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

Second Annual Status Report

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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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LIST OF ILLUSTRATIONS

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 Tractions Vector
GEAE	-	GE Aircraft Engines
G(x,y,z)	-	Value of Function at Any Point (x,y,z)
$G(x_i,y_i,z_i)$	-	Value of Function at Node Point i
$\vec{H}$	-	Magnetic Field Strength
h	-	Convection Coefficient
H_i	-	Isoparametric Shape Functions
$\vec{J}$	-	Magnetic Current Density
[K]	-	Stiffness Matrix
$[K_t]$	-	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)

α	-	Surface Heat Transfer Coefficient
γ	-	Reciprocal Permeability
λ_i	-	ith Eigenvalue
μ	-	Magnetic Permeability
ρ	-	Resistivity
ϕ_i	-	ith 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.

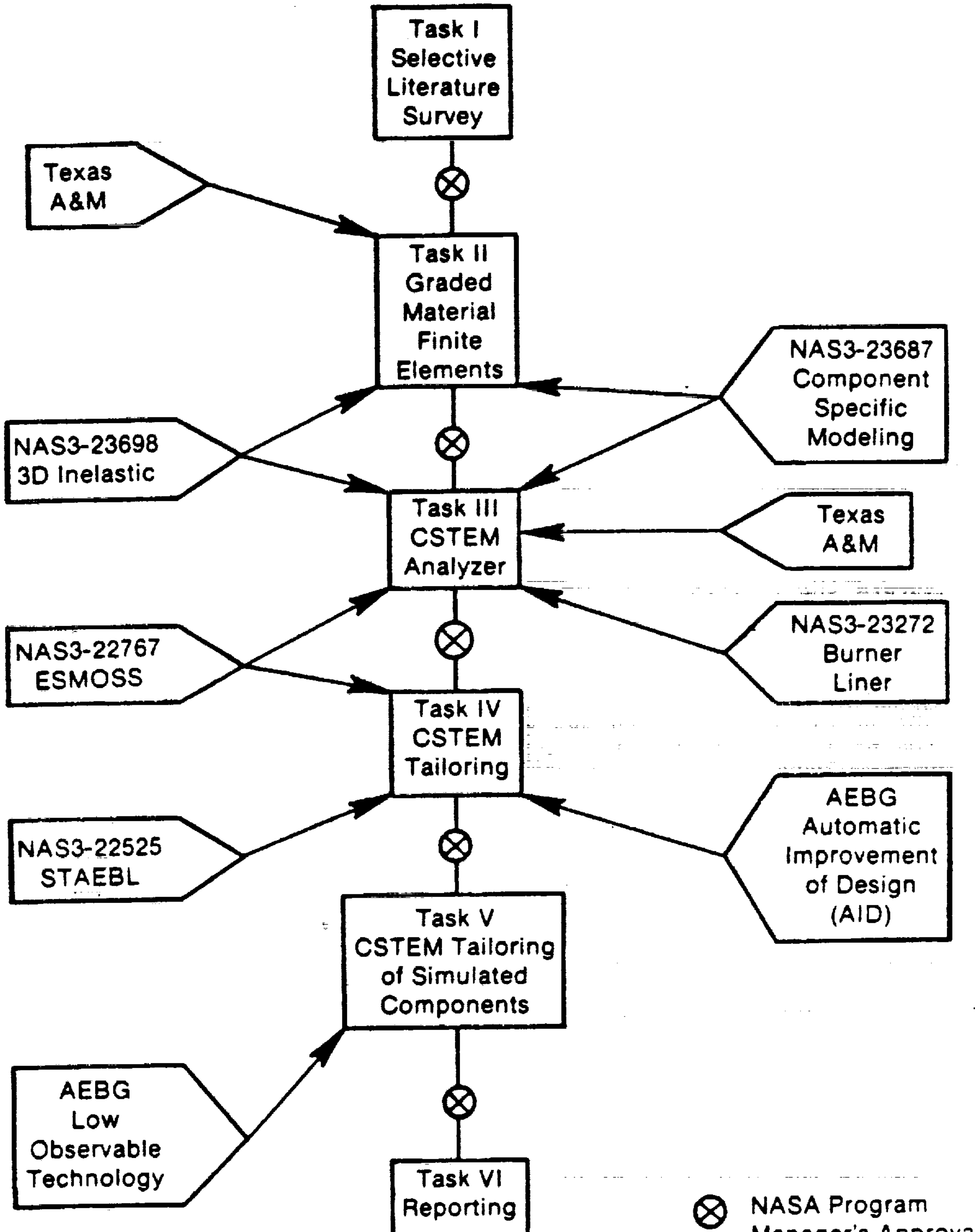


Figure 1. Program Flowchart.

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, anistropic 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.

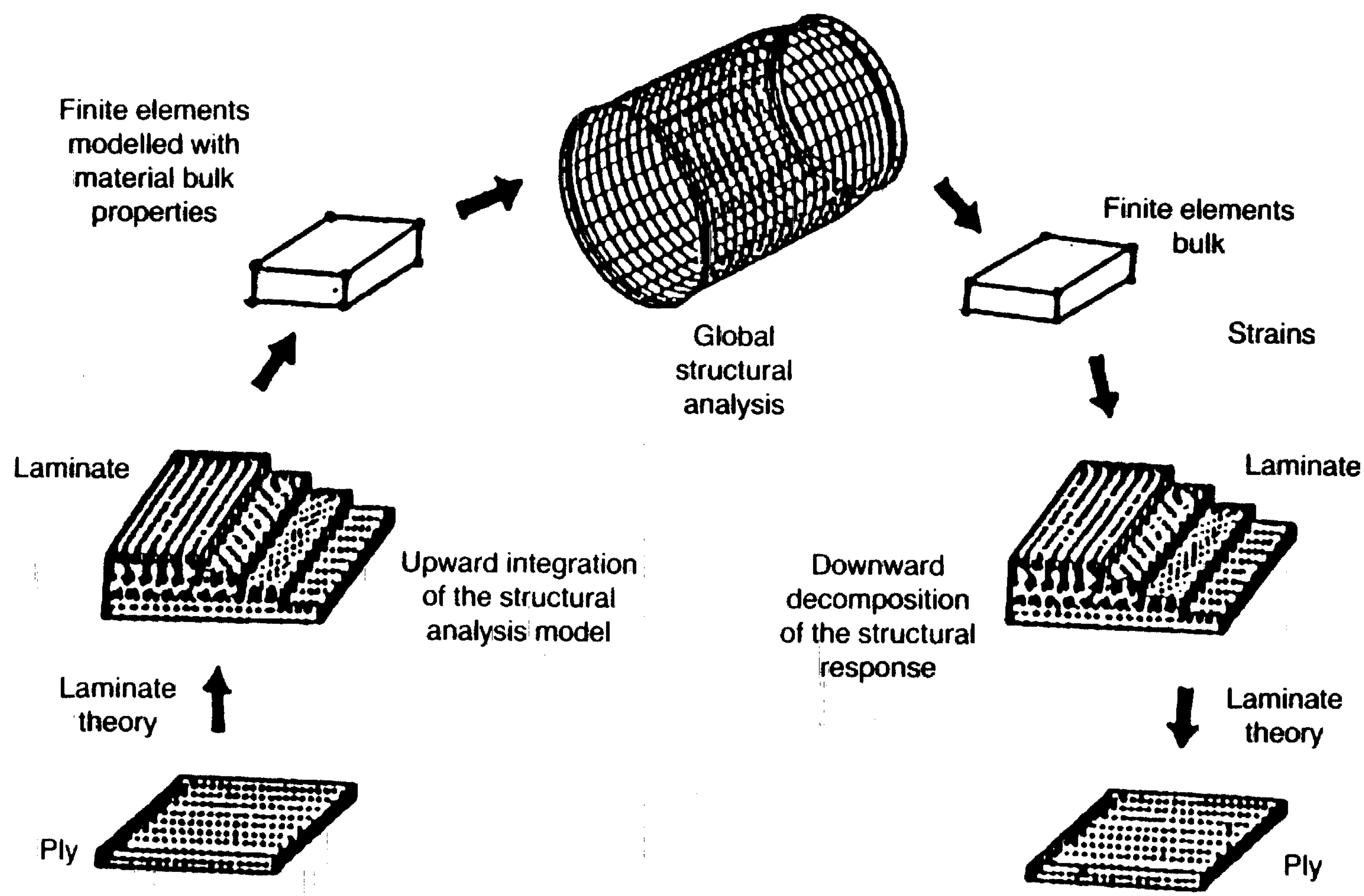


Figure 2. Composite Analysis System.

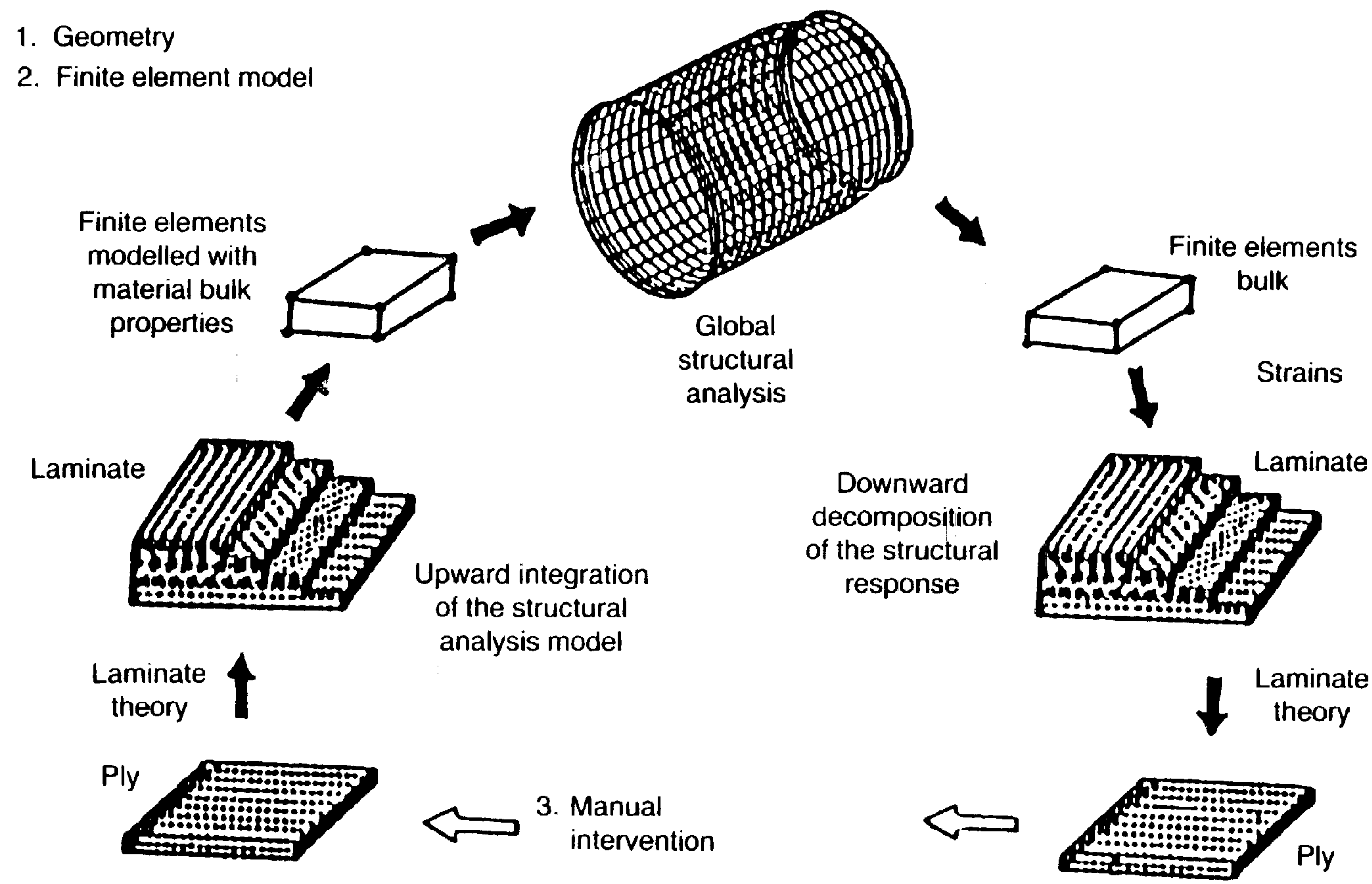


Figure 3. Total Composite Analysis System.

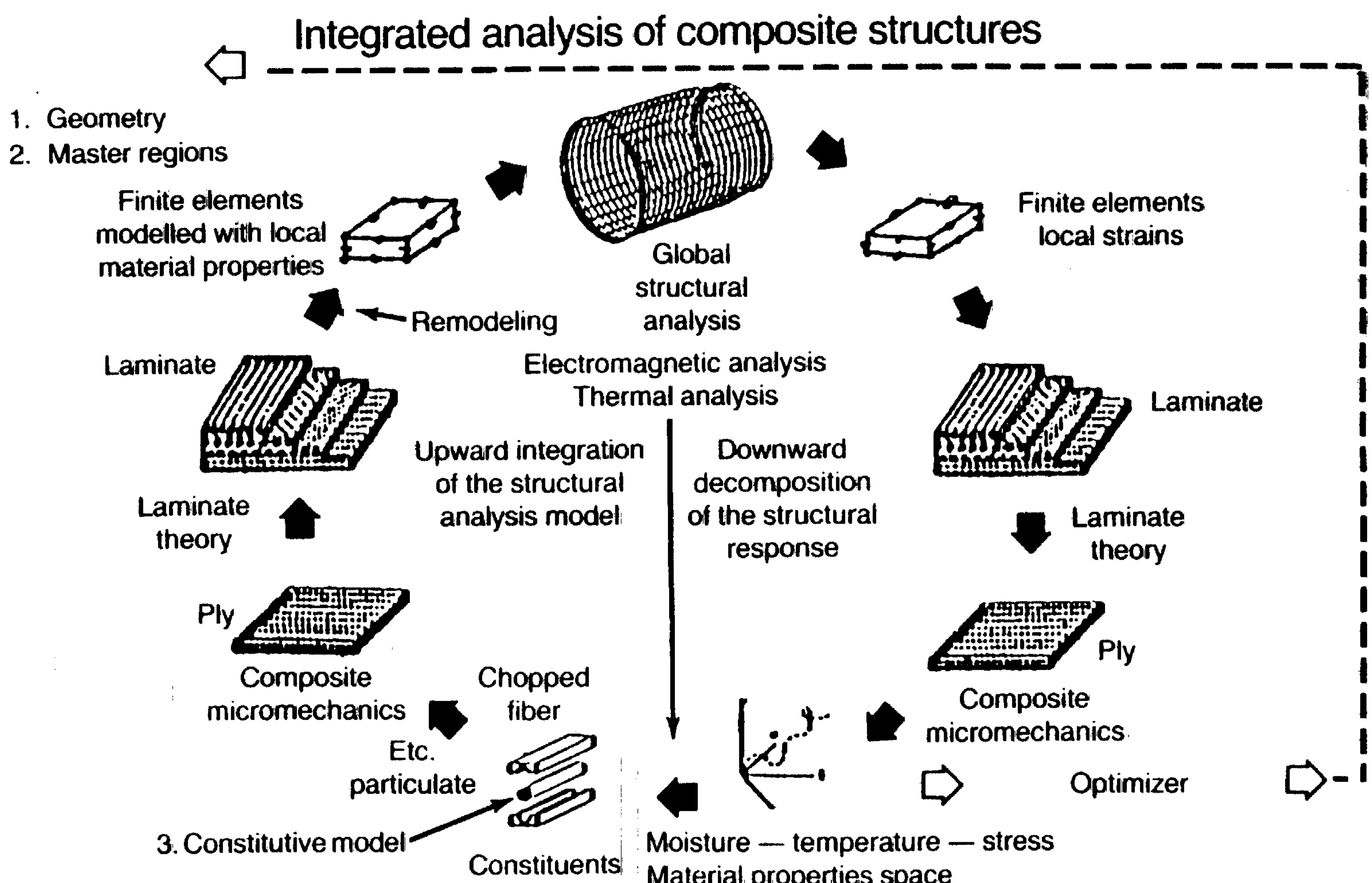


Figure 4. CSTEM System.

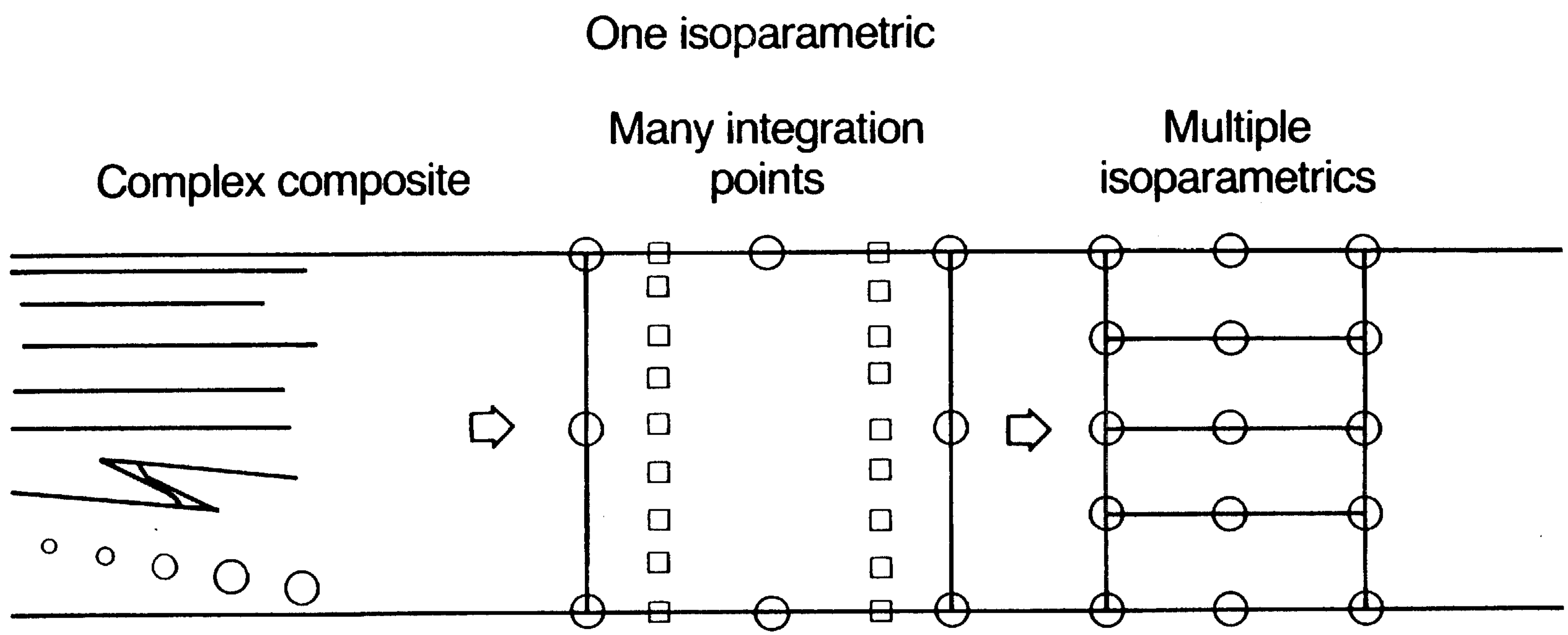


Figure 5. Constitutive Model - Structural Model Interaction.

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	---	$\varepsilon(T)$	---	$\varepsilon(T,t)$
• 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

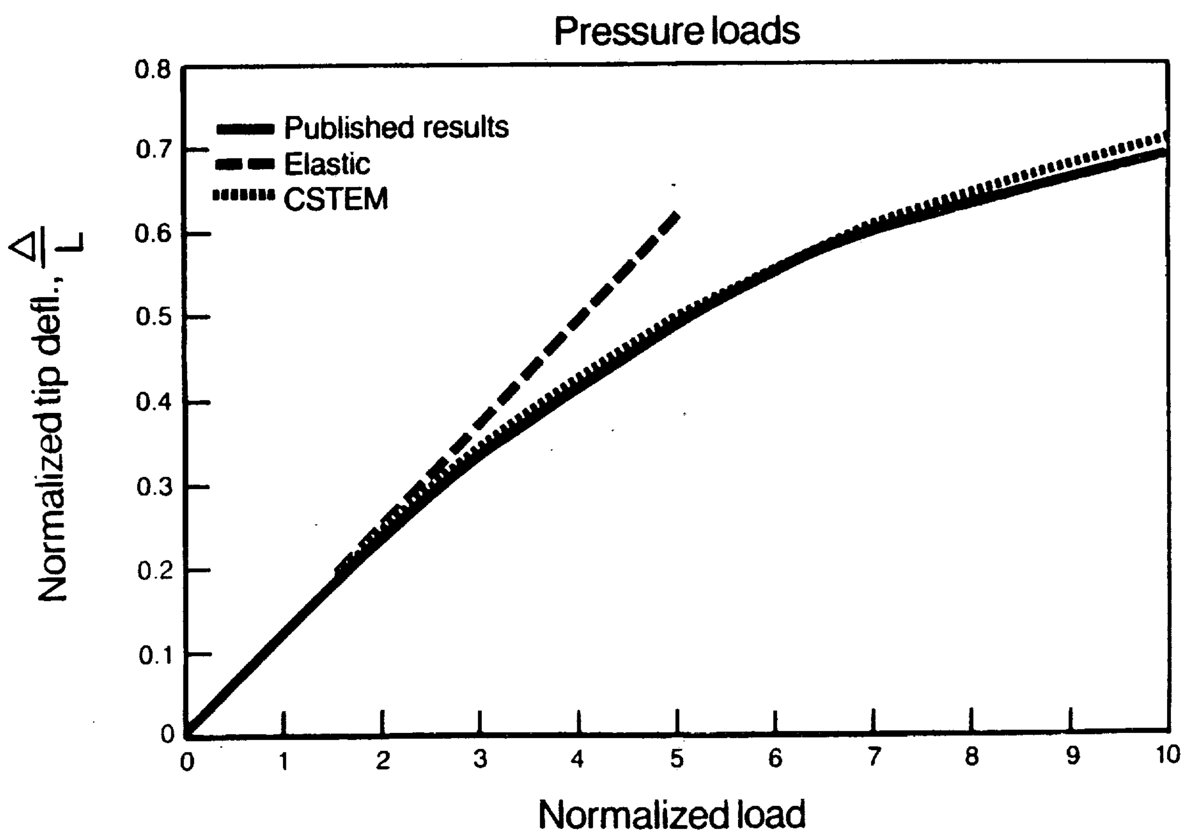


Figure 6. 10-Inch Cantilever.

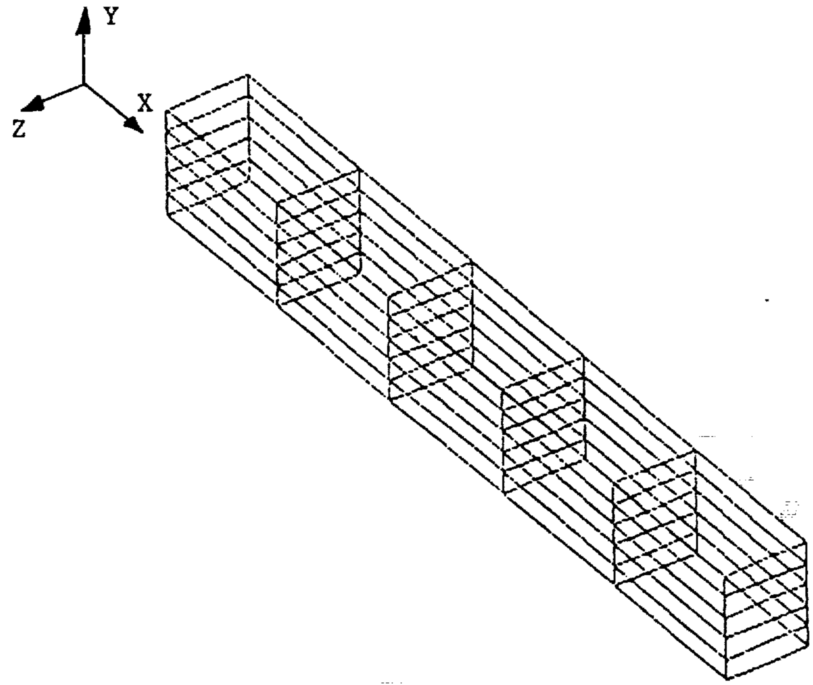


Figure 7. 25 Element Model.

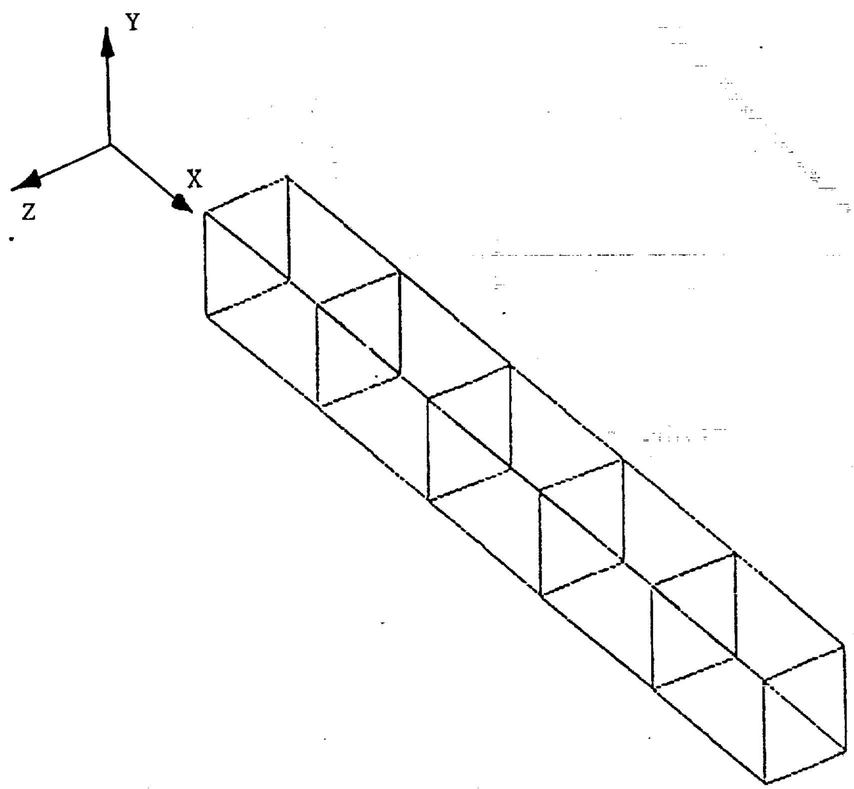


Figure 8. 5 Element Model.

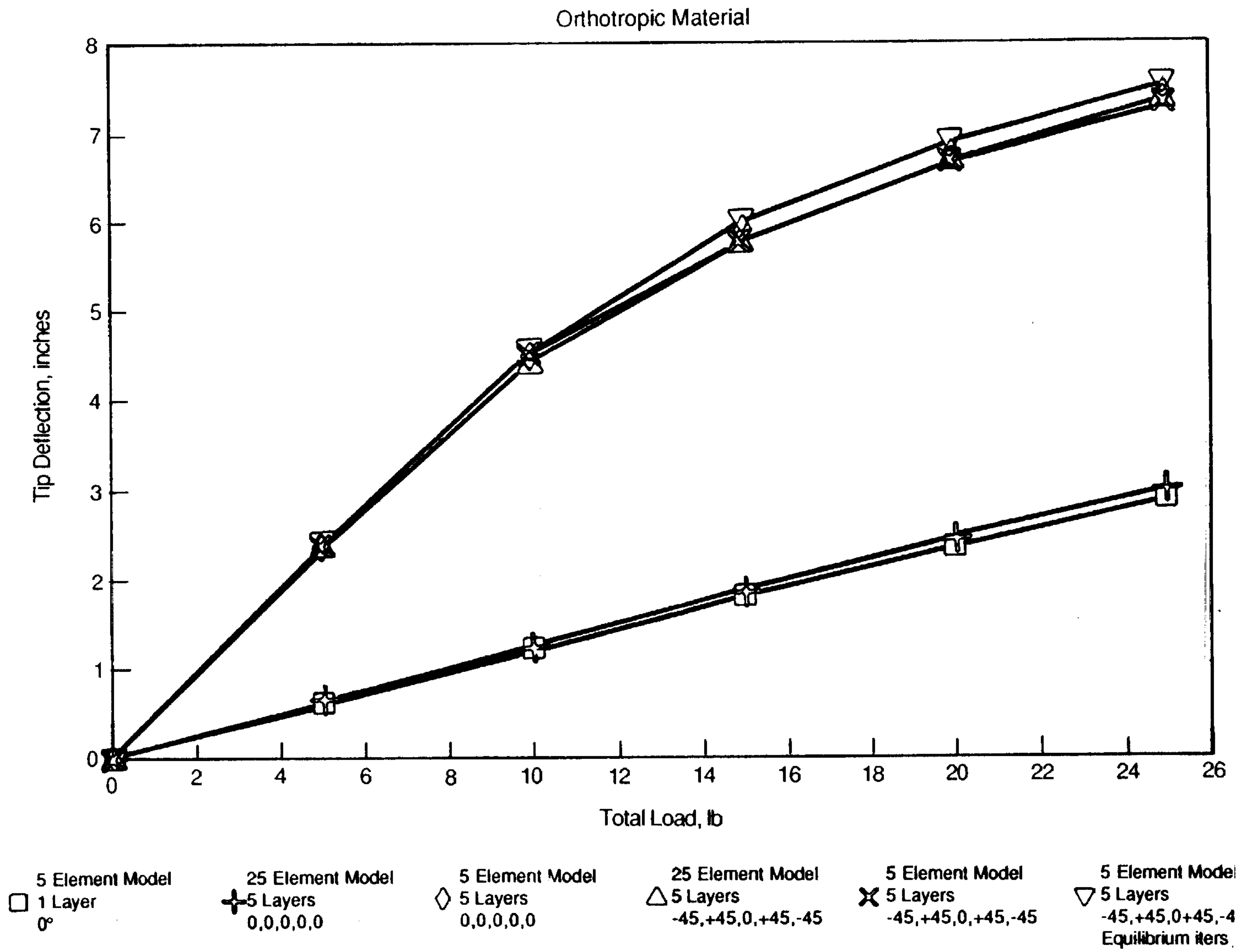
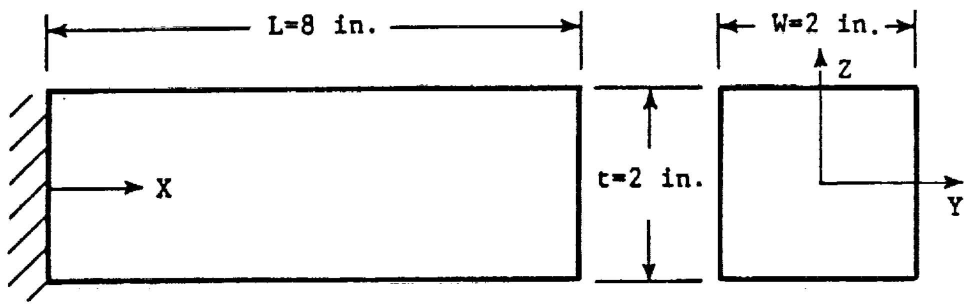


Figure 9. 10-Inch Cantilever.

Table 11. Eigenshift and Rayleigh Quotient Example.



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

Mode Shape (Axis-About)	Eigen Values	
	Subspace Iterations	Eigenvalue Shift and Rayleigh Quotient
1st $Bend_E$	0.357145302	0.3 + 0.057520891
1st $Bend_Y$	0.362975676	0.4 - 0.037155197
1st $Tors_X$	6.24068457	6.0 + 0.24067101
2nd $Bend_Z$		8.0 + 0.79694164
2nd $Bend_Y$	9.53097761	10.0 - 0.46902631
1st $Axial_X$		16.0 - 0.98479339
3rd $Bend_E$		44 + 0.82830848
3rd $Bend_Y$	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.

$$\frac{\partial}{\partial x}\left(\frac{1}{\varepsilon_{dx}}\frac{\partial\phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{1}{\varepsilon_{dy}}\frac{\partial\phi}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{1}{\varepsilon_{dz}}\frac{\partial\phi}{\partial z}\right) + w^2\mu_o\varepsilon_o\phi = 0 \qquad (1)$$

where

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

w = Wave Frequency

μo = Permeability of free space

ε_o = Permittivity of free space

ε_d = Permittivity of the dielectric

the relationship between $\vec{E}$ and $\vec{H}$ is $\nabla \times \vec{E} = - \sqrt{-1}\, w\mu_o \vec{H}$

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

$$K_x',\ K_y',\ K_z' = \frac{1}{\varepsilon dx},\ \frac{1}{\varepsilon dy},\ \frac{1}{\varepsilon dz}\ \lambda^2 = W^2\mu_o\varepsilon_o$$

Using finite element notation

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

where

$$[K]^e = \int_v B^T \cdot [\bar{K}'] \cdot BdV$$

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

Summing up equation (2) for the entire structure:

$$\{[K] - X[M]\}\{\phi\} = 0 \qquad (3)$$

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:

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

where

$$\phi = \Sigma N_i \phi_i = [H_1, H_2 \ldots H_i] \begin{Bmatrix} \phi_1 \\ \phi_2 \\ \\ \phi_i \end{Bmatrix}$$

$$\frac{\partial \phi}{\partial x} = \sum_{i=1} \frac{\partial H_i}{\partial x} \phi i = [\frac{\partial H_1}{\partial x} \ \ldots \ \frac{\partial H_i}{\partial x}] \{\phi\}^e$$

$$\frac{\partial}{\partial \phi_i} \left(\frac{\partial \phi}{\partial x}\right) = \frac{\partial H}{\partial x}{}^i$$

Therefore, equation (4) becomes

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

Absorbed energy will convert to internal heat energy as:

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

where

$[K_T] = \int_v B^T \cdot [k] \cdot BdV$

$[K_T]$ = Thermal conductivity matrix

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

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

$$[K_T] \{T\} = \alpha[K_e] \{\phi\} \tag{7}$$

where

α = 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

Wout = Win * (1.0 - absorptivity)

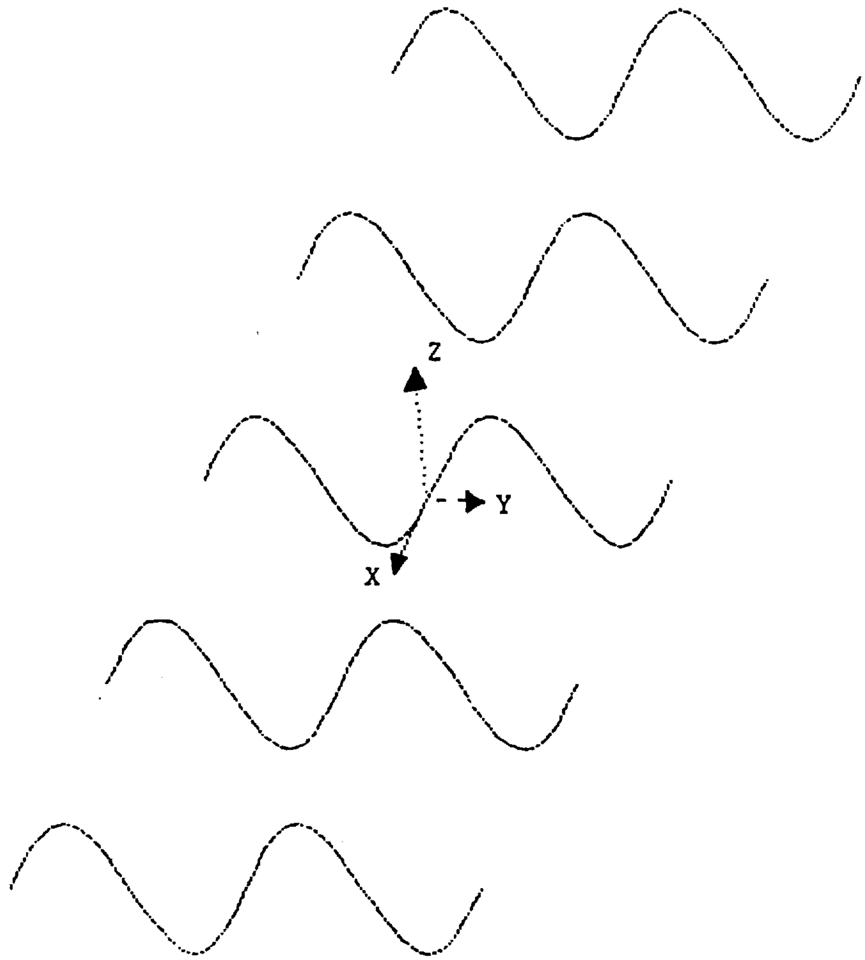


Figure 10. Wave with 90° Polarization.

where Win 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 udpated 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 udpated 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

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

where

$${}^{t}_{t}\left[K_L\right] = \int_{{}^{t}v} {}^{t}_{t}\left[B_L\right]^T \; {}_{t}^{t}\left[C\right] \; {}^{t}_{t}\left[B_L\right] \, dV$$

$${}^{t}_{t}\left[K_{NL}\right] = \int_{{}^{t}v} {}^{t}_{t}\left[B_{NL}\right]^T \; {}^{t}\left\{\tau\right\} \; {}^{t}_{t}\left[B_{NL}\right] \, dV$$

$${}^{t+\Delta t}_{t+\Delta t}\left\{F\right\} = \int_{{}^{t}v} {}^{t}_{t}\left[B_{NL}\right]^T \; {}^{t}\left[\tau\right] \, dV$$

and

${}^{t+\Delta t}\left\{R\right\}$ 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

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

where

$${}^t_o\left[K_L\right] = \int_{{}^oV} {}^t_o\left[B_L\right]^T\, {}^t_o\left[C\right]\, {}^t_o\left[B_L\right]\, dV$$

$${}^t_o\left[K_{NL}\right] = \int_{{}^oV} {}^t_o\left[B_{NL}\right]^T\, {}^t_o\left\{S\right\}\, {}^t_o\left[B_{NL}\right]\, dV$$

$${}^{t+\Delta t}_{o}\left\{F\right\} = \int_{{}^oV} {}^t_o\left[B_{NL}\right]^T\, {}^t_o\left[S\right]\, dV$$

and

${}^{t+\Delta t}\left\{R\right\}$ 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

$${}^t_o\left[B_L\right] = {}^t_o\left[B_{L_0}\right] + {}^t_o\left[B_{L_1}\right]$$

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

$${}^t_t\varepsilon_{ij} = \tfrac{1}{2}\left({}^t_tU_{i,j} + {}^t_tU_{j,i} - {}^t_tU_{k,i}\, {}^t_tU_{k,j}\right)$$

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

$$ {}^{t}_{o}\varepsilon_{ij} = \tfrac{1}{2}\left({}^{t}_{o}U_{i,j} + {}^{t}_{o}U_{j,i} + {}^{t}_{o}U_{k,i}\, {}^{t}_{o}U_{k,j} \right) $$

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

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

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

$$ {}^{t}_{o}S_{ij} = {}^{t}_{o}C_{ijrs}\, {}^{t}_{o}\varepsilon_{rs} $$

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

$$ {}^{t}_{o}[X] = \left({}_{o}\nabla\, {}^{t}\{x\}^{T} \right)^{T} $$

where

$$ {}_{o}\nabla = \begin{Bmatrix} \dfrac{\partial}{\partial {}^{o}x_1} \\ \dfrac{\partial}{\partial {}^{o}x_2} \\ \dfrac{\partial}{\partial {}^{o}x_3} \end{Bmatrix} \quad \text{and} \quad {}^{t}\{x\} = \begin{Bmatrix} {}^{t}x_1 \\ {}^{t}x_2 \\ {}^{t}x_3 \end{Bmatrix} $$

and T refers to the transpose.

Using tensor notation the relations between the different measures are

$$ {}^{t}\tau_{mn} = \frac{{}^{t}\rho}{{}^{o}\rho}\, {}^{t}_{o}x_{m,i}\, {}^{t}_{o}S_{ij}\, {}^{t}_{o}x_{n,j} $$

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

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

where ρ is the density and

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

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 (±1,±1,±1) and of the 12 remaining nodes are (0±1,±1), (±1,0,±1), (±1,±1,0). The temperature within the element is defined in terms of the nodal temperatures by

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

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

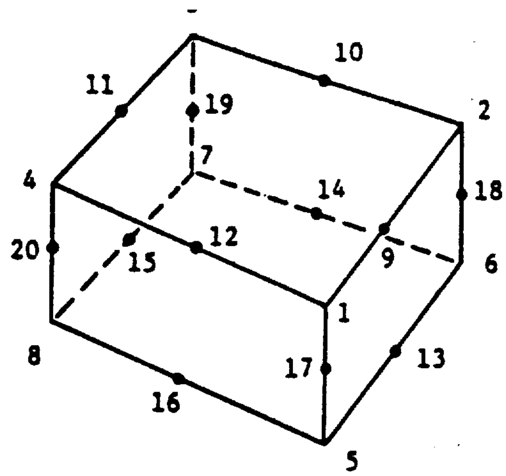
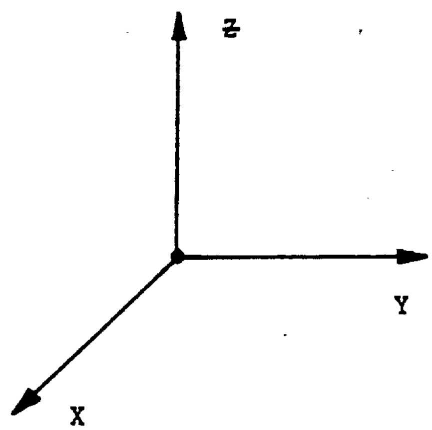


Figure B-1. Eight, 16, and 20 Node 3D Solid Elements.

Shape Function:



$$H_1 = g_1 - (g_9 + g_{12} + g_{16})/_2$$
$$H_2 = g_2 - (g_9 + g_{10} + g_{18})/_2$$
$$H_3 = g_3 - (g_{10} + g_{11} + g_{19})/_2$$
$$H_4 = g_4 - (g_{11} + g_{12} + g_{20})/_2$$
$$H_5 = g_5 - (g_{13} + g_{16} + g_{17})/_2$$
$$H_6 = g_6 - (g_{13} + g_{14} + g_{18})/_2$$
$$H_7 = g_7 - (g_{14} + g_{15} + g_{19})/_2$$
$$H_8 = g_8 - (g_{15} + g_{16} + g_{20})/_2$$

$H_i = g_i$ for (i = q .... 20)

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

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

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

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

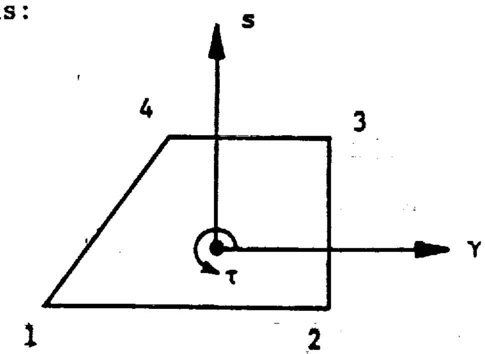
Jacobi's Operator [J] is

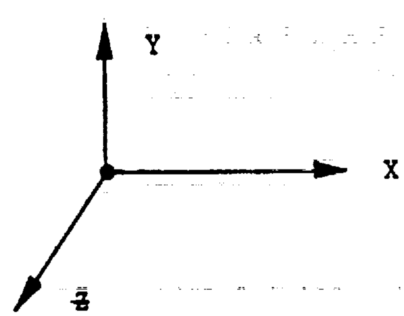
The displacement functions:

$X = \Sigma\ H_i x_i$

$Y = \Sigma\ H_i y_i$

$Z = \Sigma\ H_i z_i$





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

where r, s, t are the local coordinates.

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

$$\left\{ \begin{array}{l} \theta^{(m)}_{t+\Delta t} = H^{(m)} \theta_{t+\Delta t} \\ \theta^{s(m)} = H^{s(m)} \theta_{t+\Delta t} \\ \theta'^{(m)} = B^{(m)} \cdot \theta_{t+\Delta t} \end{array} \right\}$$

$\theta_{t+\Delta t}$ - a vector of all nodal point temperatures at $t+\Delta t$

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

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:

$$qx = -\ kx \frac{\partial \theta}{\partial x},\ qy = -\ ky \frac{\partial \theta}{\partial y},\ qz = -kz \frac{\partial \theta}{\partial z}$$

where qx, qy, and qz are the heat flows conducted per unit area, θ is the temperature of the body, and kx, ky, and kz 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

$$\frac{\partial}{\partial x} (kx \frac{\partial \theta}{\partial x}) + \frac{\partial}{\partial y} (ky \frac{\partial \theta}{\partial y}) + \frac{\partial}{\partial z} (kz \frac{\partial \theta}{\partial z}) = -\ qb \qquad (1)$$

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

$$\theta \Big|_{s1} = \theta e \qquad (2)$$

$$k_n \left. \frac{\partial \theta}{\partial n} \right|_{S2} = qs \qquad (3)$$

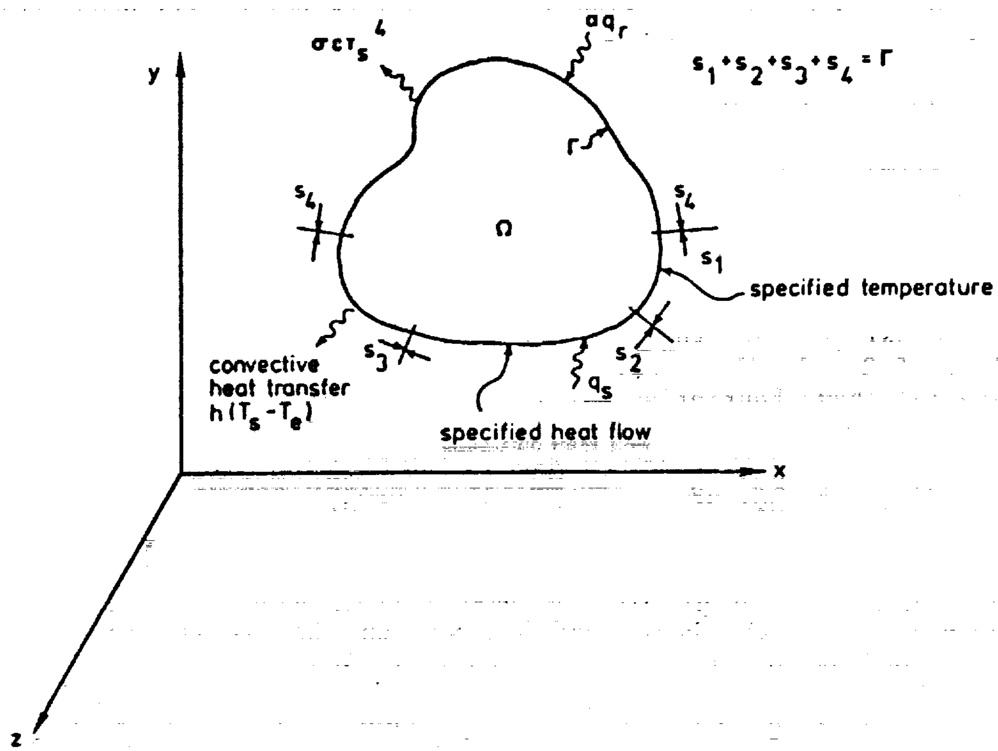


Figure B-2. Three-Dimensional Solution Domain for General Heat Conduction.

where θe 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

$$q^s = h\ (\theta_e - \theta^s) \tag{4}$$

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

where θ_r is the temperature of the external radiative source and K is a coefficient:

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

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.

$$\Pi = \int_v 1/2 \ \{kx \left(\frac{\partial\theta}{\partial x}\right)^2 + ky \left(\frac{\partial\theta}{\partial y}\right)^2 + kz \left(\frac{\partial\theta}{\partial z}\right)^2\} \ dv$$

$$- \int_v \theta \ q^b \ dv - \int_{S2} \theta^s \ q^s \ ds - \Sigma_i \ \theta_i \ Q_i \qquad (7)$$

where θ^i are the concentrated heat flow inputs. Using the condition of stationarity of II we obtain

$$\int_v \delta\bar{\theta}'t \ \bar{k} \ \bar{\theta} \ d\bar{v} = \int_v \delta\bar{\theta} \ q^b \ dv + \int_{s2} \delta\bar{\theta}^s \ q^s \ d\bar{s}$$

$$+ \sum_i \delta \ \bar{\theta}^i \ \bar{Q}^i \qquad (8)$$

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

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

With the initial condition $\theta^{(o)}_{t+\Delta t} = \theta_t$ 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.

I) Linear Steady-State Conditions

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

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

where K^k is the conductivity matrix

$$K^k = \sum_{m=1}^{m} \int_v B^{(m)T} \ . \ K^{(m)} \ . \ B^{(m)} \ . \ dV \qquad (I)$$

K^c is the convection matrix

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

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

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

Where

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

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

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:

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

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

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

where (e) denotes element m

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

$$^{t+\Delta t}\theta = [^{t+\Delta t}\theta_1 \quad ^{t+\Delta t}\theta_2 \quad ------ \quad ^{t+\Delta t}\theta_i]$$

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

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

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

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

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

$\theta_{e\ t+\Delta t}$ - 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

θ_e - the environmental temperature

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

h - the convection coefficient

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

θ - 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 ${}^{t+\Delta t}\theta_e$

$$ {}^{t+\Delta t}Q.^{e} = \sum_{m=1}^{m} \int_{sc} h \cdot H^{s(m)T} \cdot H^{s(m)} \cdot {}^{t+\Delta t}\theta_e \cdot ds $$

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

$$ [{}^{t}K^k + {}^{t}K^c + {}^{t}K^r] \; \Delta\theta^{(i)} = t + \Delta t_{Qt} \; t + \Delta t_Q c \; (i-1) $$

$$ + \; t - \Delta t_Q r \; (i - 1) - t + \Delta t_Q k \; (i - 1) $$

where $${}^{t}K^{k}\,\Delta\theta^{(i)} = \left[\Sigma\int_{v} B^{T}\,{}^{t}K_{e}^{k}\,B\,dV\right]\Delta\theta^{(i)}$$

$${}^{t}K^{c}\,\Delta\theta^{(i)} = \left[\Sigma\int_{sc} {}^{t}h\,H_{s}^{T}\,H_{s}\,ds\right]\Delta\theta^{(i)}$$

$${}^{t}K^{r}\,\Delta\theta^{(i)} = \left[\Sigma\int_{sr} t\alpha\,H_{s}^{T}\,H_{s}\,ds\right]\Delta\theta^{(i)}$$

$${}^{t+\Delta t}Q^{c}\,(i-1) = \Sigma\int_{sc} {}^{t+\Delta t}h^{(i-1)}$$

$$\left[H_{s}\left({}^{t+\Delta t}\theta_{e} - {}^{t+\Delta t}\theta^{(i-1)}\right)\right]ds$$

$${}^{t+\Delta t}Q^{r}\,(i-1) = \Sigma\int_{s\alpha} {}^{t+\Delta t}\alpha^{(i-1)}\,H_{s}^{T}$$

$$\left[H_{s}\left({}^{t+\Delta t}\theta_{r} - {}^{t+\Delta t}\theta^{(i-1)}\right)\right]ds$$

$${}^{t+\Delta t}Q^{k}\,(i-1) = \Sigma\int_{v} {}^{t+\Delta t}B^{T}\left[{}^{t+\Delta t}K_{e}^{(i-1)}\,{}^{t+\Delta t}B\,\theta^{(i-1)}\right]dV$$

$${}^{t+\Delta t}Q = {}^{t+\Delta t}Q_{b} + {}^{t+\Delta t}Q_{s} + {}^{t+\Delta t}Q_{c}$$

$${}^{t+\Delta t}Q_{b} = \Sigma\int_{v} H^{T}\,{}^{t+\Delta t}g^{b}\,dV$$

$${}^{t+\Delta t}Q_{s} = \Sigma\int_{s} H_{S}^{T}\,{}^{t+\Delta t}q^{s}\,ds$$

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

k = Thermal conductivity

h = Convection coefficient

α = Radiation coefficient

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

5.667×10^{-8} = Stefan - Boltzman Constant

ε = Emissivity

f = Viewfactor

θ_s = Surface temperature

θ_r = Temperature of radiated body

The thermal conductivity, k, and radiation emissivity, ε, 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:

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

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

The coefficients k, h, and α 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;

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

then

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

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,

$$^{t+\Delta t}\bar{C}^{(i)}\ {}^{t+\Delta t}\dot{\bar{\theta}}^{(i)} + ({}^{t}\bar{K}^k + {}^{t}K^e + {}^{t}K^r)\ \Delta\bar{\theta}^{(i)}$$

$$= {}^{t+\Delta t}Q + {}^{t+\Delta t}Q^{c(i-1)} + {}^{t+\Delta t}Q^{r(i-1)} - {}^{t+\Delta t}Q^{k(i-1)}$$

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

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

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

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 ζ, 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.

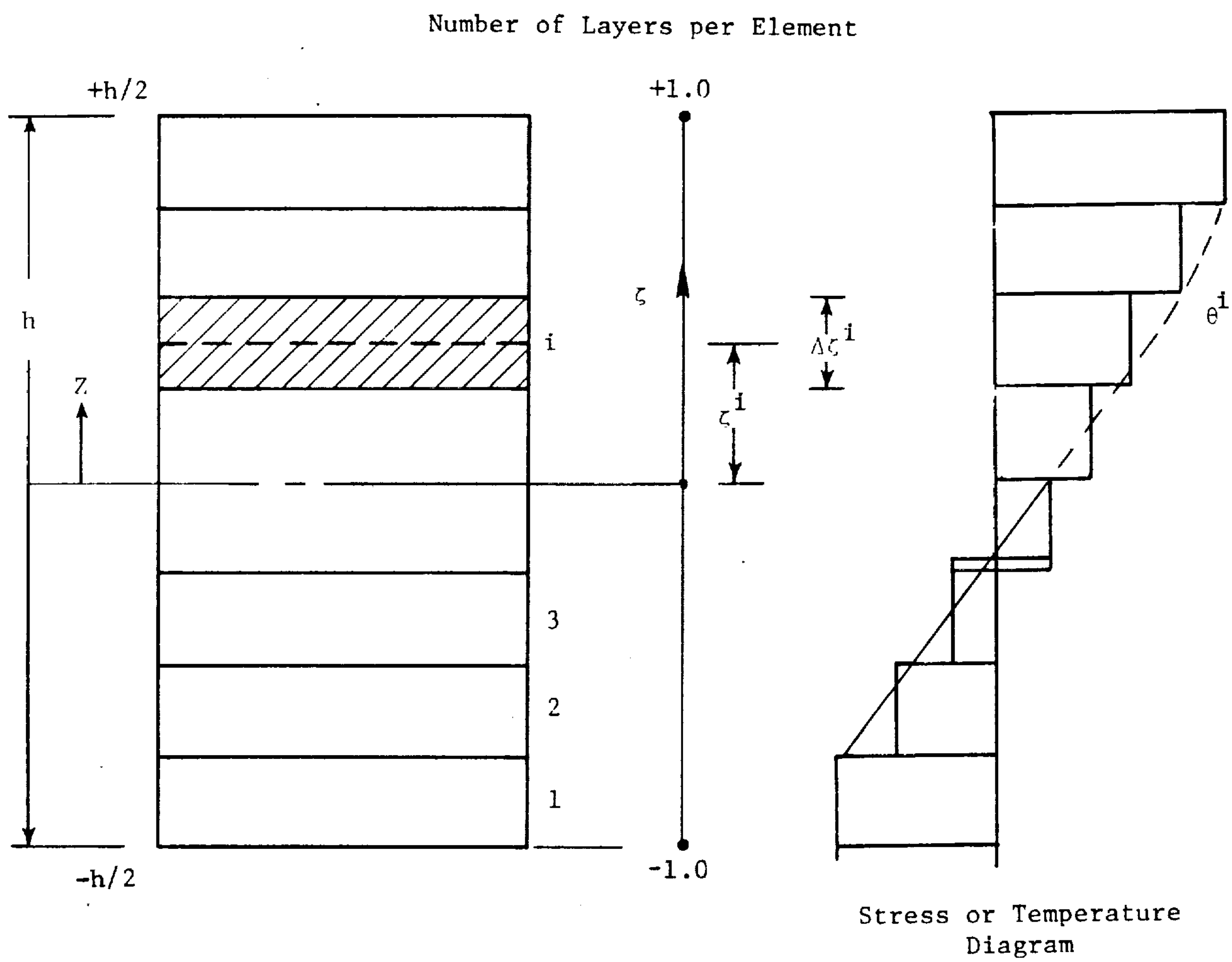


Figure B-3. Layered Model and the Corresponding Stress (Temperature) Representation.

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

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

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

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

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.

$$[K] = \begin{bmatrix} kxx & kxy & kxz \\ kyx & kyy & kyz \\ kzy & kzy & kzz \end{bmatrix}^{(m)}$$

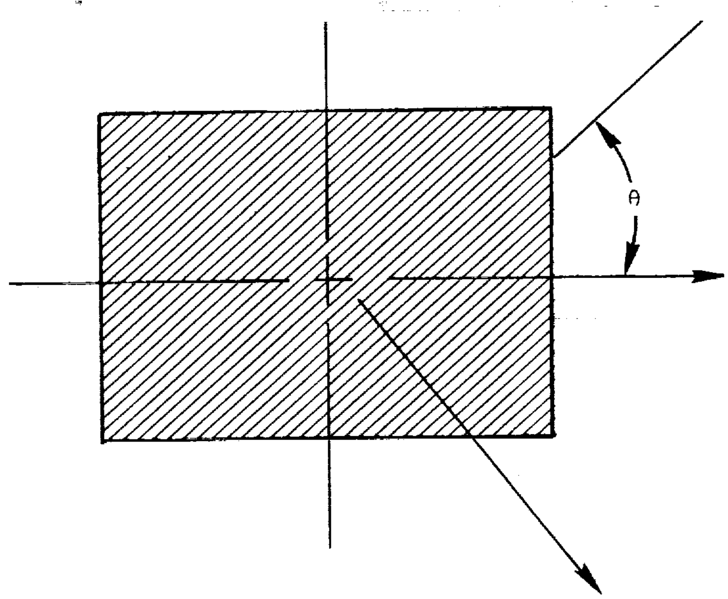
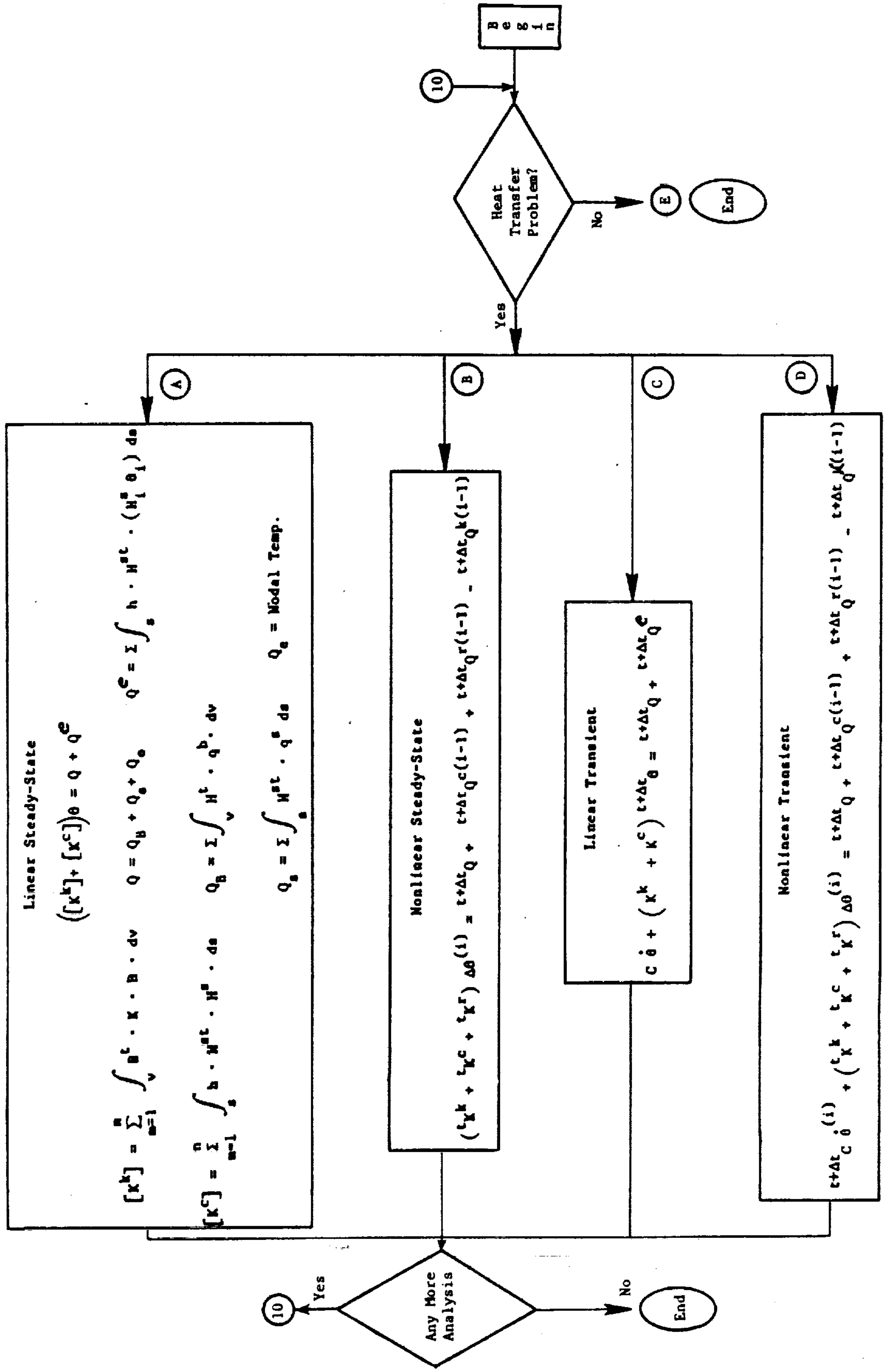


Figure B-4. Inclination of the Principal Axes of Anisotropy.

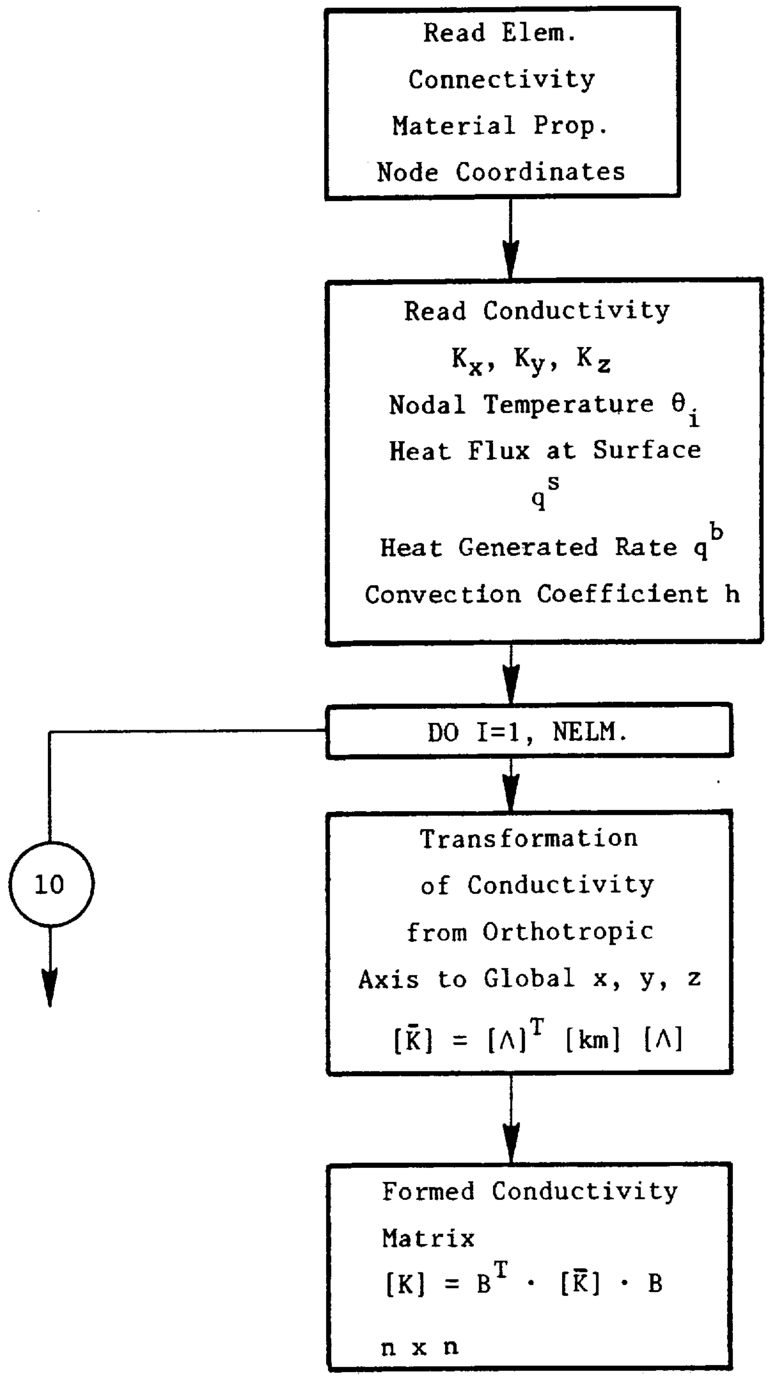
Computer Program - Flow Charts

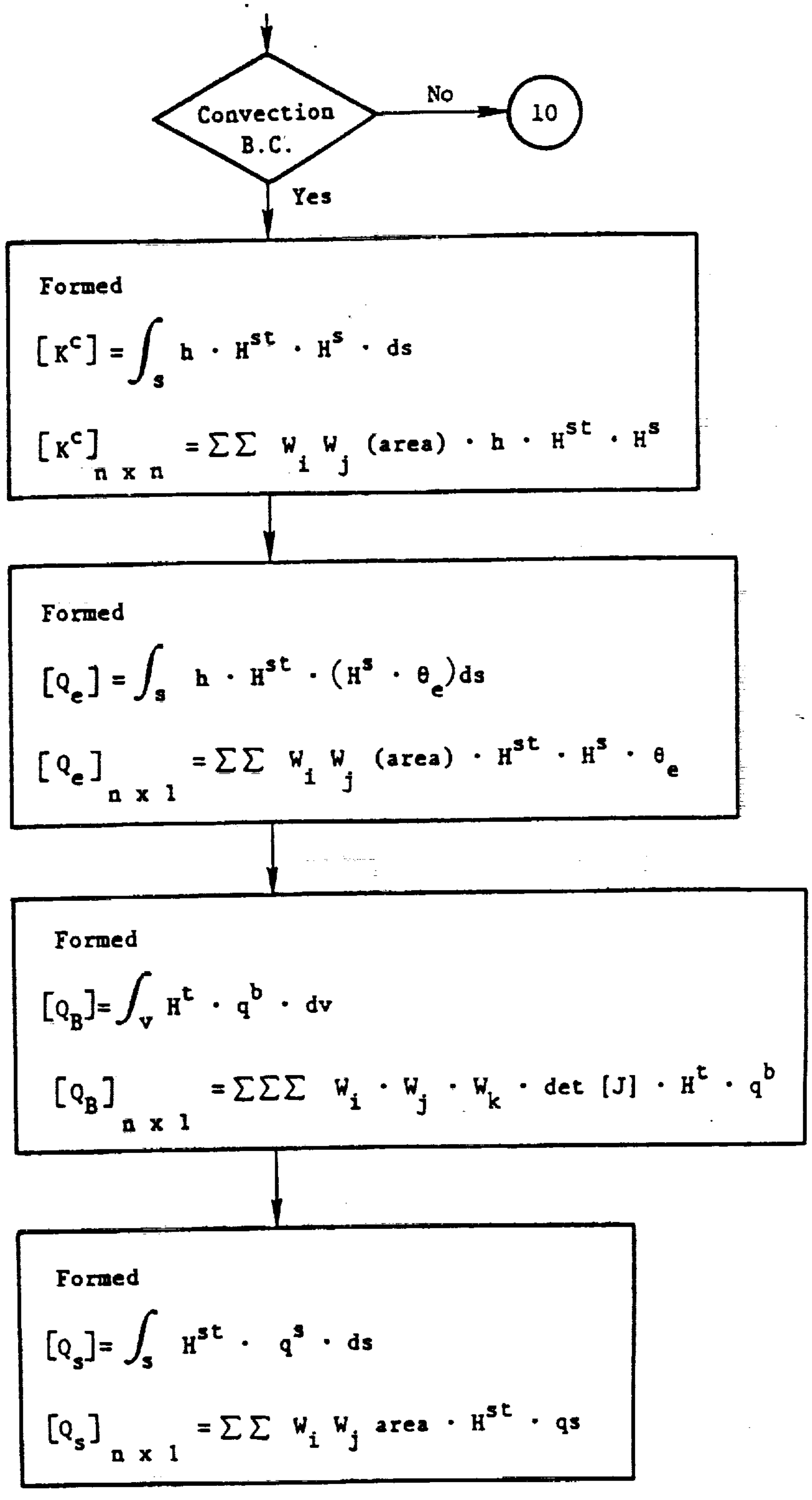
The present computer code considers the graded composite structures. It will handle the linear and nonlinear, steady-state, and transient heat transfer problems by using the "COLSOL" solution technique and the Modified Newton-Raphson iteration scheme to solve the graded composite structures.

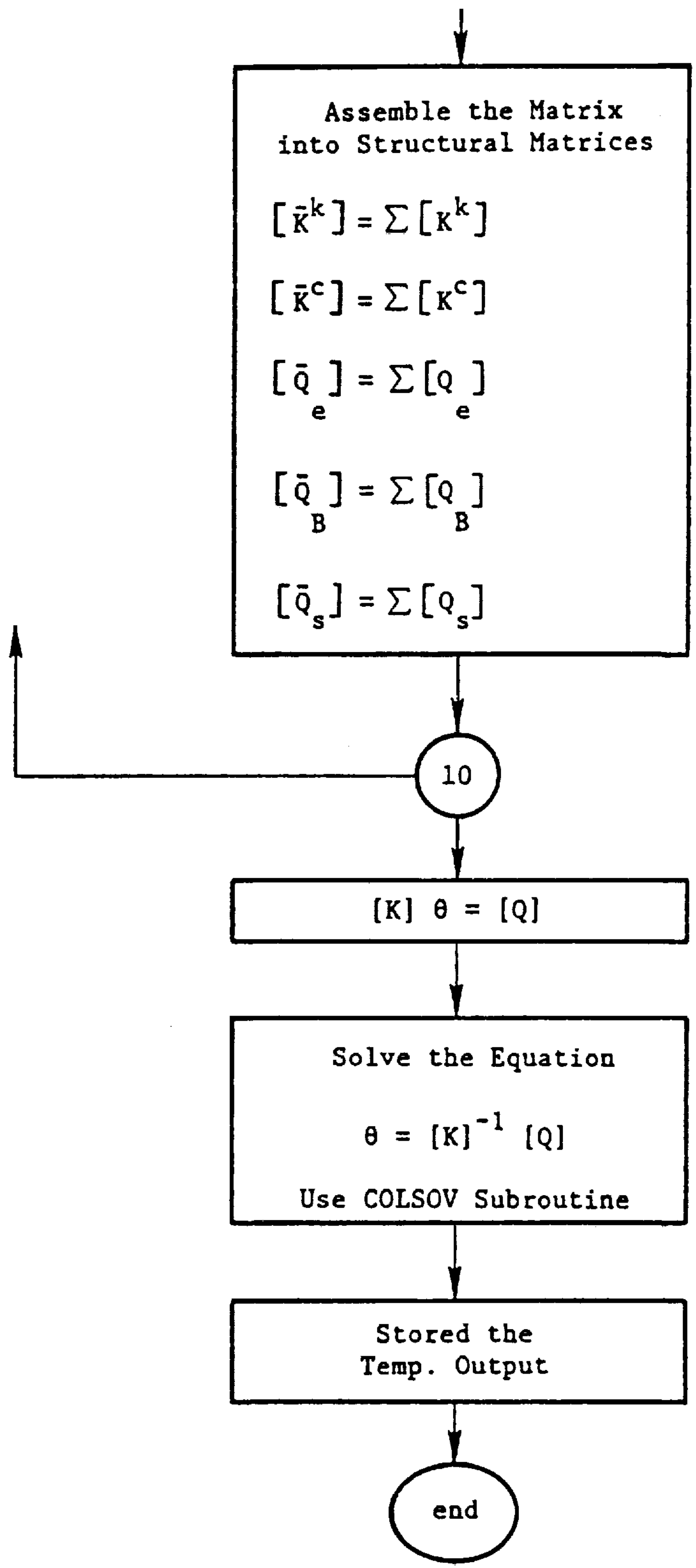
The computer program flow chart is as follows:


Begin
10
Heat Transfer Problem?
No
E
End
Yes
A
B
C
D
Linear Steady-State
Q_s = Nodal Temp.
Nonlinear Steady-State
Linear Transient
Nonlinear Transient
Any More Analysis
Yes
10
No
End

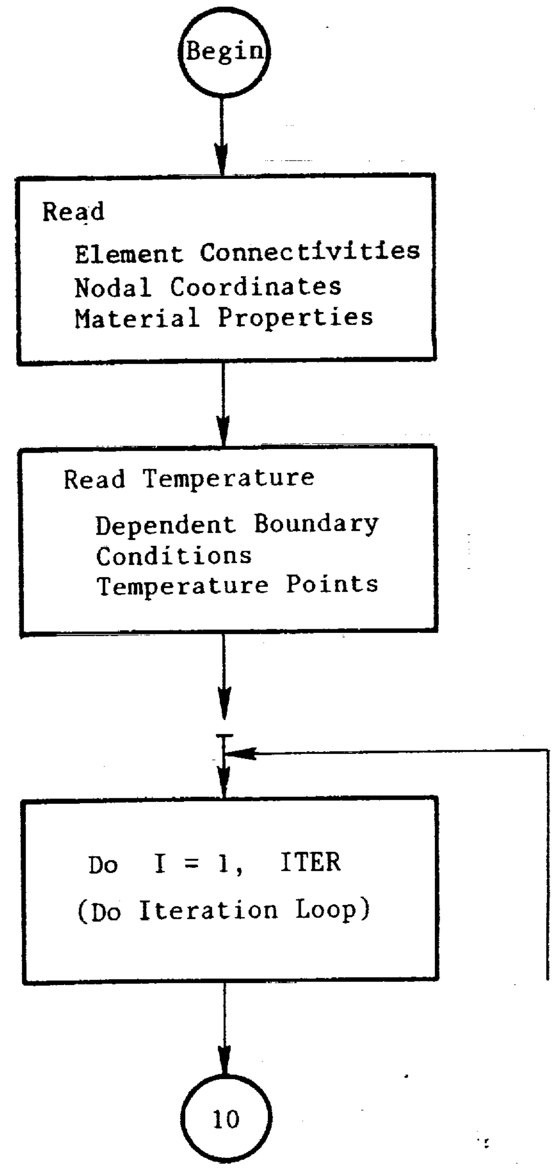
A. Linear Steady-State:

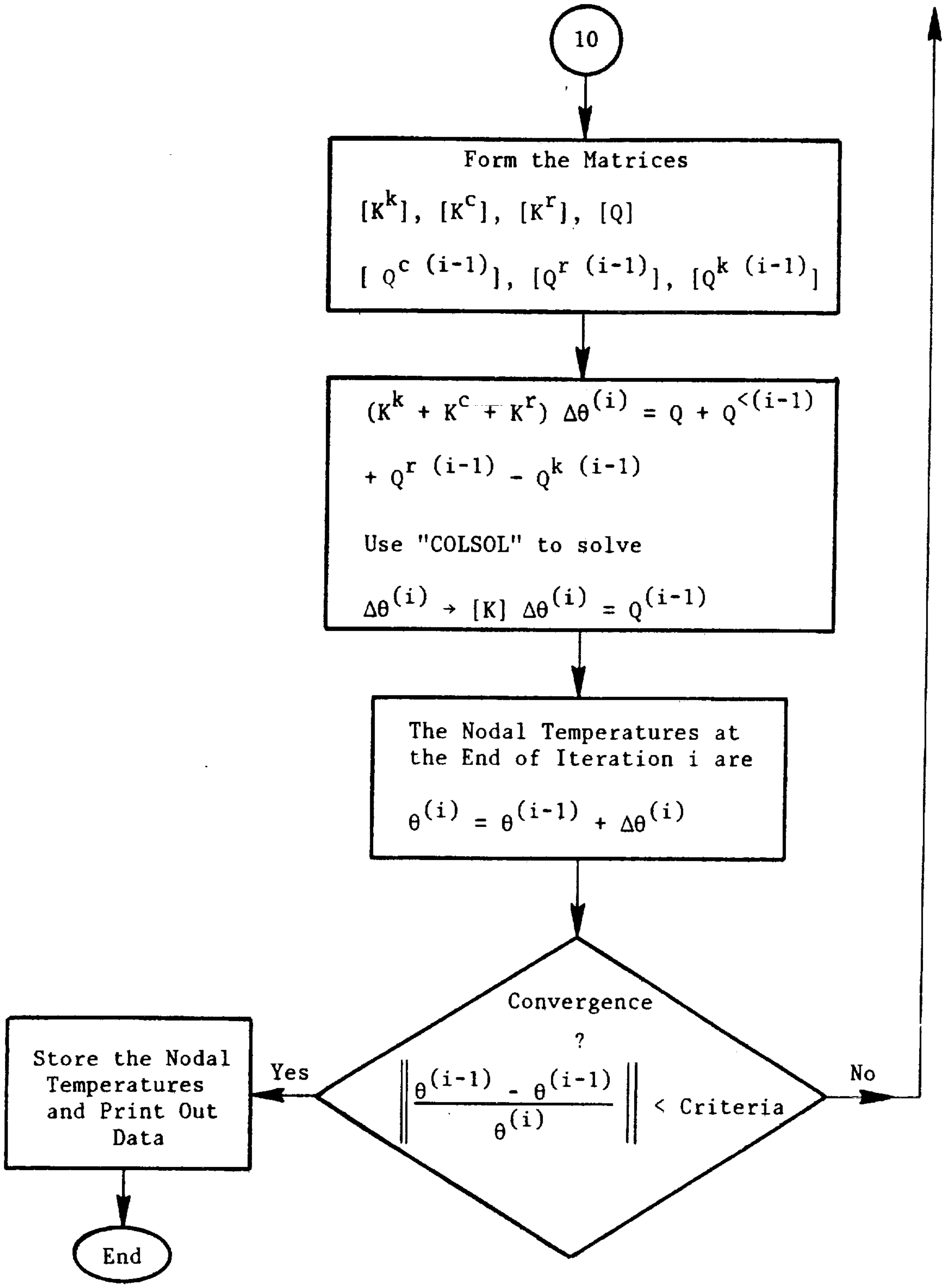



Convection B.C.
No
10
Yes
Formed
$[K^c] = \int_s h \cdot H^{st} \cdot H^s \cdot ds$
$[K^c]_{n \times n} = \sum\sum W_i W_j \text{ (area)} \cdot h \cdot H^{st} \cdot H^s$
Formed
$[Q_e] = \int_s h \cdot H^{st} \cdot (H^s \cdot \theta_e) ds$
$[Q_e]_{n \times 1} = \sum\sum W_i W_j \text{ (area)} \cdot H^{st} \cdot H^s \cdot \theta_e$
Formed
$[Q_B] = \int_v H^t \cdot q^b \cdot dv$
$[Q_B]_{n \times 1} = \sum\sum\sum W_i \cdot W_j \cdot W_k \cdot \det [J] \cdot H^t \cdot q^b$
Formed
$[Q_s] = \int_s H^{st} \cdot q^s \cdot ds$
$[Q_s]_{n \times 1} = \sum\sum W_i W_j \text{ area} \cdot H^{st} \cdot qs$

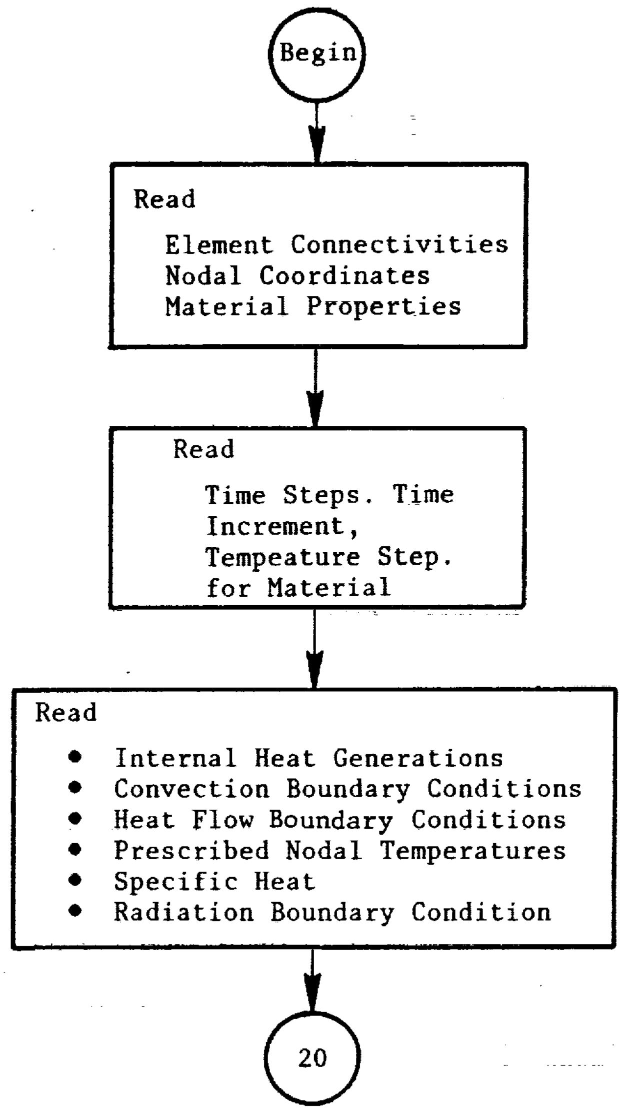

Assemble the Matrix into Structural Matrices
$[\bar{K}^k] = \Sigma [K^k]$
$[\bar{K}^c] = \Sigma [K^c]$
$[\bar{Q}_e] = \Sigma [Q_e]$
$[\bar{Q}_B] = \Sigma [Q_B]$
$[\bar{Q}_s] = \Sigma [Q_s]$
10
$[K]\ \theta = [Q]$
Solve the Equation
$\theta = [K]^{-1} [Q]$
Use COLSOV Subroutine
Stored the Temp. Output
end

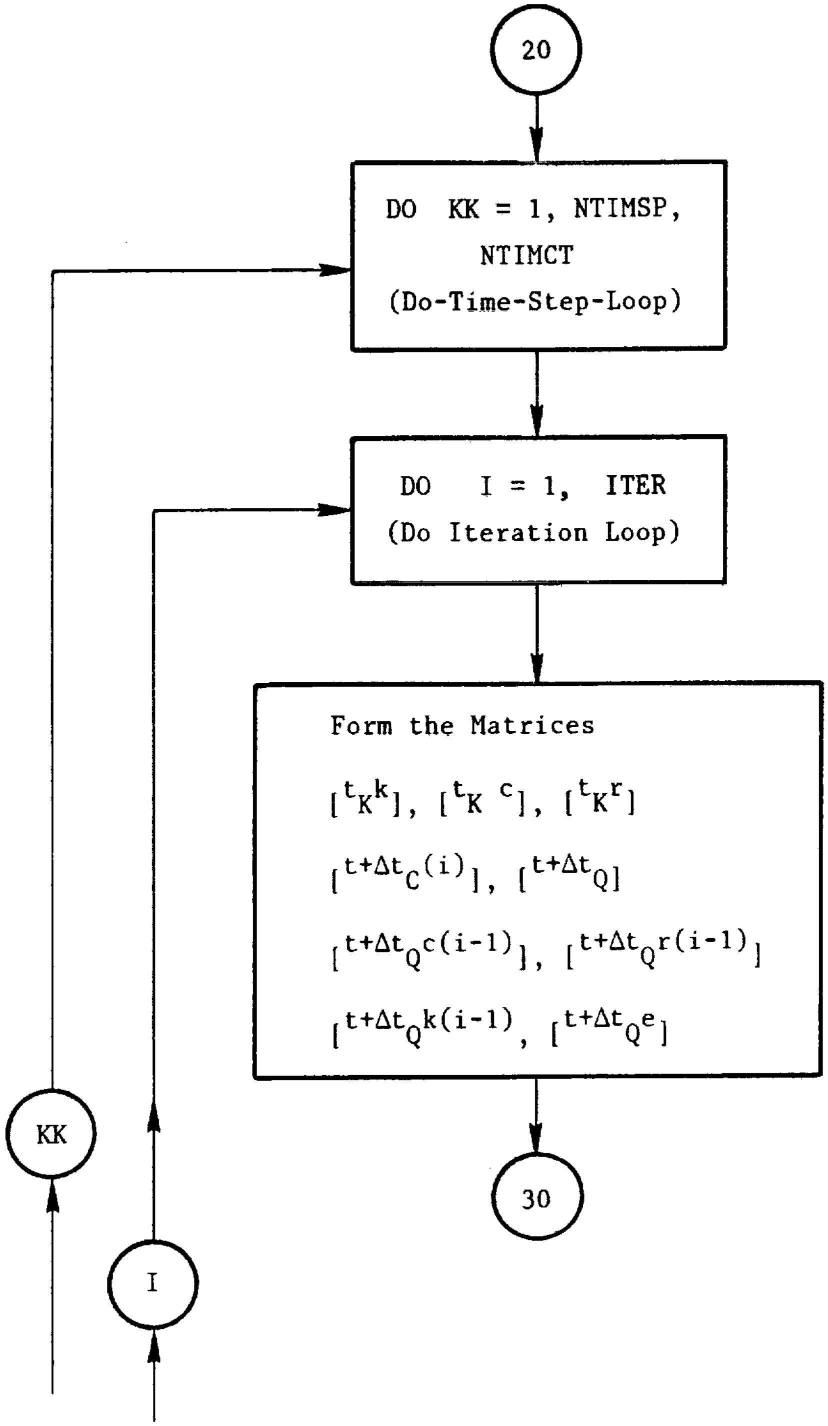
Nonlinear Steady-State Analysis

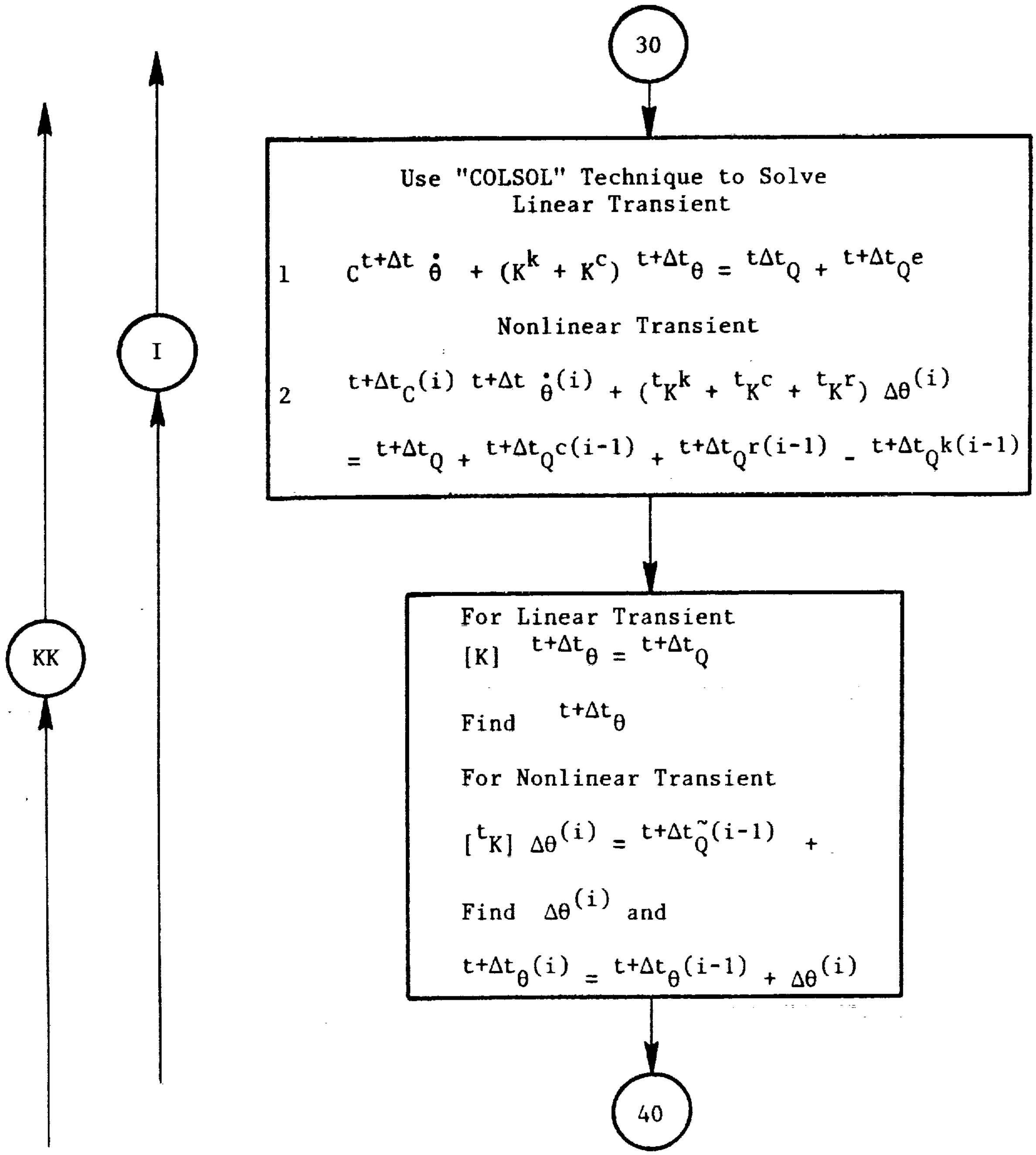


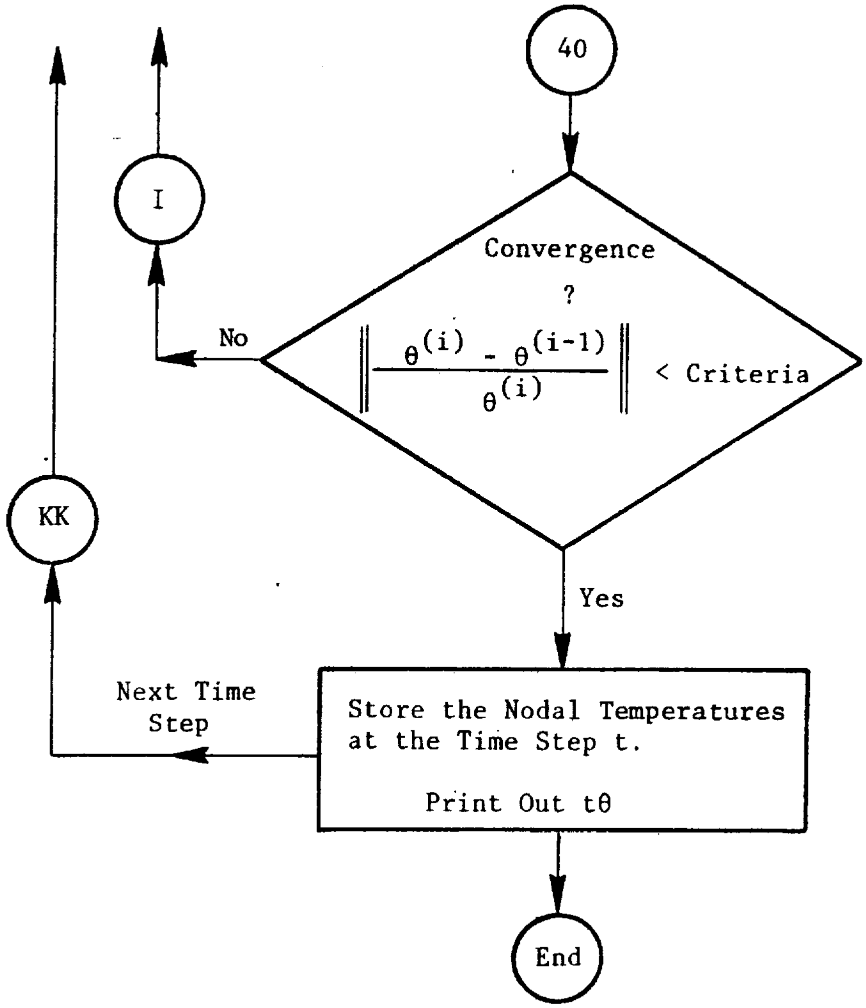

10
Form the Matrices
$[K^k]$, $[K^c]$, $[K^r]$, $[Q]$
$[Q^{c\,(i-1)}]$, $[Q^{r\,(i-1)}]$, $[Q^{k\,(i-1)}]$
$(K^k + K^c + K^r)\ \Delta\theta^{(i)} = Q + Q^{<(i-1)}$
$+ Q^{r\,(i-1)} - Q^{k\,(i-1)}$
Use "COLSOL" to solve
$\Delta\theta^{(i)} \rightarrow [K]\ \Delta\theta^{(i)} = Q^{(i-1)}$
The Nodal Temperatures at the End of Iteration i are
$\theta^{(i)} = \theta^{(i-1)} + \Delta\theta^{(i)}$
Convergence
?
$\left\| \frac{\theta^{(i-1)} - \theta^{(i-1)}}{\theta^{(i)}} \right\| <$ Criteria
Yes
No
Store the Nodal Temperatures and Print Out Data
End

Transient Analysis




20
DO KK = 1, NTIMSP,
NTIMCT
(Do-Time-Step-Loop)
DO I = 1, ITER
(Do Iteration Loop)
Form the Matrices
[${}^{t}K^{k}$], [${}^{t}K^{c}$], [${}^{t}K^{r}$]
[${}^{t+\Delta t}C^{(i)}$], [${}^{t+\Delta t}Q$]
[${}^{t+\Delta t}Q^{c(i-1)}$], [${}^{t+\Delta t}Q^{r(i-1)}$]
[${}^{t+\Delta t}Q^{k(i-1)}$, [${}^{t+\Delta t}Q^{e}$]
30
KK
I


30
Use "COLSOL" Technique to Solve
Linear Transient
1 $C \, {}^{t+\Delta t}\dot{\theta} + (K^k + K^c) \, {}^{t+\Delta t}\theta = {}^{t\Delta t}Q + {}^{t+\Delta t}Q^e$
Nonlinear Transient
2 ${}^{t+\Delta t}C^{(i)} \, {}^{t+\Delta t}\dot{\theta}^{(i)} + ({}^tK^k + {}^tK^c + {}^tK^r) \, \Delta\theta^{(i)}$
$= {}^{t+\Delta t}Q + {}^{t+\Delta t}Q^{c(i-1)} + {}^{t+\Delta t}Q^{r(i-1)} - {}^{t+\Delta t}Q^{k(i-1)}$
For Linear Transient
$[K] \, {}^{t+\Delta t}\theta = {}^{t+\Delta t}Q$
Find ${}^{t+\Delta t}\theta$
For Nonlinear Transient
$[{}^tK] \, \Delta\theta^{(i)} = {}^{t+\Delta t}\tilde{Q}^{(i-1)} +$
Find $\Delta\theta^{(i)}$ and
${}^{t+\Delta t}\theta^{(i)} = {}^{t+\Delta t}\theta^{(i-1)} + \Delta\theta^{(i)}$
40
I
KK


40
I
KK
Convergence
?
$\left\| \frac{\theta^{(i)} - \theta^{(i-1)}}{\theta^{(i)}} \right\| < \text{Criteria}$
No
Yes
Next Time Step
Store the Nodal Temperatures at the Time Step t.
Print Out tθ
End

HEAT TRANSFER

CSTEM USER'S MANUAL

by

HSIN-TIEN HUANG

(REV. FEB. 1 1988)

CSTEM INPUT SHEETS

I. HEADING AND CONTROL INFORMATION
   I.1 Title Card
   I.2 Problem Size Data

II. NODAL COORDINATES

IV. ELEMENT DEFINITIONS
   IV.1 Header Line For Each Element Type
   IV.14 8 Noded Solid
   IV.15 16 Noded Solid
   IV.16 20 Noded Solid

V. ELEMENT SKEW MATERIAL COORDINATE SYSTEMS

VI. ELEMENT LAYER DEFINITIONS

VI. SKEW COORDINATE SYSTEM DEFINITIONS

VIII. FIXED BOUNDARY CONDITIONS

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

1). SUBTITLE

1.2). LOAD CASE INFORMATIONS

2). LOAD CASES CONTROL FLAG

2B). TIME STEPS

2C). TEMPERATURE STEPS

3). THERMAL CONDUCTIVITIES

4). INTERNAL HEAT GENERATION

5). INITIAL CONDITIONS

6). CONVECTION BOUNDARY CONDITIONS

7). HEAT FLUX AT THE SURFACE OF THE BODY

8). NODAL POINT OF HEAT FLOW

9). PRESCRIBED NODAL TEMPERATURES

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 ex = A11*i + A12*j + A13*k
A21, A22,	A23 = direction cosines defining local y axis. The local y axis is defined by ey = A21*i + A22*j + A23*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 CONDUCTIVITES
(IF NICAN .NE.0 SKIP THIS LINE, GO TO ITEM 4)
(REPEAT MMAT TIMES)

MMAT

KXX(MMT,1),	KYY(MMT,1),	KZZ(MMT,1)
.	.	.
KXX(MMT,NTEMP),	KYY(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 SOUUCE (TIME DEPENDENT).

NSETHQ

HQAT(1,1)..............HQAT(1,NTIMSP)
....

HQAT(NSETHQ,1).........HQAT(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
HQAT(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). <u>CONVECTION BOUNDARY CONDITION</u>.
(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 ENVIROMENTS

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.

9a). <u>PRESCRIBED NODAL TEMPERATURES</u>
(THIS ITEM MUST BE INPUT; IT LIKES STRUCTURAL SUPPORT, WITHOUT THIS INPUT IT WILL CREAT A RIDGE-BODY MOTION)

```
NN, NSPR, NEND, INC
 ........
0(LAST LINE)
```

9b).TEMPERATURES AT EACH TIME STEP

```
NSETPR
PRESTM(1,1)...............PRESTM(1,NTIMSP)

....

PRESTM(NSETPR,1)..........PRESTM(NSETPR,NTIMSP)
```

NOTES:

NN	The beginning node # in the group.
NSPR	The data set # in this group.
NSETPR	TOTAL DAT SET on this group.
PRESTM(NSETPR,NTIMSP) -	The prescribed nodal temperature. (degree F or C). at each data set and each time step.
NEND	The end of the node in this group.
INC	Increment of the node in this group.

10).SPECIFIC HEAT (only for transient analysis).
(if steady-stata analysis skip this line go to 11).

```
MASS(1)................MASS(MMAT)
HSPC(1,1)................HSPC(1,NTEMP)

....
HSPC(MMAT,1)..............HSPC(MMAT,NTEMP)
```

NOTES:

MASS(MMAT)	Mass density (Kg or lb.m) at the material MMAT
HSPC(MMAT,NTEMP)	THE SPECIFIC HEAT of the material MMAT, at each temp. point. (KJ/kg-C) or (BTU/lbm-F)

11a). <u>RADIATION BOUNDARY CONDITIONS</u>
(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)

<u>NEL, IFACE, NSR, NEND, INC</u>
.....
0(LAST LINE)

11b). <u>RADIATION TEMPERATURES.</u>

<u>NSETRA</u>
<u>TEMPRA(1,1)........ TEMPRA(1,NTIMSP)</u>
.....
<u>TEMPRA(NSETRA,1).......TEMPRA(NSETRA,NTIMSP)</u>

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). <u>VIEWFACTOR</u>

<u>NEL, P(1)........P(6),NEND, NINC</u>
......
....
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)
....
....

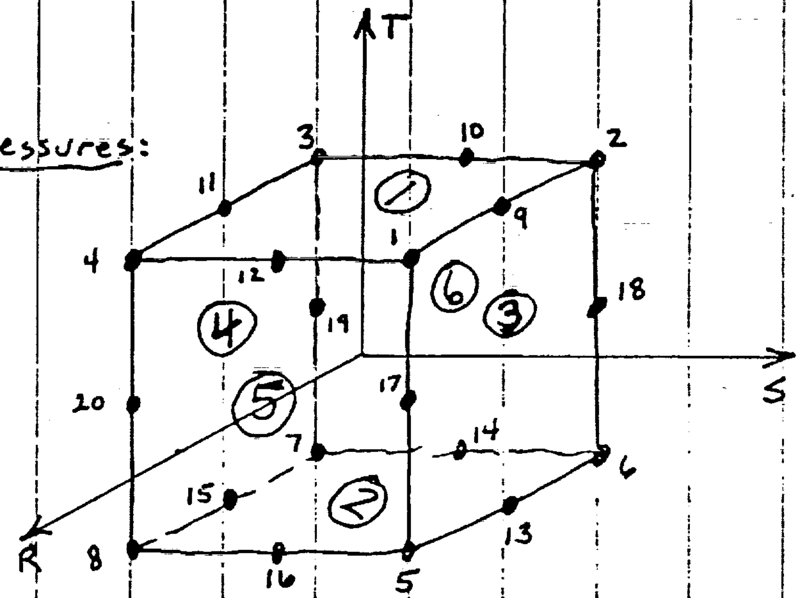
NOTES:

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

(1)

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

Pressures:



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

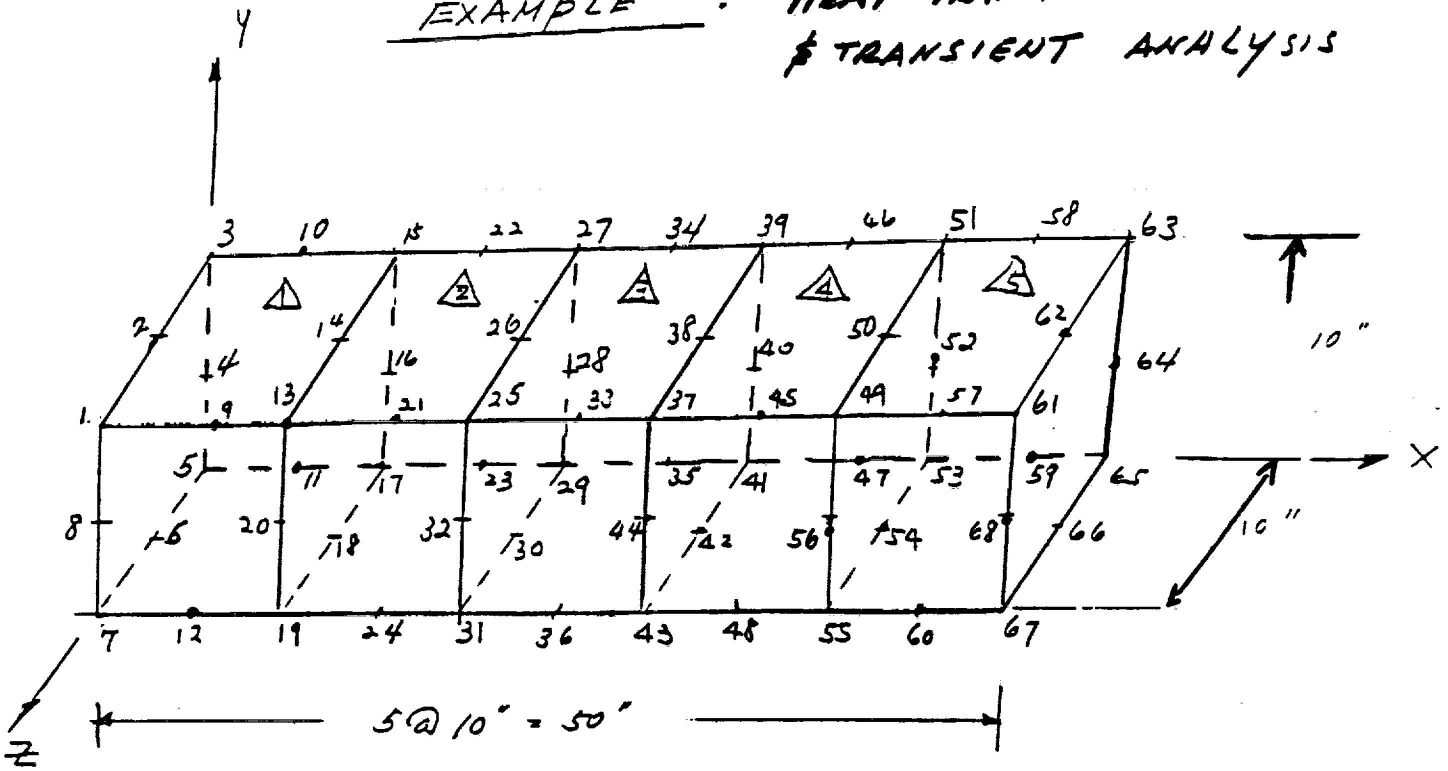
	NODE 1	NODE 2	NODE 3	NODE 4	NODE 5	NODE 6	NODE 7	NODE 8
FACE 1	1	2	3	4	9	10	11	12
FACE 2	5	6	7	8	13	14	15	16
FACE 3	1	2	6	5	9	18	13	17
FACE 4	3	4	8	7	11	20	15	19
FACE 5	1	4	8	5	12	20	16	17
FACE 6	2	3	7	6	10	19	14	18

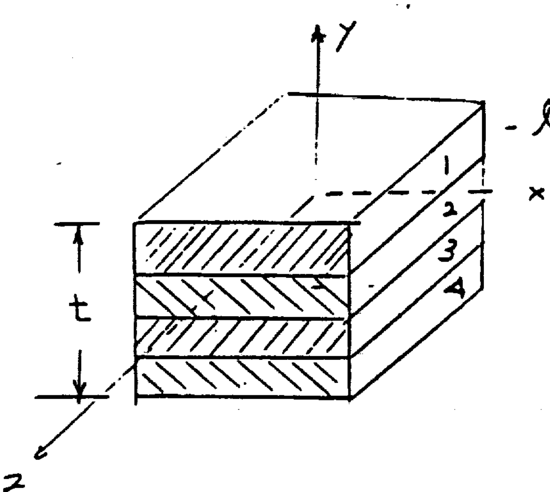
THERMAL ANALYZER VERIFICATION CASES

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° R.H.R
{ 1 & 4 : 45° R.H.R.

MATERIAL — LAMINATE

Case 1:

LINEAR HEAT TRANSFER - COMPOSITE STRUCTURES

* INPUT-DATA DECK
* OUTPUT DATA

2DAT20C.120

NONLINEAR HEAT-TRANSFER - composite structures

INPUT DATA

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

```
2
1, 0.0, -45.0,  0.0
2,  0.0,  45.0,   0.0
NONLINEAR TRANSIENT HEAT TRANSFER
4,  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
6
0., 100.,  200., 300., 400., 600.
1
0.        0.       0.
 40.,     40.  40.
 60.,     60.   60.
 80.,     80.   80.
 90.,     90.  90.
 100.,    100. 100.
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  15.0  20.0  25.0  30.0  35.0
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 10.0 10.0 10.0 10.0 10.0
0
0
NONLINEAR STEADY-STATE HEAT TRANSFER
2,  0,  0
1, 1, 1,  1, 0, 0, 200, 0.01
6
 0., 100., 200., 300., 400., 600.
1
0.,        0.,        0.
  60.,     40. 40.
 80.,       60. 60.
 95.,       75. 75.
 105.,      80. 80.
 115.,      85. 85.
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  15.0  20.0  25.0   30.0   35.0
0
2, 3, 1, 3, 1
0
1
80.0
0
0
1,  1,   8  1
0
1
100.0
0
0
NONLINEAR STEADY-STATE HEAT TRANSFER
2, 0, 0
1,  1, 1, 1, 1, 0, 200, 0.001
6
 0., 100., 200., 300., 400., 600.
1
0.,      0.,      0.
 60.,     40.  40.
 80.,      60. 60.
 95.,     75.  75.
 105.,     80. 80.
 115.,     85. 85.
0
1,  1,  5, 1
0
1
70.
0
1,  70, 68,  1
0
5, 6, 1, 5, 1
0
1
45.0
0
10.0   15.0   20.0  25.0   30.0   35.0
0
2, 3, 1, 3, 1
0
1
100.0
0
0
1,  1,  8, 1
0
1
100.0
0
4, 2, 1, 4, 1
0
1
60.0
0
4,  1.0, 1.0, 1.0, 1.0, 1.0, 1.0, 4, 1
0
0.15,  0.1,  0.08,  0.05,  0.01, 0.008
0
```

NONLINEAR - HEAT TRANSFER composite stru. output

ZOUT 20C.120

HEADING AND CONTROL INFORMATION

TITLE CARD

NONLINEAR HEAT-TRANSFER - composite structures

PROBLEM SIZE DATA

NN	NELTYP	MMAT	NLC	INGEOM	IHTR	NDATCK
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

NTYPEL NELEMS INCOMP INTORD

2.

20	5	1	3

ELEMENT TYPE 20
20 NODED ISOPARAMETRIC BRICKS

NEL	N1	N2	N3	N4	N5	N6	N7	N8				
N9	N10	N11	N12	N13	N14	N15	N16	N17	N18	N19	N20	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	56	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

ELEMENT SKEW MATERIAL COORDINATE SYSTEMS

NSKEWE
0

ELEMENT MATERIAL LAYER SETS

NELAY
1

NEL	NLAYR	LAX	NEND	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

REFERENCE NODES

NSKEWR
0

DIRECTION COSINES

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

NN	NE	NMAT	NTYPEL	NLC	IUNIT	IANALY
68	5	1	20	3	1	4

****

LOAD CASE CONTROL INFORMATION, LOAD CASE = 1NONLINEAR TRANSIENT HEAT TRANSFER

LOAD CASE CONTROL CARDS

IHT	NICAN	NTEM
1	0	0

LOAD CASE CONTROL INFORMATION

LOAD CASE CONTROL CARD

NHGEN	NCBC	NFBC	NITEM	NPRES	NRBC	NODFLW	ITER	CDELTA
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   NEND.  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
 --------------------------------

   N   TEMP    NEND    NINC
  1    70.00    68      1

  0

  CONVECTION NODAL 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 ENVIROMENT TEMP(1,2,...NTIMSP)


  40.00   40.00   50.00   70.00   80.00  100.00
     0

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


  10.00   15.00   20.00   25.00   30.00   35.00
     0

     HEAT FLUX IN THE SURFACE -----------------------------


 ELE.    FACE   NDATA   NEND  NINC

    0

      NODAL POINT HEAT FLOW INPUT
   ----------------------------------------

      N1    NDATA    NEND    NINC

       0

     PRESCRIBED NODAL TEMPERATURES
     ----------------------------------------


     N   NDATA   NEND   NINC
      1      1      8      1
      0

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



```
  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,.....NTEMPT)


  10.00   10.00   10.00   10.00   10.00   10.00


    0

   RADIATION NODAL TEMPERATURES
  ------------------------------------
  NEL   IFACE  NDATA  NEND  INC

   0



  **************************************************




    THE FINAL RESULT OF NODAL 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
```

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
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 NODAL 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
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

****

THE FINAL RESULT OF NODAL 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	138.54
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
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 NODAL TEMP
LOAD CASE= 1 TIME STEP= 4 TIME = 3.5000

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	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

6

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

7.

```
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


   *******************************************


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

 LOAD CASE CONTROL CARDS


   IHT   NICAN   NTEM
     2       0       0

 LOAD CASE CONTROL INFORMATION

     LOAD CASE CONTROL CARD

 NHGEN   NCBC   NFBC   NITEM   NPRES   NRBC   NODFLW   ITER   CDELTA


     1      1      1       1       1      0        0    200   0.010000
***** 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


         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

INTERNAL HEAT GENERATION
 -------------------------------------
   ELE.  NDATA   NEND.  INC.

   1       1       5      1

   0
```

9.0

```
THE TOTAL DATA SET =      1

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

   INITIAL NODAL TEMPERATURES
  ----------------------------------

    N   TEMP     NEND     NINC
   1     70.00    68       1

   0

   CONVECTION NODAL TEMPERATURES ---------------------

  ELM   IFACE   NOS  NEND NINC

    5      6      1      5      1

    0

TIME DEPENDENT COEFF. OF CONVECTION
**************************************************************
 THE TOTAL DATA SET =      1
THE TIME DEPENDENT ENVIROMENT TEMP(1,2,...NTIMSP)

  50.00
    0

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

  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

   NODAL POINT HEAT FLOW INPUT
 ----------------------------------------

   N1    NDATA    NEND    NINC

    0

   PRESCRIBED NODAL TEMPERATURES
   ----------------------------------------

   N   NDATA   NEND   NINC
   1      1      8      1
   0

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

  100.00
    0

   RADIATION NODAL TEMPERATURES
  ----------------------------------
  NEL   IFACE  NDATA  NEND  INC

   0

*****************************************************

 THE FINAL RESULT OF NODAL 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
```

```
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


 ********************************************


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

LOAD CASE CONTROL CARDS

IHT   NICAN   NTEM
```

```
    2       0       0

LOAD CASE CONTROL INFORMATION

   LOAD CASE CONTROL CARD

NHGEN   NCBC   NFBC   NITEM   NPRES   NRBC   NODFLW   ITER   CDELTA


   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  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


         60.000000     40.000000     40.000000

   THE TEMPERATURE POINT =      3


         80.000000     60.000000     60.000000

   THE TEMPERATURE POINT =      4
```

10.

```
     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.  INC.

 1      1      5      1

 0

THE TOTAL DATA SET =      1


THE INTERNAL HEAT GENERATED RATE
   QRATE(1),.........,QRATE(TIME STEP)
    70.00
   0

  INITIAL NODAL TEMPERATURES
 -----------------------------------


   N   TEMP     NEND     NINC
  1     70.00     68       1

  0

  CONVECTION NODAL 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 ENVIROMENT TEMP(1,2,...NTIMSP)


 45.00
   0

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


 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

    NODAL POINT HEAT FLOW INPUT
  ----------------------------------------


    N1    NDATA    NEND    NINC

     0
```

PRESCRIBED NODAL TEMPERATURES

```
N   NDATA   NEND   NINC
1     1       8      1
0

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

 100.00
   0
```

RADIATION NODAL TEMPERATURES

```
NEL   IFACE  NDATA  NEND  INC

 4      2      1      4     1
 0
```

TEMP. DEPENDENT COEFF. OF RADIATION
TIME DEPENDENT ENVIROMENT TEMPERATURES

THE TOTAL DATA SET =   1

DATA SET=   1

TIME DEPENDENT TEMP
TEMP(1,2..........,TIME STEP)

```
 60.000
  0

ELM   VIEW FACTOR AT FACE 1 TO 6          NEND   NINC

 4  1.00000  1.00000  1.00000  1.00000  1.00000  1.00000    4    1

 0
```


EMISSIVITY COEFF. TABLE

VALUE (1,2........)

```
0.150    0.100    0.080    0.050    0.010    0.008
0
```

****

THE FINAL RESULT OF NODAL TEMP
LOAD CASE=   3   ITERATION=   12

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	167.52
10	167.48
11	167.48
12	167.52
13	165.46
14	165.22
15	165.13
16	165.13
17	165 13
18	165.22
19	165.46
20	165.46
21	163.41
22	162.80
23	162.80
24	163.41
25	160.71
26	160.18
27	160.06
28	160.04
29	160.05
30	160.17
31	160.70
32	160.69
33	157.37
34	156.71
35	156.66
36	157.32
37	153.54
38	153.03
39	152.87
40	152.82
41	152.62
42	152.80
43	153.29
44	153.49
45	149.28
46	148.60
47	148.19
48	148.87
49	144.47
50	143.89
51	143.78
52	143.74
53	143.53
54	143.65
55	144.22
56	144.43
57	139.06
58	138.37
59	138.31
60	139.00
61	133.06
62	132.71
63	132.38
64	132.33
65	132.35
66	132.68
67	133.03
68	133.01

Case APPENDIX 2 :

NONLINEAR HEAT - TRANSFER - COMPOSITE STRUCTURES

* INPUT DATA

* OUTPUT DATA

1

LINEAR HEAT-TRANSFER COMPOSITE STRUCTURES   ZUAT20C.L01

LINEAR - H.T.

INPUT DATA

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

```
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
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
```

2.

BOUT20C.L01

LINEAR H.T. Composite Structure. - OUTPUT.

HEADING AND CONTROL INFORMATION

TITLE CARD

LINEAR HEAT-TRANSFER COMPOSITE STRUCTURES

PROBLEM SIZE DATA

NN	NELTYP	NMAT	NLC	INGEOM	IHTR	NDATCK
68	1	1	2	0	3	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

NTYPEL NELEMS INCOMP INTORD

2

```
   20      5      1      3

 ELEMENT TYPE 20
 20 NODED ISOPARAMETRIC BRICKS

 NEL    N1    N2    N3    N4    N5    N6    N7    N8
  N9   N10   N11   N12   N13   N14   N15   N16   N17   N18   N19   N20   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    56    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

ELEMENT SKEW MATERIAL COORDINATE SYSTEMS

  NSKEWE
      0

ELEMENT MATERIAL LAYER SETS

  NELAY
      1

   NEL  NLAYR  LAX  NEND  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

   REFERENCE NODES

  NSKEWR
      0

    DIRECTION COSINES

  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

NN    NE   NMAT  NTYPEL  NLC  IUNIT  IANALY
68     5     1     20     2     1      3


    *********************************************


LOAD CASE CONTROL INFORMATION, LOAD CASE =  1LINEAR TRANSIENT HEAT TRANSFER

LOAD CASE CONTROL CARDS


   IHT  NICAN  NTEM
    3     0      0

LOAD CASE CONTROL INFORMATION

    LOAD CASE CONTROL CARD

 NHGEN  NCBC  NFBC  NITEM  NPRES  NRBC  NODFLW  ITER  CDELTA

   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

MATERIAL  1 THERMAL CONDUCTIVITY TABLE

CONDUCTIVITY KXX,         KYY,         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   50.00   50.00   50.00   50.00   50.00
    0

   INITIAL NODAL TEMPERATURES
 ----------------------------------

    N   TEMP     NEND     NINC

    1     70.00     68      1

    0

    CONVECTION NODAL 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 ENVIROMENT TEMP(1,2,...NTIMSP)

  40.00   40.00   50.00   70.00   80.00  100.00
    0

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

  ..00
    0

    HEAT FLUX IN THE SURFACE ---------------------------

 ELE.    FACE   NDATA   NEND  NINC

   0

     NODAL POINT HEAT FLOW INPUT
  ---------------------------------------

    N1    NDATA    NEND    NINC

     0

    PRESCRIBED NODAL TEMPERATURES
    ---------------------------------------
```

4

```
 N  NDATA  NEND  NINC
 1    1      8     1
 0

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

  70.00    70.00   100.00   100.00   120.00   120.00
   0

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

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


 10.00

   0
```

****

THE FINAL RESULT OF NODAL 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
8	70.00
9	69.92
10	69.93
11	69.93
12	69.92
13	69.76
14	69.78
15	69.79
16	69.79
17	69.79
18	69.78
19	69.77
20	69.76
21	69.55
22	69.58
23	69.58
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	68.59
42	68.55
43	58.50
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 FINAL RESULT OF NODAL TEMP
LOAD CASE= 1   TIME STEP= 2   TIME =   1.5000

NODE	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
17	75.56
18	75.93
19	76.32
20	76.37
21	73.62
22	73.18
23	73.14
24	73.58
25	71.55
26	71.40
27	71.26
28	71.27
29	71.24
30	71.38
31	71.52
32	71.54
33	69.93
34	69.78
35	69.77
36	69.92
37	68.57
38	68.53
39	68.48
40	68.49
41	68.48
42	68.52
43	68.56
44	68.57
45	67.35
46	67.32
47	67.32
48	67.35
49	66.18
50	66.18
51	66.19
52	66.19
53	66.19
54	66.18
55	66.18
56	66.18
57	64.99
58	65.01
59	65.02
60	64.99
61	63.76
62	63.81
63	63.80
64	63.79
65	63.80
66	63.82
67	63.76
68	63.76

****

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

NODE	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
24	84.54
25	80.50
26	80.28
27	80.06
28	80.10
29	80.03
30	80.24
31	80.46
32	80.49
33	77.03
34	76.69
35	76.66
36	77.00
37	74.08
38	73.92
39	73.76
40	73.78
41	73.73
42	73.89
43	74.05
44	74.07
45	71.60
46	71.36
47	71.34
48	71.58
49	69.49
50	69.37
51	69.27
52	69.29
53	69.25
54	69.35
55	69.47
56	69.48
57	67.69
58	67.52
59	67.50
60	67.67
61	66.16
62	66.11
63	65.98
64	66.00
65	65.97
66	66.09
67	66.14
68	66.15

****

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

NODE	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
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

****

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

NODE	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

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	79.87
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 INFORMATION, LOAD CASE = 2LINEAR STEADY-STATE HEAT TRANSFER

LOAD CASE CONTROL CARDS

IHT	NICAN	NTEM
1	0	0

LOAD CASE CONTROL INFORMATION

LOAD CASE CONTROL CARD

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

MATERIAL 1 THERMAL CONDUCTIVITY TABLE

CONDUCTIVITY KXX, KYY, 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

INITIAL NODAL TEMPERATURES

N	TEMP	NEND	NINC
1	70.00	68	1

0

```
CONVECTION NODAL TEMPERATURES ------------------------------------------------

 ELM   IFACE   NOS  NEND NINC

    5      6      1      5      1

    0

TIME DEPENDENT COEFF. OF CONVECTION
*************************************************************
 THE TOTAL DATA SET =       1
THE TIME DEPENDENT ENVIROMENT TEMP(1,2,...NTIMSP)


  50.00
     0

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


  10.00
     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
```

```
 NODAL POINT HEAT FLOW INPUT
-----------------------------------------

 N1    NDATA    NEND    NINC

  0

PRESCRIBED NODAL TEMPERATURES
-----------------------------------------


N   NDATA   NEND   NINC
 1      1      8      1
 0

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

 100.00
    0



      ******************************** ********************


         THE FINAL RESULT OF NODAL TEMPERATURES

  NODE        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
```

9

14	99.58
15	99.53
16	99.53
17	99.53
18	99.58
19	99.73
20	99.73
21	99.38
22	99.00
23	99.00
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
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

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Accomplishments are described for the third years effort of a 5-year program to develop a methodology for coupled structural/thermal/electromagnetic analysis/tailoring of graded composite structures. These accomplishments include: (1) structural analysis capability specialized for graded composite structures including large deformation and deformation position eigenanalysis technologies; (2) a thermal analyzer specialized for graded composite structures; (3) absorption of electromagnetic waves by graded composite structures, (4) coupled structural thermal/electromagnetic analysis of graded composite structures.

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