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# Coupled Structural/Thermal/Electromagnetic Analysis/Tailoring of Graded Composite Structures

## Second Annual Status Report

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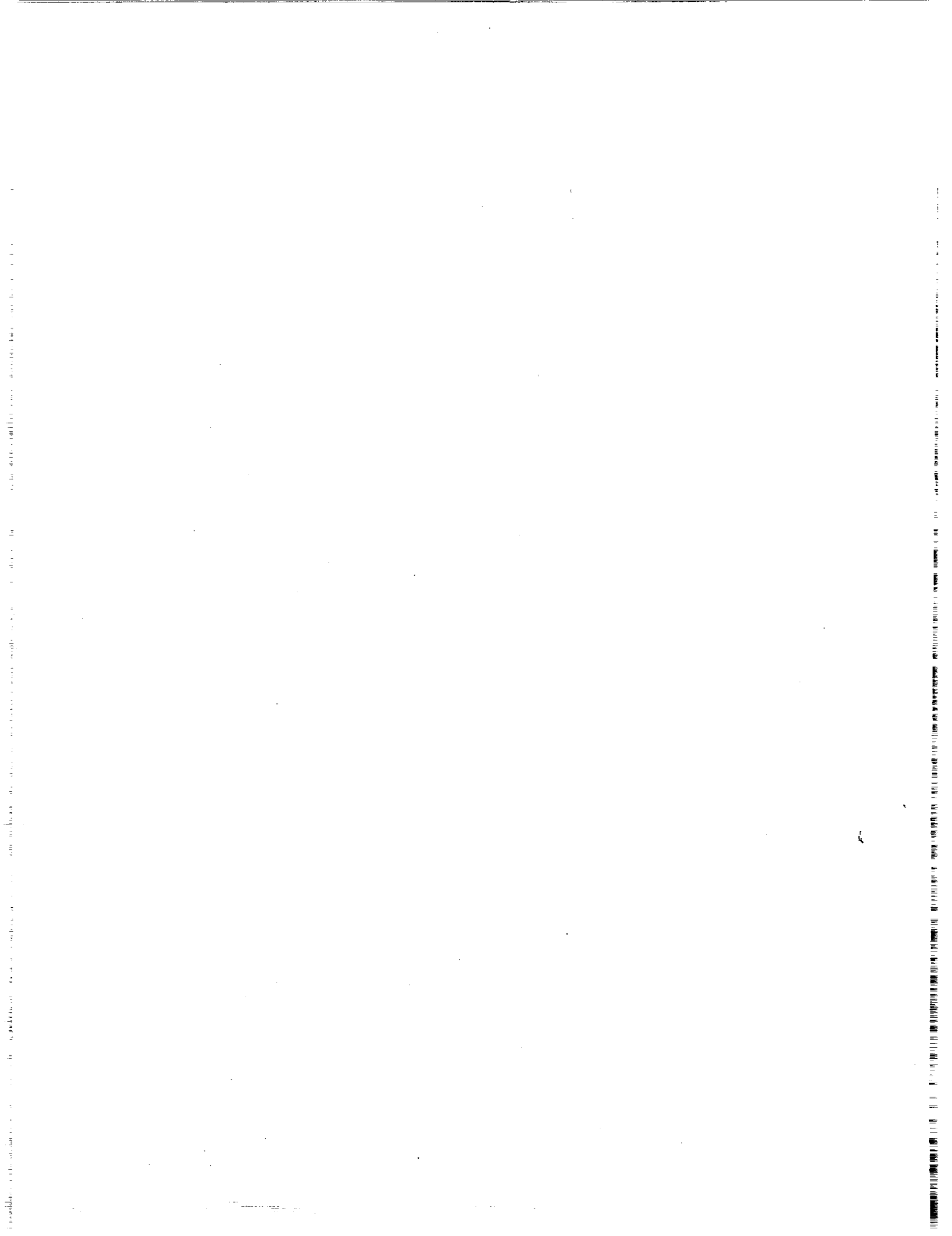


(NASA-CR-189151) COUPLED  
STRUCTURAL/THERMAL/ELECTROMAGNETIC  
ANALYSIS/TAILORING OF GRADED  
COMPOSITE STRUCTURES Annual Status  
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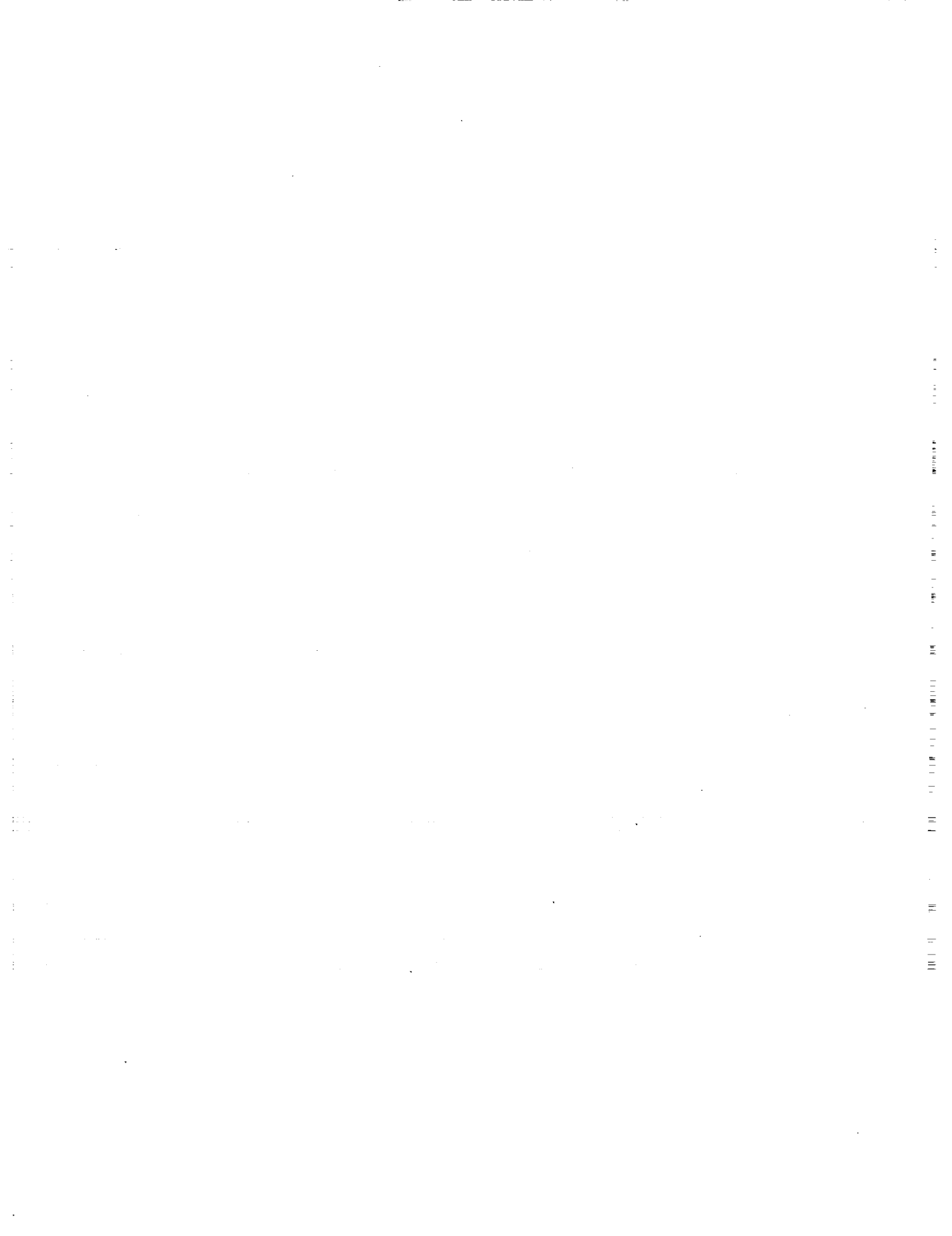
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## FOREWORD

This report has been prepared to expedite early dissemination of the information generated under the contract. The data and conclusions must be considered preliminary and subject to change as further progress is made on this program. This is a progress report covering the work done during the third 12 months of the contract; it is not a final report. The NASA Program Manager is Dr. C.C. Chamis.



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## NOMENCLATURE

AID	- Automatic Improvement of Design
$\vec{B}$	- Magnetic Flux Density
C	- Specific Heat
[C]	- Damping Matrix
COLSOL	- Linear Equations Solution Routine
COLSOV	- Version of COLSOL for Heat Transfer
CSTEM	- Coupled Structural/Thermal/Electromagnetic Analysis/Tailoring of Graded Composite Structures
ESMOSS	- Engine Structures Modeling Software System
FEM	- Finite Element Method
$\{F_B\}$	- Body Force Vector
$\{F_I\}$	- Initial Strains Vector
$\{F_{NL}\}$	- Nonlinear Strains Vector
$\{F_S\}$	- Surface Traction Vector
GEAE	- GE Aircraft Engines
G(x,y,z)	- Value of Function at Any Point (x,y,z)
G(x <sub>i</sub> ,y <sub>i</sub> ,z <sub>i</sub> )	- Value of Function at Node Point i
$\vec{H}$	- Magnetic Field Strength
h	- Convection Coefficient
H <sub>i</sub>	- Isoparametric Shape Functions
$\vec{J}$	- Magnetic Current Density
[K]	- Stiffness Matrix
[K <sub>t</sub> ]	- Magnetic Permeability Matrix
[M]	- "Consistent" Mass Matrix
n	- Number of Nodes in an Element
$\{Q_B\}$	- Element Heat Generation Vector
$\{Q_C\}$	- Nodal Heat Flow Vector
$\{Q_S\}$	- Boundary Heat Flow Vector
$\{q\}$	- Element Heat Capacity Vector
STAEBL	- Structural Tailoring of Engine Blades
TB	- Boundary Temperature
w	- Frequency

## NOMEMCLATURE (Concluded)

$\alpha$	- Surface Heat Transfer Coefficient
$\gamma$	- Reciprocal Permeability
$\lambda_i$	- $i$ th Eigenvalue
$\mu$	- Magnetic Permeability
$\rho$	- Resistivity
$\phi_i$	- $i$ th Eigenvector



## 1.0 INTRODUCTION

This technical program is the work of the Engineering Mechanics and Life Management Section of GE Aircraft Engines in response to NASA RFP 3-537260, "Coupled Structural/Thermal/Electromagnetic (CSTEM) Analysis/Tailoring of Graded Composite Structures." The overall objective of this program is to develop and verify analysis and tailoring capability for graded composite engine structures taking into account the coupling constraints imposed by mechanical, thermal, acoustic, and electromagnetic loadings.

The first problem that will be attacked is the development of plate and shell finite elements capable of accurately simulating the structural/thermal/electromagnetic response of graded composite engine structures. Because of the wide diversity of engine structures and the magnitudes of the imposed loadings, the analysis of these is very difficult and demanding when they are composed of isotropic, homogeneous materials. The added complexity of directional properties which can vary significantly through the thickness of the structures will challenge the state of the art in finite element analysis. We are applying AE's 25 years of experience in developing and using structural analysis codes and the exceptional expertise of our University consultants toward the successful conclusion of this problem. To assist in this, we are drawing heavily on previously funded NASA programs.

We are drawing on NASA programs NAS3-23698, 3D Inelastic Analysis Methods For Hot Section Components, and NAS3-23687, Component Specific Modeling, in our development work on the plate and shell elements. In addition to these two programs, we will draw on NAS3-22767, Engine Structures Modeling Software System (ESMOSS), and NAS3-23272, Burner Liner Thermal/Structural Load Modeling, in Task III when we generate a total CSTEM Analysis System around these finite elements. This will guarantee that we are using the latest computer software technology and will produce an economical, flexible, easy to use system.

In our development of a CSTEM tailoring system, we will build on NASA Program NAS3-22525, Structural Tailoring of Engine Blades (STAEBL) and AE program, Automatic Improvement of Design (AID), in addition to the program system philosophy of ESMOSS. Because of the large number of significant parameters and design constraints, this tailoring system will be invaluable in promoting the use of graded composite structures.

All during this program, we will avail ourselves of the experience and advice of our Low Observables Technology group. This will be particularly true in the Task V proof-of-concept. Their input will be used to assure the relevance of the total program.

Figure 1 shows our program and major contributions in flowchart form. This gives a visual presentation to the synergism that will exist between this program and other activities.

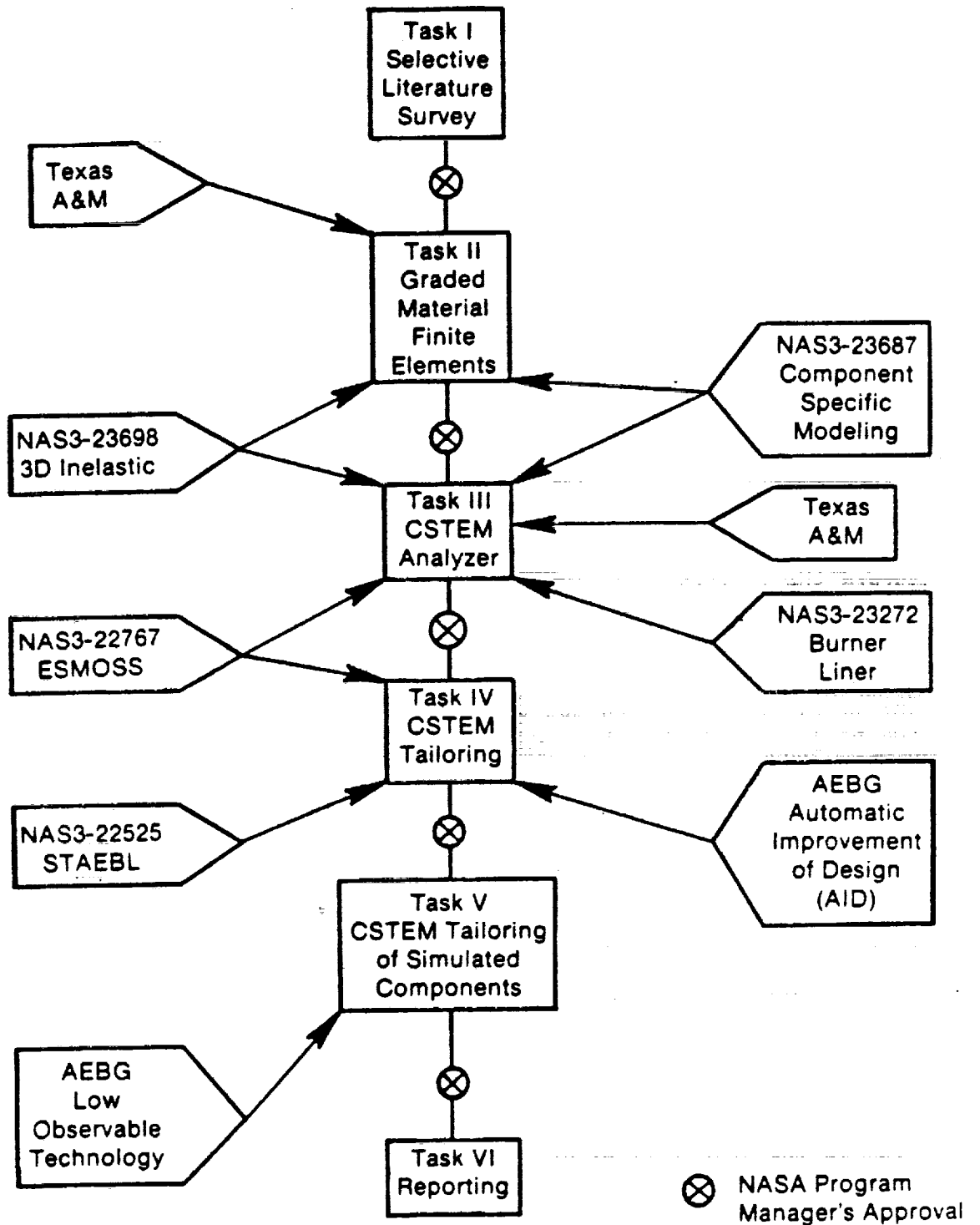


Figure 1. Program Flowchart.

Figure 2 depicts an integrated analysis of composite structures currently under development in the composite users' community. The severe limitations of such a system are not highlighted because three major steps in the process are not shown. Figure 3 adds these steps. The analysis system really begins with a definition of geometry. A user then defines a finite element model simulating this geometry and the anticipated loading. The process then moves to defined Step 3. One cycle through the process ends with the prediction of individual ply average stresses and strains. Now comes a significant productivity drain, namely, manual intervention to evaluate these stresses and strains against strength and durability limits. Based on this, the user must decide to (1) change the finite element model, (2) change the composite laminate, (3) both of the above, or (4) stop here.

Obviously, there is a considerable cost savings to be obtained by selecting Number 4. The CSTEM system will obviate the reasons for selecting Number 4. This system, shown in Figure 4, begins with the definition of geometry, as before, but then proceeds to a definition of master regions which contain all of the necessary information about geometry, loading, and material properties. Step 3 is a constitutive model which develops the necessary structural, thermal, and electromagnetic properties based on a micromechanics approach. Furthermore, this constitutive model will contain the logic to generate the global finite element model based on the variation of the properties, as depicted in Figure 5. Using a nonlinear incremental technique, these global models will be solved for their structural, thermal, and electromagnetic response. Based on this response the global characteristics will be evaluated, with convergence criteria and decisions made on remodeling. Once the global characteristics meet the accuracy requirements, the local characteristics are interrogated and decisions made on remodeling because of strength, durability, or hereditary effects. Once this cycle has been stabilized, optimization will be performed based on design constraint. Our goal in Task II is to develop finite elements whose characteristics make this system possible. Although the structural properties have been highlighted, the thermal and electromagnetic properties have as much or more variation, and less work has been done in these areas.

## 1.1 EXECUTIVE SUMMARY

"CSTEM" is the acronym for the computer program being developed under the NASA contract, "Coupled Structural/Thermal/Electromagnetic Analysis/Tailoring of Graded Composite Structures." The technical objectives for this program are to produce radar signal transparent structures having high structural performance and low cost. The multidisciplines involved are all highly nonlinear. They include anisotropic, large deformation structural analysis, anisotropic thermal analysis, anisotropic electromagnetic analysis, acoustics, and coupled discipline tailoring. The CSTEM system is a computerized multidiscipline simulation specialized to the design problems of radar absorbing structures. The enabling technical capabilities are implemented in a special 3D finite element formulated to simultaneously tailor the geometrical, material, loading and environment complexities of radar transparent structures for cost effective optimum performance.

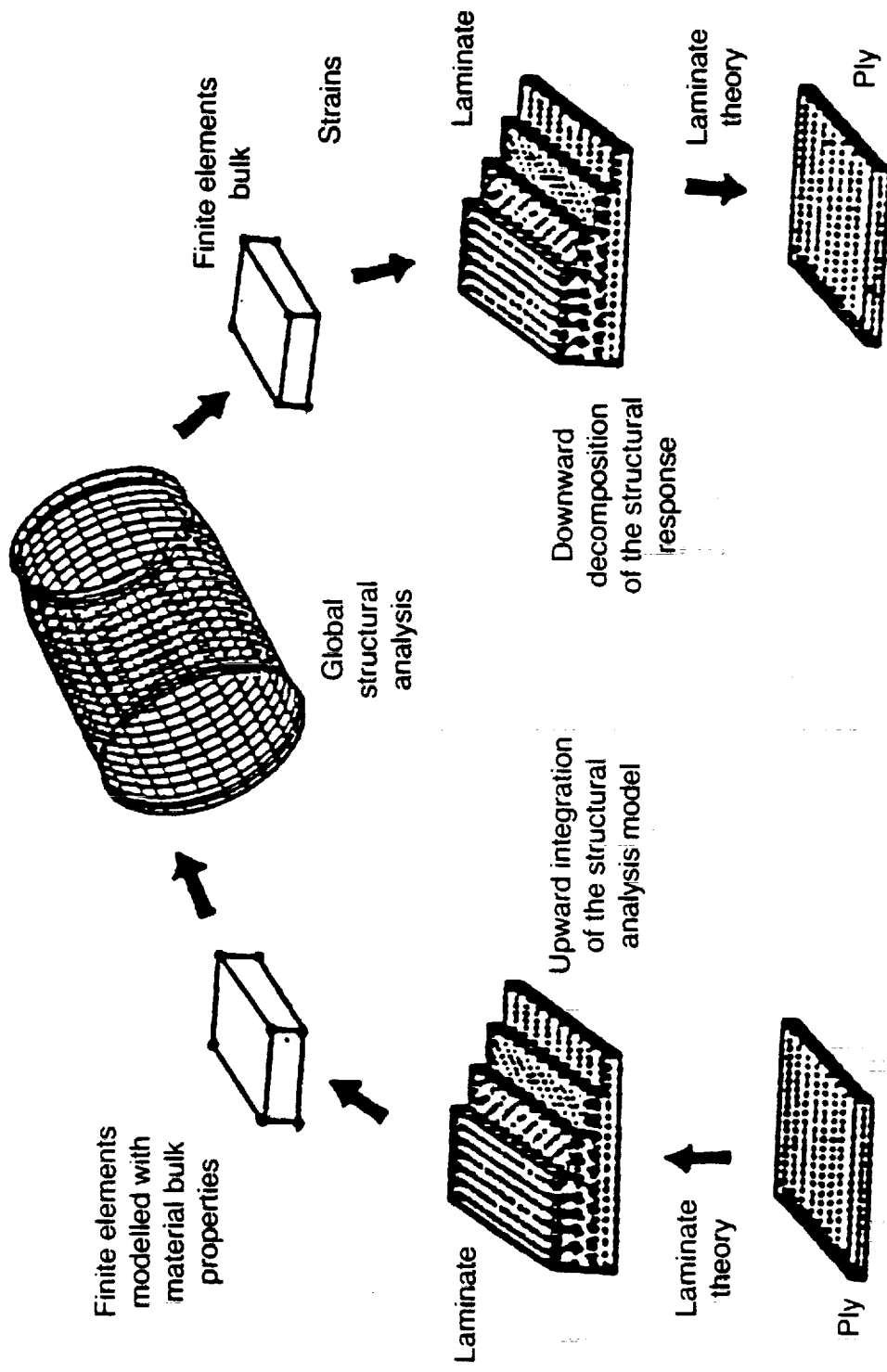


Figure 2. Composite Analysis System.

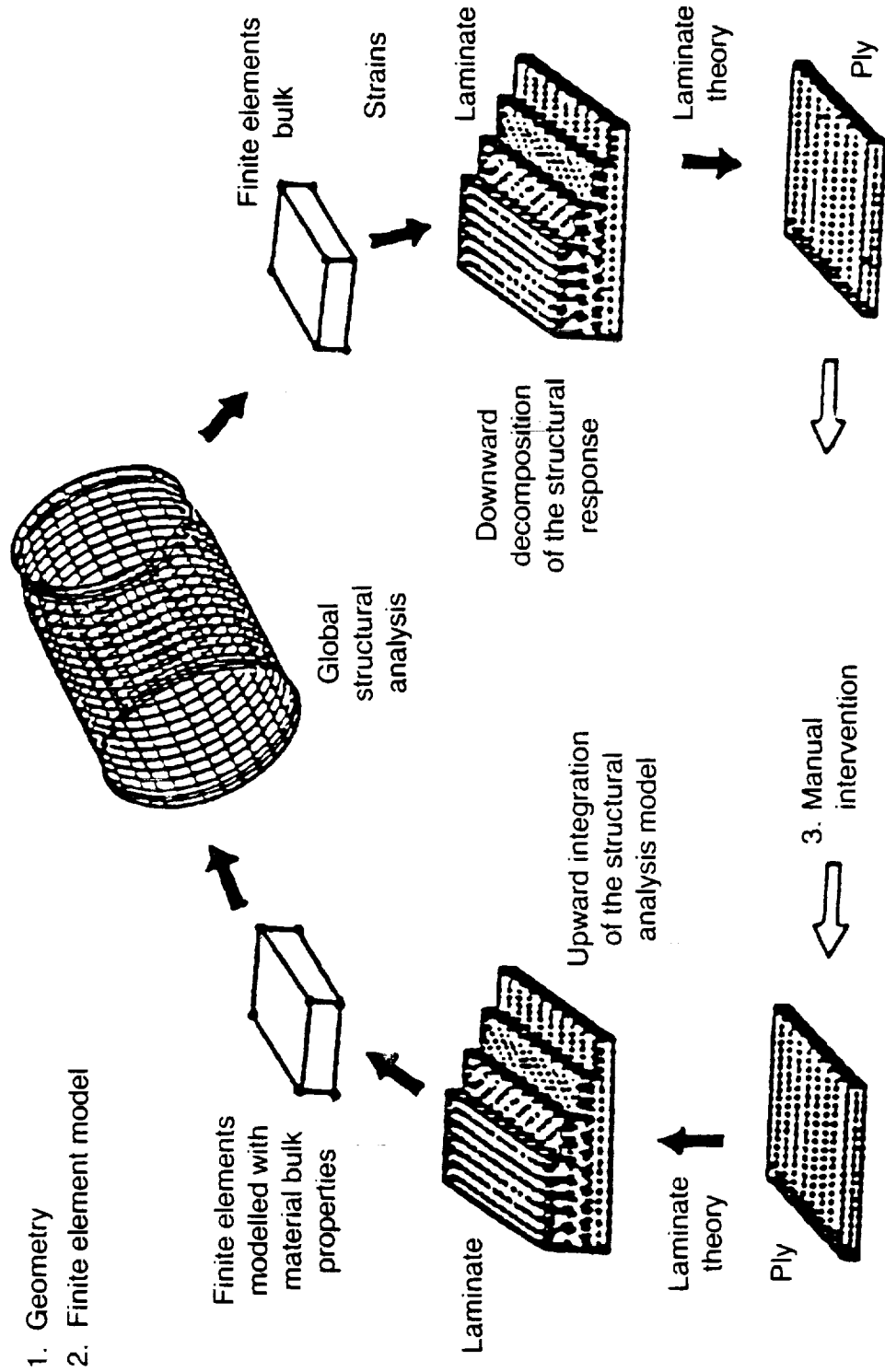


Figure 3. Total Composite Analysis System.

# Integrated analysis of composite structures

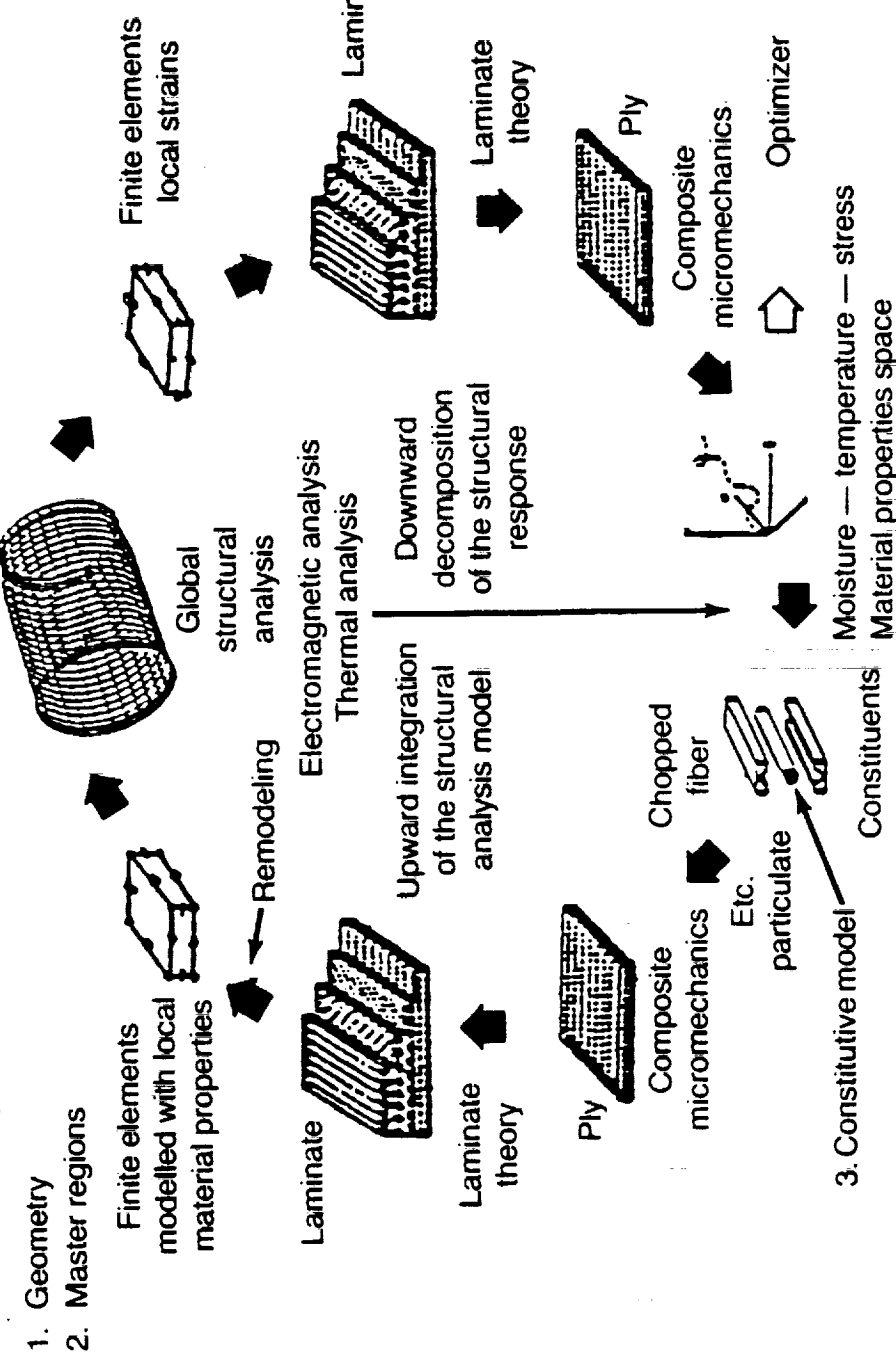


Figure 4. CSTEM System.

One isoparametric

Many integration points

Multiple isoparametrics

Complex composite

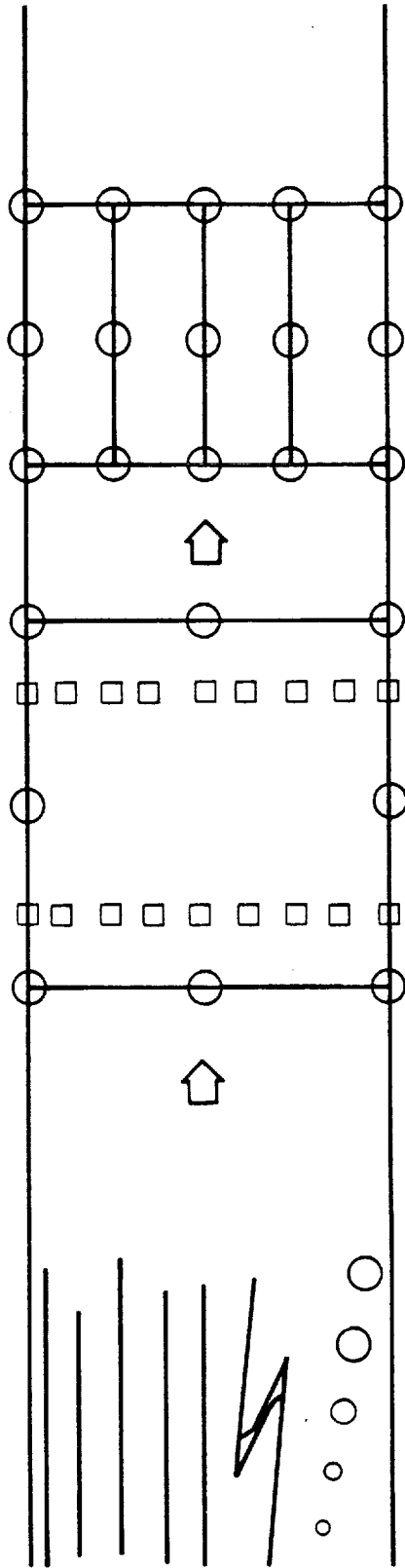


Figure 5. Constitutive Model - Structural Model Interaction.

In each enabling technical discipline a decoupled stand-alone 3D finite element code has been developed. An executive program with controlling iterative solution techniques performs the nonlinear coupling among the participating technical disciplines. A geometry and finite element model generator specialized for graded composites has been developed as an intimate part of this analysis system.

The structural analyzer is built around the 8-, 16-, and 20-noded isoparametric finite elements with emphasis on the 20 noded. A graded composite constitutive model has been developed for these elements which uses the NASA Lewis program ICAN as a subroutine to perform composite micromechanics and supply, to the analyzer, the requisite composite properties. The composite stiffness gradient controls the finite element definition of a structure with two major parameters to vary the number of elements through the thickness and the number of numerical quadrature points within an element. A unique set of local stiffness characteristics is developed for each numerical integration point. Integration of these local characteristics over the volume of the element provides total element simulation of composite structures including such effects as twist-bend coupling.

The structural analyzer also performs large deformation analysis using a unique incremental updated Lagrangian approach with iterative refinement. Testing of this capability against classical large deformation problems has shown it to be both more accurate and more economical than available alternatives. Connected with this technical capability is a deformed position eigenanalysis capability. All or selected portions of the nonlinear stiffness terms can be incorporated into these eigenanalyses. This capability has been checked out against available test data and other computer codes.

In future years of the NASA contract, these capabilities will be combined with an optimizer to perform a totally automated integrated analysis of graded composite structures. A final task in the program will be a design demonstration of the tailoring capabilities of the CSTEM system.

In order to reach the thermal analysis goals set for CSTEM, the same 8-, 16-, and 20-noded isoparametric finite elements are utilized. Four heat transfer solution options are available: linear steady state, nonlinear steady state, linear transient, and nonlinear transient. To overcome the previous economic penalty associated with finite element vis-a'-vis finite difference heat transfer, a unique solution technique is employed. This is a Newton-Raphson iterative technique with right hand side pseudo-fluxes. The code will perform the heat transfer analysis of a thermally anisotropic material considering conduction, convection, and radiation. Table I lists the parameters involved.

Routines for the calculation of absorption of electromagnetic waves have been written and checked out. The method followed is based on a data bank of absorptivity values for given material types specified at discrete values of temperatures, frequency, and polarization angle. The information for a specific material or materials is read from the data bank file into arrays



which are used by the program. The absorptivity is linearly interpolated from these discrete values to the local values of temperature, frequency and polarization angle.

Table I. Thermal Analyzer.

Thermal Parameters and Boundary Conditions	Steady State		Transient	
	Linear	Nonlinear	Linear	Nonlinear
• Temperature	T	T	T(t)	T(t)
• Time	---	---	t	t
• Thermal Conductivity	kij	kij(T)	kij(t)	kij(T,t)
• Convection Coefficient	h	h(T)	h(t)	h(T,t)
• Internal Heat Generation	$Q_i$	$Q_i$	$Q_i(t)$	$Q_i(t)$
• Surface Heat Flux	$Q_s$	$Q_s$	$Q_s(t)$	$Q_s(t)$
• Convection Boundary	$Q_c$	$Q_c$	$Q_c(t)$	$Q_c(t)$
• Specified Nodal Temperatures	$T_s$	$T_s$	$T_s(t)$	$T_s(t)$
• Heat Capacity	---	$C_\rho(T)$	---	$C_\rho(T,t)$
• Radiation Emissivity	---	$\epsilon(T)$	---	$\epsilon(T,t)$
• Viewing Factor	---	f	---	f(t)

## 2.0 TECHNICAL PROGRESS

### 2.1 STRUCTURAL ANALYZER

The CSTEM goals not only require that the finite element be specialized for graded composites, but also that it produce accurate large deformation analysis and deformed position eigenanalysis both for lower frequency system modes and higher frequency acoustic modes. An updated Lagrange large displacement analysis has been successfully implemented in the CSTEM code. Verification and validation were performed using the 20-noded isoparametrics to predict the displacements of a pressure loaded cantilever beam. CSTEM results correlate very well with published analytical and numerical results as shown in Figure 6. For this example, 20 equally spaced nonfollower pressure load increments were applied, resulting in a final tip displacement of 7.1 inches. Appendix A covers the CSTEM large displacement theory.

Test cases have also been run for the large displacement problem involving layered composites using the same 10-inch long, 1-square inch cross section cantilever beam model with transverse pressure loads and five anisotropic layers. Since no analytical results were available for this problem, two different finite element models were used to produce verification and validation. One model has a single element through the thickness of the beam and five elements along the length while the second model has five elements through the thickness and five elements along the length. The models and comparison of analytical results are shown in Figures 7, 8, and 9.

To perform the deformed position eigenanalysis, two eigen extraction techniques have been incorporated. These are the Determinant Search and Subspace Iteration methods with both lumped mass and consistent mass matrices. In the determinant search technique, a Sturm sequence check is used to perform an eigenshift to the neighborhood of the desired eigenvalue. Then a Rayleigh quotient is employed to iterate the trial vector until convergence is achieved. The subspace iteration technique employs a vector transformation to reduce the size of the eigenspace. Table II shows an example which highlights the benefit of the eigenshift and Rayleigh quotient.

### 2.2 THERMAL ANALYZER

The CSTEM thermal analyzer utilizes the same 8-, 16-, and 20-noded isoparametric finite elements as the structural analyzer. These elements have been modified such that they can perform the heat transfer analysis of graded composite structures. These structures have in the past presented a large obstacle to heat transfer analysis. This difficulty arose because of their anisotropic thermal properties and the large gradients in these properties that can exist. To overcome these problems, multiple integration points are used through the thickness as in the structural element.

A second major difficulty has to do with the nature of finite element heat transfer analysis. In the past, developers have approached the solution

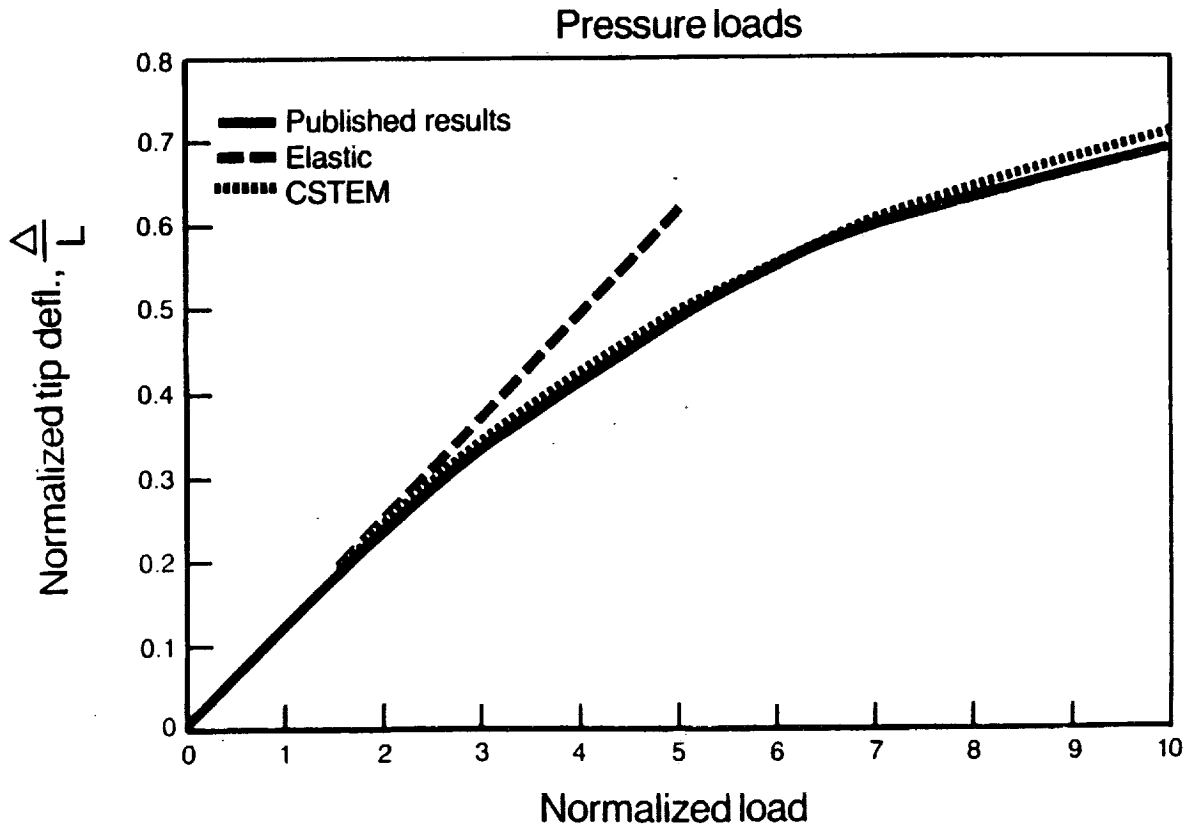


Figure 6. 10-Inch Cantilever.

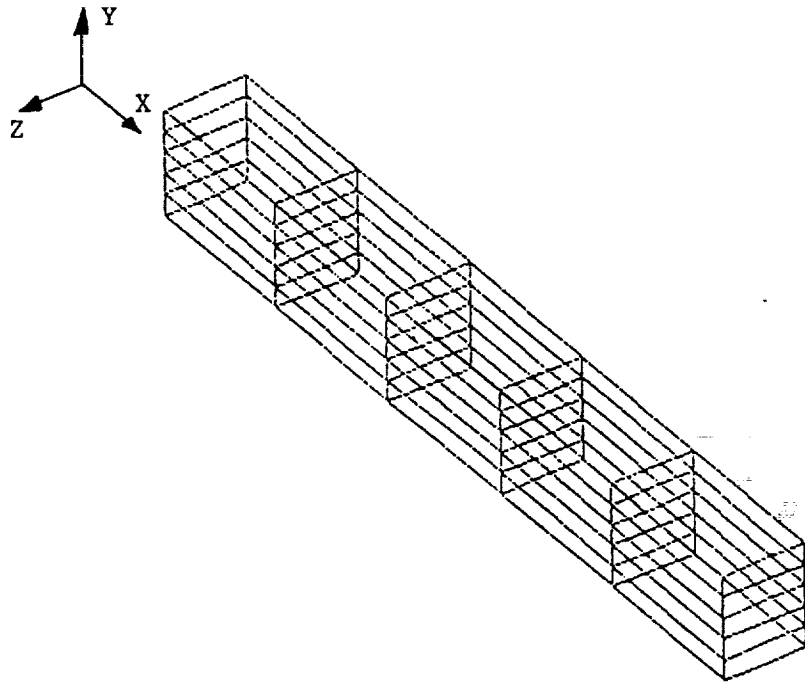


Figure 7. 25 Element Model.

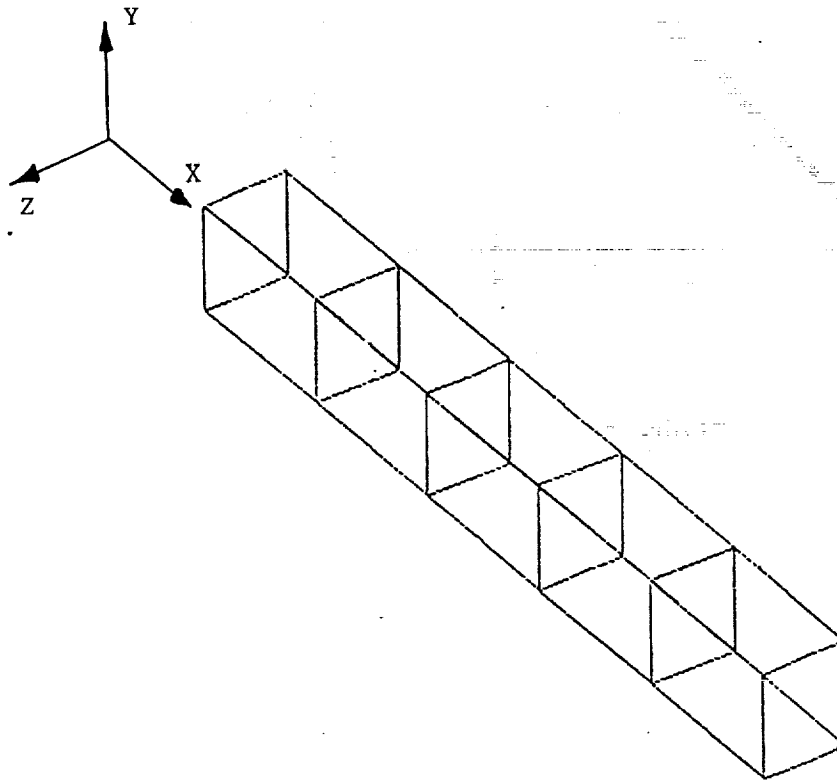


Figure 8. 5 Element Model.

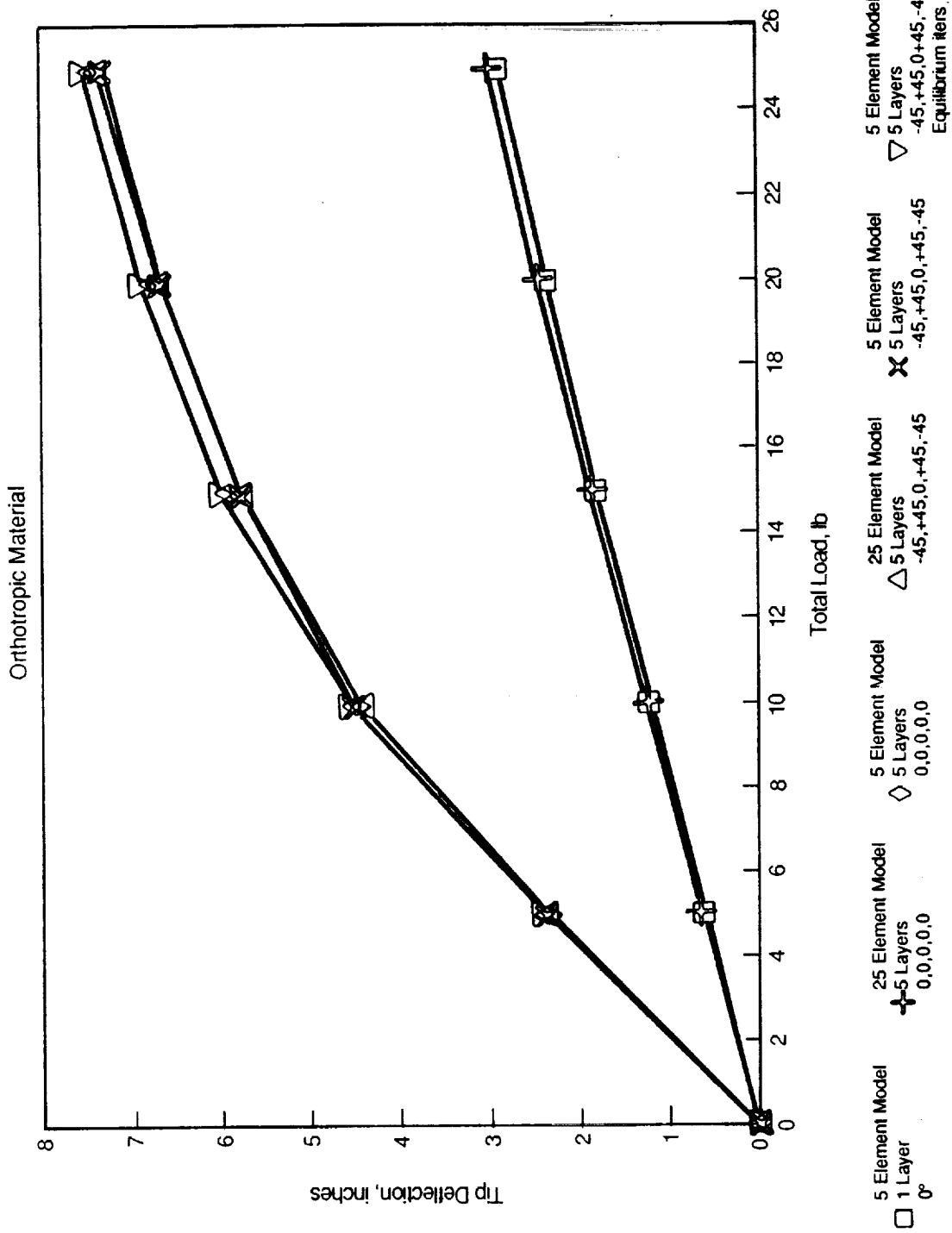
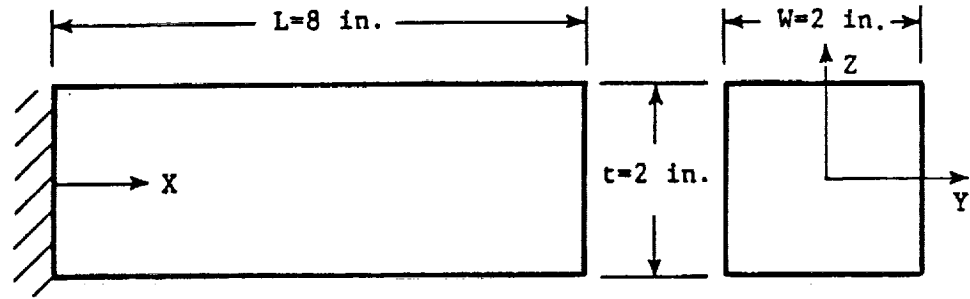


Figure 9. 10-Inch Cantilever.

Table 11. Eigenshift and Rayleigh Quotient Example.



$$E = 30 \times 10^6 \text{ psi}, \nu = 0.3, \rho = 0.298 \times 10^8 \text{ lb/in}^3$$

Mode Shape (Axis-About)	Eigen Values	
	Subspace Iterations	Eigenvalue Shift and Rayleigh Quotient
1st Bend <sub>E</sub>	0.357145302	0.3 + 0.057520891
1st Bend <sub>Y</sub>	0.362975676	0.4 - 0.037155197
1st Tors <sub>X</sub>	6.24068457	6.0 + 0.24067101
2nd Bend <sub>Z</sub>		8.0 + 0.79694164
2nd Bend <sub>Y</sub>	9.53097761	10.0 - 0.46902631
1st Axial <sub>X</sub>		16.0 - 0.98479339
3rd Bend <sub>E</sub>		44 + 0.82830848
3rd Bend <sub>Y</sub>	49.4069934	49 + 0.40698682

of finite element heat transfer in a manner similar to the tangent modulus technique for material nonlinearity in structural analysis. This has proved to be excessively time consuming in computer resources and noncompetitive with finite difference approaches. To overcome this problem, the CSTEM analyzer uses a right-hand side pseudo flux technique. This strategy not only overcomes the computer time penalty but also lends itself to coupled solutions.

The CSTEM thermal analyzer has four solution options:

- Steady state, linear
- Steady state, nonlinear
- Transient, linear
- Transient, nonlinear.

In steady-state analysis, the imposed thermal boundary conditions do not change with time. In a linear analysis, the thermal properties are constant, in a nonlinear analysis the thermal properties are a function of temperature. In a transient analysis, the imposed thermal boundary conditions vary with time. For a linear transient analysis, the thermal properties are only a function of time; for a nonlinear transient analysis, the thermal properties are a function of both time and temperature.

The CSTEM thermal analyzer can perform the heat transfer analysis of a three-dimensional graded composite structure considering conduction, convection, and radiation with internal heat generation. Imposed boundary conditions can be nodal temperatures, surface heat fluxes, fluid temperatures, and convection coefficients, radiating body temperatures, view factors, and emissivities. Appendix B is a draft of the theory and User's Manual.

### 2.3 ELECTROMAGNETIC ANALYZER

The coupled electromagnetic problem for the aircraft engine will be treated in two steps: the first is the electromagnetic wave absorption problem and the second is the conversion of the electromagnetic energy into heat. The engine structure is assumed to be a dielectric material. For any electromagnetic wave propagating through space and impinging on this structure, an amount of the electromagnetic energy will be absorbed. The propagation of an electromagnetic wave in a dielectric material obeys the following equation.

$$\frac{\partial}{\partial x} \left( \frac{1}{\epsilon_{dx}} \frac{\partial \phi}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{1}{\epsilon_{dy}} \frac{\partial \phi}{\partial y} \right) + \frac{\partial}{\partial z} \left( \frac{1}{\epsilon_{dz}} \frac{\partial \phi}{\partial z} \right) + \omega^2 \mu_o \epsilon_o \phi = 0 \quad (1)$$

where

$\phi$  = A component of the magnetic field strength vector  $\vec{H}$  or a component of the electric field vector  $\vec{E}$

$\omega$  = Wave Frequency

$\mu_0$  = Permeability of free space

$\epsilon_0$  = Permittivity of free space

$\epsilon_d$  = Permittivity of the dielectric

the relationship between  $\vec{E}$  and  $\vec{H}$  is  $\nabla \times \vec{E} = -\sqrt{-1} \omega \mu_0 \vec{H}$

Equation (1) may be rewritten as a minimum potential function:

$$I(\phi) = 1/2 \int_V \left[ K'_x \left( \frac{\partial \phi}{\partial x} \right)^2 + K'_y \left( \frac{\partial \phi}{\partial y} \right)^2 + K'_z \left( \frac{\partial \phi}{\partial z} \right)^2 - \lambda^2 \phi^2 \right] dV$$

where

$$K'_x, K'_y, K'_z = \frac{1}{\epsilon dx}, \frac{1}{\epsilon dy}, \frac{1}{\epsilon dz} \quad \lambda^2 = \omega^2 \mu_0 \epsilon_0$$

Using finite element notation

$$[K]^e \{\phi\}^e - \lambda [M]^e \{\phi\}^e = 0 \quad (2)$$

where

$$[K]^e = \int_V B^T \cdot [K'] \cdot B dV$$

$$[M]^e = \int_V [H_i]^T \cdot [H] dv$$

Summing up equation (2) for the entire structure:

$$\{[K] - \lambda [M]\} \{\phi\} = 0 \quad (3)$$



The solution to equation (3),  $\{\phi\}$ , gives the nodal electromagnetic field strength vector  $\vec{E}$  or  $\vec{H}$ . Portions of the energy will be absorbed by the dielectric structure and converted to heat. The external energy due to the electromagnetic field may be written as:

$$\frac{\partial W}{\partial \phi} = \int_V [K'_x \frac{\partial \phi}{\partial x} \frac{\partial}{\partial \phi_i} (\frac{\partial \phi}{\partial x}) + K'_y \frac{\partial \phi}{\partial y} \frac{\partial}{\partial \phi_i} (\frac{\partial \phi}{\partial y}) + K'_z \frac{\partial \phi}{\partial z} \frac{\partial}{\partial \phi_i} (\frac{\partial \phi}{\partial z})] dv \quad (4)$$

where

$$\phi = \sum_i N_i \phi_i = [H_1, H_2 \dots H_i] \begin{pmatrix} \phi_1 \\ \phi_2 \\ \vdots \\ \phi_i \end{pmatrix}$$

$$\frac{\partial \phi}{\partial x} = \sum_{i=1} \frac{\partial H_i}{\partial x} \phi_i = \left[ \frac{\partial H_1}{\partial x} \quad \dots \quad \frac{\partial H_i}{\partial x} \right] \{\phi\}^e$$

$$\frac{\partial}{\partial \phi_i} \left( \frac{\partial \phi}{\partial x} \right) = \frac{\partial H_i}{\partial x}$$

Therefore, equation (4) becomes

$$\frac{\partial W(\phi)}{\partial \phi_i} = \left[ \int_V B^T [K'] B dv \right] \{\phi\} = [K']^e \{\phi\}^e \quad (5)$$

Absorbed energy will convert to internal heat energy as:

$$\frac{\partial W_i(T)}{\partial T} = [K_T] \{T\} \quad (6)$$

where

$$[K_T] = \int_V B^T \cdot [k] \cdot B dv$$

$[K_T]$  = Thermal conductivity matrix

$\{T\}$  = Vector of nodal temperatures

Equating a percentage of (5) to (6), we get

$$[K_T] \{T\} = \alpha [K_e] \{\phi\} \quad (7)$$

where

$\alpha$  = the percentage of energy absorbed.

Equation (7) thus gives the increase in nodal temperature due to absorbed electromagnetic energy.

Routines for the calculation of absorption of electromagnetic waves have been written and checked out. The method followed is based on a data bank of absorptivity values for given material types specified at discrete values of temperature, frequency, and polarization angle. The information for a specific material or materials is read from the data bank file into arrays which are used by the program. The absorptivity is linearly interpolated from these discrete values to the local values of temperature, frequency, and polarization angle.

Calculations are made for one given frequency, orientation, and path of an electromagnetic wave at a time. Multiple frequencies and/or different paths travelled through the structure are handled by separate calculations for the different parameters.

The orientation of the wave is input in the same manner as skew boundary conditions where a wave coordinate system is associated with the electromagnetic wave. This wave coordinate system is defined such that the direction of propagation is along the positive y axis and polarization is measured from the positive x axis as shown in Figure 10. Polarization of the wave is defined only from 0 to 180 degrees.

The element face upon which the wave impinges is input and the angle of incidence of the wave is calculated from the dot product of the inward normal of the layer subsurfaces and the positive y axis of the wave coordinate system. The angle of incidence must be between 0 and 90 degrees in absolute value. The temperature is calculated using the element shape functions.

The polarization angle is calculated using the dot product between the projection of the wave polarization on the layer midsurface and the material principle direction. The polarization angle is calculated as being between 0 and 90 degrees.

The absorptivity values in the data bank are essentially percentage absorption values. The strength of the electromagnetic wave emerging on the other side of the layer is calculated as

$$W_{out} = W_{in} * (1.0 - \text{absorptivity})$$

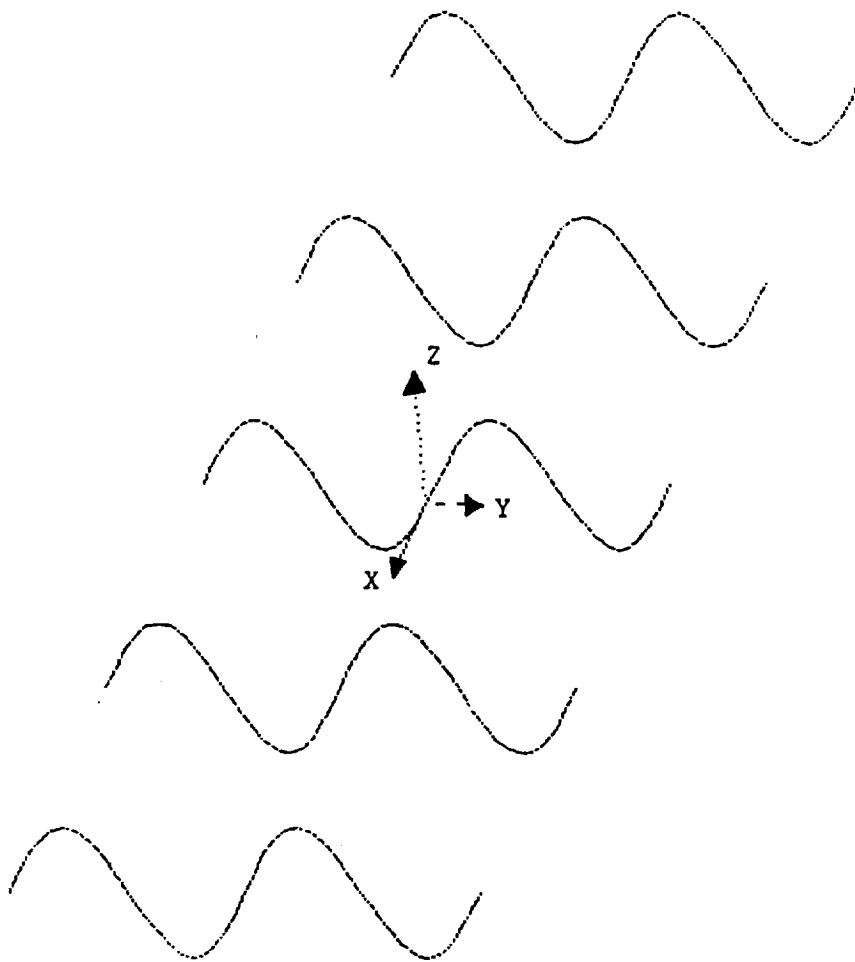


Figure 10. Wave with 90° Polarization.

where  $W_{in}$  is the magnitude of the normal component of the impinging wave. Presently, the wave is assumed to pass through the structure on a straight path with absorption occurring on the magnitude of the normal component only.

## 2.4 CSTEM COUPLED ANALYSIS

The CSTEM code is a finite element code which has the capability to solve structural, thermal, and electromagnetic absorption problems in such a way that the effects of one of these phenomena on another are accounted for. Some unique features of the code are a 20-noded isoparametric brick with multilayer capability, large displacement analysis capability, finite element heat transfer analysis with transient capability, generation of material properties from constituent properties, an internal composites analyzer, internal mesh generation, and calculation of electromagnetic absorption using an easily modified data bank of material absorption properties.

The main executive routine of CSTEM allows the user to perform separate structural, thermal, or electromagnetic multiple load case analyses. In addition, a combination of any two or all three types of analyses together may be done. This is possible due to the modular form of the code. Each module is self contained, passing only the required input geometry and control information between the modules as well as returning any results which may be required as input for an analysis by a following module.

The structural module uses a 20-noded isoparametric brick and is similar to many other isoparametric finite element codes in several ways. It has the capability for centrifugal, acceleration, nodal displacement, nodal force, temperature, and pressure loadings. The solution technique used is a multi-block column solver which allows solution of very large problems since it can work on portions of the set of equations separately.

The more advanced features of the structural module include its orthotropic material capability. Material properties can be input relative to the material axes and then skewed on an element by element basis to obtain the desired orientation of the material with the global coordinate system. The structural module can also generate the orthotropic material properties it needs for composite materials using the constituent properties making up the composite. This is done using an internal adaptive version of the computer program INHYD, which accesses a data bank containing the material properties of the constituents. The properties are calculated based on the volume ratios of the constituents.

Another advanced feature of the CSTEM structural module is its multiple layer capability. This allows the modeling of composite structures with many material layers without the necessity of using an element for each layer. This stiffness of an element with multiple layers is calculated using integration points located on the midplane of each layer within the element. The stress and strain are then recovered at these same integration points. There is a requirement that the element shape follows the layup of the structure so that the layers cut through opposite faces of the element at the same height

and not diagonally across the element. This requirement points to the use of a mesh generator, which is a part of the CSTEM structural module.

The CSTEM mesh generator is capable of producing various solids of revolution from a minimum of input parameters. The generator can produce flat surfaces, cylinders, cones, and general double curved surfaces of up to 360° rotation. At present these different surface types cannot be generated together without some manual intervention.

Another capability that can be used together with the multiple layer capability is a composites analyzer, which is adapted from the ICAN computer program. This capability must also be used together with the INHYD generation of material properties. The composites analyzer takes the stress/strain results from the structural module and integrates them through the thickness of the structure at some user specified location. This results in a loading which can be used by the composites analyzer to do a microanalysis of the composite at that particular location.

The electromagnetic absorption module is based on a data bank of absorption properties for different material types. This data bank contains absorption properties for the material at discrete values of temperature, frequency, and polarization angle. The absorption of electromagnetic energy of a specific frequency and polarization by a given material at a specific temperature is calculated by linearly interpolating from the discrete data bank values. The orientation of an electromagnetic wave is specified similar to a skew material so that a coordinate system is associated with the wave propagation. This wave coordinate system is defined such that the direction of propagation is along the positive Y axis and polarization is measured from the positive X axis. The orientation of the wave coordinate system with the global coordinate system is specified using skew transformations.

The element face upon which the electromagnetic wave is impinging is specified by the input as well as the path of elements encountered by the wave as it passes through the structure. Absorption calculations are made for each material encountered and are carried out using midsurface centroid values of temperature and orientation. The impingement angle is calculated as a dot product of the wave coordinate system Y axis and the midsurface centroid normal. The polarization angle is calculated as the dot product of the projection on the layer midsurface of the wave polarization and the material orientation.

Absorption calculations are done for one given frequency, orientation, and wavepath at a time. If it is necessary to calculate results for several frequencies, orientations, or wavepaths, a separate calculation must be done for each combination.

As mentioned these modules may be run separately through the main executive routine by the appropriate specification of input variables. However, the main intent of CSTEM is to use the results of one module as input to another so that the coupling effects of the various phenomena can be deduced. The most general procedure followed is to set up a heat transfer input deck which describes a time history of heat transfer loadings as well

as any temperature dependency of heat transfer properties. A structural input deck is then set up with changes in structural loadings with time. Structural load case time points must be coincident with heat transfer load case time points, although either can contain time points between the coincident points to account for changes in loadings in one analysis while the other remains constant, or to get printout for some intermediate point. Finally, a series of electromagnetic absorption analyses are specified at each coincident time point if desired.

The solution proceeds by reading the first structural load case, which includes the geometry, structural material properties, and loadings, as well as the global control parameters. If a heat transfer analysis is to be done along with this particular structural load case the heat transfer module is entered and the heat transfer analysis begins by reading the input it requires and performing the type of heat transfer analysis requested. The heat transfer analysis continues, stepping along in time until it reaches the time point where a structural solution is desired. The resultant nodal temperatures are passed back to the structural module and the structural solution is performed based on the stiffness and loadings at these temperatures. After the displacements, stresses and strains are calculated. At this time point the analysis of requested cross sections by the composites analyzer is done. If any electromagnetic absorption calculations have been requested, they are done next using the previously calculated temperatures and deformed configuration. This would be the end of a structural load case. It may or may not be the end of a heat transfer load case. In either case, the next structural load case is read and the process is repeated. This continues until the end of the analysis is reached.

## APPENDIX A

### CSTEM LARGE DISPLACEMENT THEORY

Large displacement analysis methods can be divided into two types: updated Lagrange and total Lagrange. In updated Lagrange large displacement analysis the nodal positions are continuously updated to the current equilibrium position and all stress and strain measures are referred to this updated configuration. In contrast, the total Lagrange approach retains the original nodal coordinates throughout the analysis with all stress and strain measures referred to this original configuration. The updated Lagrange method handles the effects of previous displacements automatically due to the fact that the nodal coordinates include these displacements. In the total Lagrange method these effects are included by the use of an additional term in the linear stiffness and internal force calculations.

The basic equations are derived from consideration of equilibrium, stating that externally applied forces must be balanced by the stresses generated internally. For this balance to be correctly achieved mathematically, care must be taken to use the proper stress and strain measures. For updated Lagrange these are the Cauchy stress and Almansi strain, whereas for total Lagrange these are the 2nd Piola-Kirchoff stress and Green strain.

Both methods use an iterative incremental type of approach. The equilibrium equations to be solved for the updated Lagrange method are

$$\left( {}^t [K_L] + {}^t [K_{NL}] \right) \{ \Delta U \}^{(i)} = {}^{t + \Delta t} \{ R \} - \frac{{}^{t + \Delta t} \{ F \} - {}^t \{ F \}}{t + \Delta t} (i-1)$$

where

$${}^t [K_L] = \int_{t_v} {}^t [B_L]^T {}^t [C] {}^t [B_L] dV$$

$${}^t [K_{NL}] = \int_{t_v} {}^t [B_{NL}]^T {}^t \{ \tau \} {}^t [B_{NL}] dV$$

$$\frac{{}^{t + \Delta t} \{ F \} - {}^t \{ F \}}{t + \Delta t} = \int_{t_v} {}^t [B_{NL}]^T {}^t [ \tau ] dV$$

and

${}^{t + \Delta t} \{ R \}$  are applied loads at time  $t + \Delta t$ .

In this notation, the left superscript refers to the time when the quantity is measured or calculated, the left subscript refers to the configuration that the quantity is referenced to and the superscript in parentheses refers to the iteration number.

The equivalent equations for the total Lagrange method are

$$\begin{pmatrix} t \\ o \end{pmatrix} [K_L] + \begin{pmatrix} t \\ o \end{pmatrix} [K_{NL}] \left\{ \Delta U \right\}^{(i)} = \begin{pmatrix} t + \Delta t \\ o \end{pmatrix} \{ R \} - \begin{pmatrix} t + \Delta t \\ o \end{pmatrix} \{ F \}^{(i-1)}$$

where

$$\begin{pmatrix} t \\ o \end{pmatrix} [K_L] = \int_{o_v} \begin{pmatrix} t \\ o \end{pmatrix} [B_L]^T \begin{pmatrix} t \\ o \end{pmatrix} [C] \begin{pmatrix} t \\ o \end{pmatrix} [B_L] dV$$

$$\begin{pmatrix} t \\ o \end{pmatrix} [K_{NL}] = \int_{o_v} \begin{pmatrix} t \\ o \end{pmatrix} [B_{NL}]^T \begin{pmatrix} t \\ o \end{pmatrix} \{ S \} \begin{pmatrix} t \\ o \end{pmatrix} [B_{NL}] dV$$

$$\begin{pmatrix} t + \Delta t \\ o \end{pmatrix} \{ F \} = \int_{o_v} \begin{pmatrix} t \\ o \end{pmatrix} [B_{NL}]^T \begin{pmatrix} t \\ o \end{pmatrix} [S] dV$$

and

$\begin{pmatrix} t + \Delta t \\ o \end{pmatrix} \{ R \}$  are applied loads at time  $t + \Delta t$ .

For the total Lagrange method an additional term to account for previous displacements is included in the linear strain-displacement matrix, so this can be written as

$$\begin{pmatrix} t \\ o \end{pmatrix} [B_L] = \begin{pmatrix} t \\ o \end{pmatrix} [B_{L_0}] + \begin{pmatrix} t \\ o \end{pmatrix} [B_{L_1}]$$

The Almansi strain, the strain referenced to the current configuration, is used in the updated Lagrange method. The definition of Almansi strain is

$$\begin{pmatrix} t \\ t \end{pmatrix} \epsilon_{ij} = \frac{1}{2} \left( \begin{pmatrix} t \\ t \end{pmatrix} U_{i,j} + \begin{pmatrix} t \\ t \end{pmatrix} U_{j,i} - \begin{pmatrix} t \\ t \end{pmatrix} U_{k,i} \begin{pmatrix} t \\ t \end{pmatrix} U_{k,j} \right)$$

where tensor notation is used and the left superscript refers to the time when the strain occurs and the left subscript refers to the configuration that the strain is referenced to.

The Green strain, the strain referenced to the original configuration, is used in the total Lagrange method and is defined as



$${}^t_0 \varepsilon_{ij} = \frac{1}{2} \left( {}^t_0 U_{i,j} + {}^t_0 U_{j,i} + {}^t_0 U_{k,i} {}^t_0 U_{k,j} \right)$$

These strains are related to the stresses as follows for the Almansi strain and Cauchy stress

$${}^t \tau_{mn} = {}^t C_{mnpq} {}^t \varepsilon_{pq}$$

and for the Green strain and 2nd Piola-Kirchoff stress

$${}^t_0 S_{ij} = {}^t_0 C_{ijrs} {}^t_0 \varepsilon_{rs}$$

These measures with respect to the current and original configurations can be related to each other (or referred to any other configuration) through the use of the deformation gradient. The deformation gradient is defined in matrix notation as

$${}^t_0 [X] = \left( {}^t_0 \nabla {}^t \{X\}^T \right)^T$$

where

$${}^t_0 \nabla = \left\{ \begin{array}{c} \frac{\partial}{\partial {}^t_0 X_1} \\ \frac{\partial}{\partial {}^t_0 X_2} \\ \frac{\partial}{\partial {}^t_0 X_3} \end{array} \right\} \quad \text{and} \quad {}^t \{X\} = \left\{ \begin{array}{c} {}^t X_1 \\ {}^t X_2 \\ {}^t X_3 \end{array} \right\}$$

and T refers to the transpose.

Using tensor notation the relations between the different measures are

$${}^t \tau_{mn} = \frac{{}^t \rho}{{}^t_0 \rho} {}^t X_{m,i} {}^t_0 S_{ij} {}^t X_{n,j}$$

$${}^t \varepsilon_{mn} = {}^o X_{i,m} {}^t \varepsilon_{ij} {}^o X_{j,n}$$

$${}^t C_{mnpq} = \frac{{}^t \rho}{{}^o \rho} {}^t X_{m,i} {}^t X_{n,j} {}^o C_{ijrs} {}^t X_{p,r} {}^t X_{q,s}$$

where  $\rho$  is the density and

$${}^o \rho = {}^t \rho \left| \frac{{}^t [X]}{{}^o [X]} \right|$$

APPENDIX B  
CSTEM THERMAL ANALYZER

DRAFT  
THEORY AND USER'S MANUAL

## INTRODUCTION

In recent years the finite element idealization has become a general approach for the stress analysis of complex structural system. In order to minimize the preparation of data for a thermal stress problem it is desirable that the same finite element model be used in the stress and heat transfer analysis. For this reason considerable effort is currently being devoted to the development of compatible heat transfer and stress analysis programs.

In general, the stress and heat transfer analysis of solids are coupled. The coupling of structural mechanical loads, heat transfer, and electromagnetic are discussed in the main programs. Here, we are only talking about the heat-transfer portion of the whole program. In heat-transfer analysis nonlinearities may be due to temperature dependent material properties and, in particular, be caused by nonlinear boundary conditions.

The heat transfer analysis of graded-composite structural problems idealized by finite elements is currently in the developmental and experimental stage. The procedures of the treatment of temperature dependent material properties, and the nonlinear boundary conditions in graded-composite structures are covered in the following text.

The purpose of this report is to explain development of the techniques that permit the practical analysis of complex three dimensional heat transfer problems of graded-composite structures.

### The Finite Element Formulation

The three-dimensional isoparametric solid elements are employed. The mesh size can be varied and bodies of arbitrary shape can be considered without difficulty. Material properties can be varied without difficulty. Material properties can be different for each element. In general, mixed boundary conditions can be handled directly. The equations which govern the response of the discrete system generally involve matrices which are symmetric and positive definite. Therefore, effective solution techniques can be employed for the solution of both the steady state and transient problems.

An eight, 16, and 20-node, three-dimensional solid element is shown in Figure B-1. The natural coordinates  $(x,y,z)$  of the eight corner nodes are  $(\pm 1, \pm 1, \pm 1)$  and of the 12 remaining nodes are  $(0, \pm 1, \pm 1)$ ,  $(\pm 1, 0, \pm 1)$ ,  $(\pm 1, \pm 1, 0)$ . The temperature within the element is defined in terms of the nodal temperatures by

$$\theta(x,y,z,t) = \sum_i H_i(x,y,z) \theta_i(t).$$

To express the interpolation functions in a simple form it is convenient to define the following

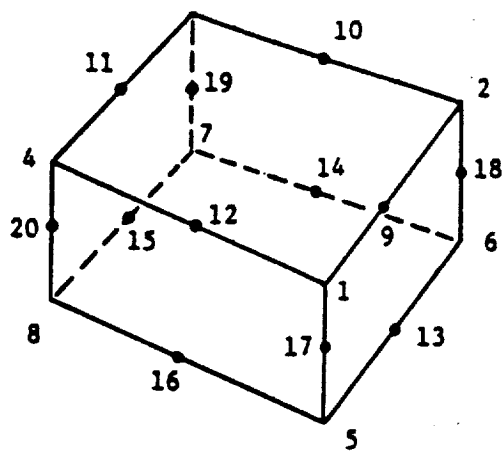
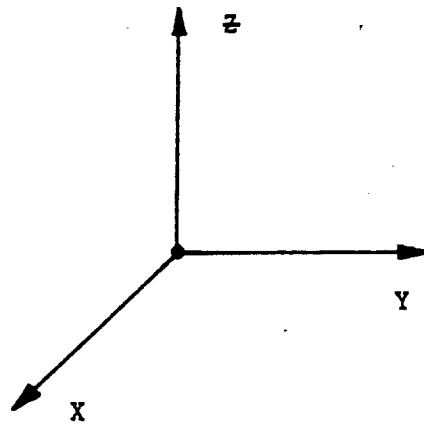


Figure B-1. Eight, 16, and 20 Node 3D Solid Elements.

Shape Function:



$$H_1 = g_1 - (g_9 + g_{12} + g_{16})/2$$

$$H_2 = g_2 - (g_9 + g_{10} + g_{18})/2$$

$$H_3 = g_3 - (g_{10} + g_{11} + g_{19})/2$$

$$H_4 = g_4 - (g_{11} + g_{12} + g_{20})/2$$

$$H_5 = g_5 - (g_{13} + g_{16} + g_{17})/2$$

$$H_6 = g_6 - (g_{13} + g_{14} + g_{18})/2$$

$$H_7 = g_7 - (g_{14} + g_{15} + g_{19})/2$$

$$H_8 = g_8 - (g_{15} + g_{16} + g_{20})/2$$

$$H_i = g_i \text{ for } (i = q \dots 20)$$

$g_i = 0$  if node  $i$  is not included; otherwise:

$$g_i = G(r, r_i) G(s, s_i) G(t, t_i)$$

$$G(\beta, \beta_i) = 1/2 (1 + \beta_i \beta) \text{ for } \beta_i = \pm 1$$

$$G(\beta, \beta_i) = (1 - \beta^2) \text{ for } \beta_i = 0$$

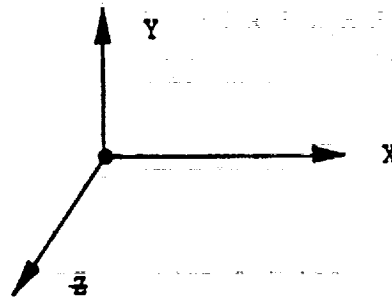
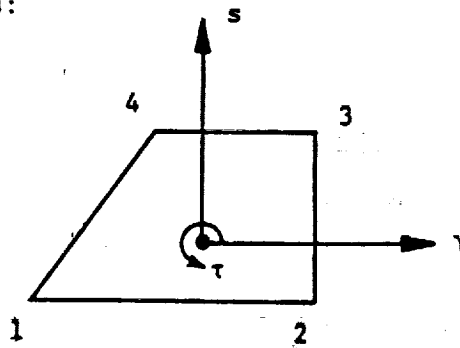
Jacobi's Operator [J] is

The displacement functions:

$$X = \sum H_i x_i$$

$$Y = \sum H_i y_i$$

$$Z = \sum H_i z_i$$



$$[J] = \begin{matrix} \frac{\partial x}{\partial r} & \frac{\partial y}{\partial r} & \frac{\partial z}{\partial r} \\ \frac{\partial x}{\partial s} & \frac{\partial y}{\partial s} & \frac{\partial z}{\partial s} \\ \frac{\partial x}{\partial t} & \frac{\partial y}{\partial t} & \frac{\partial z}{\partial t} \end{matrix}$$

where  $r, s, t$  are the local coordinates.

$$[B] = [J] \begin{bmatrix} \frac{\partial H_1}{\partial r} & \dots & \frac{\partial H_i}{\partial r} \\ \frac{\partial H_1}{\partial s} & \dots & \frac{\partial H_i}{\partial s} \\ \frac{\partial H_1}{\partial t} & \dots & \frac{\partial H_i}{\partial t} \end{bmatrix}$$

$$\left\{ \begin{array}{l} \theta_{t+\Delta t}^{(m)} = H^{(m)} \theta_{t+\Delta t} \\ \theta^{s(m)} = H^{s(m)} \theta_{t+\Delta t} \\ \theta^{(m)} = B^{(m)} \cdot \theta_{t+\Delta t} \end{array} \right\} \quad \theta_{t+\Delta t} - \text{a vector of all nodal point temperatures at } t+\Delta t$$

$$\theta_{t+\Delta t}^T = [\theta_{1_{t+\Delta t}} \quad \theta_2 \quad \theta_m]_{t+\Delta t}$$

### Equations for Heat Transfer Analysis

Consider the three-dimensional heat-transfer conditions as shown in Figure B-2. In the analysis of heat transfer conditions, we assume that the material obeys Fourier's law of heat conduction:

$$q_x = -k_x \frac{\partial \theta}{\partial x}, \quad q_y = -k_y \frac{\partial \theta}{\partial y}, \quad q_z = -k_z \frac{\partial \theta}{\partial z}$$

where  $q_x$ ,  $q_y$ , and  $q_z$  are the heat flows conducted per unit area,  $\theta$  is the temperature of the body, and  $k_x$ ,  $k_y$ , and  $k_z$  are the thermal conductivities corresponding to the principal axes  $x$ ,  $y$ , and  $z$ .

Considering the heat flow equilibrium in the interior of the body we thus obtain

$$\frac{\partial}{\partial x} (k_x \frac{\partial \theta}{\partial x}) + \frac{\partial}{\partial y} (k_y \frac{\partial \theta}{\partial y}) + \frac{\partial}{\partial z} (k_z \frac{\partial \theta}{\partial z}) = -q^b \quad (1)$$

where  $q^b$  is the rate of heat generated per unit volume. On the surfaces of the body the following conditions must be satisfied:

$$\theta|_{s1} = \theta_e \quad (2)$$

$$k \left. \frac{\partial \theta}{\partial n} \right|_{s2} = q_s \quad (3)$$

**Heat Transfer Problems**

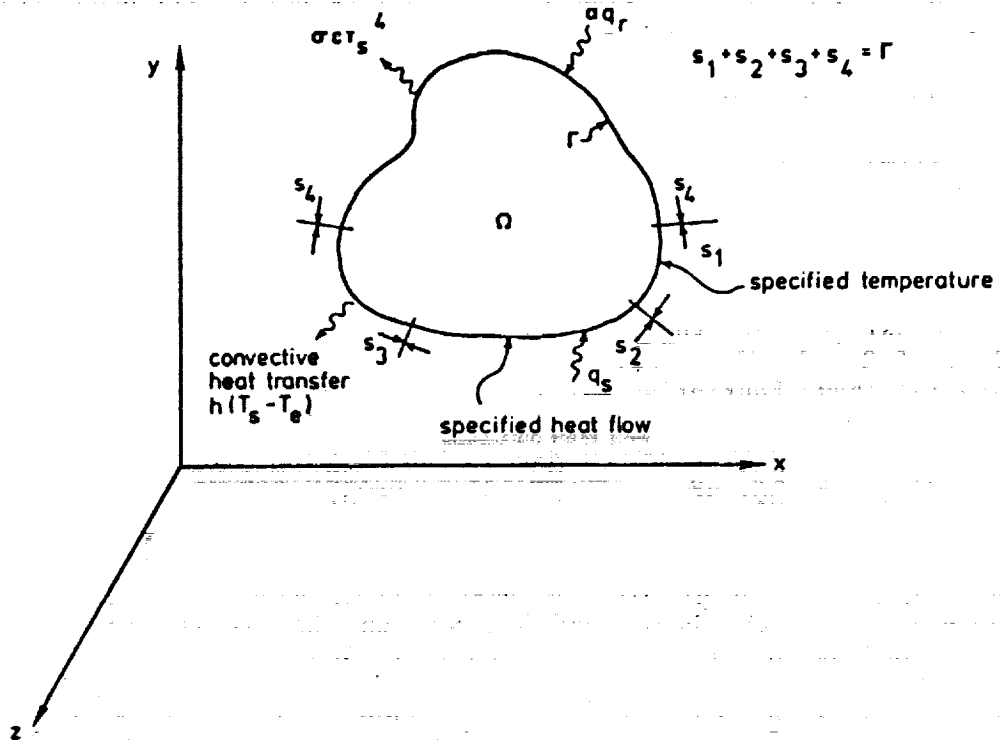


Figure B-2. Three-Dimensional Solution Domain for General Heat Conduction.



where  $\theta_e$  is the environmental temperature,  $kn$  is the body thermal conductivity,  $n$  denotes the direction of the normal to the surface (outward) and  $q^s$  is the heat flow input to the surface of the body.

### Boundary Conditions

1. Temperature Conditions - The temperature may be prescribed at specific points and surfaces of the body, denoted by  $S_1$  in Equation (2)
2. Heat Flow Conditions - The heat flow input may be prescribed at specific points and surfaces of the body. The heat-flow boundary conditions are specified in Equation (3)
3. Convection Boundary Conditions - Included in Equation (3) are convection boundary conditions, where

$$q^s = h (\theta_e - \theta^s) \quad (4)$$

4. Radiation Boundary Conditions - Radiation boundary conditions are also specified in Equation (3) with  $q^s = k (\theta_r - \theta^s)$  (5)

where  $\theta_r$  is the temperature of the external radiative source and  $K$  is a coefficient:

$$K = h_r [\theta_r^2 + (\theta^s)^2] [\theta_r + \theta^s] \quad (6)$$

The variable  $h_r$  is determined from the Stefan-Boltzman constant, the emissivity of the radiant and absorbing materials and the geometric view factors. In addition to these boundary conditions also the initial conditions must be specified in a transient analysis.

### Solution Scheme

For the development of a finite element scheme either a Galerkin formulation operating on the differential equation of equilibrium or a variational formulation of the heat-transfer problem can be employed. In the variational formulation a function  $II$  is defined such that when invoking the stationarity of  $II$ , the governing differential Equation (1) to (3) are obtained.

$$\begin{aligned} \Pi = & \int_V 1/2 \left\{ k_x \left( \frac{\partial \theta}{\partial x} \right)^2 + k_y \left( \frac{\partial \theta}{\partial y} \right)^2 + k_z \left( \frac{\partial \theta}{\partial z} \right)^2 \right\} dv \\ & - \int_V \theta q^b dv - \int_{S_2} \theta^s q^s ds - \sum_i \theta_i Q_i \end{aligned} \quad (7)$$

where  $\theta^i$  are the concentrated heat flow inputs. Using the condition of stationarity of  $\Pi$  we obtain

$$\begin{aligned} \int_V \delta \bar{\theta}^t \bar{k} \bar{\theta} d\bar{v} = & \int_V \delta \bar{\theta} q^b dv + \int_{S_2} \delta \bar{\theta}^s q^s ds \\ & + \sum_i \delta \bar{\theta}^i \bar{Q}^i \end{aligned} \quad (8)$$

For a general solution scheme of both linear and nonlinear, steady-state and transient problems we aim to develop incremental equilibrium equations. The modified Newton-Raphson iteration for heat flow equilibrium is used, in which

$$\theta^{(i)}(t+\Delta t) = \theta^{(i-1)}(t+\Delta t) + \Delta \theta^{(i)}$$

With the initial condition  $\theta^{(0)}(t+\Delta t) = \theta_t$  and  $\Delta \theta^{(i)}$  is the temperature increment. In the iteration procedure, the stiffness matrix  $[K]$  is constant and any change is reflected by an update of the right hand side load vectors  $[Q]^{(i)}$  at each iteration. Also the "COLSOL" technique is used to solve the matrix for the nodal temperature.

There are four generic heat transfer problems, they are discussed in the following.

### 1) Linear Steady-State Conditions

The governing equation of linear steady-state can be written as:

$$(K^k + K^c) \theta^{t+\Delta t} = \theta^{t+\Delta t} Q + \theta^{t+\Delta t} Q^e \quad (A)$$

where  $K^k$  is the conductivity matrix

$$K^k = \sum_{m=1}^m \int_V B^{(m)T} \cdot K^{(m)} \cdot B^{(m)} \cdot dv \quad (I)$$

$K^C$  is the convection matrix

$$K^C = \sum_{m=1}^m \int_{sc} h^{(m)} \cdot H^{s(m)T} \cdot H^{s(m)} \cdot ds \quad (II)$$

The nodal point heat flow input vector  ${}^{t+\Delta t}Q$

$${}^{t+\Delta t}Q = {}^{t+\Delta t}Q_B + {}^{t+\Delta t}Q_s + {}^{t+\Delta t}Q_c \quad (B)$$

Where

$${}^{t+\Delta t}Q_B = \sum_{m=1}^m \int_v H^{(m)T} \cdot {}^{t+\Delta t}q^b(m) \cdot dv \quad (III)$$

$${}^{t+\Delta t}Q_s = \sum_{m=1}^m \int_{s_2} H^{s(m)T} \cdot {}^{t+\Delta t}q^s(m) \cdot ds \quad (IV)$$

Where  ${}^{t+\Delta t}Q_c$  is a vector of concentrated nodal point heat flow input.

The nodal point heat flow contribution  ${}^{t+\Delta t}Q_e$  is due to the convection boundary condition

$q^b$  - the rate of heat generated in element

$q^s$  - the surface heat flow input

At that time:

$${}^{t+\Delta t}\theta(e) = H(e) \cdot {}^{t+\Delta t}\theta \quad (1a)$$

$${}^{t+\Delta t}\theta^s(e) = H^s(e) \cdot {}^{t+\Delta t}\theta \quad (1b)$$

$${}^{t+\Delta t}\theta(e) = B(e) \cdot {}^{t+\Delta t}\theta \quad (1c)$$

where (e) denotes element m

$t+\Delta t \theta$  a vector of all nodal point temperatures at  $t+\Delta t$

$$t+\Delta t \theta = [t+\Delta t \theta_1 \quad t+\Delta t \theta_2 \quad \dots \quad t+\Delta t \theta_i]$$

The matrix  $H^{(e)}$  → Element Temperature

$B^{(e)}$  → Temperature gradient interpolation matrix

$H^s(e)$  → The surface temperature interpolation matrix

$[B]$  → derivative of the shape function with respect to  $r, s, t$  and premultiplication by  $J^{-1}$

$$t+\Delta t Q^e = \sum_m \int_{sc} h \cdot H^{s(m)T} \cdot H^{s(m)} \cdot t+\Delta t \theta_e \cdot ds^{(m)} \quad (V)$$

$\theta_e$  - The given nodal point environmental temperatures.

from this equation we find the  $t+\Delta t Q^e$  (i.e.  $t+\Delta t Q_e$  and  $h$  are given)

$q^b$  - the rate of heat generated per unit volume

$\theta_e$  - the environmental temperature

$q^s$  - the heat flow input to the surface of the body

$h$  - the convection coefficient

$$q^s = h(\theta_e - \theta^s)$$

$\theta$  - is the temperature of the body

a) From Equations (I), (II) we can find the

$$(K^k + K^c)$$

b) From Equation (B) the nodal point heat flow input

$$t+\Delta t Q = t+\Delta t Q_B + t+\Delta t Q_s + t+\Delta t Q_c$$

where

$${}^{t+\Delta t}Q_B = \sum_{m=1}^m \int_V H^{(m)T} \cdot {}^{t+\Delta t}q_b^{(m)} \cdot dv$$

$${}^{t+\Delta t}Q_s = \sum_{m=1}^m \int_{S_2} H^{s(m)T} \cdot {}^{t+\Delta t}q_s^{(m)} \cdot ds$$

${}^{t+\Delta t}Q_c$  is a vector of concentrated nodal point heat flow input

It can be solved for  ${}^{t+\Delta t}Q$

c) From Equation (V) the given nodal point environment temperatures are

$${}^{t+\Delta t}\theta_e$$

$${}^{t+\Delta t}Q_e = \sum_{m=1}^m \int_{S_c} h \cdot H^{s(m)T} \cdot H^{s(m)} \cdot {}^{t+\Delta t}\theta_e \cdot ds$$

We can solve for  ${}^{t+\Delta t}Q^e$  (nodal point heat distribution).

From Items (a), (b), (c), substitute, into Equation A.

$$(K^k + K^c) {}^{t+\Delta t}\theta = {}^{t+\Delta t}Q + {}^{t+\Delta t}Q^e$$

The nodal point temperatures in each element can be found by using Equations (1a), (1b), (1c).

## II) Nonlinear Steady-State Conditions

The governing equation of nonlinear steady-state heat transfer is

$$[t_{K^k} + t_{K^c} + t_{K^r}] \Delta\theta^{(i)} = t + \Delta t_{Qt} \quad t + \Delta t_{Qc} \quad (i-1) \\ + t - \Delta t_{Qr} \quad (i-1) - t + \Delta t_{Qk} \quad (i-1)$$

where

$$t_{K^k} \Delta \theta^{(i)} = \left[ \sum_V B^T t_{K_e^k} B dV \right] \Delta \theta^{(i)}$$

$$t_{K^c} \Delta \theta^{(i)} = \left[ \sum_{sc} t_h H_s^T H_s ds \right] \Delta \theta^{(i)}$$

$$t_{K^r} \Delta \theta^{(i)} = \left[ \sum_{sr} t_\alpha H_s^T H_s ds \right] \Delta \theta^{(i)}$$

$$t + \Delta t_{Q^c} (i-1) = \sum_{sc} t + \Delta t_h (i-1)$$

$$\left[ H_s \left( t + \Delta t_{\theta_e} - t + \Delta t_{\theta} (i-1) \right) \right] ds$$

$$t + \Delta t_{Q^r} (i-1) = \sum_{sa} t + \Delta t_\alpha (i-1) H_s^T$$

$$\left[ H_s \left( t + \Delta t_{\theta_r} - t + \Delta t_{\theta} (i-1) \right) \right] ds$$

$$t + \Delta t_{Q^k} (i-1) = \sum_V t + \Delta t_{B^T} \left[ t + \Delta t_{K_e} (i-1) t + \Delta t_B \theta (i-1) \right] dV$$

$$t + \Delta t_Q = t + \Delta t_{Q_b} + t + \Delta t_{Q_s} + t + \Delta t_{Q_c}$$

$$t + \Delta t_{Q_b} = \sum_V H^T t + \Delta t_g^b dV$$

$$t + \Delta t_{Q_s} = \sum_s H_s^T t + \Delta t_q^s ds$$

$t + \Delta t Q_c$  = Vector of concentrated nodal point heat flow input

$k$  = Thermal conductivity

$h$  = Convection coefficient

$\alpha$  = Radiation coefficient

$$\alpha = 5.667 \times 10^{-8} \epsilon f (\theta_r^2 + \theta_s^2) (\theta_r + \theta_s)$$

$$5.667 \times 10^{-8} = \text{Stefan - Boltzman Constant}$$

$\epsilon$  = Emissivity

$f$  = Viewfactor

$\theta_s$  = Surface temperature

$\theta_r$  = Temperature of radiated body

The thermal conductivity,  $k$ , and radiation emissivity,  $\epsilon$ , are temperature dependent. The convection coefficients,  $h$ , are both time and temperature dependent. Because of this, an iterative procedure must be used to solve these equations. A Newton-Raphson method is used to iterate to convergence the following equation:

$$t + \Delta t_{\theta}(i) = t - \Delta t_{\theta}(i - 1) + t + \Delta t_{\Delta\theta}(i)$$

Convergence is evaluated by both of the following:

$$| \theta^{(i)} - \theta^{(i - 1)} | \leq \delta_1$$

$$| \frac{\alpha^{(i)} - \alpha^{(i - 1)}}{\alpha^{(i - 1)}} | \leq \delta_2$$

The coefficients  $k$ ,  $h$ , and  $\alpha$  are input data. They are set up as a data base (or data table) and stored on a file for use during the iterative procedure.

### III Transient Analysis

In transient heat transfer analysis the heat capacity effects must be included in the analysis as part of the rate of heat generated. If the Euler backward implicit time integration is employed the heat flow equilibrium equations used are obtained directly from the equations of steady-state conditions;

$$\dot{\bar{\theta}}^{(m)}(x,y,z) = \bar{H}^{(m)}(x,y,z) \dot{\bar{\theta}}(t)$$

then

$${}^{t+\Delta t}Q_B = \sum_m \int_{V^m} \bar{H}^{(m)T} \cdot ({}^{t+\Delta t}q_b^{(m)} - {}^{t+\Delta t}c^{(m)} \cdot \bar{H}^{(m)} \cdot {}^{t+\Delta t}\dot{Q}) \, dv$$

where  ${}^{t+\Delta t}q_b$  no longer includes the rate at which heat is stored within the material. Thus, the transient conditions are, in linear analysis,

$$\bar{C} \, {}^{t+\Delta t}\dot{\bar{\theta}} + (\bar{K}^k + \bar{K}^c) \, {}^{t+\Delta t}\bar{\theta} = {}^{t+\Delta t}Q + {}^{t+\Delta t}Q^e$$

and in nonlinear analysis,

$$\begin{aligned} & {}^{t+\Delta t}\bar{C}^{(i)} \, {}^{t+\Delta t}\dot{\bar{\theta}}^{(i)} + ({}^{t}\bar{K}^k + {}^{t}\bar{K}^e + {}^{t}\bar{K}^r) \, \Delta \bar{\theta}^{(i)} \\ & = {}^{t+\Delta t}Q + {}^{t+\Delta t}Q^c(i-1) + {}^{t+\Delta t}Q^r(i-1) - {}^{t+\Delta t}Q^k(i-1) \end{aligned}$$

where  $\bar{C}$ ,  ${}^{t+\Delta t}C^{(i)}$  are the heat capacity matrices,

$$\bar{C} = \sum_m \int_{V^m} \bar{H}^{(m)T} \cdot C^{(m)} \cdot \bar{H}^{(m)} \cdot dv^{(m)}$$

$${}^{t+\Delta t}\bar{C}^{(i)} = \sum_m \int_{V^{(m)}} \bar{H}^{(m)T} \cdot {}^{t+\Delta t}C^{(m)}(i) \cdot \bar{H}^{(m)} \cdot dv^{(m)}$$



## Graded-Composite Structures

The structure is built up from a series of layers of different materials, such that the material properties are discontinuous functions of  $\zeta$ , an appropriate integration through the thickness has to be carried out. For the CSTEM finite element code we use a layered approach, wherein a midpoint rule integration scheme is adopted for each layer.

Layers are numbered sequentially, starting at the bottom surface of the shell. Each layer contains stress points (or temperature) on its mid-surface. The stress components of the layer are computed at these stress points and are assumed to be constant over the thickness of each layer, so that the actual stress distribution of the shell is modelled by a piecewise constant approximation as shown in Figure B-3. Layers of different thickness can be employed, as well as different number of layers per element.

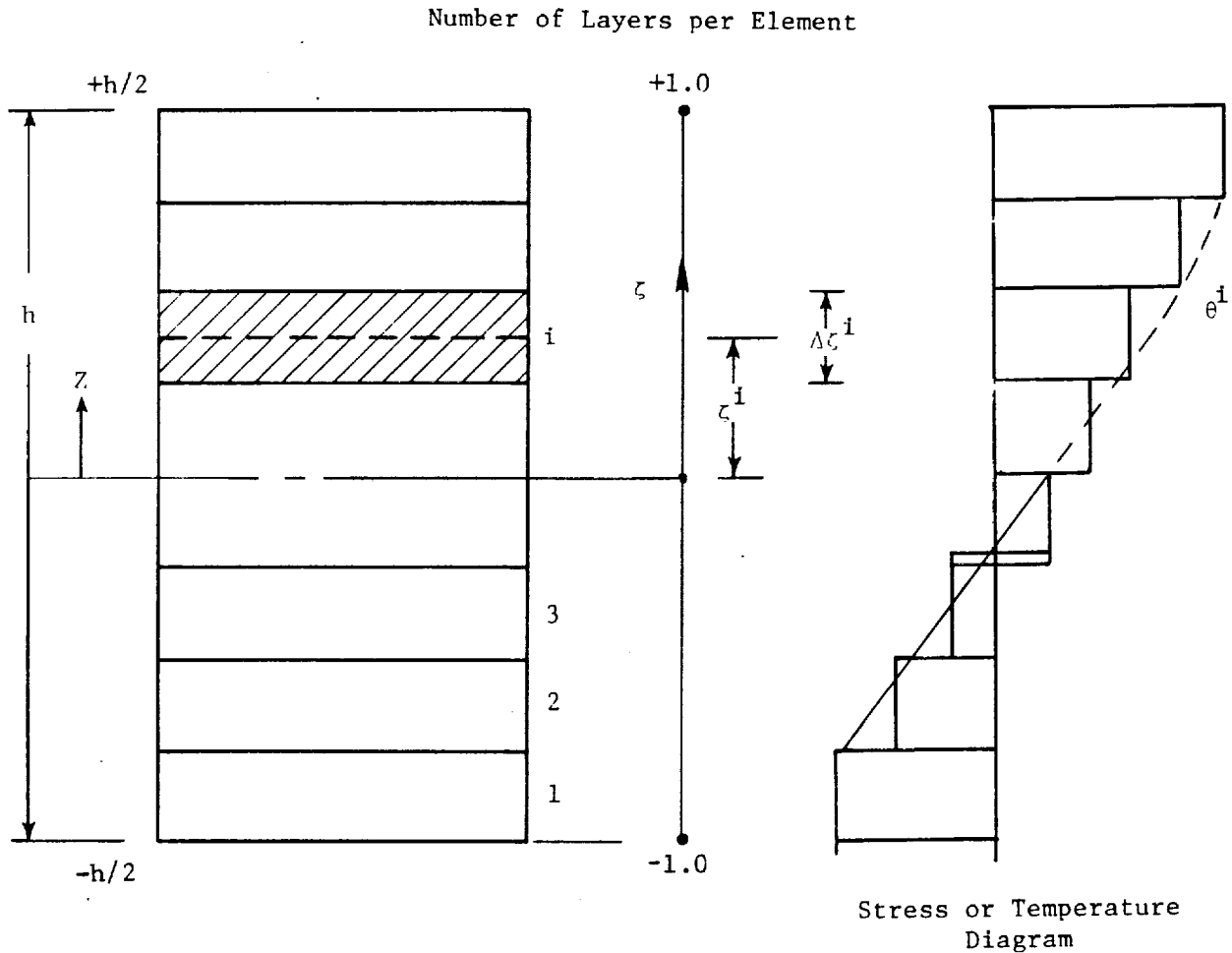


Figure B-3. Layered Model and the Corresponding Stress (Temperature) Representation.

The matrices for the heat transfer equations are obtained by the integration of each layer in the element.

$$K^k = \sum_{i=1}^h \int_v B^{(i)T} t K^{(i)} B^{(i)} dv^{(i)}$$

$$t+\Delta t_Q k^{(j-1)} = \sum_{i=1}^h \int_v B^{(i)T} [t+\Delta t_K^{(i)}(j-1) B^{(i)} t+\Delta t_\theta(j-1)] dv^{(i)}$$

$$C = \sum_{i=1}^h \int_v H^{(i)T} \underline{C}^{(i)} H^{(i)} dv^{(i)}$$

where  $i$  is number of the layer and  $j$  is iteration point number.

The thermal conductivity matrix  $[k]$  is written as follows to handle the orthotropic material properties at each layer of the element.

$$[K] = \begin{bmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zy} & k_{zy} & k_{zz} \end{bmatrix}^{(m)}$$

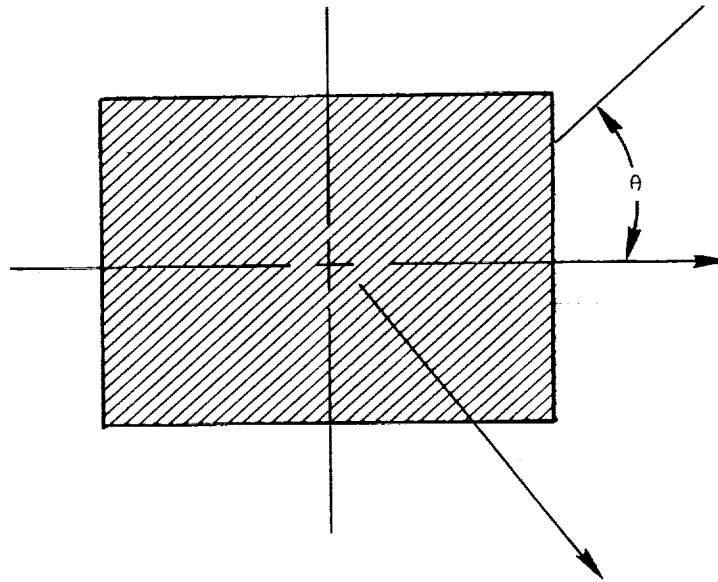


Figure B-4. Inclination of the Principal Axes of Anisotropy.

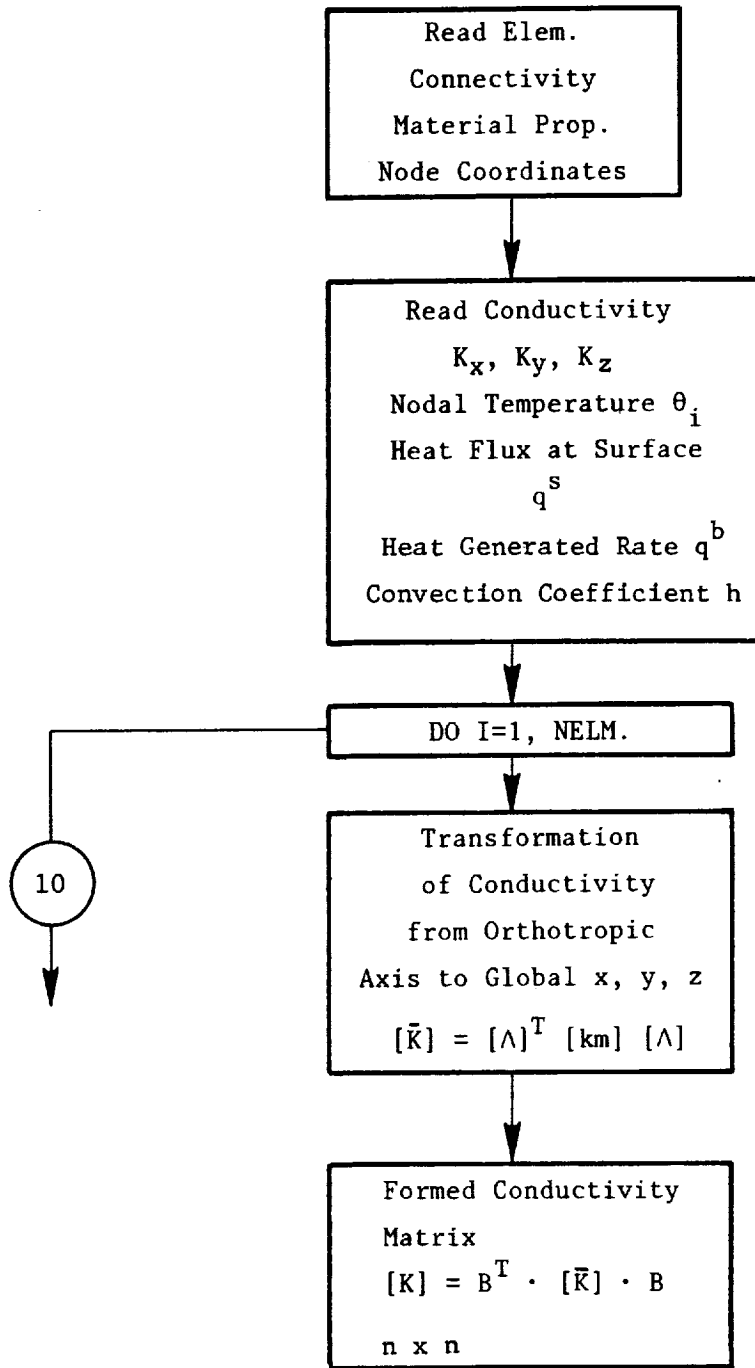
## Computer Program - Flow Charts

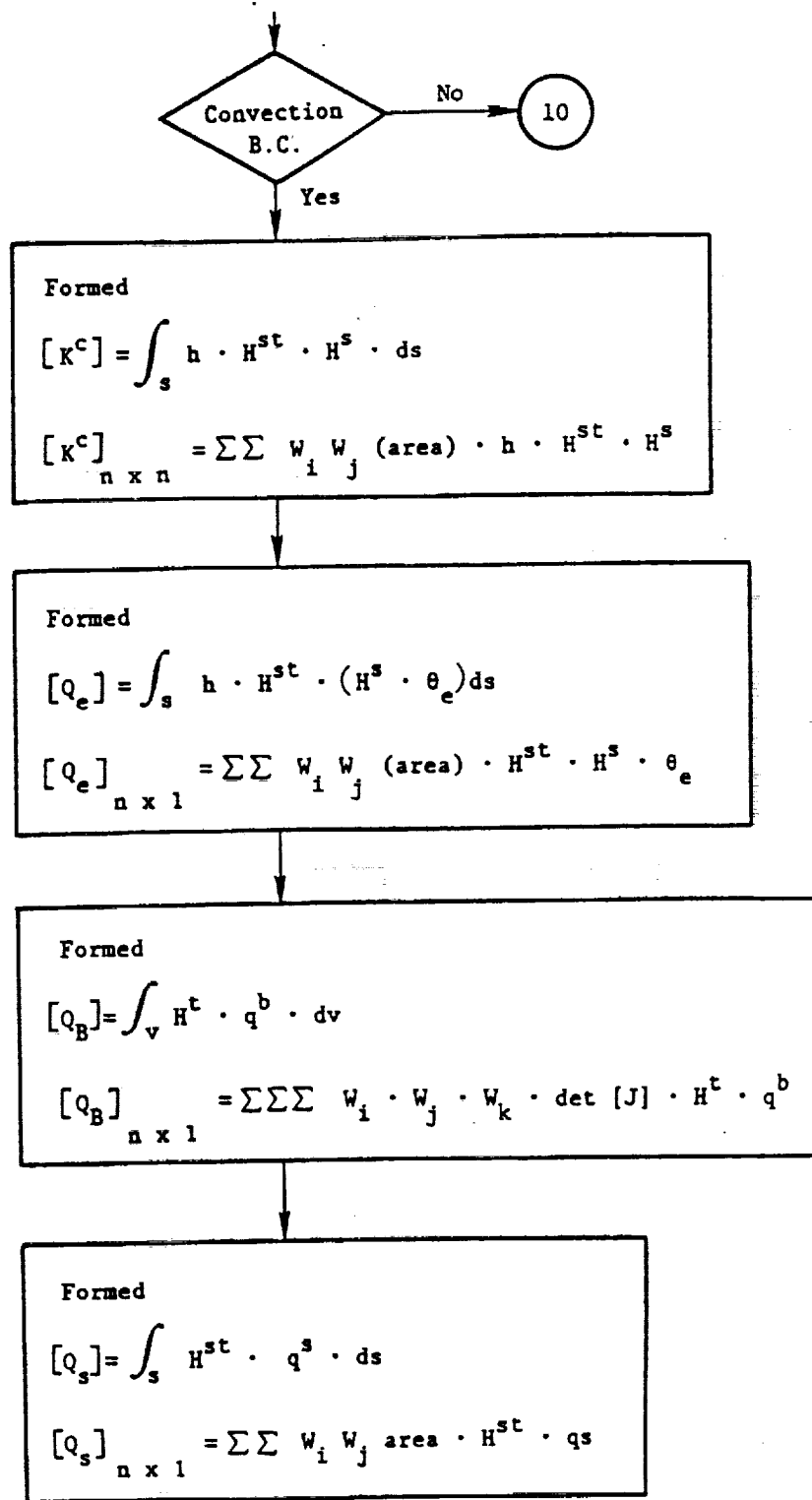
The present computer code considers the graded composite structures. It will handle the linear and nonlinear, steady-state, and transient heat transfer problems by using the "COLSOL" solution technique and the Modified Newton-Raphson iteration scheme to solve the graded composite structures.

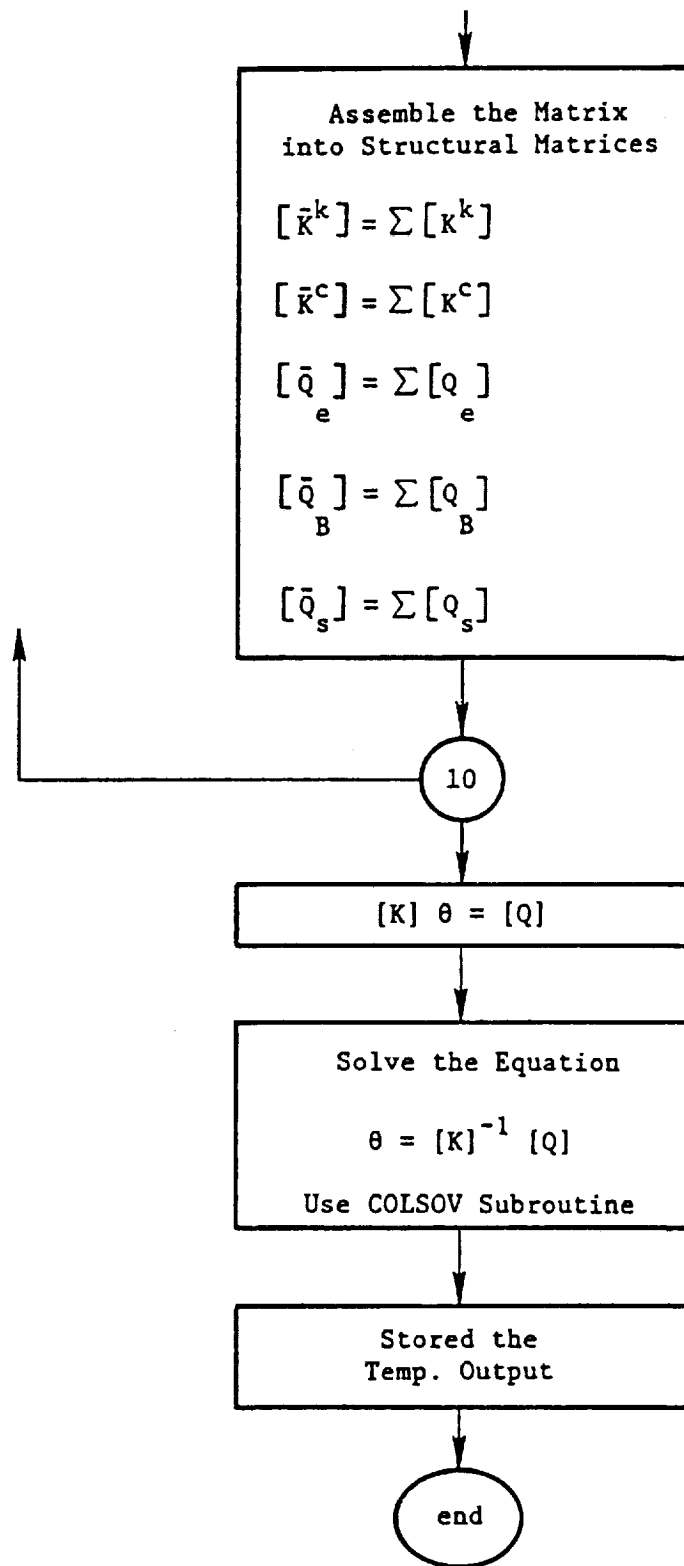
The computer program flow chart is as follows:



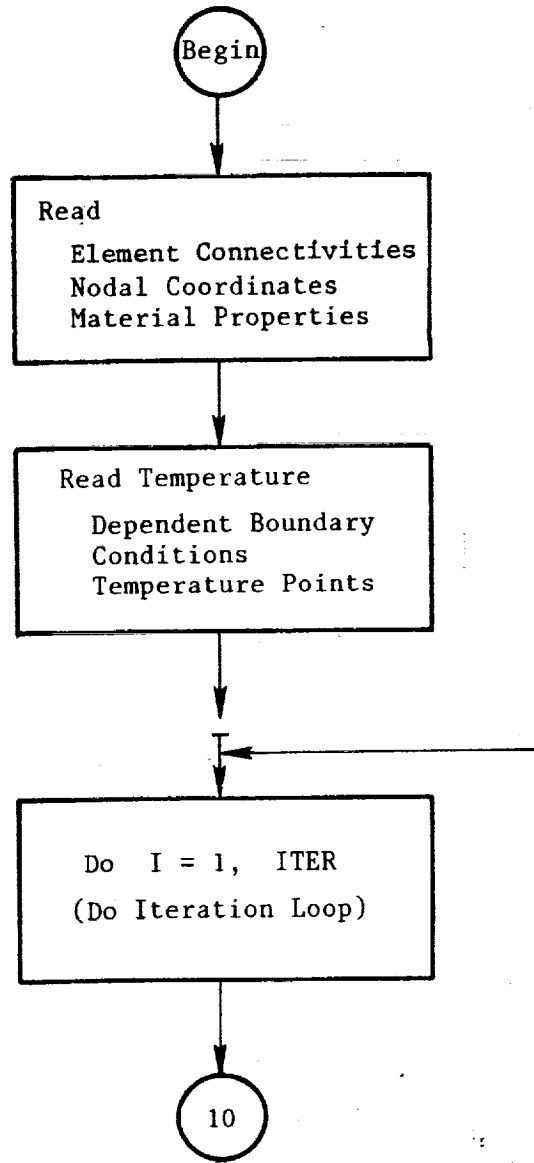
A. Linear Steady-State:



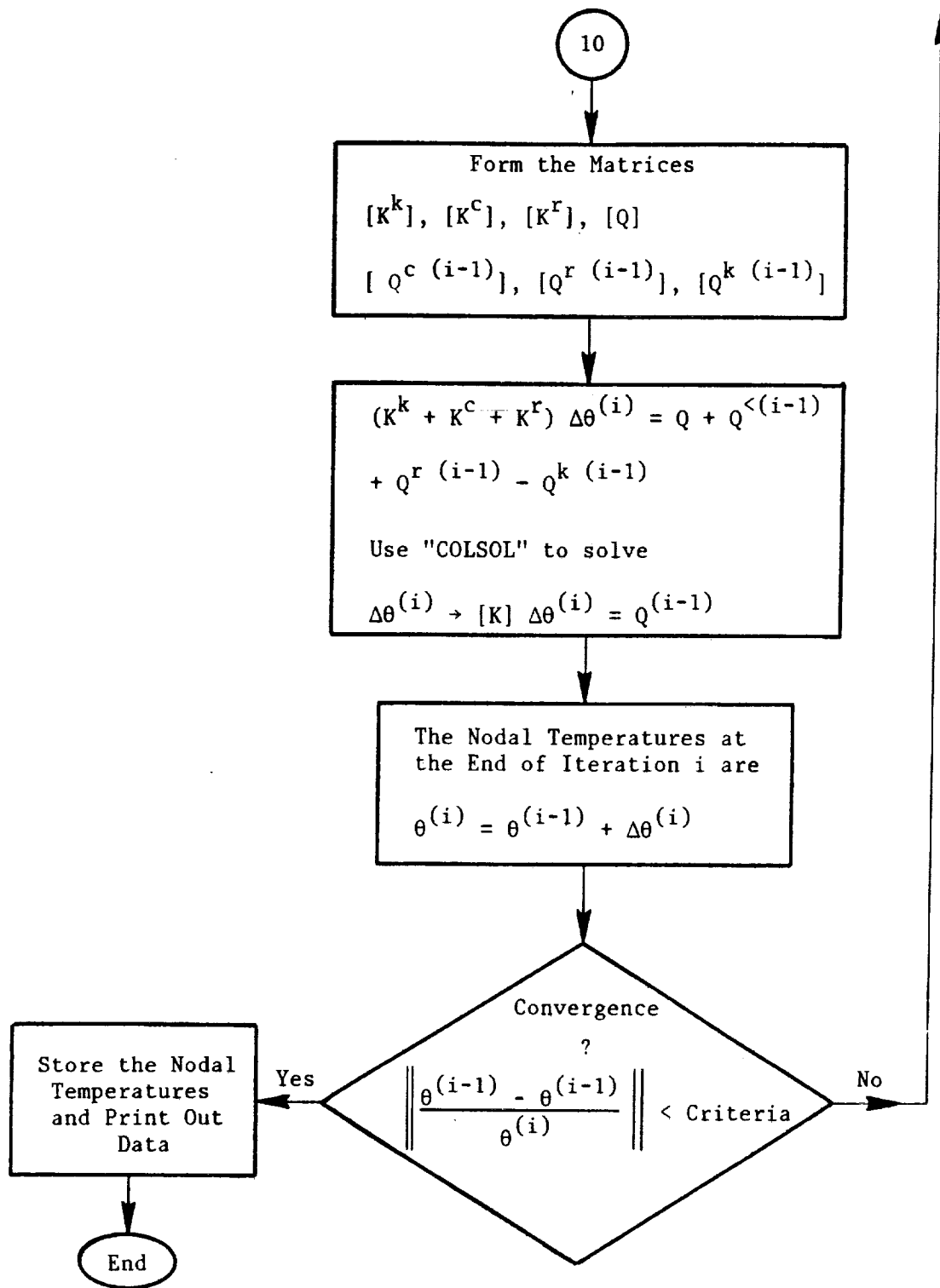




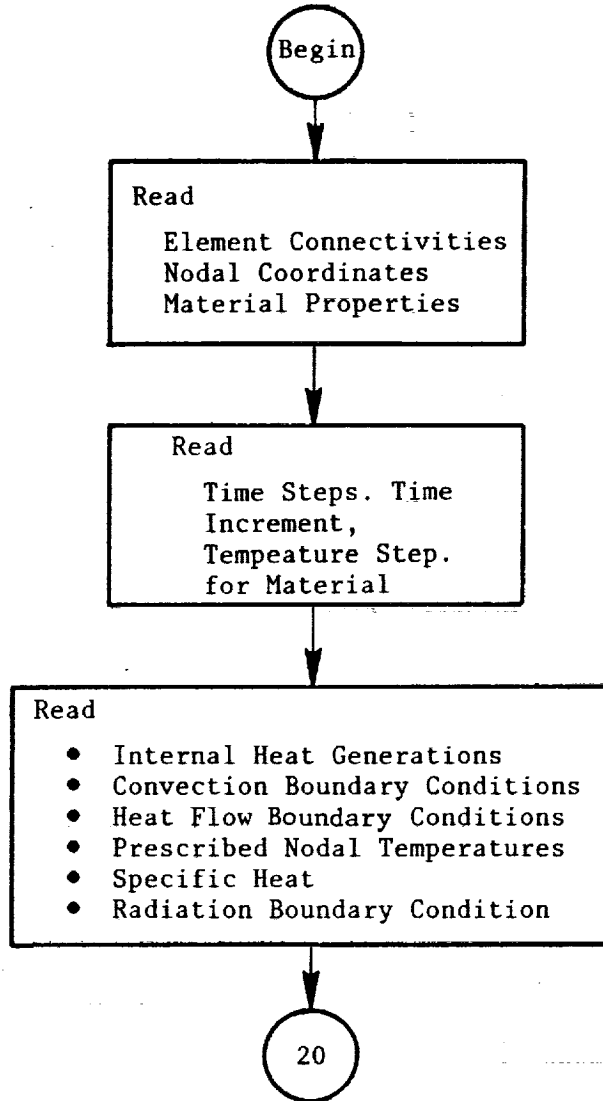
# Nonlinear Steady-State Analysis

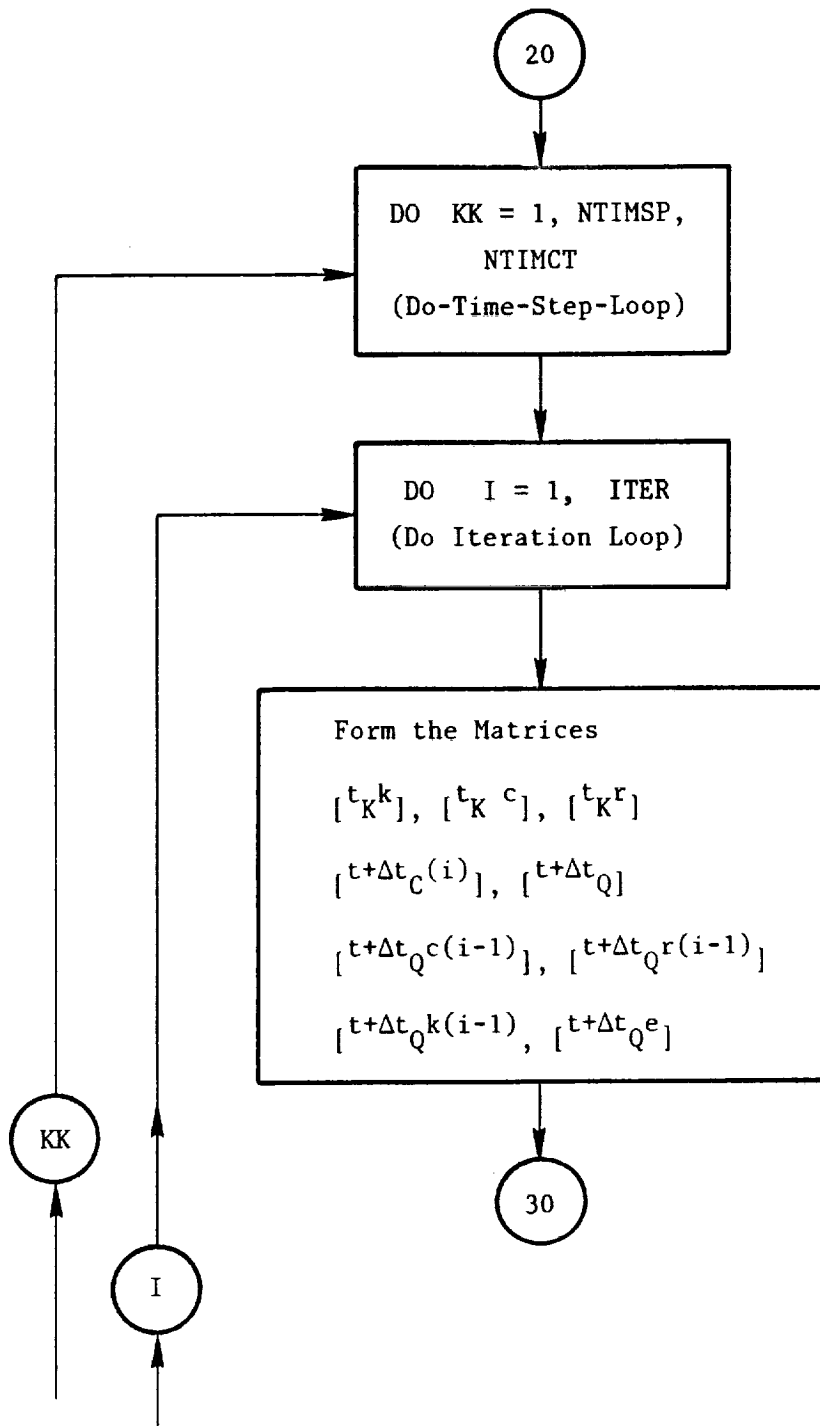


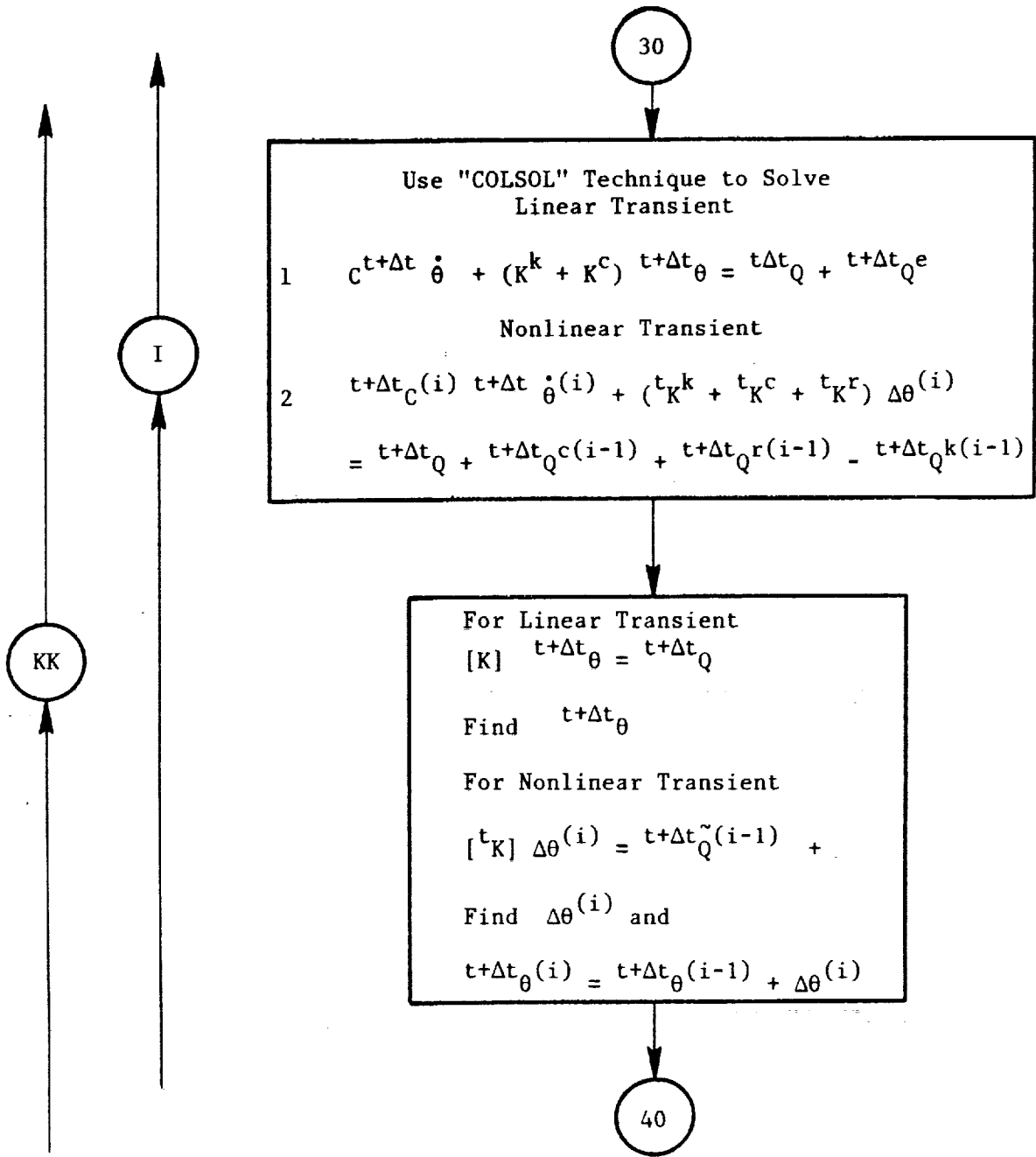


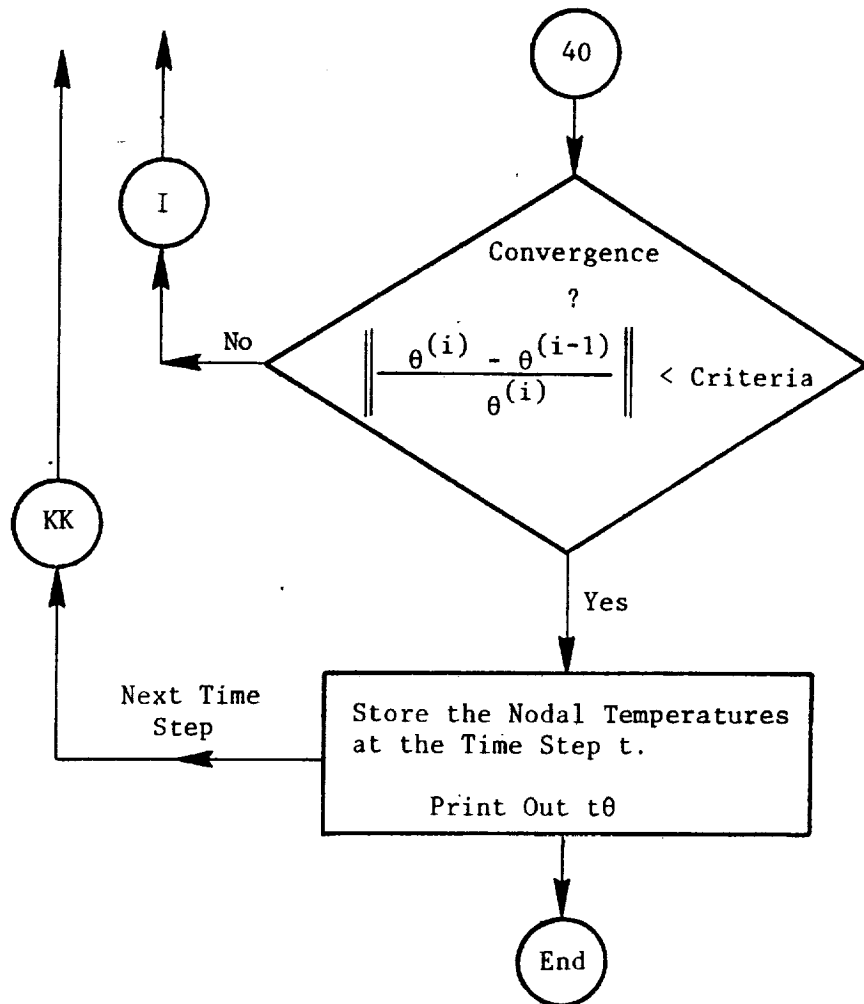


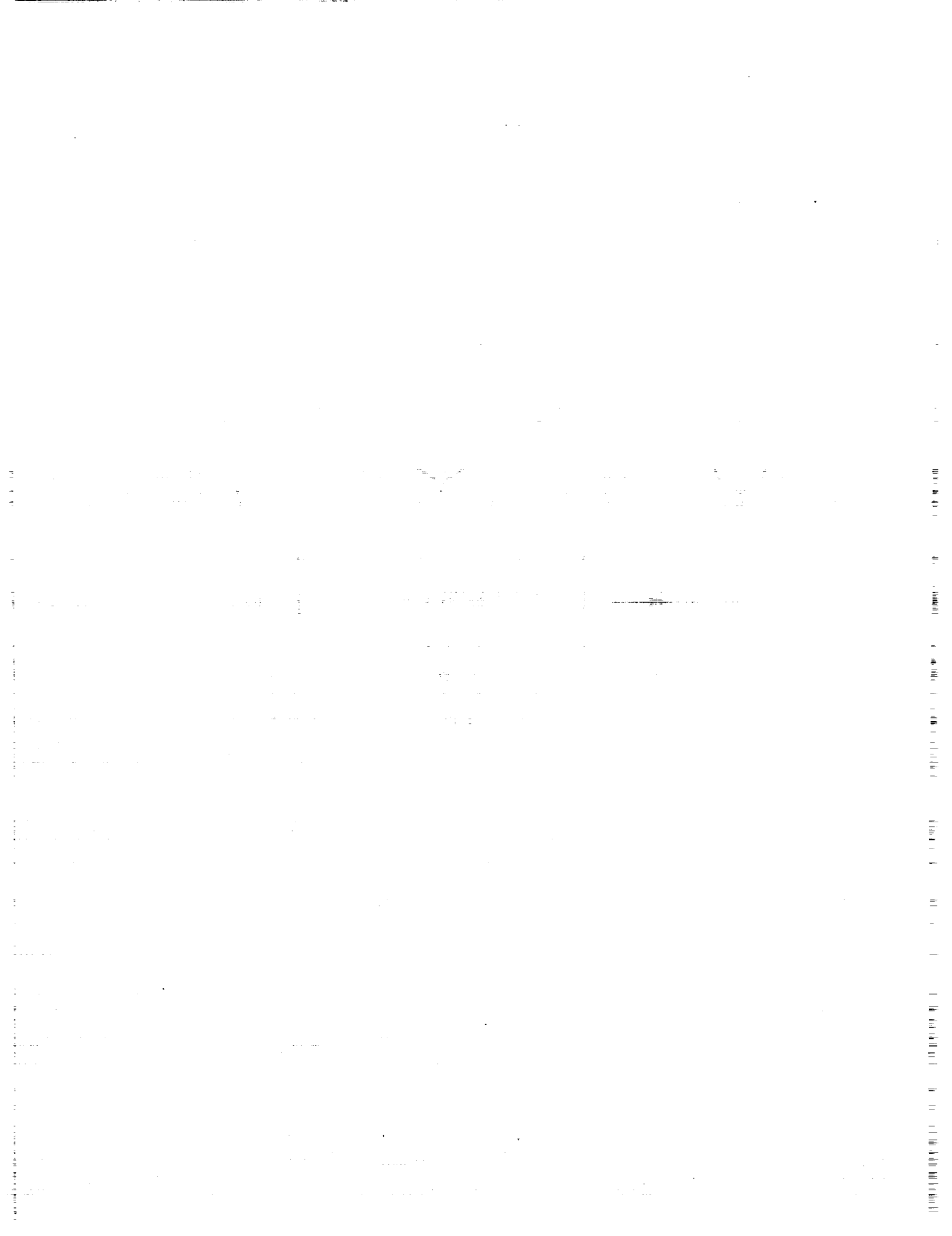
# Transient Analysis











**HEAT TRANSFER**  
**CSTEM USER'S MANUAL**

by

**HSIN-TIEN HUANG**  
**( REV. FEB. 1 1988 )**

# CSTEM INPUT SHEETS

## I. HEADING AND CONTROL INFORMATION

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## VI. SKEW COORDINATE SYSTEM DEFINITIONS

## VIII. FIXED BOUNDARY CONDITIONS

\*\*\*\*\*  
HEAT TRANSFER INPUT DATA  
\*\*\*\*\*

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- 1.2). LOAD CASE INFORMATIONS
- 2). LOAD CASES CONTROL FLAG
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- 4). INTERNAL HEAT GENERATION
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- 10). SPECIFIC HEAT
- 11). RADIATION BOUNDARY CONDITIONS

## I. HEADING AND CONTROL INFORMATION

### I.1 Title Card

#### IDENTIFICATION

Up to 60 characters for identification

### I.2 Problem Size Data

NN MMAT NLC INGEOM IHTR NDATCK

**NN** number of nodes in the model  
**MMAT** number of different materials in the model  
**NLC** number of load cases  
**INGEOM** geometry generation flag  
= 0 geometry read in on input file  
= 1 geometry pregenerated  
(contained on 3 pregenerated files:  
node-element, transformation, material layer)  
**IHTR** HEAT TRANSFER OPTIONS:  
= 1 linear steady-state analysis  
= 2 nonlinear steady-state analysis  
= 3 linear transient analysis  
= 4 nonlinear transient analysis  
(English units used if IHTR >0, metric units  
used if IHTR < 0)  
**NDATCK** =data check flag 0 < data check only  
> 1=run the problem

## II. NODAL COORDINATES

(enter NN lines of II. only if INGEOM equals zero)

N X Y Z

**N** node number  
**X** X coordinate of the node ( in. or cm.)  
**Y** Y coordinate of the node ( in. or cm.)  
**Z** Z coordinate of the node ( in. or cm.)

#### IV. ELEMENT DEFINITION

(enter NELTYP of the following)

##### IV.1 Header Line For Each Element Type

NTYPEL NELEMS INCOMP INTORD

NTYPEL element type; 8=8 nodes; 16=16 nodes;  
20=20 nodes  
NELEMS number of elements in this group  
(not relevant when using pregenerated geometry)  
INCOMP 0 = include incompatible modes (if applicable )  
1 = do not include incompatible modes  
INTORD integration order ( if applicable ie. 2 or 3)

(enter element definition lines IV.2 - IV.16 only if no generated or pregenerated geometry (INGEOM=0))

##### IV.14 8 Noded Solid (NTYPEL = 8)

NEL N1 N2 N3 N4 N5 N6 N7 N8 IMAT

NEL element number  
N1--N8 nodes defining the element, labeled as in Fig.1  
IMAT material number (-1 if element removed)

##### IV.15 16 Noded Solid (NTYPEL = 16)

NEL N1 N2 N3 N4 N5 N6 N7 N8  
N9 N10 N11 N12 N13 N14 N15 N16 IMAT

NEL element number  
N1--N16 nodes defining the element, labeled as in Fig.2  
IMAT material number (-1 if element removed)

##### IV.16 20 Noded Solid (NTYPEL = 20)

NEL N1 N2 N3 N4 N5 N6 N7 N8 N9 N10  
N11 N12 N13 N14 N15 N16 N17 N18 N19 N20 IMAT

NEL element number  
N1--N20 nodes defining the element, labeled as in Fig.3  
IMAT material number (-1 if element removed)

## V. ELEMENT SKEW MATERIAL COORDINATE SYSTEMS

(enter V, only if INGEOM equals zero  
if no skew, input 0, then go to VI)

(axes define principal directions for orthotropic materials)

### NESKEW

**NESKEW** -number of element skew coordinate systems defined. Enter NESKEW of the following lines.

### NEL NTRN NEND NINC

**NEL** element number having a local material coordinate system  
**NTRN** transformation number defining this skew  
**NEND** last element having this local coordinate system  
**NINC** increment on elements from NEL to NEND having this local coordinate system

## VI. ELEMENT LAYER DEFINITION

(enter VI.1 only if INGEOM equals zero; IF not composite structures input 0, then go to VII)

### VI.1 Manual Layer Input

#### NELAY

NELAY number of layer definitions to be read  
(enter NELAY of the following line sets)

#### NEL NLAYR LAX NEND NINC

NEL element for which this layer definition applies  
NLAYR number of layers in this element  
LAX local element system axis perpendicular to layers (1,2, or 3)  
NEND ending element with this layer system  
NINC increment in element number

(enter NLAYR of the following line)

(enter layers in the order as encountered when moving in + direction along LAX)

#### IMAT IPER NTRN ANG

IMAT material number of this layer  
IPER integer percentage of element thickness occupied by this layer  
NTRN transformation number of skew system, referencing orientation of material axes with respect to global (if NTRN=0, ANG is used)  
ANG angle rotated about element axis LAX, referencing orientation of material axes with respect to element local (used only if NTRN=0)

NOTE: Rotations are always positive counter-clockwise as viewed from the positive end of the axis of rotation.  
If rotating about X, 0 is referenced to the Y axis.  
If rotating about Y, 0 is referenced to the Z axis.  
If rotating about Z, 0 is referenced to the X axis.

## VII. SKEW COORDINATE SYSTEMS (NTRN REFER TO THIS SYSTEM)

### VII.1 Reference Nodes

NSKEWR (IF NO, INPUT 0, THEN GO TO VII.2)

NSKEWR= number of skew coordinate systems defined with reference nodes. Enter NSKEWR of the following lines.

NTRN NO NI NJ

NTRN transformation number associated with this skew system  
NO node on local x axis  
NI node on x axis in +x direction  
NJ node in xy plane in general direction of +y axis

### VII.2 Direction Cosines

NSKEWD (IF NO, INPUT 0 , THEN GO TO VII.3)

NSKEWD= number of skew coordinate systems defined with direction cosines. Enter NSKEWD of the following lines.

NTRN A11 A12 A13 A21 A22 A23

NTRN transformation number associated with this skew system  
A11, A12, A13 = direction cosines defining local x axis. The local x axis is defined by  $\underline{ex} = A11*\underline{j} + A12*\underline{j} + A13*\underline{k}$   
A21, A22, A23 = direction cosines defining local y axis. The local y axis is defined by  $\underline{ey} = A21*\underline{j} + A22*\underline{j} + A23*\underline{k}$ . The local z axis is in the direction such that it is a right handed coordinate system.

### VII.3 Euler Angles

**NSKEWE** (IF NO, INPUT 0, THEN GO TO X4)

**NSKEWE**= number of skew coordinate systems defined with Euler angles. Enter **NSKEWE** of the following lines

**NTRN ALPHA BETA GAMMA**

**NTRN** transformation number associated with this skew system  
**ALPHA, BETA, GAMMA** Euler angle successive right hand rotations along the local x, y, & z axes, beginning with the global system

(enter only if using ICAN routines to generate elastic material properties)

### X.1 ICAN GENERATED ELASTIC PROPERTIES

**NL NMS**

**NL** number of layers  
**NMS** number of different material systems

(Enter **NL** of the following cards.)

**INP1 IP1 TU TCU DELM**

**INP1** layer number (identifier for the layer)  
**IP1** material number (which of the mat'l cards applies to this layer)  
**TU** use temperature (used for linear steady state heat transfer analysis)  
**TCU** cure temperature

(Enter NMS of the following line)

C1 C2 VFP VVP C3 C4 VSC VFS VVS

C1 primary fiber type data bank code  
C2 primary matrix type data bank code  
VFP primary fiber volume ratio  
VVP primary void volume ratio  
C3 secondary fiber type data bank code (same as C1 for standard composite systems).  
C4 secondary matrix type data bank code (same as C2 for standard composite systems).  
VSC secondary composite system volume ratio (=0 for standard composite systems)  
VFS secondary fiber volume ratio  
VVS secondary void volume ratio

**NOTE:**

Material numbers are assigned consecutively in order of input, i.e. first material system input is material number 1, second material system input is material number 2, etc.



## HEAT TRANSFER INPUT DATA

(REPEAT NLC TIMES FROM ITEM 1 TO THE END OF LOADING CONDITIONS)

### 1). SUBTITLE (MAX. 72 characters)

SUBTITLE

### 1.2 LOAD CASE INFORMATION

IHTR, NICAN, 0

IHTR    -1 linear steady-state  
          -2 nonlinear steady-state  
          -3 linear transient  
          -4 nonlinear transient  
NICAN   -1 use ICAN to generate elastic properties  
          -0 no use ICAN

### 2). LOAD CASES CONTROL FLAGS:

NHGEN, NCBC, NFBC, NITEM, NRBC, NODFLW, ITER, CDELTA

#### NOTES:

NHGEN    ( 0= no;1=yes) internal heat generation  
NCBC     ( 0= no;1=yes) convection boundary conditions.  
NFBC     ( 0= no;1=yes) heat flux at surface boundary  
          conditions.  
NITEM    ( 0= NO;1=y\_s) initial condition  
NRBC     ( 0= no;1=yes) radiation conditions  
NODFLW   ( 0= no;1=yes) nodal point heat flow input.  
ITER     The max. iterations.  
CDELTA   Convergence criteria;  
ABS|[[ T(i)-T(i-1) ]/ T(i) ]| < CDELTA (i.e. 0.01 ).

**2b). TIME SEGMENTS (ONLY FOR TRANSIENT ANALYSIS)**  
(steady-state skips this line).

NTIMSP  
TIMSEP(1), TIMSEP(2),.....TIMSEP(NTIMSP)

TIMINC(1), TIMINC(2),.....TIMINC(NTIMSP-1)

NOTE:(IF TIME IS SECOND, THEN THE FOLLOWINF INPUT BTU/HR,  
SHOULD BE CHANGED TO BTU/Sec)

NTIMSP -number of time load cases  
TIMSEP(NTIMSP)- time at each time segment.(unit=hour)  
TIMINC(NTIMSP-1) time increment between the time  
steps.

**2c). TEMPERATURE FUNCTIONS (temp. step)**  
(only for nonlinear ANALYSIS=2 & 4 ; OTHERS skip this line)

NTEMP  
TEMPSP(1), TEMPSP(2),.....TEMPSP(NTEMP)

NOTE:

NTEMP number of the temperature points for the temp.  
dependent curves  
TEMPSP(NTEMP) Temperature at each temp. point.(degree C or F)

**3). THERMAL CONDUCTIVITIES**  
(IF NIKAN .NE.0 SKIP THIS LINE, GO TO ITEM 4)  
( REPEAT MMAT TIMES )

MMAT  
KXX(MMT,1), KYX(MMT,1), KZZ(MMT,1)  
KXX(MMT,NTEMP), KYX(MMT,NTEMP), KZZ(MMT,NTEMP)

NOTES:

MMAT NO. OF MATERIAL TYPES IN THE STRUCTURE.  
MMT MATERIAL NUMBER

KXX(MMT,NTEMP) |  
KYY(MMT,NTEMP) | Thermal conductivity table in the  
KZZ(MMT,NTEMP) | PRINCIPAL AXIS.  
(W/M-C) or (BTU/HR-FT-F)

4a). INTERNAL HEAT GENERATION(if NHGEN=0;INPUT 0, GO TO 5)

NEL, NSQ, NEND, INC  
.....  
0 (LAST LINE)

4b). DATA SET OF HEAT SOURCE (TIME DEPENDENT).

NSETHQ  
HOAT(1,1),.....HOAT(1,NTIMSP)  
.....  
HOAT(NSETHQ,1),.....HOAT(NSETHQ,NTIMSP)

NOTES:

NEL        The beginning element # in this group.  
NSQ        The data set # of this group.  
NSETHQ    The total number of data set in the internal  
          heat generator  
HOAT(NSETHQ,NTIMSP) - Heat generated rate per volume.  
          ( Wat/ [meter]\*\*3; or BTU/[hr-ft\*\*3] ).  
          at each data set of each time step  
NEND       End of the element in this group.  
INC        Increment of the element in this group.

5). INITIAL CONDITION  
(if NITEM .eq. 0, input 0, go to 6)

NN, TEMP, NEND, INC  
.....  
0 (LAST LINE)

NOTES:

NN    -    The beginning node number # in this group.  
TEMP -    Initial nodal temperature. (degree of F;  
          or degree of C).  
NEND -    End of the node in this group.  
INC    -    Increment of the node in this group.

6a). CONVECTION BOUNDARY CONDITION.  
(if NCBC .eq. 0; input 0 and go to 7).

NEL, IFACE, NDS, NEND, INC  
.....  
0 (LAST LINE)

6b). DATA SET OF CONVECTION TEMP. AT THE ENVIRONMENT

NSETCO  
.....  
TEMPCO(1,1).....TEMPCO(1,NTIMSP)  
.....  
TEMPCO(NSETCO,1).....TEMPCO(NSETCO,NTIMSP)

**NOTES:**

**NEL**            The beginning element # in this group.

**IFACE**        The face # in this element.(the definition see the figure).

**NDS**            The data set # in this group.

**NEND**          The end of element in this group.

**INC**            Increment of the element in this group.

**NSETCO**        The data set of convection temperatures.

**TEMPCO(NSETCO,NTIMSP)**    temperatures at each data set (NSETCO),and each time step (NTIMSP).  
(DEGREE OF C OR F)

6c). CONVECTION COEFFICIENT TABLES

(Enter NSETCO convection coefficient tables)

HCOV(1,1)....., HCOV(1,NTIMSP)  
.. .. ..  
HCOV(NSETCO,1),.....,HCOV(NSETCO,NTIMSP)

NOTES:

MMT Material number  
NTEMP No of temp. points in the coeff. curve  
HCOV (NTEMP,MMAT) Coeff. of convection,  
of each material at each temperature  
point (temp dependent)  
( Wat/[meter\*\*2-degree C] or BTU/[ hr-ft\*\*2-degree F] ).

7a). HEAT FLUX AT THE SURFACE

( if NFBC .eq. 0 then input 0 , go to item 8)

NEL, IFACE, NSF, NEND, INC  
.....  
0(LAST LINE)

7b).HEAT FLUX TEMPERATURES.

NSETFL  
TEMPFL(1,1)....., TEMPFL(1,NTIMSP)  
.....  
TEMPFL(NSETFL,1).....,TEMPFL(NSETFL,NTIMSP)

NOTES:

NEL The beginning element # in this group.  
IFACE Heat flux at the surface # in the element NEL.  
(the face definition see the figure.)  
NSF The data set # in this group.  
NSETFL Total dat set in this group.  
TEMPFL(NSETFL,NTIMSP) - Heat Flux at the surface,  
at each data set and each time step.  
(Wat/[meter\*\*2]; or BTU/[ hr-ft\*\*2] ).  
NEND The end of the element in this group.  
INC Increment of the element in this group.

8a). NODAL POINT HEAT FLUX  
( If NODFLW .eq. 0; input 0, go to item 9)

N1, NSP, NEND, INC

.....

.....

0(LAST LINE)

8b). DATA SET OF NODAL TEMPERATURES

NSETPQ

PQ(1,1), ..... .. PQ(1,NTIMSP)

.....

PQ(NSETPQ,1),..... .. PQ(NSETPQ,NTIMSP)

NOTES:

N1 The beginning node # in this group.

NSP The data set # in this group.

NSETPQ Total data set in this group.

PQ(NSETPQ,NTIMSP) Heat flux nodal point input.  
at each data set and each time step  
( Wat. or BTU/hr ).

NEND The end of node # in this group.

INC Increment of the node # in this group.



**11a). RADIATION BOUNDARY CONDITIONS**

(if IANALY .eq. 2 or IANALY .eq. 4 input this line;  
otherwise skip 11, GO TO ITEM 1 FOR NEXT LOAD CASE)  
(if NRBC .eq. 0 input 0)

NEL, IFACE, NSR, NEND, INC

.....  
0(LAST LINE)

**11b). RADIATION TEMPERATURES.**

NSETRA

TEMPRA(1,1).....TEMPRA(1,NTIMSP)

.....  
TEMPRA(NSETRA,1).....TEMPRA(NSETRA,NTIMSP)

**NOTES:**

NEL           The beginning element # in this group.  
IFACE        The face of the element which the radiation  
              occurs.  
TEMPRA(NSETRA,NTIMSP) - The temperatures at the  
                          surface nodes in the data set and each time  
                          step. (degree of F or C ).  
NSR           The data set # in this group.  
NSETRA       Total data set in the group.  
NEND         The end of the element in this group.  
INC          Increment of the element in this group.

**11c). VIEWFACTOR**

NEL, P(1).....P(6),NEND, NINC

.....  
.....  
0 (LAST LINE)

**NOTES:**

NEL           # OF ELEMENT  
P(6)         THE VIEW FACTOR AT THE FACE OF ELEMENT  
NEND         LAST ELEMENT OF THIS GROUP  
NINC         INCREMENT OF THE ELEMENT



11d). EMISSIVITY TABLES- (enter MMAT times).

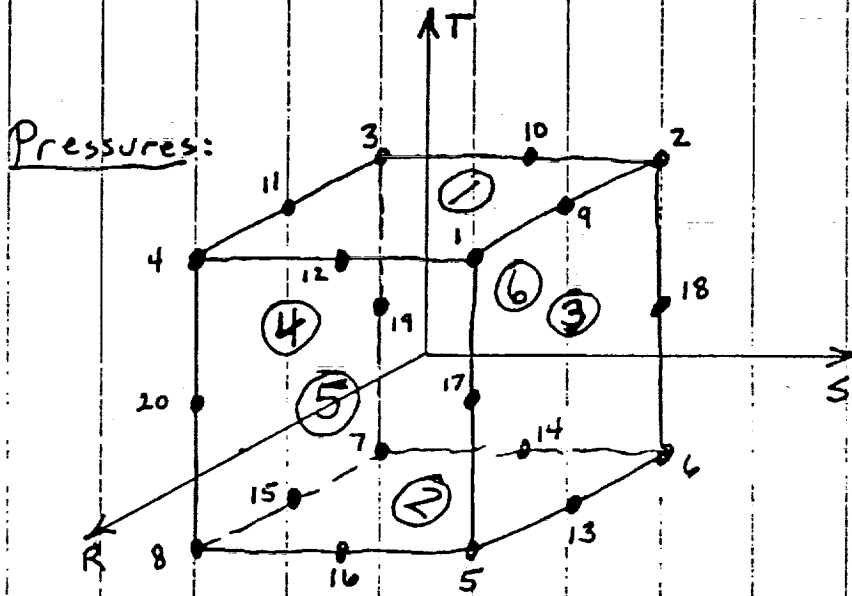
EMCOV(MMT,1), EMCOV(MMT,2),.....,EMCOV(MMT,NTEMP)  
.....  
.....

NOTES:

EMCOV(MMT,NTEMP)    The emissivity coeff. at each temp. point

①

NODAL FACE FOR PRESSURES,  
Heat transfer - INPUT (8, 16, 20 Nodes, same)



- FACE 1:  $T = 1$
- FACE 2:  $T = -1$
- FACE 3:  $S = 1$
- FACE 4:  $S = -1$
- FACE 5:  $R = 1$
- FACE 6:  $R = -1$

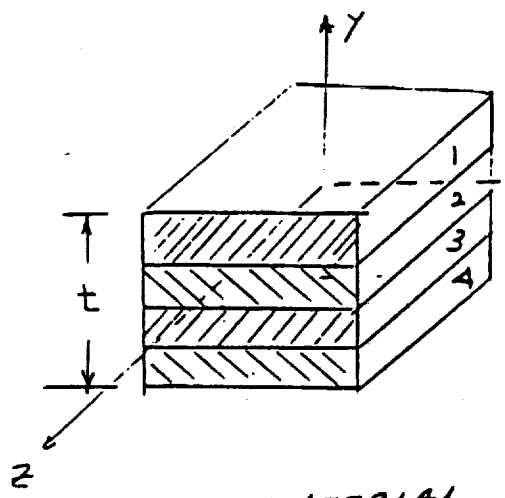
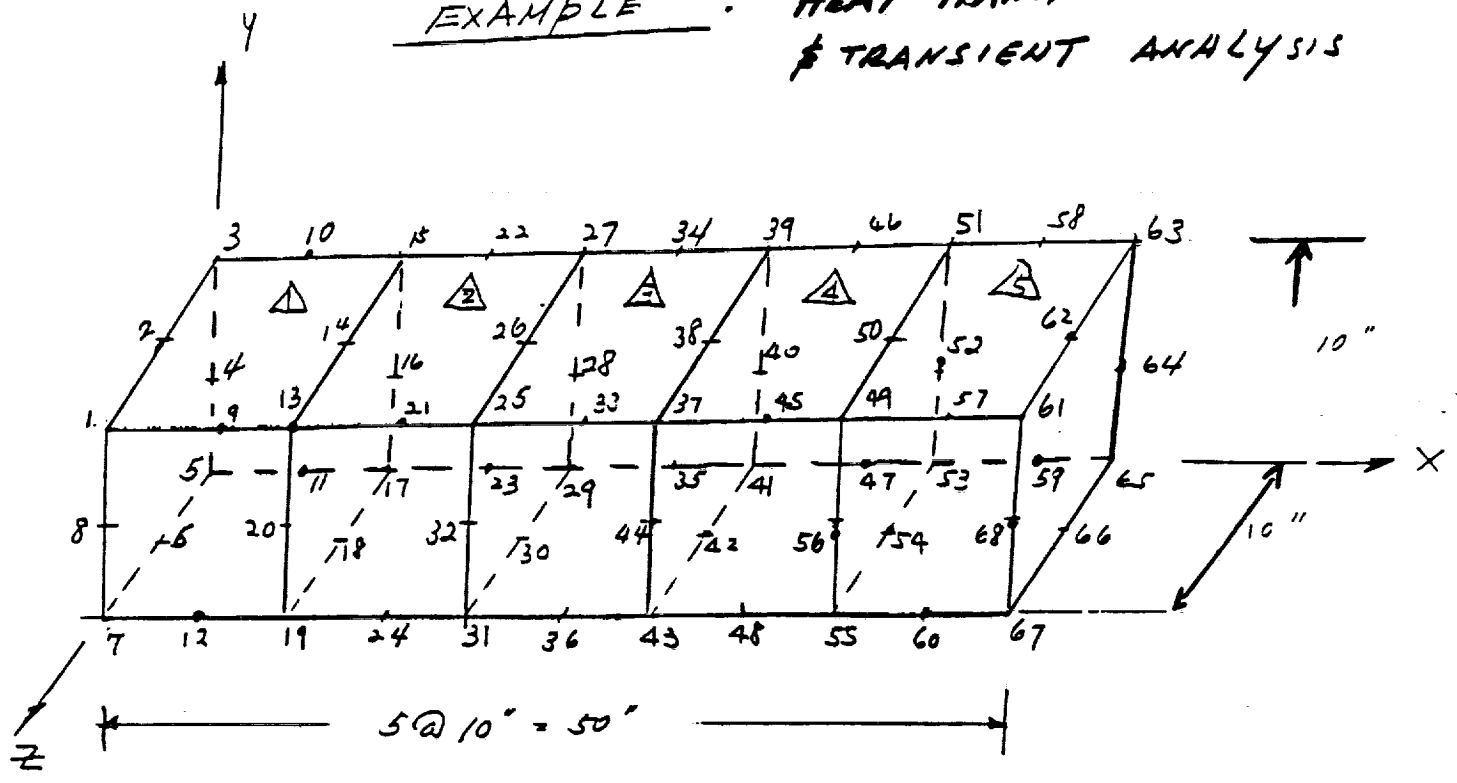
	NODE	NODE	NODE	NODE	NODE	NODE	NODE	NODE
	1	2	3	4	5	6	7	8
FACE 1	1	2	3	4	9	10	11	12
FACE 2	5	6	7	8	13	14	15	16
FACE 3	1	2	6	5	9	18	13	17
FACE 4	3	4	8	7	11	20	15	19
FACE 5	1	4	8	5	12	20	16	17
FACE 6	2	3	7	6	10	19	14	18

THERMAL ANALYZER VERIFICATION CASES

Case 1 - Linear Heat Transfer - Composite Structures.

Case 2 - Nonlinear Heat Transfer - Composite Structures.

EXAMPLE : HEAT TRANSFER - STEADY-STATE & TRANSIENT ANALYSIS



Rotate about Y-axis  
 - layer { 2 & 3 :  $-45^\circ$  R.H.R.  
 { 1 & 4 :  $45^\circ$  R.H.R.

MATERIAL - LAMINATE.

Case

1:

LINEAR HEAT TRANSFER - COMPOSITE STRUCTURES

\* INPUT-DATA DECK

\* OUTPUT DATA



2	2, 0, 0	60., 40, 40.
1	1, 1, 1, 1, 0, 0, 200, 0.01	80., 60, 60.
6	0., 100., 200., 300., 400., 600.	95., 75, 75.
1	0., 0., 0., 0.	105., 80, 80.
0	60., 40, 40.	115., 85, 85.
8	80., 60, 60.	1, 1, 5, 1
0.5	95., 75, 75.	0
6	105., 80, 80.	1
1	115., 85, 85.	70.
0	1, 1, 5, 1	0
40.	40, 40.	1, 70, 68, 1
60.	60, 60.	0
80.	80, 80.	5, 6, 1, 5, 1
90.	90, 90.	0
100.	100, 100.	1
0	1, 1, 5, 1	45.0
1	50.0	0
0	1, 70, 68, 1	10.0 15.0 20.0 25.0 30.0 35.0
1	5, 6, 1, 5, 1	0
0	0	2, 3, 1, 3, 1
1	50.0	0
50.0	10.0 15.0 20.0 25.0 30.0 35.0	1
0	0	100.0
1	1, 70., 68, 1	0
0	0	0
5, 6, 1, 5, 1	2, 3, 1, 3, 1	1, 1, 8, 1
0	0	0
1	1	1
40.0 40.0 50.0 70.0 80.0 100.0	80.0	100.0
0	0	0
10.0 15.0 20.0 25.0 30.0 35.0	0	4, 2, 1, 4, 1
0	1, 1, 8 1	0
0	0	1
0	1	60.0
1, 1, 8, 1	100.0	0
0	0	4, 1.0, 1.0, 1.0, 1.0, 1.0, 4, 1
1	0	0
70.0 70.0 100.0 100.0 120.0 120.0	NONLINEAR STEADY-STATE HEAT TRANSFER	0.15, 0.1, 0.08, 0.05, 0.01, 0.008
0	2, 0, 0	0
0.2	1, 1, 1, 1, 1, 0, 200, 0.001	
10.0 10.0 10.0 10.0 10.0 10.0	6	
0	0., 100., 200., 300., 400., 600.	
0	1	
NONLINEAR STEADY-STATE HEAT TRANSFER	0., 0., 0.	

*NONLINEAR - HEAT TRANSFER  
composite stru.*

ZOUT20C.120

HEADING AND CONTROL INFORMATION

TITLE CARD

NONLINEAR HEAT-TRANSFER - composite structures

*output*

PROBLEM SIZE DATA

NH	MELTYP	MWAT	MLC	INGEOM	IHTR	MDATCK
68	1	1	3	0	4	1

NODAL COORDINATES

N	X	Y	Z
1	0.00000	10.00000	10.00000
2	0.00000	10.00000	5.00000
3	0.00000	10.00000	0.00000
4	0.00000	5.00000	0.00000
5	0.00000	0.00000	0.00000
6	0.00000	0.00000	5.00000
7	0.00000	0.00000	10.00000
8	0.00000	5.00000	10.00000
9	5.00000	10.00000	10.00000
10	5.00000	10.00000	0.00000
11	5.00000	0.00000	0.00000
12	5.00000	0.00000	10.00000
13	10.00000	10.00000	10.00000
14	10.00000	10.00000	5.00000
15	10.00000	10.00000	0.00000
16	10.00000	5.00000	0.00000
17	10.00000	0.00000	0.00000
18	10.00000	0.00000	5.00000
19	10.00000	0.00000	10.00000
20	10.00000	5.00000	10.00000
21	15.00000	10.00000	10.00000
22	15.00000	10.00000	0.00000
23	15.00000	0.00000	0.00000
24	15.00000	0.00000	10.00000
25	20.00000	10.00000	10.00000
26	20.00000	10.00000	5.00000
27	20.00000	10.00000	0.00000
28	20.00000	5.00000	0.00000
29	20.00000	0.00000	0.00000
30	20.00000	0.00000	5.00000

31	20.00000	0.00000	10.00000
32	20.00000	5.00000	10.00000
33	25.00000	10.00000	10.00000
34	25.00000	10.00000	0.00000
35	25.00000	0.00000	0.00000
36	25.00000	0.00000	10.00000
37	30.00000	10.00000	10.00000
38	30.00000	10.00000	5.00000
39	30.00000	10.00000	0.00000
40	30.00000	5.00000	0.00000
41	30.00000	0.00000	0.00000
42	30.00000	0.00000	5.00000
43	30.00000	0.00000	10.00000
44	30.00000	5.00000	10.00000
45	35.00000	10.00000	10.00000
46	35.00000	10.00000	0.00000
47	35.00000	0.00000	0.00000
48	35.00000	0.00000	10.00000
49	40.00000	10.00000	10.00000
50	40.00000	10.00000	5.00000
51	40.00000	10.00000	0.00000
52	40.00000	5.00000	0.00000
53	40.00000	0.00000	0.00000
54	40.00000	0.00000	5.00000
55	40.00000	0.00000	10.00000
56	40.00000	5.00000	10.00000
57	45.00000	10.00000	10.00000
58	45.00000	10.00000	0.00000
59	45.00000	0.00000	0.00000
60	45.00000	0.00000	10.00000
61	50.00000	10.00000	10.00000
62	50.00000	10.00000	5.00000
63	50.00000	10.00000	0.00000
64	50.00000	5.00000	0.00000
65	50.00000	0.00000	0.00000
66	50.00000	0.00000	5.00000
67	50.00000	0.00000	10.00000
68	50.00000	5.00000	10.00000

ELEMENT DEFINITION

HEADER LINE

HTYPEL WELEMS INCOMP INTORD



20 5 1 3

0

ELEMENT TYPE 20  
20 NODDED ISOPARAMETRIC BRICKS

DIRECTION COSINES

NEL	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	IMAT	
1	1	13	15	3	7	19	17	5														
9	14	10	2	12	18	11	6	8	20	16	4	1										
2	13	25	27	15	19	31	29	17														
21	26	22	14	24	30	23	18	20	32	28	16	1										
3	25	37	39	27	31	43	41	29														
33	38	34	26	36	42	35	30	32	44	40	28	1										
4	37	49	51	39	43	55	53	41														
45	50	46	38	48	54	47	42	44	58	52	40	1										
5	49	61	63	51	55	67	65	53														
57	62	58	50	60	66	59	54	56	68	64	52	1										

NSKEWD 0

EULER ANGLES

NSKEWE 2

NTRN ALPHA BETA GAMMA  
 1 0.0000 -45.0000 0.0000  
 2 0.0000 45.0000 0.0000

HEADING AND CONTROL INFORMATION

ELEMENT SKEW MATERIAL COORDINATE SYSTEMS

NN NE HWAT WTYPEL MLC IUMIT IANALY  
 68 5 1 20 3 1 4

NSKEWE 0

ELEMENT MATERIAL LAYER SETS

MELAY 1

NEL MLAYR LAX NEMD NINC  
 1 4 2 5 1

LAYER 1 IMAT LPER LTRAN  
 1 25 1  
 LAYER 2 IMAT LPER LTRAN  
 1 25 2  
 LAYER 3 IMAT LPER LTRAN  
 1 25 2  
 LAYER 4 IMAT LPER LTRAN  
 1 25 1

SKEW COORDINATE SYSTEMS

81 REFERENCE NODES

NSKEWR

LOAD CASE CONTROL INFORMATION, LOAD CASE = INONLINEAR TRANSIENT HEAT TRANSFER

LOAD CASE CONTROL CARDS

IHT XICAN MTEM  
 1 0 0

LOAD CASE CONTROL INFORMATION

LOAD CASE CONTROL CARD

NHGEN NBCBC NFBC NITEN NPRES NRBC MODFLW ITER COELTA  
 1 1 0 1 1 0 0 200 0.010000

\*\*\*\*\* THE TIME FUNCTION \*\*\*\*\*

THE TOTAL NUMBERS OF TIME SEGMENTAL POINTS = 6

THE TIME AT EACH TIME STEP  
TIME(1),.....,TIME (n)

0.00000 1.00000 2.00000 3.00000 4.00000 5.00000

THE TIME INCREMENT BETWEEN TIME STEPS = 0.50000

\*\*\*\*\* THE TEMPERATURE FUNCTION \*\*\*\*\*

THE TOTAL NUMBERS OF TEMPERATURE POINTS = 6

THE TEMPERATURE AT EACH POINT  
TEMP(1),....., TEMP(n)

0.00 100.00 200.00 300.00 400.00 600.00

MATERIAL 1 THERMAL CONDUCTIVITY TABLE

CONDUCTIVITY KXX, KYY, KZZ

THE TEMPERATURE POINT = 1

0.000000 0.000000 0.000000

THE TEMPERATURE POINT = 2

40.000000 40.000000 40.000000

THE TEMPERATURE POINT = 3

60.000000 60.000000 60.000000

THE TEMPERATURE POINT = 4

80.000000 80.000000 80.000000

THE TEMPERATURE POINT = 5

90.000000 90.000000 90.000000

THE TEMPERATURE POINT = 6

100.000000 100.000000 100.000000

0

INTERNAL HEAT GENERATION

ELE. NDATA NEMD. INC.

1 1 5 1

0

THE TOTAL DATA SET = 1

THE INTERNAL HEAT GENERATED RATE

QRATE(1),.....,QRATE(TIME STEP)

50.00 50.00 50.00 50.00 50.00 50.00

0

INITIAL MODAL TEMPERATURES

N TEMP NEMD NINC

1 70.00 68 1

0

CONVECTION MODAL TEMPERATURES

ELM IFACE NDS NEMD NINC

5 6 1 5 1

4.

70.00 70.00 100.00 100.00 120.00 120.00  
0

THE MASS DENSITY  
MASS (1,2,...MMAT)  
0.20000

MATERIAL # = 1  
THE SPECIFIC HEAT (1,2,.....MTEMP)

10.00 10.00 10.00 10.00 10.00 10.00

0

RADIATION MODAL TEMPERATURES

-----  
NEL IFACE MDATA MEND IMC

0

\*\*\*\*\*

THE FINAL RESULT OF MODAL TEMP  
LOAD CASE= 1 TIME STEP= 1 TIME = 0.5000

1	70.00
2	70.00
3	70.00
4	70.00
5	70.00
6	70.00
7	70.00
8	70.00
9	112.92
10	110.75
11	110.52
12	112.74
13	101.13
14	100.29

0

TIME DEPENDENT COEFF. OF CONVECTION  
\*\*\*\*\*

THE TOTAL DATA SET = 1  
THE TIME DEPENDENT ENVIRONMENT TEMP(1,2,.....MTEMP)

40.00 40.00 50.00 70.00 80.00 100.00

0

\*\*\*\* THE MATERIAL NUMBER = 1  
THE CONVECTION COEFF H(1,2,... MTEMP)

10.00 15.00 20.00 25.00 30.00 35.00

0

HEAT FLUX IN THE SURFACE -----

ELE. FACE MDATA MEND MIMC

0

MODAL POINT HEAT FLOW INPUT

-----  
M1 MDATA MEND MIMC

0

PRESCRIBED MODAL TEMPERATURES

N MDATA MEND MIMC

1 1 6 1

0

DATA SET = 1  
PRESCRIBED MODAL TEMP.  
TEMP(1),TEMP(2), ...TEMP(TIME STEP)

5.

26	95.20
27	94.43
28	94.54
29	94.30
30	95.07
31	95.85
32	95.93
33	88.08
34	86.92
35	86.81
36	87.97
37	81.59
38	81.08
39	80.57
40	80.66
41	80.49
42	81.00
43	81.50
44	81.56
45	76.33
46	75.67
47	75.61
48	76.26
49	71.88
50	71.62
51	71.40
52	71.43
53	71.36
54	71.57
55	71.83
56	71.86
57	67.96
58	67.69
59	67.66
60	67.94
61	64.37
62	64.35
63	64.16
64	64.18
65	64.15
66	64.34
67	64.35
68	64.37

60	66.56
61	63.55
62	63.84
63	63.98
64	63.92
65	64.01
66	63.88
67	63.58
68	63.55

\*\*\*\*\*

THE FINAL RESULT OF MODAL TEMP  
LOAD CASE= 1 TIME STEP= 2 TIME = 1.5000

1	85.00
2	85.00
3	85.00
4	85.00
5	85.00
6	85.00
7	85.00
8	85.00
9	130.86
10	128.19
11	127.94
12	130.61
13	117.12
14	116.34
15	115.56
16	115.85
17	115.44
18	116.21
19	116.99
20	117.08
21	105.70
22	104.10
23	103.95
24	105.55
25	95.98

15	99.39
16	99.65
17	99.22
18	100.14
19	101.00
20	101.07
21	91.40
22	89.52
23	89.34
24	91.23
25	83.77
26	82.90
27	82.04
28	82.19
29	81.90
30	82.76
31	83.62
32	83.73
33	78.36
34	77.27
35	77.17
36	78.26
37	74.45
38	74.09
39	73.72
40	73.78
41	73.67
42	74.03
43	74.39
44	74.43
45	71.58
46	71.29
47	71.26
48	71.55
49	69.10
50	69.09
51	69.12
52	69.12
53	69.13
54	69.09
55	69.10
56	69.10
57	66.54
58	66.80
59	66.82

6

3	110.00
4	110.00
5	110.00
6	110.00
7	110.00
8	110.00
9	170.12
10	167.30
11	167.05
12	169.84
13	153.83
14	153.35
15	152.88
16	153.12
17	152.81
18	153.27
19	153.74
20	153.81
21	139.69
22	138.44
23	138.32
24	139.57
25	126.62
26	125.91
27	125.20
28	125.30
29	125.08
30	125.79
31	126.50
32	126.58
33	114.91
34	113.67
35	113.55
36	114.79
37	104.49
38	103.83
39	103.15
40	103.26
41	103.03
42	103.71
43	104.38
44	104.45
45	95.46
46	94.34
47	94.23

37	92.90
38	92.21
39	91.50
40	91.62
41	91.39
42	92.09
43	92.79
44	92.86
45	85.15
46	84.10
47	84.00
48	85.05
49	78.66
50	78.14
51	77.67
52	77.75
53	77.59
54	78.06
55	78.57
56	78.63
57	73.27
58	72.53
59	72.46
60	73.20
61	68.83
62	68.57
63	68.11
64	68.17
65	68.05
66	68.51
67	68.77
68	68.81

THE FINAL RESULT OF MODAL TEMP  
 LOAD CASE= 1 TIME STEP= 3 TIME = 2.5000

1	100.00
2	100.00
3	100.00
4	100.00
5	100.00
6	100.00
7	100.00
8	100.00
9	154.20
10	151.85
11	151.64
12	153.98
13	139.01
14	138.61
15	138.21
16	138.39
17	138.13
18	136.54
19	138.94
20	138.98
21	125.43
22	124.06
23	123.92
24	125.30
25	113.00
26	112.17
27	111.33
28	111.48
29	111.19
30	112.02
31	112.86
32	112.95
33	102.19
34	100.79
35	100.66
36	102.06

\*\*\*\*\*

THE FINAL RESULT OF MODAL TEMP  
 LOAD CASE= 1 TIME STEP= 4 TIME = 3.5000

1	110.00
2	110.00

48	95.36
49	87.70
50	87.09
51	86.53
52	86.62
53	86.43
54	86.99
55	87.60
56	87.66
57	81.20
58	80.23
59	80.14
60	81.11
61	75.92
62	75.53
63	74.92
64	75.01
65	74.83
66	75.45
67	75.83
68	75.90

\*\*\*\*\*

THE FINAL RESULT OF NODAL TEMP  
LOAD CASE= 1 TIME STEP= 5 TIME = 4.5000

1	120.00
2	120.00
3	120.00
4	120.00
5	120.00
6	120.00
7	120.00
8	120.00
9	188.42
10	186.67
11	186.51
12	188.29
13	173.03

14	172.87
15	172.67
16	172.78
17	172.62
18	172.83
19	173.01
20	173.01
21	157.82
22	156.69
23	156.58
24	157.71
25	143.32
26	142.60
27	141.88
28	142.02
29	141.76
30	142.48
31	143.20
32	143.28
33	130.16
34	128.85
35	128.73
36	130.03
37	118.30
38	117.58
39	116.85
40	116.97
41	116.73
42	117.46
43	118.17
44	118.25
45	107.90
46	106.66
47	106.54
48	107.78
49	98.89
50	98.20
51	97.56
52	97.66
53	97.44
54	98.08
55	98.78
56	98.85
57	91.30
58	90.17

8.

59 90.06  
 60 91.19  
 61 85.13  
 62 84.67  
 63 83.94  
 64 84.05  
 65 83.84  
 66 84.57  
 67 85.03  
 68 85.11

CONDUCTIVITY KXX, KYY, KZZ

THE TEMPERATURE POINT = 1

0.000000 0.000000 0.000000

THE TEMPERATURE POINT = 2

60.000000 40.000000 40.000000

THE TEMPERATURE POINT = 3

80.000000 60.000000 60.000000

THE TEMPERATURE POINT = 4

95.000000 75.000000 75.000000

THE TEMPERATURE POINT = 5

105.000000 80.000000 80.000000

THE TEMPERATURE POINT = 6

115.000000 85.000000 85.000000

0

LOAD CASE CONTROL INFORMATION, LOAD CASE = 2NONLINEAR STEADY-STATE HEAT TRANSFER

LOAD CASE CONTROL CARDS

IHT NHCAN NITEM  
 2 0 0

LOAD CASE CONTROL INFORMATION

LOAD CASE CONTROL CARD

NHGEN NCBG NFBG NITEM NPRES NRBC MODFLW ITER CDELTA

1 1 1 1 1 0 0 200 0.010000

\*\*\*\*\* THE TEMPERATURE FUNCTION \*\*\*\*\*

THE TOTAL NUMBERS OF TEMPERATURE POINTS = 6

INTERNAL HEAT GENERATION

THE TEMPERATURE AT EACH POINT

TEMP(1),....., TEMP(n)

-----  
 ELE. NDATA NEMD. INC.

1 1 5 1

0.00 100.00 200.00 300.00 400.00 600.00

MATERIAL 1 THERMAL CONDUCTIVITY TABLE

THE TOTAL DATA SET = 1

THE INTERNAL HEAT GENERATED RATE  
QRATE(1).....QRATE(TIME STEP)  
50.00  
0

INITIAL MODAL TEMPERATURES

N TEMP NEND NINC  
1 70.00 68 1

CONVECTION MODAL TEMPERATURES

ELM IFACE NDS NEND NINC

5 6 1 5 1

0

TIME DEPENDENT COEFF. OF CONVECTION

THE TOTAL DATA SET = 1

THE TIME DEPENDENT ENVIRONMENT TEMP(1,2,...,NTINSP)

50.00  
0

\*\*\*\* THE MATERIAL NUMBER = 1  
THE CONVECTION COEFF H(1,2,..., NTEMP)

10.00 15.00 20.00 25.00 30.00 35.00

0

HEAT FLUX IN THE SURFACE

ELE. FACE NDATA NEND NINC

2 3 1 3 1

0

TOTAL NUMBERS OF DATA SET= 1

DATA SET = 1

HEAT FLOW AT SURFACE (1,2,...,TIME STEPS)

80.00

0

MODAL POINT HEAT FLOW INPUT

M1 MDATA NEND NINC

0

PRESCRIBED MODAL TEMPERATURES

M NDATA NEND NINC

1 1 8 1

0

DATA SET = 1

PRESCRIBED MODAL TEMP.  
TEMP(1),TEMP(2),...TEMP(TIME STEP)

100.00

0

RADIATION MODAL TEMPERATURES

NEL IFACE NDATA NEND NINC

0

THE FINAL RESULT OF MODAL TEMP

LOAD CASE= 2 ITERATION= 8

1 100.00

2 100.00

3 100.00

4 100.00

5 100.00

6 100.00

7 100.00

8 100.00

9 166.81

10 166.77

11 166.77

12 166.81

13 164.78

14 164.59

15 164.53

16 164.53

17 164.53

18 164.59

19 164.78

20 164.78

21 162.56

22 162.09

23 162.09

24 162.56

25 159.82

26 159.40

27 159.31

28 159.31

29 159.31

30 159.40

31 159.82

32 159.82

33 156.53

34 156.01

35 156.01

36 156.53



10.

37 152.81  
 38 152.41  
 39 152.27  
 40 152.27  
 41 152.27  
 42 152.41  
 43 152.81  
 44 152.81  
 45 148.67  
 46 148.12  
 47 148.12  
 48 148.67  
 49 144.05  
 50 143.58  
 51 143.50  
 52 143.50  
 53 143.50  
 54 143.58  
 55 144.05  
 56 144.05  
 57 138.85  
 58 138.30  
 59 138.30  
 60 138.85  
 61 133.11  
 62 132.85  
 63 132.56  
 64 132.56  
 65 132.56  
 66 132.85  
 67 133.11  
 68 133.11

2 0 0

LOAD CASE CONTROL INFORMATION

LOAD CASE CONTROL CARD

NHGEN NCBC NFBC NITEM NPRES NRBC MODFLW ITER CODELTA  
 1 1 1 1 1 1 0 200 0.001000

\*\*\*\*\* THE TEMPERATURE FUNCTION \*\*\*\*\*

THE TOTAL NUMBERS OF TEMPERATURE POINTS = 6

THE TEMPERATURE AT EACH POINT  
TEMP(1),....., TEMP(n)

0.00 100.00 200.00 300.00 400.00 500.00

MATERIAL 1 THERMAL CONDUCTIVITY TABLE

CONDUCTIVITY KXX, KYY, KZZ

THE TEMPERATURE POINT = 1

0.000000 0.000000 0.000000

THE TEMPERATURE POINT = 2

60.000000 40.000000 40.000000

THE TEMPERATURE POINT = 3

80.000000 60.000000 60.000000

THE TEMPERATURE POINT = 4

\*\*\*\*\*

LOAD CASE CONTROL INFORMATION, LOAD CASE = 3NONLINEAR STEADY-STATE HEAT TRANSFER

LOAD CASE CONTROL CARDS

90 95.000000 75.000000 75.000000

THE TEMPERATURE POINT = 5

105.000000 80.000000 80.000000

THE TEMPERATURE POINT = 6

115.000000 85.000000 85.000000

0

INTERNAL HEAT GENERATION

ELE. NDATA NEND. IINC.

1 1 5 1

0

THE TOTAL DATA SET = 1

THE INTERNAL HEAT GENERATED RATE  
QRATE(1).....QRATE(TIME STEP)

70.00

0

INITIAL MODAL TEMPERATURES

N TEMP NEND NINC

1 70.00 68 1

0

CONVECTION MODAL TEMPERATURES

ELM IFACE NDS NEND NINC

5 6 1 5 1

0

TIME DEPENDENT COEFF. OF CONVECTION

THE TOTAL DATA SET = 1

THE TIME DEPENDENT ENVIRONMENT TEMP(1,2,...,NTIMSP)

45.00

0

\*\*\*\* THE MATERIAL NUMBER = 1

THE CONVECTION COEFF H(1,2,..., NTEMP)

10.00 15.00 20.00 25.00 30.00 35.00

0

HEAT FLUX IN THE SURFACE

ELE. FACE NDATA NEND NINC

2 3 1 3 1

0

TOTAL NUMBERS OF DATA SET= 1

DATA SET = 1

HEAT FLOW AT SURFACE (1,2,...,TIME STEPS)

100.00

0

MODAL POINT HEAT FLOW INPUT

N1 NDATA NEND NINC

0



Case  
APPENDIX 2:

NONLINEAR HEAT-TRANSFER - COMPOSITE STRUCTURES

\* INPUT DATA

\* OUTPUT DATA

LINEAR HEAT-TRANSFER COMPOSITE STRUCTURES ZUAT 200 C. L. 01

68, 1, 2, 0, 3, 1	1, 0., 10., 10.	44, 30., 5., 10.	5., 10.	10.
1, 0., 10., 5.	45, 35., 10., 0.	45, 10., 10., 0.	10., 0.	10.
2, 0., 10., 0.	46, 35., 0., 10.	46, 10., 0., 10.	10., 0.	10.
3, 0., 5., 0.	47, 35., 0., 10.	47, 0., 0., 10.	0., 10.	10.
4, 0., 0., 0.	48, 35., 0., 10.	48, 0., 0., 10.	0., 10.	10.
5, 0., 0., 0.	49, 40., 10., 5.	49, 10., 10., 5.	10., 5.	5.
6, 0., 0., 0.	50, 40., 10., 0.	50, 10., 10., 0.	10., 0.	0.
7, 0., 0., 0.	51, 40., 10., 0.	51, 10., 10., 0.	10., 0.	0.
8, 0., 0., 0.	52, 40., 5., 0.	52, 5., 0., 0.	5., 0.	0.
9, 5., 10., 10.	53, 40., 0., 0.	53, 0., 0., 0.	0., 0.	0.
10, 5., 10., 0.	54, 40., 0., 5.	54, 0., 0., 5.	0., 5.	5.
11, 5., 0., 0.	55, 40., 0., 10.	55, 0., 0., 10.	0., 10.	10.
12, 5., 0., 0.	56, 40., 5., 10.	56, 5., 10., 10.	5., 10.	10.
13, 10., 10., 0.	57, 45., 10., 0.	57, 10., 10., 0.	10., 0.	0.
14, 10., 10., 5.	58, 45., 10., 0.	58, 10., 0., 0.	10., 0.	0.
15, 10., 10., 0.	59, 45., 0., 0.	59, 0., 0., 0.	0., 0.	0.
16, 10., 5., 0.	60, 45., 0., 10.	60, 0., 10., 10.	0., 10.	10.
17, 10., 0., 0.	61, 50., 10., 5.	61, 10., 5., 5.	10., 5.	5.
18, 10., 0., 5.	62, 50., 10., 0.	62, 10., 0., 0.	10., 0.	0.
19, 10., 0., 10.	63, 50., 10., 0.	63, 10., 0., 0.	10., 0.	0.
20, 10., 5., 10.	64, 50., 5., 0.	64, 5., 0., 0.	5., 0.	0.
21, 15., 10., 10.	65, 50., 0., 0.	65, 0., 0., 0.	0., 0.	0.
22, 15., 10., 0.	66, 50., 0., 5.	66, 0., 5., 10.	0., 5.	10.
23, 15., 0., 0.	67, 50., 0., 10.	67, 0., 10., 10.	0., 10.	10.
24, 15., 0., 10.	68, 50., 5., 10.	68, 5., 10., 10.	5., 10.	10.
25, 20., 10., 10.	20, 5, 1, 3			
26, 20., 10., 5.	1, 1, 13, 15, 3, 7, 19, 17, 5			
27, 20., 10., 0.	9, 14, 10, 2, 12, 18, 11, 6, 8, 20, 16, 4, 1			
28, 20., 5., 0.	2, 13, 25, 27, 15, 19, 31, 29, 17			
29, 20., 0., 0.	21, 26, 22, 14, 24, 30, 23, 18, 20, 32, 28, 16, 1			
30, 20., 0., 5.	3, 25, 37, 39, 27, 31, 43, 41, 29			
31, 20., 0., 10.	33, 38, 34, 26, 36, 42, 35, 30, 32, 44, 40, 28, 1			
32, 20., 5., 10.	4, 37, 49, 51, 39, 43, 55, 53, 41			
33, 25., 10., 10.	45, 50, 45, 38, 48, 54, 47, 42, 44, 56, 52, 40, 1			
34, 25., 10., 0.	5, 49, 61, 63, 51, 55, 67, 65, 53			
35, 25., 0., 0.	57, 62, 58, 50, 60, 66, 59, 54, 56, 68, 64, 52, 1			
36, 25., 0., 10.	0			
37, 30., 10., 10.	1			
38, 30., 10., 5.	1, 4, 2, 5, 1			
39, 30., 10., 0.	1, 25, 1, 0			
40, 30., 5., 0.	1, 25, 2, 0			
41, 30., 0., 0.	1, 25, 2, 0			
42, 30., 0., 5.	1, 25, 1, 0			
43, 30., 0., 10.	0			

LINEAR - H.T.  
INPUT DATA

2  
 1. 0.0, -45.0, 0.0  
 2. 0.0, 45.0, 0.0  
 LINEAR TRANSIENT HEAT TRANSFER  
 3. 0, 0  
 1. 1. 0, 1. 0, 0, 200., 0.01  
 6  
 0.0 1.0 2.0 3.0 4.0 5.0  
 0.5  
 1  
 80., 80., 80.  
 0  
 1. 1. 5, 1  
 0  
 1  
 50.0 50.0 50.0 50.0 50.0 50.0  
 0  
 1. 70., 68, 1  
 0  
 5, 6, 1, 5, 1  
 0  
 1  
 40.0 40.0 50.0 70.0 80.0 100.0  
 0  
 10.0  
 0  
 0  
 0  
 0  
 1, 1, 8, 1  
 0  
 1  
 70.0 70.0 100.0 100.0 120.0 120.0  
 0  
 0.2  
 10.0  
 0  
 LINEAR STEADY-STATE HEAT TRANSFER  
 1. 0, 0  
 1. 1. 1. 1. 0, 0, 200, 0.01  
 1  
 80., 80. 80.  
 0  
 1. 1. 5, 1  
 0  
 1

50.0  
 0  
 1. 70., 68, 1  
 0  
 5. 6, 1, 5, 1  
 0  
 1  
 50.0  
 0  
 10.0  
 0  
 2, 3, 1, 3, 1  
 0  
 1  
 80.0  
 0  
 0  
 1, 1, 8, 1  
 0  
 1  
 100.0  
 0

ROUT 200, L&I

HEADING AND CONTROL INFORMATION

LINEAR H-T. composite  
structure. - output.

TITLE CARD

LINEAR HEAT-TRANSFER COMPOSITE STRUCTURES

PROBLEM SIZE DATA

MN MELTYP MMAT MLC INGEOM IMTR MDATCK  
68 1 1 2 0 3 1

MODAL COORDINATES

N	X	Y	Z
1	0.00000	10.00000	10.00000
2	0.00000	10.00000	5.00000
3	0.00000	10.00000	0.00000
4	0.00000	5.00000	0.00000
5	0.00000	0.00000	0.00000
6	0.00000	0.00000	5.00000
7	0.00000	0.00000	10.00000
8	0.00000	5.00000	10.00000
9	5.00000	10.00000	10.00000
10	5.00000	10.00000	0.00000
11	5.00000	0.00000	0.00000
12	5.00000	0.00000	10.00000
13	10.00000	10.00000	10.00000
14	10.00000	10.00000	5.00000
15	10.00000	10.00000	0.00000
16	10.00000	5.00000	0.00000
17	10.00000	0.00000	0.00000
18	10.00000	0.00000	5.00000
19	10.00000	0.00000	10.00000
20	10.00000	5.00000	10.00000
21	15.00000	10.00000	10.00000
22	15.00000	10.00000	0.00000
23	15.00000	0.00000	0.00000
24	15.00000	0.00000	10.00000
25	20.00000	10.00000	10.00000
26	20.00000	10.00000	5.00000
27	20.00000	10.00000	0.00000
28	20.00000	5.00000	0.00000
29	20.00000	0.00000	0.00000
30	20.00000	0.00000	5.00000

31	20.00000	0.00000	10.00000
32	20.00000	5.00000	10.00000
33	25.00000	10.00000	10.00000
34	25.00000	10.00000	0.00000
35	25.00000	0.00000	0.00000
36	25.00000	0.00000	10.00000
37	30.00000	10.00000	10.00000
38	30.00000	10.00000	5.00000
39	30.00000	10.00000	0.00000
40	30.00000	5.00000	0.00000
41	30.00000	0.00000	0.00000
42	30.00000	0.00000	5.00000
43	30.00000	0.00000	10.00000
44	30.00000	5.00000	10.00000
45	35.00000	10.00000	10.00000
46	35.00000	10.00000	0.00000
47	35.00000	0.00000	0.00000
48	35.00000	0.00000	10.00000
49	40.00000	10.00000	10.00000
50	40.00000	10.00000	5.00000
51	40.00000	10.00000	0.00000
52	40.00000	5.00000	0.00000
53	40.00000	0.00000	0.00000
54	40.00000	0.00000	5.00000
55	40.00000	0.00000	10.00000
56	40.00000	5.00000	10.00000
57	45.00000	10.00000	10.00000
58	45.00000	10.00000	0.00000
59	45.00000	0.00000	0.00000
60	45.00000	0.00000	10.00000
61	50.00000	10.00000	10.00000
62	50.00000	10.00000	5.00000
63	50.00000	10.00000	0.00000
64	50.00000	5.00000	0.00000
65	50.00000	0.00000	0.00000
66	50.00000	0.00000	5.00000
67	50.00000	0.00000	10.00000
68	50.00000	5.00000	10.00000

ELEMENT DEFINITION

HEADER LINE

NTYPE NELEMS INCOMP INTORD

20 5 1 3

ELEMENT TYPE 20  
20 NODDED ISOPARAMETRIC BRICKS

NEL	N1	N2	N3	N4	N5	N6	N7	N8
N9	N10	N11	N12	N13	N14	N15	N16	N17
N18	N19	N20	N21	N22	N23	N24	N25	N26
N27	N28	N29	N30	N31	N32	N33	N34	N35
N36	N37	N38	N39	N40	N41	N42	N43	N44
N45	N46	N47	N48	N49	N50	N51	N52	N53
N54	N55	N56	N57	N58	N59	N60	N61	N62
N63	N64	N65	N66	N67	N68	N69	N70	N71
N72	N73	N74	N75	N76	N77	N78	N79	N80
N81	N82	N83	N84	N85	N86	N87	N88	N89
N90	N91	N92	N93	N94	N95	N96	N97	N98
N99	N100	N101	N102	N103	N104	N105	N106	N107
N108	N109	N110	N111	N112	N113	N114	N115	N116
N117	N118	N119	N120	N121	N122	N123	N124	N125
N126	N127	N128	N129	N130	N131	N132	N133	N134
N135	N136	N137	N138	N139	N140	N141	N142	N143
N144	N145	N146	N147	N148	N149	N150	N151	N152
N153	N154	N155	N156	N157	N158	N159	N160	N161
N162	N163	N164	N165	N166	N167	N168	N169	N170
N171	N172	N173	N174	N175	N176	N177	N178	N179
N180	N181	N182	N183	N184	N185	N186	N187	N188
N189	N190	N191	N192	N193	N194	N195	N196	N197
N198	N199	N200	N201	N202	N203	N204	N205	N206
N207	N208	N209	N210	N211	N212	N213	N214	N215
N216	N217	N218	N219	N220	N221	N222	N223	N224
N225	N226	N227	N228	N229	N230	N231	N232	N233
N234	N235	N236	N237	N238	N239	N240	N241	N242
N243	N244	N245	N246	N247	N248	N249	N250	N251
N252	N253	N254	N255	N256	N257	N258	N259	N260
N261	N262	N263	N264	N265	N266	N267	N268	N269
N270	N271	N272	N273	N274	N275	N276	N277	N278
N279	N280	N281	N282	N283	N284	N285	N286	N287
N288	N289	N290	N291	N292	N293	N294	N295	N296
N297	N298	N299	N300	N301	N302	N303	N304	N305
N306	N307	N308	N309	N310	N311	N312	N313	N314
N315	N316	N317	N318	N319	N320	N321	N322	N323
N324	N325	N326	N327	N328	N329	N330	N331	N332
N333	N334	N335	N336	N337	N338	N339	N340	N341
N342	N343	N344	N345	N346	N347	N348	N349	N350
N351	N352	N353	N354	N355	N356	N357	N358	N359
N360	N361	N362	N363	N364	N365	N366	N367	N368
N369	N370	N371	N372	N373	N374	N375	N376	N377
N378	N379	N380	N381	N382	N383	N384	N385	N386
N387	N388	N389	N390	N391	N392	N393	N394	N395
N396	N397	N398	N399	N400	N401	N402	N403	N404
N405	N406	N407	N408	N409	N410	N411	N412	N413
N414	N415	N416	N417	N418	N419	N420	N421	N422
N423	N424	N425	N426	N427	N428	N429	N430	N431
N432	N433	N434	N435	N436	N437	N438	N439	N440
N441	N442	N443	N444	N445	N446	N447	N448	N449
N450	N451	N452	N453	N454	N455	N456	N457	N458
N459	N460	N461	N462	N463	N464	N465	N466	N467
N468	N469	N470	N471	N472	N473	N474	N475	N476
N477	N478	N479	N480	N481	N482	N483	N484	N485
N486	N487	N488	N489	N490	N491	N492	N493	N494
N495	N496	N497	N498	N499	N500	N501	N502	N503
N504	N505	N506	N507	N508	N509	N510	N511	N512
N513	N514	N515	N516	N517	N518	N519	N520	N521
N522	N523	N524	N525	N526	N527	N528	N529	N530
N531	N532	N533	N534	N535	N536	N537	N538	N539
N540	N541	N542	N543	N544	N545	N546	N547	N548
N549	N550	N551	N552	N553	N554	N555	N556	N557
N558	N559	N560	N561	N562	N563	N564	N565	N566
N567	N568	N569	N570	N571	N572	N573	N574	N575
N576	N577	N578	N579	N580	N581	N582	N583	N584
N585	N586	N587	N588	N589	N590	N591	N592	N593
N594	N595	N596	N597	N598	N599	N600	N601	N602
N603	N604	N605	N606	N607	N608	N609	N610	N611
N612	N613	N614	N615	N616	N617	N618	N619	N620
N621	N622	N623	N624	N625	N626	N627	N628	N629
N630	N631	N632	N633	N634	N635	N636	N637	N638
N639	N640	N641	N642	N643	N644	N645	N646	N647
N648	N649	N650	N651	N652	N653	N654	N655	N656
N657	N658	N659	N660	N661	N662	N663	N664	N665
N666	N667	N668	N669	N670	N671	N672	N673	N674
N675	N676	N677	N678	N679	N680	N681	N682	N683
N684	N685	N686	N687	N688	N689	N690	N691	N692
N693	N694	N695	N696	N697	N698	N699	N700	N701
N702	N703	N704	N705	N706	N707	N708	N709	N710
N711	N712	N713	N714	N715	N716	N717	N718	N719
N720	N721	N722	N723	N724	N725	N726	N727	N728
N729	N730	N731	N732	N733	N734	N735	N736	N737
N738	N739	N740	N741	N742	N743	N744	N745	N746
N747	N748	N749	N750	N751	N752	N753	N754	N755
N756	N757	N758	N759	N760	N761	N762	N763	N764
N765	N766	N767	N768	N769	N770	N771	N772	N773
N774	N775	N776	N777	N778	N779	N780	N781	N782
N783	N784	N785	N786	N787	N788	N789	N790	N791
N792	N793	N794	N795	N796	N797	N798	N799	N800
N801	N802	N803	N804	N805	N806	N807	N808	N809
N810	N811	N812	N813	N814	N815	N816	N817	N818
N819	N820	N821	N822	N823	N824	N825	N826	N827
N828	N829	N830	N831	N832	N833	N834	N835	N836
N837	N838	N839	N840	N841	N842	N843	N844	N845
N846	N847	N848	N849	N850	N851	N852	N853	N854
N855	N856	N857	N858	N859	N860	N861	N862	N863
N864	N865	N866	N867	N868	N869	N870	N871	N872
N873	N874	N875	N876	N877	N878	N879	N880	N881
N882	N883	N884	N885	N886	N887	N888	N889	N890
N891	N892	N893	N894	N895	N896	N897	N898	N899
N900	N901	N902	N903	N904	N905	N906	N907	N908
N909	N910	N911	N912	N913	N914	N915	N916	N917
N918	N919	N920	N921	N922	N923	N924	N925	N926
N927	N928	N929	N930	N931	N932	N933	N934	N935
N936	N937	N938	N939	N940	N941	N942	N943	N944
N945	N946	N947	N948	N949	N950	N951	N952	N953
N954	N955	N956	N957	N958	N959	N960	N961	N962
N963	N964	N965	N966	N967	N968	N969	N970	N971
N972	N973	N974	N975	N976	N977	N978	N979	N980
N981	N982	N983	N984	N985	N986	N987	N988	N989
N990	N991	N992	N993	N994	N995	N996	N997	N998
N999	N1000	N1001	N1002	N1003	N1004	N1005	N1006	N1007
N1008	N1009	N1010	N1011	N1012	N1013	N1014	N1015	N1016
N1017	N1018	N1019	N1020	N1021	N1022	N1023	N1024	N1025
N1026	N1027	N1028	N1029	N1030	N1031	N1032	N1033	N1034
N1035	N1036	N1037	N1038	N1039	N1040	N1041	N1042	N1043
N1044	N1045	N1046	N1047	N1048	N1049	N1050	N1051	N1052
N1053	N1054	N1055	N1056	N1057	N1058	N1059	N1060	N1061
N1062	N1063	N1064	N1065	N1066	N1067	N1068	N1069	N1070
N1071	N1072	N1073	N1074	N1075	N1076	N1077	N1078	N1079
N1080	N1081	N1082	N1083	N1084	N1085	N1086	N1087	N1088
N1089	N1090	N1091	N1092	N1093	N1094	N1095	N1096	N1097
N1098	N1099	N1100	N1101	N1102	N1103	N1104	N1105	N1106
N1107	N1108	N1109	N1110	N1111	N1112	N1113	N1114	N1115
N1116	N1117	N1118	N1119	N1120	N1121	N1122	N1123	N1124
N1125	N1126	N1127	N1128	N1129	N1130	N1131	N1132	N1133
N1134	N1135	N1136	N1137	N1138	N1139	N1140	N1141	N1142
N1143	N1144	N1145	N1146	N1147	N1148	N1149	N1150	N1151
N1152	N1153	N1154	N1155	N1156	N1157	N1158	N1159	N1160
N1161	N1162	N1163	N1164	N1165	N1166	N1167	N1168	N1169
N1170	N1171	N1172	N1173	N1174	N1175	N1176	N1177	N1178
N1179	N1180	N1181	N1182	N1183	N1184	N1185	N1186	N1187
N1188	N1189	N1190	N1191	N1192	N1193	N1194	N1195	N1196
N1197	N1198	N1199	N1200	N1201	N1202	N1203	N1204	N1205
N1206	N1207	N1208	N1209	N1210	N1211	N1212	N1213	N1214
N1215	N1216	N1217	N1218	N1219	N1220	N1221	N1222	N1223
N1224	N1225	N1226	N1227	N1228	N1229	N1230	N1231	N1232
N1233	N1234	N1235</						



THE TIME AT EACH TIME STEP  
 TIME(1),.....,TIME (n)

0.00000 1.00000 2.00000 3.00000 4.00000 5.00000

THE TIME INCREMENT BETWEEN TIME STEPS = 0.50000

MATERIAL 1 THERMAL CONDUCTIVITY TABLE

CONDUCTIVITY KXX, KY, KZZ

THE TEMPERATURE POINT = 1

80.000000 80.000000 80.000000

INTERNAL HEAT GENERATION

ELE. NDATA MEND INC.

1 1 5 1

0

THE TOTAL DATA SET = 1

THE INTERNAL HEAT GENERATED RATE

QRATE(1),.....,QRATE(TIME STEP)

50.00 50.00 50.00 50.00 50.00 50.00

0

INITIAL NODAL TEMPERATURES

69 N TEMP MEND NINC

1 70.00 68 1

0

CONVECTION NODAL TEMPERATURES

ELM IFACE NDS MEND NINC

5 6 1 5 1

0

TIME DEPENDENT COEFF. OF CONVECTION

\*\*\*\*\*

THE TOTAL DATA SET = 1

THE TIME DEPENDENT ENVIRONMENT TEMP(1,2,...,NTIHSP)

40.00 40.00 50.00 70.00 80.00 100.00

0

\*\*\*\* THE MATERIAL NUMBER = 1

THE CONVECTION COEFF H(1,2,... NTEHPT)

0.00  
0

HEAT FLUX IN THE SURFACE

ELE. FACE NDATA MEND NINC

0

NODAL POINT HEAT FLOW INPUT

N1 NDATA MEND NINC

0

PRESCRIBED NODAL TEMPERATURES

```

8      70.00      67.34
9      69.92      67.26
10     69.93      67.19
11     69.93      67.18
12     69.92      66.22
13     69.76      66.37
14     69.78      66.38
15     69.79      66.24
16     69.79      65.04
17     69.79      65.16
18     69.78      65.22
19     69.77      65.20
20     69.76      65.23
21     69.55      65.18
22     69.58      65.06
23     69.59      65.05
24     69.55
25     69.28
26     69.30
27     69.33
28     69.32
29     69.33
30     69.31
31     69.28
32     69.28
33     68.93
34     69.00
35     69.00
36     68.94
37     68.49
38     68.54
39     68.58
40     68.57
41     68.58
42     68.55
43     68.50
44     68.49
45     67.92
46     68.02
47     68.03
48     67.93
49     67.18
50     67.24
51     67.32
52     67.31

```

```

53      67.34
54      67.26
55      67.19
56      67.18
57      66.22
58      66.37
59      66.38
60      66.24
61      65.04
62      65.16
63      65.22
64      65.20
65      65.23
66      65.18
67      65.06
68      65.05

```

```

*****

```

```

THE MASS DENSITY
MASS (1,2,...,MMAT)
0.20000

MATERIAL # = 1
THE SPECIFIC HEAT (1,2,...,NTMP)
10.00
0

```

```

*****

```

```

THE FINAL RESULT OF MODAL TEMP
LOAD CASE= 1 TIME STEP= 1 TIME = 0.5000

```

```

NODE      TEMPERATURE
1         70.00
2         70.00
3         70.00
4         70.00
5         70.00
6         70.00
7         70.00

THE FINAL RESULT OF MODAL TEMP
LOAD CASE= 1 TIME STEP= 2 TIME = 1.5000

```

```

MODE      TEMPERATURE
1         85.00
2         85.00
3         85.00
4         85.00
5         85.00
6         85.00
7         85.00
8         85.00
9         80.25
10        79.61
11        79.55
12        80.18
13        76.38
14        76.00
15        75.61

```

16	75.72	61	63.76	24	84.54
17	75.56	62	63.81	25	80.50
18	75.93	63	63.80	26	80.28
19	76.32	64	63.79	27	80.06
20	76.37	65	63.80	28	80.10
21	73.62	66	63.82	29	80.03
22	73.18	67	63.76	30	80.24
23	73.14	68	63.76	31	80.46
24	73.58			32	80.49
25	71.55			33	77.03
26	71.40			34	76.69
27	71.26			35	76.66
28	71.27			36	77.00
29	71.24			37	74.08
30	71.38			38	73.92
31	71.52			39	73.76
32	71.54			40	73.78
33	69.93			41	73.73
34	69.78			42	73.89
35	69.77			43	74.05
36	69.92			44	74.07
37	68.57			45	71.60
38	68.53			46	71.36
39	68.48			47	71.34
40	68.49			48	71.58
41	68.48			49	69.49
42	68.52			50	69.37
43	68.56			51	69.27
44	68.57			52	69.29
45	67.35			53	69.25
46	67.32			54	69.35
47	67.32			55	69.47
48	67.35			56	69.48
49	66.18			57	67.69
50	66.18			58	67.52
51	66.19			59	67.50
52	66.19			60	67.67
53	66.19			61	66.16
54	66.18			62	66.11
55	66.18			63	65.98
56	66.18			64	66.00
57	64.99			65	65.97
58	65.01			66	66.09
59	65.02			67	66.14
60	64.99			68	66.15

\*\*\*\*\*

THE FINAL RESULT OF MODAL TEMP  
LOAD CASE= 1 TIME STEP= 3 TIME = 2.5000

MODE	TEMPERATURE
1	100.00
2	100.00
3	100.00
4	100.00
5	100.00
6	100.00
7	100.00
8	100.00
9	94.49
10	94.25
11	94.22
12	94.46
13	89.26
14	89.05
15	88.82
16	88.87
17	88.78
18	89.01
19	89.23
20	89.25
21	84.58
22	84.17
23	84.13

32	86.85
33	82.90
34	82.56
35	82.53
36	82.87
37	79.47
38	79.30
39	79.13
40	79.16
41	79.10
42	79.27
43	79.44
44	79.46
45	76.53
46	76.26
47	76.23
48	76.50
49	74.01
50	73.86
51	73.73
52	73.76
53	73.71
54	73.84
55	73.99
56	74.00
57	71.87
58	71.64
59	71.62
60	71.84
61	70.07
62	70.00
63	69.84
64	69.86
65	69.82
66	69.98
67	70.05
68	70.07

MODE TEMPERATURE

1	120.00
2	120.00
3	120.00
4	120.00
5	120.00
6	120.00
7	120.00
8	120.00
9	113.37
10	113.17
11	113.15
12	113.35
13	106.98
14	106.79
15	106.60
16	106.64
17	106.57
18	106.76
19	106.95
20	106.97
21	101.04
22	100.67
23	100.63
24	101.01
25	95.68
26	95.46
27	95.24
28	95.28
29	95.20
30	95.42
31	95.64
32	95.67
33	90.93
34	90.55
35	90.51
36	90.89
37	86.75
38	86.55
39	86.35

THE FINAL RESULT OF MODAL TEMP  
LOAD CASE= 1 TIME STEP= 4 TIME = 3.5000

MODE TEMPERATURE

1	110.00
2	110.00
3	110.00
4	110.00
5	110.00
6	110.00
7	110.00
8	110.00
9	103.06
10	102.57
11	102.52
12	103.01
13	96.80
14	96.47
15	96.14
16	96.22
17	96.09
18	96.42
19	96.74
20	96.78
21	91.47
22	90.99
23	90.95
24	91.42
25	86.86
26	86.65
27	86.43
28	86.46
29	86.39
30	86.61
31	86.83

40 86.38  
 41 86.31  
 42 86.52  
 43 86.72  
 44 86.74  
 45 83.16  
 46 82.82  
 47 82.79  
 48 83.13  
 49 80.09  
 50 79.90  
 51 79.74  
 52 79.76  
 53 79.71  
 54 78.87  
 55 80.06  
 56 80.08  
 57 77.50  
 58 77.20  
 59 77.18  
 60 77.47  
 61 75.37  
 62 75.26  
 63 75.05  
 64 75.08  
 65 75.03  
 66 75.23  
 67 75.34  
 68 75.36

LOAD CASE CONTROL CARD

NHGEN NCBC NFBC NITEM NPRES NRBC MODFLW ITER CDELTA  
 1 1 1 1 1 1 0 0 200 0.010000

MATERIAL 1 THERMAL CONDUCTIVITY TABLE

CONDUCTIVITY KXX, KYY, KZZ  
 KZZ

THE TEMPERATURE POINT = 1

80.000000 80.000000 80.000000

0

INTERNAL HEAT GENERATION

ELE. NDATA NEND. INC.

1 1 5 1

0

THE TOTAL DATA SET = 1

\*\*\*\*\*

THE INTERNAL HEAT GENERATED RATE

QRATE(1),.....QRATE(TIME STEP)

50.00

0

LOAD CASE CONTROL INFORMATION, LOAD CASE - 2 LINEAR STEADY-STATE HEAT TRANSFER

LOAD CASE CONTROL CARDS

IHT NITEM NITEM  
 1 0 0

N TEMP NEND NINC  
 1 70.00 68 1

LOAD CASE CONTROL INFORMATION

0

CONVECTION MODAL TEMPERATURES

ELM IFACE MDS MEND MINC

5 6 1 5 1  
0

TIME DEPENDENT COEFF. OF CONVECTION

THE TOTAL DATA SET = 1  
THE TIME DEPENDENT ENVIRONMENT TEMP(1,2,...,NTIMSP)

50.00  
0

\*\*\*\* THE MATERIAL NUMBER = 1  
THE CONVECTION COEFF H(1,2,..., NTIMPT)

10.00  
0

HEAT FLUX IN THE SURFACE

ELE. FACE MDATA MEND MINC

2 3 1 3 1  
0

TOTAL NUMBERS OF DATA SET= 1

DATA SET = 1

HEAT FLOW AT SURFACE (1,2,...,TIME STEPS)

80.00  
0

MODAL POINT HEAT FLOW INPUT

M1 MDATA MEND MINC

0

PRESCRIBED MODAL TEMPERATURES

M MDATA MEND MINC

1 1 0 1  
0

DATA SET = 1  
PRESCRIBED MODAL TEMP.  
TEMP(1),TEMP(2), ...TEMP(TIME STEP)

100.00  
0

HEAT FLUX IN THE SURFACE

THE FINAL RESULT OF MODAL TEMPERATURES

MODE TEMPERATURE

1 100.00  
2 100.00  
3 100.00  
4 100.00  
5 100.00  
6 100.00  
7 100.00  
8 100.00  
9 99.89  
10 99.85  
11 99.85  
12 99.89  
13 99.73

59	90.58
60	90.58
61	88.60
62	88.65
63	88.60
64	88.60
65	88.60
66	88.65
67	88.60
68	88.60

14	99.58
15	99.53
16	99.53
17	99.53
18	99.58
19	99.73
20	99.73
21	98.38
22	98.00
23	98.00
24	99.38
25	98.64
26	98.30
27	98.24
28	98.24
29	98.24
30	98.30
31	98.64
32	98.64
33	97.50
34	97.11
35	97.11
36	97.50
37	95.96
38	95.80
39	95.75
40	95.75
41	95.75
42	95.80
43	95.96
44	95.96
45	94.22
46	94.19
47	94.19
48	94.22
49	92.45
50	92.44
51	92.44
52	92.44
53	92.44
54	92.44
55	92.45
56	92.45
57	90.58
58	90.58

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