	NOT USED	NOT USED

TABLE 5.31 : DEMO. CASE # 9B

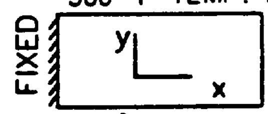
FIBER / MATRIX SYSTEM HMSF / IMHS FVR: 0.60				LOAD CONDITION	 300 ° F TEMP. THIS FACE FIXED y x 100 ° F TEMP. THIS FACE
OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)			308.4221	330.1665
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	0.0000
			2	18.0000	– 2.2610
			3	36.0000	14.5310
			4	54.0000	53.8850
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0060	0.0473
			2	0.0959	0.0820
			3	0.2229	0.4064
			4	0.2522	0.9946
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED

TABLE 5.32 : DEMO. CASE # 9C

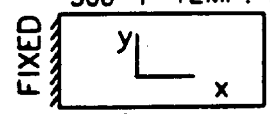
FIBER / MATRIX SYSTEM				LOAD CONDITION	
HMSF / IMHS // SGLA / IMHS FVR: 0.60 FVR: 0.60 % PLY: 80 % PLY: 20				300° F TEMP. THIS FACE  100° F TEMP. THIS FACE	
OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)			261.1997	281.1252
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	0.0000
			2	18.0000	0.2130
			3	36.0000	0.2600
			4	54.0000	38.4200
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 − MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0091	0.0101
			2	0.0357	0.0107
			3	0.0775	0.0109
			4	0.1132	0.1771
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED

TABLE 5.33 : DEMO. CASE # 10A

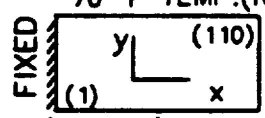
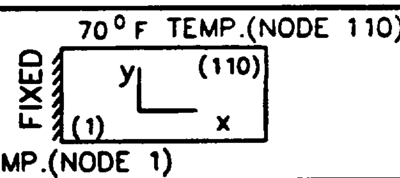
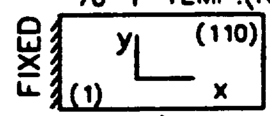
FIBER/MATRIX SYSTEM AS / IMHS FVR: 0.60				LOAD CONDITION 	
OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)			175.4686	188.3968
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	0.0000
			2	18.0000	− 0.4310
			3	36.0000	− 0.5720
			4	54.0000	50.8310
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 − MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0058	0.0035
			2	0.0143	0.0036
			3	0.0313	0.0035
			4	0.0460	0.0553
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED

TABLE 5.34 : DEMO. CASE # 10B

FIBER/MATRIX SYSTEM	LOAD CONDITION
HMSF / IMHS FVR: 0.60	

OPTIMIZATION VARIABLES				INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)			308.3884	332.1479
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM #	1	0.0000	0.0000
			2	18.0000	− 0.0780
			3	36.0000	0.5690
			4	54.0000	35.1000
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 − MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM #	1	0.0045	0.0837
			2	0.0728	0.0848
			3	0.1686	0.0951
			4	0.1894	0.8240
			5	NOT USED	NOT USED
			6	NOT USED	NOT USED
			7	NOT USED	NOT USED

TABLE 5.35 : DEMO. CASE # 10C

FIBER / MATRIX SYSTEM				LOAD CONDITION
HMSF / IMHS // SGLA / IMHS FVR: 0.60 FVR: 0.60 % PLY: 80 % PLY: 20				70 ° F TEMP.(NODE 110)  300 ° F TEMP.(NODE 1)
OPTIMIZATION VARIABLES			INITIAL DESIGN	FINAL DESIGN
OBJECTIVE FUNCTION	NASTRAN BENDING MODULUS: G11 (ELEMENT 12/13)		261.1580	281.0925
DESIGN VARIABLES	PLY ANGLES (DEGREES)	MATERIAL SYSTEM # 1	0.0000	0.0000
		2	18.0000	0.0040
		3	36.0000	– 0.1720
		4	54.0000	21.2350
		5	NOT USED	NOT USED
		6	NOT USED	NOT USED
		7	NOT USED	NOT USED
CONSTRAINT VARIABLES	STRESS FAILURE CRITERIA F = 1.0 – MDEIE NO FAILURE : F < 1 INCIPIENT : F = 1 FAILURE : F > 1	MATERIAL SYSTEM # 1	0.0064	0.0065
		2	0.0243	0.0031
		3	0.0535	0.0015
		4	0.0788	0.0441
		5	NOT USED	NOT USED
		6	NOT USED	NOT USED
		7	NOT USED	NOT USED

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 1992	Technical Memorandum

4. TITLE AND SUBTITLE
Thermostructural Tailoring of Fiber Composite Structures

5. FUNDING NUMBERS
WU-505-90-52

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
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8. PERFORMING ORGANIZATION REPORT NUMBER
E-7349

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, D.C. 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM-105882

11. SUPPLEMENTARY NOTES
Responsible person, Thomas H. Acquaviva, (216) 433-8020.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 24

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

A significant area of interest in design of complex structures involves the study of multidisciplined problems. The coordination of several different intricate areas of study to obtain a particular design of a structure is a new and pressing area of research. In the past, each discipline would perform its task consecutively using the appropriate inputs from the other disciplines. This process usually required several time-consuming iterations to obtain a satisfactory design. The alternative pursued here is combining various participating disciplines and specified design requirements into a formal structural computer code. The main focus of this research is to develop a multidisciplines structural tailoring method for select composite structures and to demonstrate its application to specific areas. The development of an integrated computer program involves the coupling of three independent computer programs using an executive module. This module will be the foundation for integrating a structural optimizer, a composites analyzer and a thermal analyzer. With the completion of the executive module, the first step was taken toward the evolution of multidiscipline software in the field of composite mechanics. Through the use of an array of cases involving a variety of objective functions/constraints and thermal-mechanical load conditions, it became evident that simple composite structures can be designed to a combined loads environment.

14. SUBJECT TERMS
Fiber composite; Multidiscipline design; Thermostructural tailoring

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	