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Optimization of Residual Stresses in MMC's Using Compensating/ Compliant Interfacial Layers

Part II—OPTCOMP User's Guide

Marek-Jerzy Pindera, Robert S. Salzar,
and Todd O. Williams
University of Virginia
Charlottesville, Virginia

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PREFACE

A user's guide for the computer program **OPTCOMP** is presented in this report. This program provides a capability to optimize the fabrication or service-induced residual stresses in unidirectional metal matrix composites subjected to combined thermo-mechanical axisymmetric loading using compensating or compliant layers at the fiber/matrix interface. The user specifies the architecture and the initial material parameters of the interfacial region, which can be either elastic or elastoplastic, and defines the design variables, together with the objective function, the associated constraints and the loading history through a user-friendly data input interface. The optimization procedure is based on an efficient solution methodology for the elastoplastic response of an arbitrarily layered multiple concentric cylinder model that is coupled to the commercial optimization package **DOT**. The solution methodology for the arbitrarily layered cylinder is based on the *local-global stiffness matrix formulation* and Mendelson's iterative technique of *successive elastic solutions* developed for elastoplastic boundary-value problems. The optimization algorithm employed in **DOT** is based on the *method of feasible directions*.

Notice: The **OPTCOMP** code is being made available strictly as a research tool. Neither the authors of the code nor NASA-Lewis Research Center assume liability for application of the code beyond research needs. Any questions or related items concerning this computer code can be directed to either Professor Marek-Jerzy Pindera, Dr. Robert S. Salzar or Mr. Todd O. Williams at the Civil Engineering & Applied Mechanics Department, University of Virginia, Charlottesville, VA 22903 (Tel: 804-924-1040, e-mail: marek@virginia.edu, rss2t@virginia.edu or tow2a@virginia.edu).

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1.0 INTRODUCTION

This user's guide provides a description of the operation and use of an efficient, computer-based algorithm for optimizing residual thermal stresses in metal matrix composites (MMC's) based on the concept of multiple elastic and/or inelastic layers at the fiber/matrix interface. The development of the optimization algorithm **OPTCOMP** was motivated by the need to reduce high residual stresses, and thus the potential for cracking, in advanced MMC's such as SiC/Ti that arise due to the lack of matrix ductility, the large mismatch in the thermal expansion coefficients of the fiber and matrix phases, and the high processing temperature [1]. The goal is to tailor the geometry, thermal and elastoplastic properties of the interfacial region in a way that "smooths out" or reduces the apparent thermal expansion mismatch between the fiber and matrix phases as discussed by Arnold et al. [2,3]. This is accomplished through the use of multiple interfacial layers producing appropriate material property gradients in the interfacial region.

The computer program **OPTCOMP** enables the user to identify those geometrical arrangements and elastoplastic properties of the interfacial layers, herein called design variables, that optimize (i.e., minimize or maximize) residual thermal stresses or some other objective function describing the response of the composite under combined axisymmetric thermo-mechanical loading for the specified set of constraint variables. The definitions for the optimization terminology employed throughout this report are given below.

Objective function: An expression for the dependent variable such as a stress or strain component, or a combination of these components (e.g., strain energy density function) that is to be minimized or maximized by the optimization algorithm.

Design variable(s): The independent variable(s), such as a thermal expansion coefficient, Young's modulus or layer thickness, used in determining an improved (optimum) design.

Constraint: A limiting value placed on a dependent variable, which is not an objective function, necessary to achieve a feasible (physically meaningful) design.

Side constraint(s): Upper and lower bounds placed on an independent design variable necessary for maintaining it within physically meaningful values.

The calculation of residual stresses is based on a micromechanics multiple concentric cylinder model, Figure 1, and utilizes a novel analytical technique for the solution of axisymmetric, elastoplastic boundary-value problems recently developed by Pindera et al. [4,5,6]. This solution technique combines elements of the *local/global stiffness matrix formulation* originally developed for efficient analysis of elastic multi-layered media [7,8], and Mendelson's iterative method of *successive elastic solutions* for elastoplastic boundary-value problems [9]. The actual optimization algorithm is based on the *method of feasible directions* and utilizes the commercially-available package **DOT** [10].

In addition to the optimization capability, the user has the option of generating the response of a given composite system subject to specified axisymmetric thermo-mechanical loading for the chosen geometry and constituent materials. This is achieved by employing a subset of **OPTCOMP**, called **RTSHELL**, which is a separate program with the same menu-driven, user-friendly interface employed in the former but without the optimization subroutines and related control statements. **RTSHELL** allows analytical characterization and evaluation of different composite material systems for applications in a wide temperature range. Specifically, it is possible to evaluate new fibers and/or new coating systems on existing fibers with respect to the mismatch in the thermal expansion coefficient and other properties between fiber and matrix with a minimum of effort. An outline of the analytical solution procedure and the optimization procedure employed in **RTSHELL** and **OPTCOMP** is given in Part I of this report.

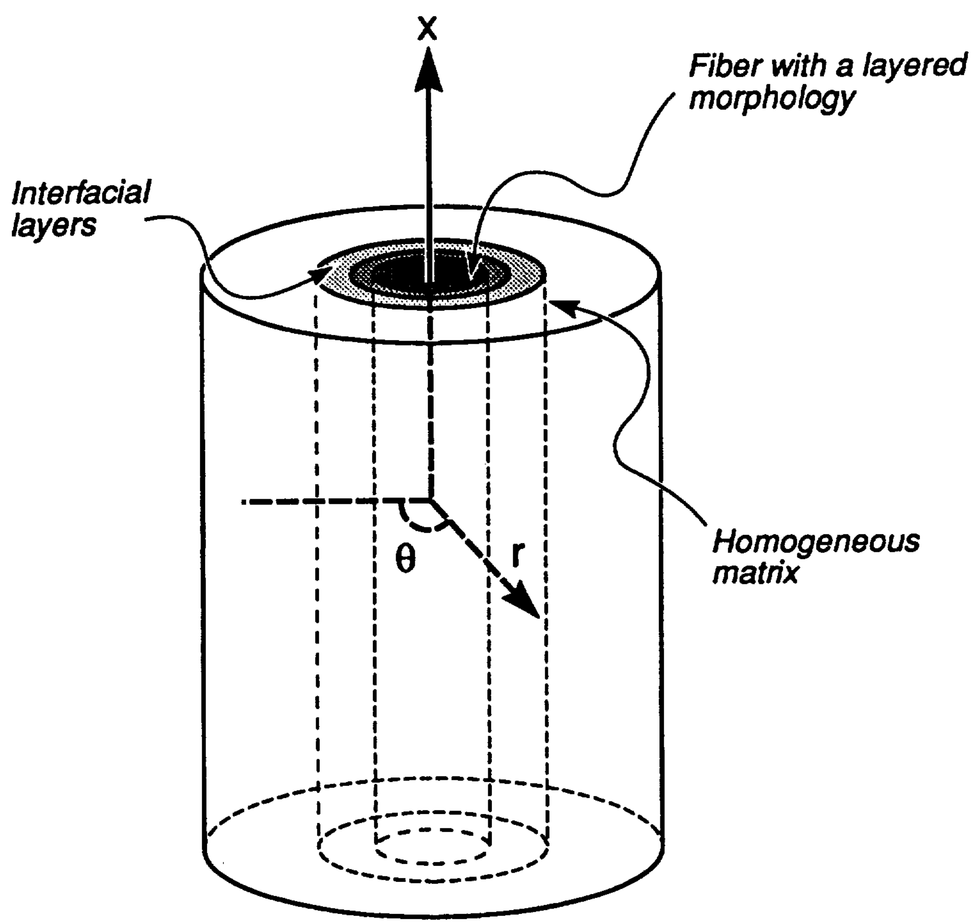

Figure 1. Multiple concentric cylinder model

2.0 PROGRAM DESCRIPTION

OPTCOMP is an executable file that is created by compiling and linking collections of subroutines that make up the total design package for identifying an optimal architecture and properties of the interfacial region in unidirectional metal matrix composites. These collections of subroutines, along with a brief description of their functions, are listed below.

- **shell.f**: menu-driven, user-friendly interface
- **mccmopt.f**: analysis source code adapted for use with **dot.f**
- **dot.f**: **DOT**[1] source code consisting of **DOT1.FOR**, ..., **DOT5.FOR** files
- **objective.f**: file containing user-defined objective function subroutine
- **constraint.f**: file containing user-defined constraint function subroutine

The flow chart outlining the logical organization and execution of these subroutines within the executable **OPTCOMP** file is given in Figure 2. In essence, the optimization algorithm is based on three modules, namely the user interface **shell.f** which provides a menu-driven, user-friendly data input environment described in Section 3.0, the analysis code **mccmopt.f** which, in addition to generating the elastoplastic solution to the concentric cylinder assemblage subjected to specified loading, also controls the execution of the optimization procedure, and the optimization package **DOT** contained in the subroutine **dot.f**. The user defines the optimization problem by responding to a sequence of menu-driven instructions executed by **shell.f**. This involves specification of the concentric cylinder geometry, materials and properties of the individual regions, objective function and constraints, and loading history. In the current version of the program, the user can select from fourteen "built-in" objective functions and eleven "built-in constraint functions. The two additional subroutines EXTOBJ and EXTCONST located in the **objective.f** and **constraint.f** files allow the user to construct his or her own objective function and associated constraints if so desired, as illustrated in Appendix I. In this case, these two subroutines have to be compiled and linked by the user. The data provided during the problem definition stage is subsequently used to generate a solution to the defined elastoplastic boundary-value problem which, in turn, is used as input in the collection of optimization subroutines **dot.f**. The features and presently available capabilities of the subroutine **mccmopt.f** and the optimization algorithm **OPTCOMP** are summarized in Table I.

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[1]License for the **DOT** source code must be purchased separately from VMA Engineering (Vanderplaats, Miura & Associates, Inc.), 5960 Mandarin Ave., Suite F, Goleta, CA 93117. Phone: (805) 967-0058.

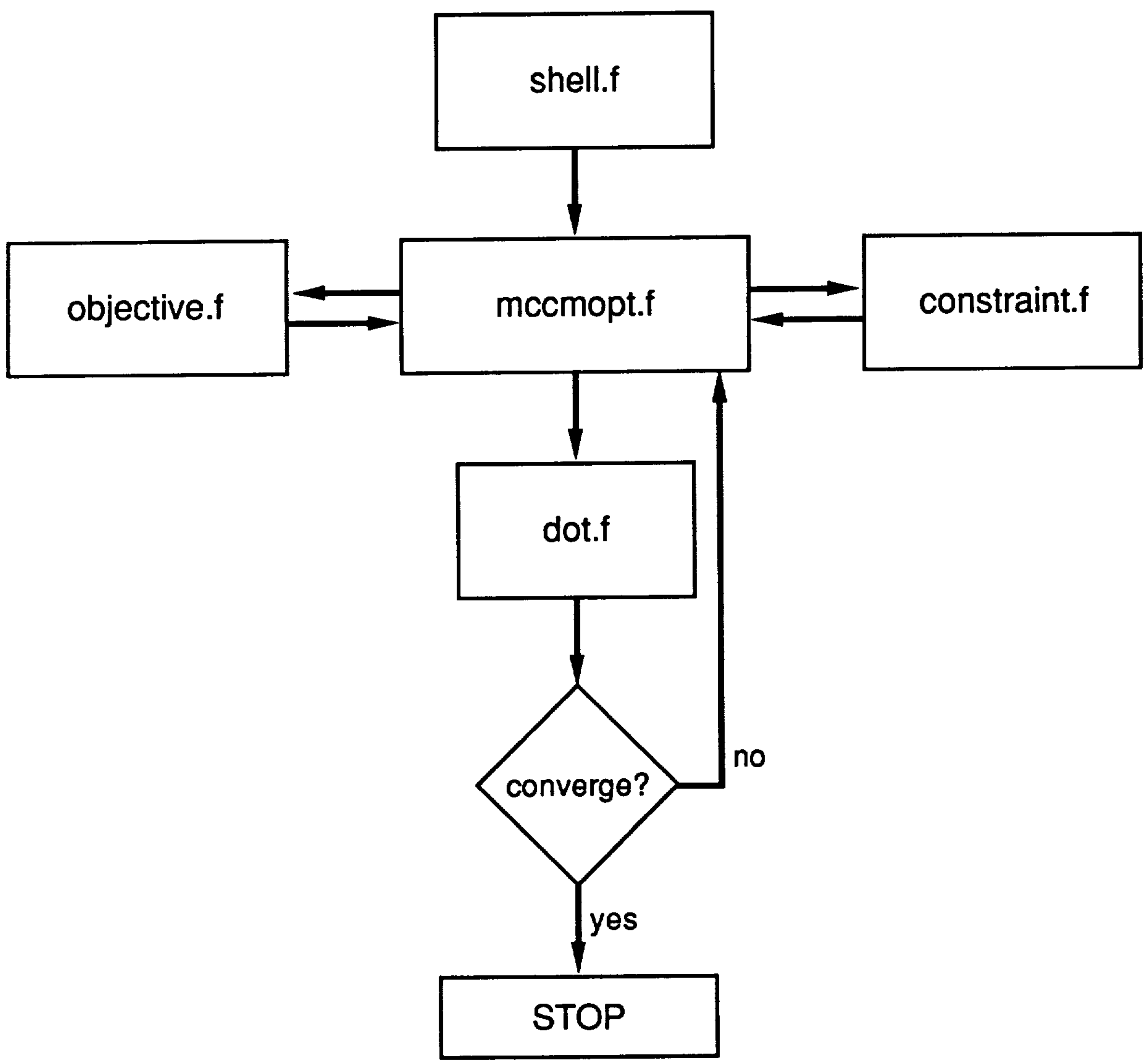


Figure 2. Flow chart for the computer program **OPTCOMP**

Table I. Current available capabilities within **OPTCOMP**.

Concentric Cylinder Geometry & Materials		
Constituent	Morphology	Constitutive model
fiber	layered	core: elastic and (transversely) isotropic shells: elastic or elastoplastic and isotropic, or elastic and orthotropic
interfacial region	layered	elastic: (transversely) isotropic, orthotropic elastoplastic: isotropic
matrix	layered	elastic: (transversely) isotropic, orthotropic elastoplastic: isotropic

Loading Capabilities	
Type	Mode and History
Thermal	Monotonic or cyclic, spatially uniform ΔT
Mechanical	Monotonic or cyclic external pressure + axial tension/compression
Combined	Monotonic or cyclic ΔT + external pressure + axial tension/compression

Optimization Features	
Design variables	Interfacial layers' CTE, elastic moduli, yield stress, hardening slope, thickness
Objective functions	Fiber radial stress; interfacial layer axial, hoop, hydrostatic and radial stress; matrix axial, hoop, hydrostatic and radial stress, and axial strain; composite axial strain; user-defined objective function
Constraints	Interfacial layer axial, hoop and radial stress; matrix axial, hoop, hydrostatic and radial stress; composite axial strain; user-defined constraint function

2.1 Input/Output Files

During execution of **OPTCOMP**, additional files are either employed or created. These files are listed and briefly described below according to the order in which they are created or employed.

- **optcomp.data**: internally created data file for the execution of **OPTCOMP**
- **optcomp.review**: review of information contained in the data file **optcomp.data**
- **fiber.data**: fiber material databank
- **matrix.data**: matrix material databank
- **refer.data**: reference material databank
- **fiber.int**: internally created direct-access file
- **matrix.int**: internally created direct-access file
- **refer.int**: internally created direct-access file
- **optcomp.history**: an execution history of **OPTCOMP**
- **optcomp.out**: initial and final (optimum) properties, geometry, stresses and inelastic strains
- **optcomp.conv**: information on the convergence of the iterative solution

The data file **optcomp.data** is created during the definition of the optimization problem through the user-friendly, menu-driven interface **shell.f**. This is done by selecting option 1 (CREATE NEW DATA FILE) from the main menu when the execution of the program is initiated by typing the command *optcomp* as described in Section 3.0. A sequence of commands is then displayed which prompts the user to define the optimization problem. The resulting data file contains all the information needed to run a complete optimization program. Included in this file is the information on the geometry of the concentric cylinder, material properties of the fiber, matrix and the interfacial layer(s), design variables, objective functions and constraints, and external loading. This file is stored so that it can be executed either immediately after its creation, or at a later time.

At the end of the **optcomp.data** creation process, the file **optcomp.review** is created which summarizes the optimization problem contained in **optcomp.data**. Unless the user has directly altered the **optcomp.data** file using an editor, the **optcomp.review** file will always reflect the problem stored in **optcomp.data**.

The data files **fiber.data** and **matrix.data** contain the name and temperature-dependent material properties of the fiber and matrix constituents that can be used to construct a given composite. The data file **refer.data** contains the name and material properties of "reference materials" that are used to define the base properties of the interfacial layers for the chosen combination of fiber and matrix constituents. The initial properties of the interfacial layers are defined in terms of ratios obtained by normalizing the actual interfacial layer properties by the properties of the reference material. The above files comprise the material property databanks, or libraries, from which different composite systems to be optimized can be constructed. These files can be created and/or modified using the three alternative methods described in Section 2.2.

The files **fiber.int**, **matrix.int** and **refer.int** are automatically generated "direct-access" internal files which are read from the corresponding files with the extension ".data". These files are necessary for the execution of **OPTCOMP**, and are re-created every time the **OPTCOMP** program is executed. Consequently, they may be deleted between optimization runs without erasing the databanks. **However, if the files with the extension ".data" are deleted, the material databanks will be lost.**

Output generated by **OPTCOMP** upon selection of option 2 (RUN EXISTING DATA FILE) is written to three files, namely **optcomp.history**, **optcomp.out** and **optcomp.conv**. The file **optcomp.history** contains the entire history of a given optimization run that includes, at each iteration of the optimization procedure, the values of the chosen design variables, their lower and upper bounds, and the specified constraints and objective function. This information can also be written to the screen during execution of the optimization procedure at the user's discretion. The information written to the file **optcomp.out** includes the initial and final (optimum) material properties, geometry, stresses and inelastic strains. Finally, the file **optcomp.conv** contains information on the convergence of the iterative solution in the form of messages. These messages inform the user whether or not convergence of the iterative solution has been achieved at the given optimization iteration, as explained in Sections 3.1.3 and 3.2. The user has the option to suppress these convergence messages.

2.2 Entering New Material Data

The material property databanks supplied with the standard version of **OPTCOMP** contain two types of fibers (i.e, SiC and Al_2O_3) and four types of matrices (i.e., Ti_3Al, NiAl, and two types of NiCrAlY, designated NiCrAlY1 and NiCrAlY2). The SiC and Al_2O_3 fiber data is stored in the file **fiber.data**, and the Ti_3Al, NiAl, NiCrAlY1 and NiCrAlY2 matrix data is stored in the file **matrix.data**. Additional fiber and matrix materials, and their properties, can be entered into the corresponding databanks in the three ways described below.

The first way one can enter new material properties into the databanks is during the creation of the **optcomp.data** data file, after option 1 (CREATE NEW DATA FILE) is chosen from the main menu during the execution of **OPTCOMP**, as described in Section 3.0. During the data file creation, the user will be prompted to select the fiber/matrix/reference material combination for the given problem. If the desired material for a given problem is not listed under the material selection menu, the user has the option to enter the new material interactively by selecting the appropriate option. Once this is completed, the user will automatically re-enter the material selection menu, with the newly entered material now available for selection. The material properties entered into the data banks in the manner described are stored in the respective files, and will be available for selection in subsequent optimization procedures as well.

The second, and most direct way to enter new material properties is to do so before creation of an executable data file. This is done by selecting option 3 (ENTER NEW MATERIALS INTO DATA BANKS) from the main menu when the execution of the program is initiated as described in Section 3.0. By selecting this option, the user will be directed through additional menus to the appropriate material property databank. As the user is prompted for the material name and properties, the data is stored in the respective files. The third way of updating the material property databanks is to edit directly the files **fiber.data, matrix.data** and **ref.data** using a text editor as described in Section 4.3 and Appendix V.

3.0 EXECUTING OPTCOMP

OPTCOMP is executed by typing the command *optcomp* after the unix system prompt. At this point, execution of the subroutine **shell.f** is initiated, providing the user with the menu given below as the first step in a sequence of commands:

1. CREATE NEW DATA FILE
2. RUN EXISTING DATA FILE
3. ENTER NEW MATERIALS INTO DATABANK
4. EXIT SHELL

The user chooses the appropriate option which prompts the sequence of events outlined in Figure 3. As indicated in the preceding section, option 1 creates a new data file that defines a given optimization problem. This file can be executed immediately, or stored for later use. If a file defining the optimization problem already exists (i.e., it has been constructed at an earlier time), then the user can execute it by choosing option 2. Choosing option 3 allows the user to enter new material properties into the appropriate material databanks for use at some later time in an optimization problem. The execution of **OPTCOMP** is terminated when option 4 is

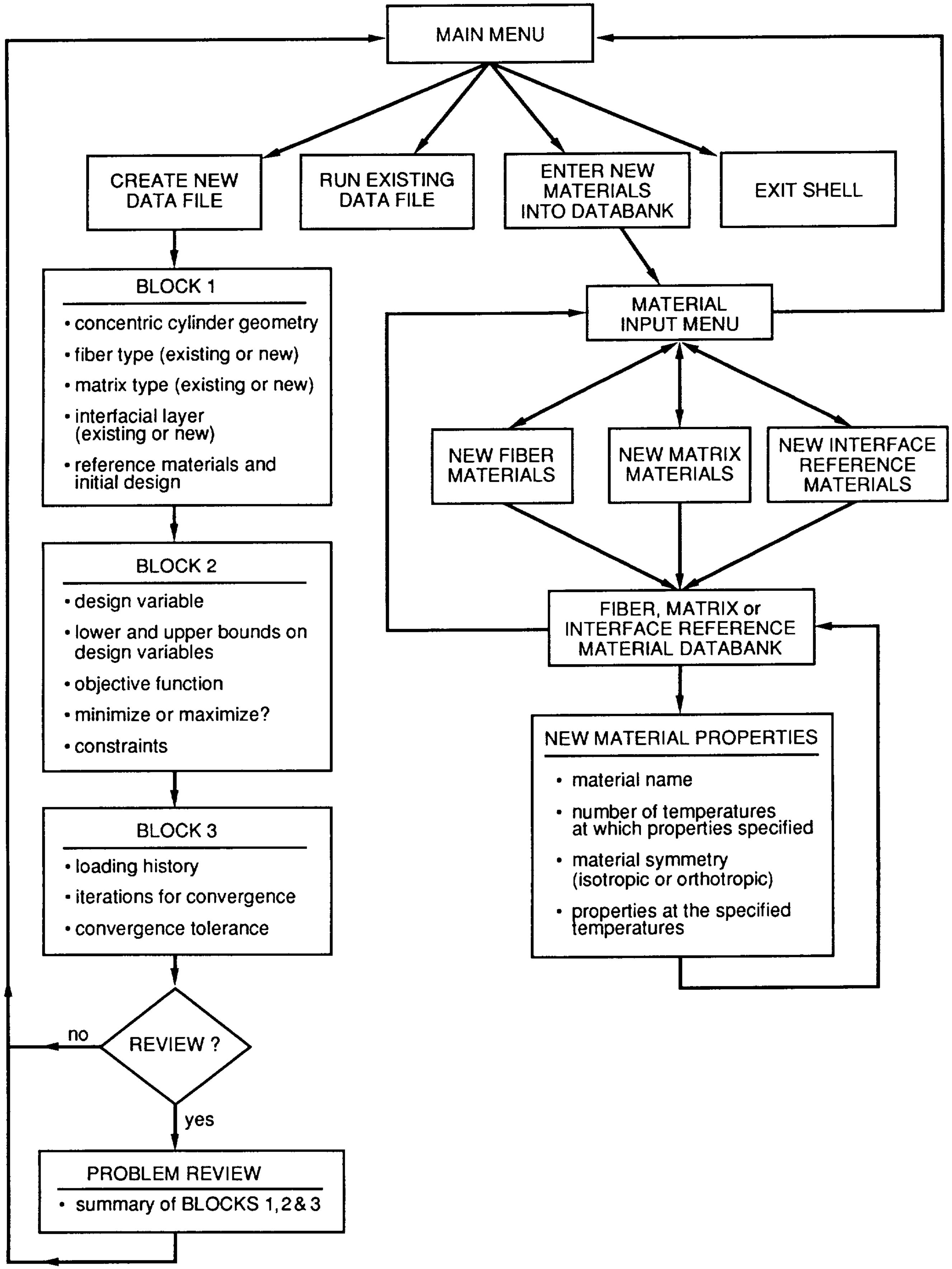


Figure 3. Flow chart for the menu-driven user interface **shell.f**

selected. The sequence of commands initiated when the above options are selected is described in the following sections. Since the data input is accomplished through a menu-driven interface, only a general outline of the above options is given. Examples are provided in the following section and in the appendices, based on actual runs, that clearly illustrate the step-by-step data input which the user is interactively prompted to supply.

3.1 Option 1: Creating A New Data File

Selection of option 1 (CREATE NEW DATA FILE) initiates a sequence of input commands that define the given optimization problem in terms of: the concentric cylinder geometry and material properties corresponding to each region (fiber, interfacial layer(s) and surrounding matrix); the choice of design variables, objective function and associated constraints; and the applied loading. The sequence of input commands is logically divided into the three distinct data input blocks that describe the geometry, optimization parameters and loading for a given problem. This information is used to create the file **optcomp.data**. Appendices II and III provide examples that illustrate the step-by-step construction of an **optcomp.data** file.

3.1.1 Block 1: Geometry/Material Data

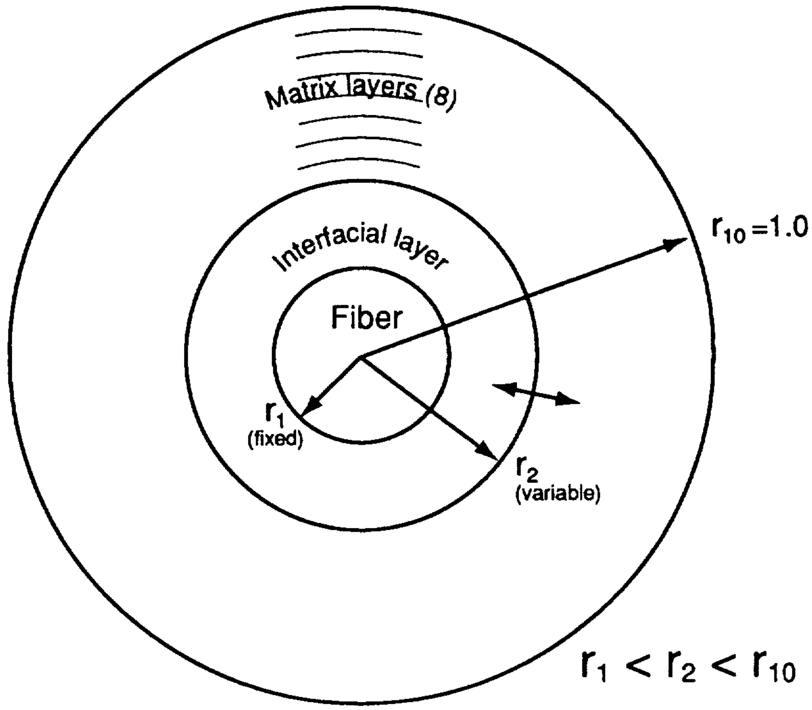
The user first specifies the concentric cylinder geometry, starting from the fiber and progressing outwards. The concentric cylinder consists of a circular fiber surrounded by a multi-layer interfacial region which, in turn, is surrounded by a matrix annulus. The fiber can be either homogeneous or layered, in order to realistically model the microstructure of certain advanced ceramic fibers (e.g., SiC SCS-6 fiber). The total number of layers used to model the response of the concentric cylinder is ten (10) and the radius of the composite cylinder is normalized to 1.0. The specification of the concentric cylinder geometry consists of providing the number of layers used to model the given region and the dimensions of each region. The dimensions are entered in two ways, depending on the region. In the case of a layered fiber, the outer radius of each layer (or core) is specified after the number of regions used to model the fiber is provided. If the fiber is homogeneous, only the outer radius of the core is specified. For the interfacial region, the relative thickness of each of the interfacial layers, entered as the ratio of the thickness of the layer to the outer radius of the fiber, is specified. After the user specifies the number of layers required to model the fiber and interfacial regions, the outer matrix region is automatically divided into the remaining number of available layers, each having equal thickness. **Since the total number of layers available for the concentric cylinder is ten in the current version of the computer code, care must be taken not to exceed nine layers in modeling the fiber and interfacial regions.** A forthcoming version of **OPTCOMP** will include the capability to specify an arbitrary number of layers to model the response of the matrix phase. Part I of this report provides general guidelines for the minimum number of layers recommended for modeling the various regions within the concentric cylinder assemblage.

After the concentric cylinder geometry is specified and verified, materials are selected for the fiber and matrix regions (whose properties are stored in the corresponding databanks), including the reference materials that will define the properties of the interfacial layers. As explained previously, new materials and their properties can be entered at this stage if so desired. If a homogeneous fiber is employed, its properties must be isotropic in the fiber databank **fiber.data** file. The program automatically sets the constitutive model for the fiber core to be elastic, suppressing the elastoplastic properties. If a layered fiber is employed, each of the fiber sublayers is treated as a different material that has to be present in the fiber databank. In entering the fiber morphology, it is important to remember that the core of the fiber must be isotropic whereas the remaining fiber sublayers may be specified as either isotropic (elastic or elastoplastic) or orthotropic (elastic), as summarized in Table I. The user has the option of specifying the interfacial and matrix sublayers as either elastic or elastoplastic.

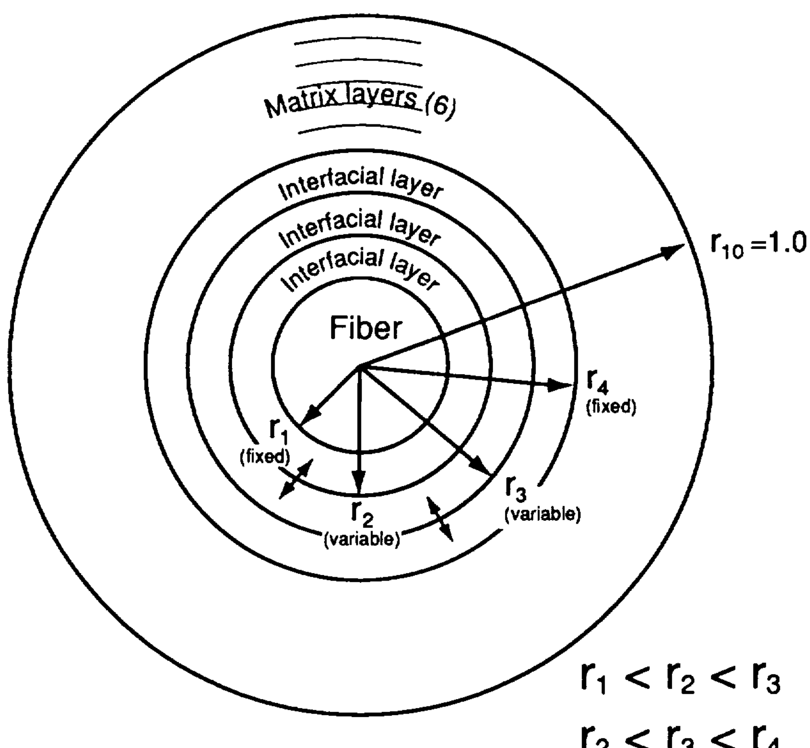
The last step in the data entry sequence of **Block 1** is the specification of the initial interface properties (or initial interface design), given in terms of the ratios of material properties in each of the interfacial layer to those of the chosen reference materials for each interfacial layer.

3.1.2 Block 2: Specification of Optimization Parameters

The user first selects the number and type of design variables for the interfacial layers specified in the data entry sequence of **Block 1**. There are five design variables that can be selected for the interfacial layers, namely: the thermal expansion coefficient; elastic modulus; yield stress; hardening slope (for a bilinear elastoplastic material); and thickness. Any number and combination of these design variables can be selected, however it must be remembered that the same design variables will be used for all interfacial layers. When the interfacial layer thickness is a chosen design variable, two cases must be distinguished as illustrated in Figure 4. In the case of a single interfacial layer, the interfacial layer thickness may vary arbitrarily in the region between the outer radii of the fiber and the concentric cylinder. In the case of multiple interfacial layers, however, the radius of the outermost interfacial layer is fixed, while the thicknesses of the inner layers may vary arbitrarily without overlapping each other. After specification of the design variables for the interfacial layers is completed, the user is prompted to enter the side constraints (i.e., lower and upper bounds) on the chosen design variables for each interfacial layer. Thus flexibility exists that allows the user to enter different lower and upper bounds on the



a.)



b.)

Figure 4. Using the interfacial layer thickness as a design variable for a concentric cylinder configuration with (a) one interfacial layer and (b) three interfacial layers.

same design variable for different layers. These lower and upper bounds provide limits on the design variables that will not be exceeded when the search for the optimum set of design variables is carried out during the actual optimization procedure within **OPTCOMP**.

Subsequently, the objective function is selected from a menu that contains fifteen objective functions, including a user-defined function. The objective functions involve point or average strain and stress quantities in the fiber, interfacial layers, and the surrounding matrix. Once the objective function is selected, the user indicates whether the function is to be minimized or maximized. The last sequence of data entry steps involves selection of the number and type of constraints that can be imposed on twelve field quantities (constraint functions), including a user-defined constraint function, in the interfacial region and the surrounding matrix.

3.1.3 Block 3: Applied Load History

The user defines the load history in terms of initial and final temperature, pressure and axial load. First, the number of load segments involving simultaneous application of these quantities is specified, followed by their initial values for the given load segment. The specification of an arbitrary number of load segments allows application of cyclic loading. Subsequently, the number of load increments is specified by the user in order to define the size of the temperature, pressure and/or axial load increment used in generating the solution to the elastoplastic boundary-value problem of a multiple concentric cylinder. This is then followed by specification of the final values of temperature, pressure and axial load for the given load segment.

Further, as the solution procedure is an iterative one at every step of applied loading (defined by the number of load increments), the user also specifies the maximum number of iterations allowed for convergence at every load increment, together with the error tolerance imposed on the differences in the effective plastic strain increments between successive iterations. The default values for the maximum number of iterations and the error tolerance are 10 and 0.01 (or 1%), respectively. Iteration is terminated at each load increment after the specified maximum number of iterations is reached regardless of whether the solution has converged or not, and the next load increment is applied. The above options have been included in the menu to allow the user a certain amount of control over the accuracy of the solution versus the execution time for a given elastoplastic boundary-value problem, and thus the associated optimization problem. Information on the convergence of the iterative solution in the form of messages described in Section 3.2 can be written to the **optcomp.conv** file if specified by the user. Finally, the user specifies whether the data recorded in the **optcomp.history** file during the actual execution of the optimization procedure is to be simultaneously written to the screen.

Past experience has shown that the number of iterations required to achieve convergence depends on the size of the applied load increment, and the elastoplastic behavior of chosen materials. In general, increasing the load increment should be accompanied by increasing the number of iterations. Also, more iterations are required for elastic-perfectly plastic materials (those with zero hardening slope) than for strain-hardening materials. Excellent results have been obtained by Williams and Pindera [11] with fewer than ten iterations for a wide range of temperature-dependent elastoplastic materials with radically different hardening behavior, including elastic-perfectly plastic materials. Part I of this report provides more details on the iterative solution scheme employed within **OPTCOMP**, including the guidelines for selecting the maximum number of iterations and the error tolerance for the chosen load increment size and the information on the currently employed convergence criterion.

3.2 Option 2: Running An Existing Data File

After the data file that defines the optimization problem has been created by executing option 1, the program returns to the main menu. At this point the user may initiate execution of the optimization procedure by selecting option 2 (RUN EXISTING DATA FILE) from the main menu. During execution of the optimization procedure, the current values of the design variables, their lower and upper bounds, and the current values of the objective function and constraints are written to the file **optcomp.history** at every iteration on the design variables. This information is also written to the screen, if so specified, thus allowing the user to both record and monitor the optimization process.

When the search for an optimum value of the objective function is completed, the information on the initial and final (optimum) values of the interfacial material properties, geometry, stresses and inelastic strains is written to the file **optcomp.out**. The material properties, associated with the cylindrical coordinate system $x - r - \theta$, are recorded at each of the specified temperatures according to the format:

```
TEMPERATURE = *.********

     EXX      ETT       ERR
     VXR      VXT       VRT
   ALFXX    ALFTT     ALFRR
       Y       HS
```

where the variables appearing in the format headers have the following meaning:

EXX	-	Young's modulus E_{xx} associated with the longitudinal direction
ETT	-	Young's modulus $E_{\theta\theta}$ associated with the circumferential direction
ERR	-	Young's modulus E_{rr} associated with the radial direction
VXR	-	Poisson's ratio ν_{xr} associated with loading in the longitudinal direction
VXT	-	Poisson's ratio $\nu_{x\theta}$ associated with loading in the longitudinal direction
VRT	-	Poisson's ratio $\nu_{r\theta}$ associated with loading in the radial direction
ALFFXX	-	thermal expansion coefficient α_{xx} associated with the longitudinal direction
ALFFTT	-	thermal expansion coefficient $\alpha_{\theta\theta}$ associated with the circumferential direction
ALFFRR	-	thermal expansion coefficient α_{rr} associated with the radial direction
Y	-	yield stress
HS	-	hardening slope based on a bilinear representation of an elastoplastic material

The stress, radial displacement, and plastic strain distributions are given at two locations within each ring, namely inner and outer radius, starting with the core and progressing outward. The program prints the following results according to the format:

RING NO.	RADIUS	STRXX	STRRR	STRTT	W
1	...	...	...	...	...
1	...	...	...	...	...
.	...	...	...	...	...
.	...	...	...	...	...
.	...	...	...	...	...
10	...	...	...	...	...
10	...	...	...	...	...

RING NO.	EPXXP	EPRRP	EPTTP	STREFF	SIGEFF
1	...	...	...	...	...
1	...	...	...	...	...
.	...	...	...	...	...
.	...	...	...	...	...
.	...	...	...	...	...
10	...	...	...	...	...
10	...	...	...	...	...

where the variables appearing in the format headers have the following meaning:

STRXX	-	axial stress σ_{xx}
STRRR	-	radial stress σ_{rr}
STRTT	-	circumferential stress $\sigma_{\theta\theta}$
W	-	radial displacement w(r)
EPXXP	-	inelastic axial strain ε^p_{xx}
EPRRP	-	inelastic radial strain ε^p_{rr}
EPTTP	-	inelastic circumferential strain $\varepsilon^p_{\theta\theta}$
STREFF	-	effective stress calculated from the actual stress fields
SIGEFF	-	effective stress calculated from the effective stress-plastic strain curve

There are two ways of calculating the effective stress based on the incremental plasticity model. STREFF is calculated according to the formula: $\bar{\sigma} = \sqrt{3/2 s_{ij} s_{ij}}$, normalized to the yield stress in uniaxial tension, where s_{ij} are the deviatoric stress components, determined directly from the solution of the elastoplastic boundary-value problem for the specified concentric cylinder configuration and loading history. SIGEFF, on the other hand, is calculated from the effective stress-plastic strain curve for an elastoplastic material with bilinear hardening that defines the current yield stress. During plastic loading, the consistency condition requires that the stress vector remain on the yield surface. Therefore, by comparing STREFF and SIGEFF during elastoplastic deformation, the user can get an idea about the quality of the solution for the chosen maximum number of iterations. Ideally, these two quantities should be the same unless elastic unloading occurs at some point during the loading cycle.

If specified by the user, more precise information on the convergence of the iterative solution for the elastoplastic boundary-value problem of the concentric cylinder assemblage is written to the file **optcomp.conv**. If convergence has been achieved at all points within the concentric cylinder assemblage along the entire loading path for a given optimization iteration, the following message is written:

```
OPTIMIZATION ITERATION # *****
ALL POINTS REACHED CONVERGENCE
```

Alternatively, if at any point along the loading history the iterative solution does not converge for a given optimization iteration, the following message is written:

```
OPTIMIZATION ITERATION # *****
NON-CONVERGENCE AT THE FOLLOWING LOADING STATES

Temperature = *.********
Radial traction = *.********
Average axial stress = *.********
```

The message informs the user that convergence has not been achieved at the indicated magnitudes of loading parameters, for the specified load increment (defined by initial and final values of the applied load and the number of load increments), the maximum number of iterations and the specified error tolerance. This is written at every occurrance of non-convergence within each iteration of the optimization algorithm. If the quality of the solution is poor, as indicated by large discrepancies between STREFF and SIGEFF, the user can either decrease the load increment or increase the maximum number of iterations, or both. Increasing the maximum number of iterations should be the first step in an attempt to obtain a convergent solution since it generally does not substantially increase the execution time relative to the option of decreasing the load increment. Examples of the **optcomp.history**, **optcomp.out** and **optcomp.conv** files are provided in Appendices II and III.

3.3 Option 3: Entering New Materials Into The Databank

The user can update the material property databanks contained in the three files **fiber.data**, **matrix.data** and **refer.data** by selecting option 3 (ENTER NEW MATERIALS INTO DATABANK) from the main menu. This option initiates a sequence of menu-driven commands by first providing the user with the following material input selection menu:

1. ENTER NEW FIBER MATERIALS
2. ENTER NEW MATRIX MATERIALS
3. ENTER NEW REFERENCE MATERIALS FOR INTERFACE LAYERS
4. RETURN TO MAIN MENU

Upon selection of options 1 through 3, the user is prompted to supply: the name of the new material; number of temperatures at which properties of this material will be specified; material symmetry type (i.e., whether the material is isotropic, transversely isotropic or orthotropic); and finally the temperatures and the corresponding material properties. The material properties supplied by the user include the Young's modulus, Poisson's ratio, instantaneous (tangential) thermal expansion coefficient, yield stress, and hardening slope (based on a bilinear stress-strain representation of the elastoplastic behavior). If the user specifies the given material as isotropic, then only one set of the above material properties is specified at each temperature. For an elastic isotropic material, the value of the yield stress should be set to a very large value (e.g., 10^6 msi), and the hardening slope should be equal to the Young's modulus. At this time, only elastic transversely isotropic and orthotropic materials can be specified. If the material is specified as either transversely isotropic or orthotropic, three sets of the above elastic material properties must be entered at each temperature due to the directional nature of such materials. The user is not prompted to enter the yield stress and the hardening slope for transversely isotropic and orthotropic materials. These quantities are automatically set to pre-assigned values within the datafile. In the case of the yield stress, a very large number (10^{99} psi or Pa) is entered, whereas for the hardening slope the value of the elastic Young's modulus is entered. These numbers are required to be present in the material databanks due to the logical structure of the search algorithm used in identifying the available materials. Appendix IV provides an example that illustrates the step-by-step construction of a material data bank.

4.0 ILLUSTRATIONS

Appendices II through V present examples that illustrate the creation of the **optcomp.data** files for unconstrained and constrained optimization problems, subsequent execution of these files together with the results of the optimization procedure, and the creation of a fiber and a matrix property databank. These examples are described in more detail in this section.

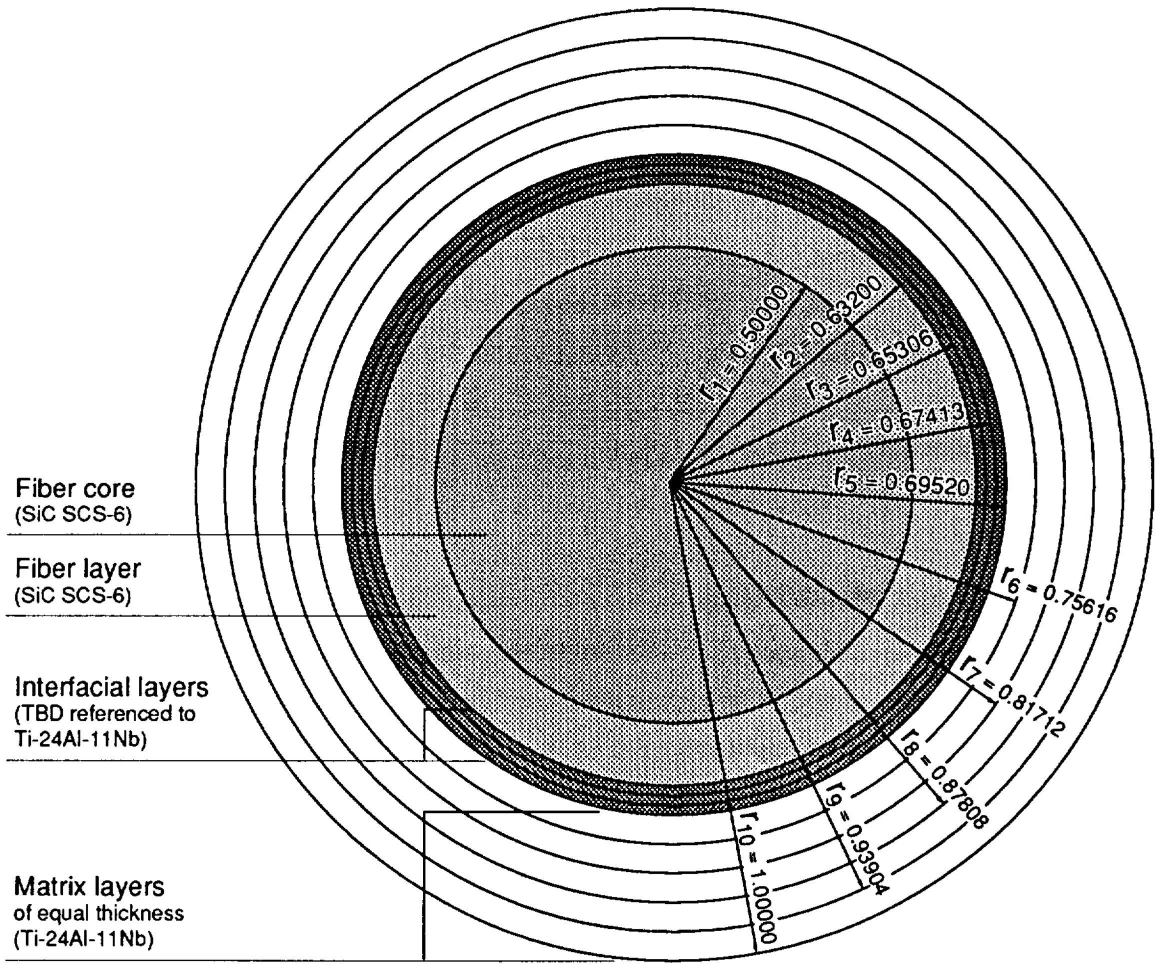
4.1 Example 1: Unconstrained Optimization Problem

This example illustrates the construction of the **optcomp.data** file, its execution, and the results of the optimization process for the problem of a SiC/TiAl composite cylinder with multiple interfacial layers subjected to a cool down from 1500°F to 75°F. The aim is to determine the thermal expansion coefficients of the interfacial layers that will minimize the hoop stress in the matrix phase at the interfacial region boundary. Therefore the design variables are the thermal expansion coefficients of the individual interfacial layers, while the objective function is the hoop stress in the matrix at the interface separating the matrix from the interfacial layers. Lower and upper limits are placed on the design variables but no constraints are employed on any of the functions listed in the contraint menu, making this an unconstrained optimization problem.

4.1.1 Construction of the optcomp.data file

Section 8.2.1 of Appendix II illustrates the construction of the **optcomp.data** file when option 1 is selected from the main menu of **OPTCOMP**. The first block defines the concentric cylinder geometry and the choice of materials for the fiber, interfacial layers and the surrounding matrix. The concentric cylinder geometry consists of a composite fiber with a core and an external coating, surrounded by three interfacial layers, that, in turn, are embedded in a homogeneous matrix, as shown in Figure 5. The properties of both the fiber core and the external coating are those of the SiC SCS-6 fiber. Consequently, specification of a layered morphology of the fiber in this particular example is for illustration purposes. The properties of the homogeneous matrix are those of the Ti-24Al-11Nb alloy, and the properties of the interfacial layers are referenced to this alloy. The initial mechanical properties (i.e., Young's modulus, yield stress and hardening slope) of the interfacial layers are half of the Ti-24Al-11Nb matrix properties, while the initial thermal expansion coefficient is twice as high.

The second block defines the optimization problem. The design variables in this example are the thermal expansion coefficients in each of the three interfacial layers, producing a total of three design variables. The lower and upper bounds on these design variables are zero and four times the corresponding properties of the reference material for the interfacial layers (in this case



r_i = outer radius of the core (i=1) or of a layer (i=2,. ., 10)

Figure 5. Concentric cylinder geometry and material assignment in Examples 1 and 2.

the Ti-24Al-11Nb matrix). The optimization problem involves minimization of the hoop stress (which is the objective function) in the matrix phase immediately adjacent to the interfacial region. No constraints are imposed on the functions available in the constraint menu.

The third and final block defines the loading history for the optimization problem. The loading involves cool down from 1500°F to 75°F without any radial pressure or axial force. The thermal loading segment is divided into 570 increments so that the temperature change per increment is 2.5°F. The maximum number of iterations allowed for convergence at each thermal load increment is changed from the default value of 10 to 15, and the default value 0.01 for the error tolerance is used. Finally, information on the convergence of the iterative elastoplastic solution is written to the file **optcomp.conv**, and the data recorded in the file **optcomp.history** during the actual execution of the optimization procedure is simultaneously written to the screen.

4.1.2 Execution of the optcomp.data file

The **optcomp.data** file constructed in the preceding step is executed when option 2 is selected from the main menu of **OPTCOMP** as illustrated in Section 8.2.2 of Appendix II. The information written to the **optcomp.history** file, as it is also written to the screen during the actual execution, provides a permanent record of the optimization process. This file contains the definition of the design variables (in this case X1 through X3), followed by the current values of these design variables relative to their lower and upper bounds, together with the value of the objective function and the specified constraint at each iteration (none in this case). For the given example, 11 iterations were necessary to find optimum values of the thermal expansion coefficients for the three interfacial layers. For this unconstrained optimization problem, the optimum thermal expansion coefficients that minimize the matrix hoop stress at the interface separating the interfacial layers from the surrounding matrix phase are the upper bounds specified during the problem definition in the preceding section. The minimum value of the hoop stress in the matrix phase adjacent to the interfacial region is -5,869 psi (Iteration # 8).

4.1.3 Results of the unconstrained optimization process

The optimum values (properties) of the design variables are written to the **optcomp.out** file that is included in Section 8.2.3 of Appendix II. This file also contains additional information that may be useful to the designer. The initial concentric cylinder configuration is given first, followed by the properties of the fiber and the matrix layers, and the initial properties of the three interfaces, all given at the ten temperatures. Provided next are the stress and inelastic strain distributions for the cool down from 1500°F to 75°F based on the initial properties and configuration of the specified concentric cylinder assemblage. The next block of data contains information on the final concentric cylinder configuration (provided for those cases when the geometry of the interfacial region is a design variable), the optimum values of the design variables at the ten temperatures, and the stress and inelastic strain distributions based on the optimum design variables. Figure 6 presents a comparison between the initial and final circumferential stress distributions $\sigma_{\theta\theta}(r)$ based on the initial and optimum values of the design variables.

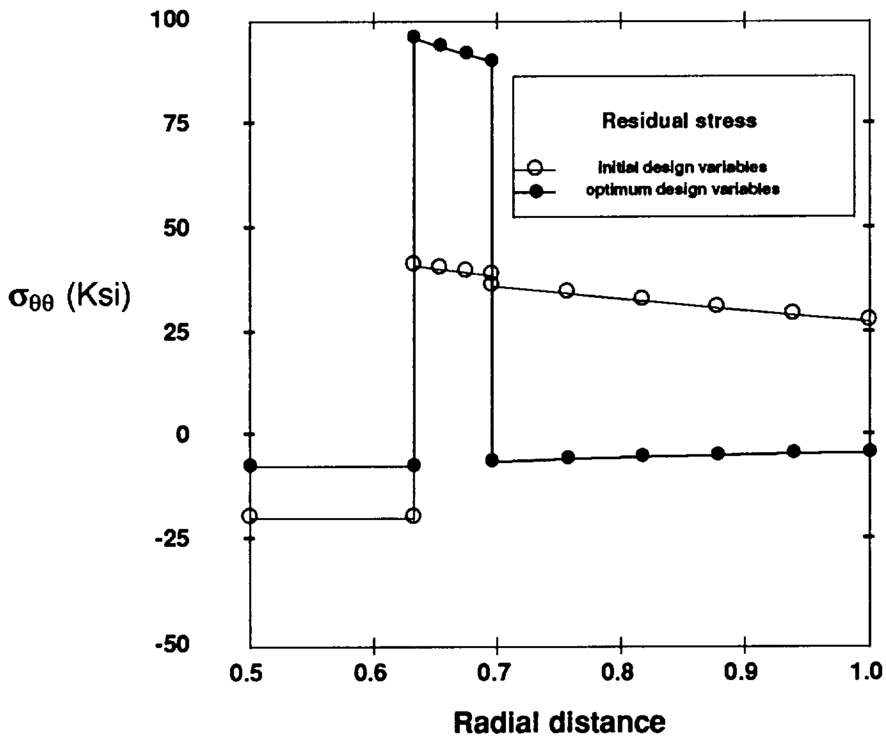


Figure 6. Initial and final $\sigma_{\theta\theta}(r)$ distributions for the unconstrained optimization problem.

Examining the stress and inelastic strain distributions based on the initial and optimum values of the design variables, one observes that the values of the effective stress, STREFF and SIGEFF, calculated using the two methods discussed in Section 3.2 are identical in the matrix layers. However, these values are somewhat different in the interfacial layers, with the STREFF magnitudes being less than SIGEFF. These differences indicate that the effective stress vector does not remain on the yield surface at each point within the interfacial region, suggesting that unloading has occurred at some point during the fabrication cool-down. This occurs when the rate of strain hardening in the interfacial region exceeds the material's capability to load plastically. The differences are greater for the optimum values of the design variables (i.e., thermal expansion coefficients in the interfacial layers) than for the initial values because the amount of plasticity, and thus strain-hardening, increases with increasing values of the interfacial layers' thermal expansion coefficients. The information about the convergence of the iterative elasto-plastic solution written to the file **optcomp.conv**, included in Section 8.2.3 of Appendix II, indicates that convergence was achieved at all points within the concentric cylinder assemblage along the entire loading history at every optimization iteration.

4.2 Example 2: Constrained Optimization Problem

This example illustrates the construction of the **optcomp.data** file, its execution, and the results of the optimization process for the problem defined in Example 1 of Section 4.1 when constraints are imposed on the field quantities in the interfacial layers. The aim is to determine the thermal expansion coefficients of the interfacial layers that will minimize the hoop stress in the matrix phase at the interfacial region boundary under the following constraints: 1) the hoop stress in the innermost interfacial layer at the fiber interface must be less than 40,000 psi; 2) the hoop stress in the outermost interfacial layer at the matrix interface must be less than 40,000 psi; and 3) the average hoop stress in the middle interfacial layer must be less than 40,000 psi. The constraint functions for the first two constraints are available in the constraint function menu, while for the last constraint a user-defined function has to be constructed in the EXCONST subroutine located in the **constraint.f** file. The construction of this function is illustrated in Appendix I.

4.2.1 Construction and execution of the optcomp.data file

Section 8.3.1 of Appendix III illustrates the construction of the **optcomp.data** file when option 1 is selected from the main menu of **OPTCOMP**. The **optcomp.data** file for this problem is identical with that of Example 1, with two exceptions. First, in defining the concentric cylinder geometry and the choice of materials for the fiber, interfacial layers and the surrounding matrix in **Block 1** of the data input, the initial thermal expansion coefficients of the innermost, middle and outermost interfacial layers are taken to be one, three, and one times those of the reference material, respectively. This differs from Example 1 where the initial thermal expansion coefficients of the three interfacial layers were taken to be twice the thermal expansion coefficient of the reference material. Secondly, in defining the optimization problem in **Block 2** of the data input, three constraint functions are specified, including the user-defined function in the EXCONST subroutine of the **constraint.f** file in Appendix I, in contrast with Example 1 where no constraints were chosen.

The **optcomp.data** file constructed in the preceding step is executed when option 2 is selected from the main menu of **OPTCOMP** as also illustrated in Section 8.3.1 of Appendix III.

In contrast with Example 1, 23 iterations were necessary in this example to find optimum values of the thermal expansion coefficients for the three interfacial layers in the presence of the imposed constraints. The optimum thermal expansion coefficients that **both** minimize the matrix hoop stress at the interface separating the interfacial layers from the surrounding matrix phase and satisfy the specified constraints are 1.9347, 1.9834 and 2.0377 times those of the reference material (see Iteration # 20). These optimum values will produce a hoop stress of 36,820 psi in the matrix phase next to the outermost interfacial layer when the SiC/TiAl composite cylinder is cooled down from the stress-free temperature of 1500°F to 75°F. This is in contrast with the corresponding matrix hoop stress of -5,869 psi obtained in Example 1 in the absence of any constraints imposed on the field quantities in the interfacial layers.

4.2.2 Results of the constrained optimization process

The results of the optimization process that include the initial and final (optimum) values of the design variables and the corresponding stress and inelastic strain distributions, as recorded in the **optcomp.out** file, are provided in Section 8.3.2 of Appendix III. Figure 7 presents a comparison between the initial and final circumferential stress distributions $\sigma_{\theta\theta}(r)$ based on the initial and optimum values of the design variables.

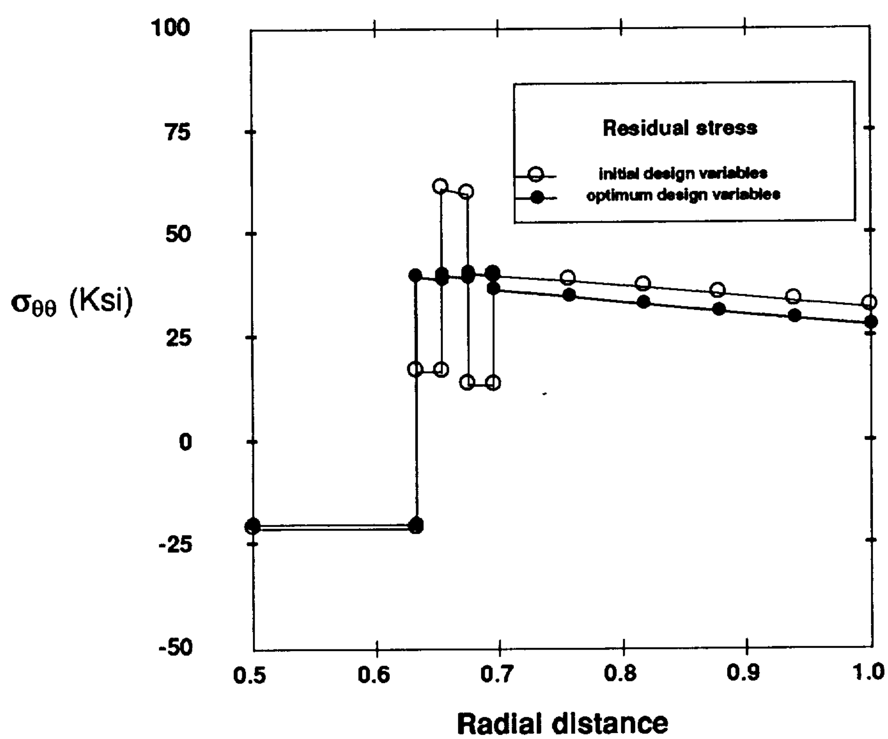


Figure 7. Initial and final $\sigma_{\theta\theta}(r)$ distributions for the constrained optimization problem.

Examining the stress and inelastic strain distributions based on the initial and optimum values of the design variables, one again observes that the values of the effective stress, STREFF and SIGEFF, are identical in the matrix layers. In the interfacial layers, however, plastic unloading takes place in those regions with a large value of the thermal expansion coefficient. For the initial values of the design variables, plastic unloading occurs in the middle interfacial layer with the thermal expansion coefficient ratio of 3.0. The inner and outer layers, on the other hand, continue loading plastically during the entire fabrication cool-down because of their low thermal expansion coefficient ratios of 1.0. In the case of the optimum values of the design variables, all three interfacial layers unload plastically at some point during the cool-down cycle. The information about the convergence of the iterative elastoplastic solution written to the file **optcomp.conv**, included in Section 8.3.2, indicates that convergence was achieved at all points within the concentric cylinder assemblage along the entire loading history at every optimization iteration but one. For the sixth optimization iteration, convergence was not attained at one or more points within the concentric cylinder assemblage at 200°F. As is readily verified, increasing the number of iterations to 20 produces perfect convergence at all points for all optimization iterations. It should be pointed out, however, that essentially identical results are obtained when 15 and 20 iterations are employed despite the lack of convergence in the one instance. This is because the criteria for convergence of the iterative elastoplastic solution applied at 21 equally-spaced points within each layer of the concentric cylinder assemblage are very demanding, as discussed in more detail in Part I of this report. Consequently, an occasional lack of convergence at some point within the concentric cylinder assemblage often will not significantly influence the accuracy of the final answer. This, however, should be verified on a case-by-case basis by either increasing the number of iterations or decreasing the load increment.

4.3 Example 3: Construction of A Material Property Databank

As mentioned in Section 2.2, the standard version of **OPTCOMP** contains material property information on two types of fibers and three types of matrix materials. The SiC and Al_2O_3 fiber data is stored in the file **fiber.data**, and the Ti_3Al, NiAl and two types of NiCrAlY matrix data, designated NiCrAlY1 and NiCrAlY2, is stored in the file **matrix.data**. The material properties of these systems that were used in constructing the fiber and matrix data files are listed in Table II, where: α is the instantaneous thermal expansion coefficient; E is the Young's modulus, ν is the Poisson's ratio; σ_y is the yield stress; and H is the hardening slope based on a bilinear representation of the elastoplastic stress-strain response. The properties of the silicon carbide fiber and the titanium matrix are given at six different temperatures, whereas the properties for the remaining material systems are given at eight different temperatures.

Table II. Material properties of SiC/Ti_3Al, Al_2O_3/NiAl, and Al_2O_3/NiCrAlY composite systems.

Material properties	75°F	392°F	797°F	1112°F	1202°F	1500°F
SiC fiber						
α (10^{-6} / °F)	1.96	2.01	2.15	2.33	2.38	2.50
E (Msi)	58.00	58.00	58.00	58.00	58.00	58.00
ν	0.25	0.25	0.25	0.25	0.25	0.25
Ti-24Al-11Nb matrix						
α (10^{-6} / °F)	5.00	5.20	5.70	5.85	5.90	6.15
E (Msi)	16.00	14.50	11.00	12.50	9.89	6.20
ν	0.26	0.26	0.26	0.26	0.26	0.26
σ_y (ksi)	53.89	59.00	53.70	42.20	39.10	24.00
H (Msi)	3.33	0.44	0.32	0.19	0.097	0.00

Material properties	70°F	800°F	1200°F	1400°F	1600°F	1800°F	2000°F	2400°F
Al_2O_3 fiber								
α (10^{-6} / °F)	3.35	4.86	5.42	5.63	5.79	5.91	5.98	5.97
E (Msi)	61.10	59.83	59.60	59.33	59.07	58.80	53.13	50.30
ν	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
NiAl matrix								
α (10^{-6} / °F)	7.12	8.24	8.76	9.01	9.23	9.45	9.69	9.95
E (Msi)	28.00	25.59	24.27	23.61	22.95	22.29	19.29	10.14
ν	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
σ_y (ksi)	45.70	22.50	16.06	13.07	10.62	7.79	5.30	3.39
H (Msi)	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
NiCrAlY1* matrix								
α (10^{-6} / °F)	5.44	7.76	9.03	9.67	10.30	10.94	11.57	12.84
E (Msi)	27.00	25.30	21.40	17.70	12.80	7.60	3.10	0.10
ν	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
σ_y (ksi)	150.00	146.00	135.80	101.20	74.90	21.90	5.00	1.00
H (Msi)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
NiCrAlY2** matrix								
α (10^{-6} / °F)	5.44	7.76	9.03	9.67	10.30	10.94	11.57	12.84
E (Msi)	19.50	16.80	14.70	11.60	8.90	5.20	2.10	0.10
ν	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
σ_y (ksi)	117.80	104.10	99.40	71.00	29.40	11.00	3.80	0.70
H (Msi)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10

* *NiCrAlY1 matrix chemical composition: Ni-10.2Cr-9.3Al-6.0Ta-0.22Hf-0.43Y*
** *NiCrAlY2 matrix chemical composition: Ni-17.8Cr-12.5Al-0.61Y-0.73Hf-20.8Co*

The example presented herein illustrates how the material properties for the SiC SCS-6 fiber and the Ti-24Al-11Nb matrix were entered into the respective databank files. Appendix IV illustrates the construction of the material property databank for the SiC SCS-6 fiber when option 3 is selected from the main menu of **OPTCOMP**. The properties of the SiC fiber are entered at the given six temperatures and are subsequently re-evaluated at ten equally-spaced temperatures in the range 75°F - 1500°F using cubic splines. Since the SiC fiber is elastic, a very high value of the yield stress (i.e., 10^6 psi) is entered at each temperature, while the hardening slope is set equal to the elastic modulus of 58 msi. The fiber properties re-evaluated at the ten temperatures are then written to the **fiber.data** file according to the format illustrated in Appendix V. A similar procedure is employed to create the material property databank for the Ti-24Al-11Nb matrix which is recorded in the **matrix.data** file and also included in Appendix V. These files can be subsequently updated by entering additional fiber and matrix materials using either option 3 from the main menu, or directly entering the properties into the files using a text editor according to the indicated format.

5.0 RTSHELL: A SUBSET OF OPTCOMP

The program **RTSHELL** is a separate program with the same analytical capabilities as **OPTCOMP**, but without the optimization option. This program facilitates efficient characterization and evaluation of different metal matrix unidirectional composites subjected to combined axisymmetric thermo-mechanical loading in the presence of different fiber and interfacial layer architectures. The program employs the same material property data banks as **OPTCOMP**, and is driven by the same user-friendly interface, with **Block 2** that defines the optimization problem deleted. The construction of the input file **rtshell.data** is carried out in the same manner as the construction of the **optcomp.data** file, while the output produced by **RTSHELL** is written to the **rtshell.out** file.

Appendix VI provides an illustration of the construction and execution of a date file for the concentric cylinder geometry, materials and loading outlined in Example 1. The results written to the **rtshell.out** file are exactly the same as the initial results in Example 1 (Appendix II, Section 8.2.3)

6.0 PLANS FOR FUTURE MODIFICATIONS OF OPTCOMP

The following enhancements will be incorporated into the **OPTCOMP** computer code during the 1994 funding period (Phase II) of the contract, in order to make it a more powerful design/analysis package for optimization of processing parameters and graded interfacial layers:

- Incorporation of viscoplasticity constitutive models for the response of individual subregions of the multiple concentric cylinder assemblage.
- Incorporation of a micromechanics model for modeling the interfacial region as a two-phase (matrix/inclusion) composite.
- Extension of the optimization capability to include processing history parameters as design variables.
- Capability to specify an arbitrary number of layers to model the matrix phase.

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8.0 APPENDICES

8.1 Appendix I: Constraint.f and Objective.f Files

8.1.1 Constraint.f file: construction of the EXTCONST subroutine

The EXTCONST subroutine contained in the **constraint.f** file that allows the user to define his or her own constraint function or functions is provided below. The constraint functions are assigned to the variable G, starting with G(ICON) and ending with G(ICON+N), where N+1 is the total number of constraint functions specified by the user. The constraints must be defined consecutively in the subroutine, starting with the first constraint, according to the format G(ICON) = ..., G(ICON+1) = ..., G(ICON+2) = ..., etc. The optimization subroutines included in **dot.f** interpret the expressions assigned to the variables G(ICON) through G(ICON+N) to be always less than or equal to zero (i.e., G(ICON) ≤ 0). Thus when formulating constraints to be included in the user-defined subroutine, the following rules need to be followed. The constraint

$$x \leq 5000.0$$

should be written

$$G(ICON) = X/5000.0 - 1.0$$

Likewise, the constraint

$$x \geq 5000.0$$

should be written

$$G(ICON) = -(X/5000.0 - 1.0)$$

To formulate an equality constraint

$$x = 5000.0$$

the following expressions should be coded

$$G(ICON) = X/5000.0 - 1.0$$

$$G(ICON+1) = -(X/5000.0 - 1.0)$$

The user has the option to construct constraint functions using the field variables specified in the common blocks BK1 through BK5 of the EXTCONST subroutine. These include stresses, total, elastic and inelastic strains, effective plastic strains, and interfacial radial displacements in each of the ten rings within the concentric cylinder assemblage. With the exception of the interfacial radial displacements, these field quantities are dimensioned as double arrays with the dimensions (10,21). The first dimension pertains to the number of layers and the second dimension to the number of radial locations within each layer at which a given quantity is calculated in the program. These radial locations are equally spaced and divide a given cylinder into 20 subcylinders for computational purposes.

The first two (commented) constraint functions included in the EXTCONST subroutine provided herein impose constraints on the value of the radial stress component σ_{rr}, STRRR(3,1), in the third ring of the concentric cylinder assemblage at the innermost radial location within the ring. The first commented constraint given by G(ICON)=STRRR(3,1)/(-10000.0)-1.0 specifies that the radial stress at the above location be greater than -10,000 (psi) (i.e., $\sigma_{rr} \geq -10{,}000$), while the second commented constraint G(ICON+1)=-(STRRR(3,1)/(-10000.0)-1.0) specifies that this stress component be less than -10,000 (psi) (i.e., $\sigma_{rr} \leq -10{,}000$). When these two constraint functions are employed together, the result is an equality constraint that requires the radial stress at the indicated location to be equal to -10,000 (psi).

The third example of a constraint function that has been employed in Example 2, G(ICON)=AVE/40000.0-1.0, specifies that the average hoop stress (AVE) in the fourth layer of the concentric cylinder assemblage (in this case the middle interfacial layer) be less than 40,000 (psi) (i.e., $\sigma_{\theta\theta}^{average} \leq 40{,}000$ (psi)). The average hoop stress is defined as:

$$(\sigma_{\theta\theta}^{4})^{average} = \frac{1}{\pi(r_4^2 - r_3^2)} \int_{r_3}^{r_4} 2\pi\sigma_{\theta\theta}(r)r\,dr$$

Using trapezoidal integration formula, the above integral is evaluated within the subroutine as follows:

$$(\sigma_{\theta\theta}^{4})^{average} = \frac{1}{\pi(r_4^2 - r_3^2)} \sum_{i=1}^{i=20} 2\pi\frac{(r_4 - r_3)}{20}[r_3 + (i - \frac{1}{2})(\frac{r_4 - r_3}{20})](\frac{\sigma_{\theta\theta}^{4}(i) + \sigma_{\theta\theta}^{4}(i+1)}{2})$$

```
C     *    *    *    *    *    *    *    *    *    *    *    *    *    *
C     *    *    *    *    *    *    *    *    *    *    *    *    *    *
C     *    *    *    *    *    *    *    *    *    *    *    *    *    *
      SUBROUTINE EXTCONST(G,ICON,KKSUBCON,R)
      REAL G(40)
      REAL*8 STRXX(10,21),STRRR(10,21),STRTT(10,21)
      REAL*8 EPSXX,EPSRR(10,21),EPSTT(10,21)
      REAL*8 EPSXXE(10,21),EPSRRE(10,21),EPSTTE(10,21)
      REAL*8 EPSXXP(10,21),EPSRRP(10,21),EPSTTP(10,21)
      REAL*8 EPEFF(10,21),W(11),R(10)
      COMMON /BK1/ STRXX,STRRR,STRTT
      COMMON /BK2/ EPSXX,EPSRR,EPSTT
      COMMON /BK3/ EPSXXE,EPSRRE,EPSTTE
      COMMON /BK4/ EPSXXP,EPSRRP,EPSTTP
      COMMON /BK5/ EPEFF,W
C
C*****************INSERT CONSTRAINTS BELOW IN THIS FORM****************
C
C      G(ICON)=STRRR(3,1)/(-10000.0)-1.0
C      G(ICON+1)=-(STRRR(3,1)/(-10000.0)-1.0)
       AVE=0.0
       DO 10 I=1,20
          RAD=(R(4)-R(3))/20.0
          AVE=AVE+2*3.141592654*(R(3)+(I-1)*RAD+
     &         RAD/2.0)*RAD*(STRTT(4,I)+STRTT(4,I+1))/2.0
10     CONTINUE
       AVE=AVE/(3.141592654*(R(4)**2.0-R(3)**2.0))
       G(ICON)=AVE/40000.0-1.0
C
C*********************************************************************
C
      ICON=ICON+KKSUBCON-1
      RETURN
      END
C     *    *    *    *    *    *    *    *    *    *    *    *    *    *
C     *    *    *    *    *    *    *    *    *    *    *    *    *    *
C     *    *    *    *    *    *    *    *    *    *    *    *    *    *

C*********************************************************************
C   STRXX(I,J), STRRR(I,J), STRTT(I,J) : THE LONGITUDINAL, RADIAL,
C             AND CIRCUMFERENTIAL STRESS AT TWENTY ONE POINTS (J) IN
C             EACH OF THE TEN LAYERS (I) OF THE CYLINDER ASSEMBLAGE.
C
C   EPSXX(I,J), EPSRR(I,J), EPSTT(I,J) : THE TOTAL LONGITUDINAL,
C             RADIAL, AND CIRCUMFERENTIAL STRAIN AT TWENTY ONE POINTS (J)
C             IN EACH OF THE TEN LAYERS (I) IN THE CYLINDER ASSEMBLAGE.
C
C   EPSXXE(I,J), EPSRRE(I,J), EPSTTE(I,J) : THE ELASTIC LONGITUDINAL,
C             RADIAL, AND CIRCUMFERENTIAL STRAIN AT TWENTY ONE POINTS (J)
C             IN EACH OF THE TEN LAYERS (I) IN THE CYLINDER ASSEMBLAGE.
C
C   EPSXXP(I,J), EPSRRP(I,J), EPSTTP(I,J) : THE INELASTIC LONGITUDINAL,
C             RADIAL, AND CIRCUMFERENTIAL STRAIN AT TWENTY ONE POINTS (J)
C             IN EACH OF THE TEN LAYERS (I) IN THE CYLINDER ASSEMBLAGE.
C
C   EPEFF(I,J) : THE EFFECTIVE PLASTIC STRAIN AT TWENTY ONE POINTS (J) IN
C             EACH OF THE TEN LAYERS (I) IN THE CYLINDER ASSEMBLAGE.
C
C   W(11) : THE TEN W(1-10) INTERFACIAL RADIAL DISPLACEMENTS, AND
C             THE AXIAL DISPLACEMENT W(11).
C*********************************************************************
```

8.1.2 Objective.f file: construction of the EXTOBJ subroutine

The EXTOBJ subroutine contained in the **objective.f** file that allows the user to define his or her own objective function is provided below. The objective function is assigned to the variable OBJ. Any combination or function of the available variables contained in the common blocks BK1 through BK5 may be used in creating a user-defined objective function. These variables are the same as those specified in the EXTCONST subroutine and described in the preceding sub-section. It should be noted that only one objective function can be defined in the subroutine. The objective function must be written in standard fortran according to the format OBJ = ...

The objective function provided in this example is the sum of the magnitudes of the differences between the plastic strains at the midpoints in the second, third and fourth layer and their mean values defined by the variable EPT.

```
C     *     *     *     *     *     *     *     *     *     *     *     *     *     *
C     *     *     *     *     *     *     *     *     *     *     *     *     *     *
C     *     *     *     *     *     *     *     *     *     *     *     *     *     *
      SUBROUTINE EXTOBF(OBJ)
      REAL OBJ
      REAL*8 STRXX(10,21),STRRR(10,21),STRTT(10,21)
      REAL*8 EPSXX,EPSRR(10,21),EPSTT(10,21)
      REAL*8 EPSXXE(10,21),EPSRRE(10,21),EPSTTE(10,21)
      REAL*8 EPSXXP(10,21),EPSRRP(10,21),EPSTTP(10,21)
      REAL*8 EPEFF(10,21),W(11)
      REAL*8 EPT,EFFDIF
      COMMON /BK1/ STRXX,STRRR,STRTT
      COMMON /BK2/ EPSXX,EPSRR,EPSTT
      COMMON /BK3/ EPSXXE,EPSRRE,EPSTTE
      COMMON /BK4/ EPSXXP,EPSRRP,EPSTTP
      COMMON /BK5/ EPEFF,W
C
C*************INSERT OBJECTIVE FUNCTION BELOW IN THIS FORM*************
C
      EPT=(EPEFF(2,10)+EPEFF(3,10)+EPEFF(4,10))/3.0
      EFFDIF=(ABS(EPEFF(2,10)-EPT)+ABS(EPEFF(3,10)-EPT)+
     &       ABS(EPEFF(4,10)-EPT))
      OBJ=EFFDIF
C
C*********************************************************************
C
      RETURN
      END
C     *     *     *     *     *     *     *     *     *     *     *     *     *     *
C     *     *     *     *     *     *     *     *     *     *     *     *     *     *
C     *     *     *     *     *     *     *     *     *     *     *     *     *     *
```

8.2 Appendix II: Example 1 - Unconstrained Optimization Problem

8.2.1 Construction of the optcomp.data file

The construction of the **optcomp.data** file for the unconstrained optimization problem of Example 1, menu-driven by the user-friendly interface **shell.f**, is illustrated below. The text that appears in Courier-type capital letters is written to the screen at each step in the construction of the **optcomp.data** file. User's responses to the menu-driven commands are shown in bold Courier-type letters. The text in bold italics preceded by the word ***Note:*** represents manually inserted comments that explain in more detail certain options available to the user.

```
        NASA-LEWIS RESEARCH CENTER, STRUCTURES DIVISION, CLEVELAND OHIO
                  *********************************************
                  ***              OPTCOMP                  ***
                  ***                                       ***
                  ***    CONCENTRIC CYLINDER OPTIMIZATION   ***
                  ***   PROGRAM FOR THE DETERMINATION OF    ***
                  *** IDEALIZED INTERFACIAL LAYER PROPERTIES***
                  ***             WRITTEN BY                ***
                  ***                                       ***
                  ***         ROBERT SCOTT SALZAR           ***
                  ***        TODD OAKHILL WILLIAMS          ***
                  ***         MAREK-JERZY PINDERA           ***
                  ***                                       ***
                  ***                 OF                    ***
                  ***      THE UNIVERSITY OF VIRGINIA       ***
                  ***           SEPTEMBER, 1993             ***
                  ***                                       ***
                  *** DEVELOPED FOR THE FATIGUE AND FRACTURE***
                  ***  BRANCH OF NASA-LEWIS RESEARCH CENTER ***
                  ***        UNDER CONTRACT NAS3-26571      ***
                  ***  DR. S. M. ARNOLD (CONTRACT MONITOR)  ***
                  *********************************************

 HIT RETURN TO CONTINUE ->

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b.  assumes any liabilities with respect to the use of, or for damages
    resulting from use of this software.

-----------------------------------------------------------------------------

 HIT RETURN TO CONTINUE ->
```

```
******MAIN MENU******

 1.  CREATE NEW DATA FILE
 2.  RUN EXISTING DATA FILE
 3.  ENTER NEW MATERIALS INTO DATABANK
 4.  EXIT SHELL
ENTER CHOICE -> 1
```

Note: The main menu allows the user to: 1. create a new data file to be stored in OPTCOMP.DATA; 2. execute the data file in OPTCOMP.DATA; 3. enter new or additional materials into the material databank, or; 4. exit the OPTCOMP program.

```
***********************************BLOCK 1***********************************
              SPECIFY CONCENTRIC CYLINDER GEOMETRY, MATERIALS
                          INCLUDING PROPERTIES
```

***********IMPORTANT************

Note: The model is set to consist of 10 independent layers. Layers not associated with the fiber or the interface are automatically assigned to the matrix.

```
IF FIBER IS HOMOGENEOUS, ENTER: 1
IF FIBER IS LAYERED, ENTER: 2
CHOICE -> 2
```

Note: Select choice 1 for a solid, homogeneous fiber. Select choice 2 if the fiber has a layered morphology. If a layered fiber is selected, the user will be asked to supply the number of layers in the fiber, including the core. The normalized radius of each of the fiber layers is then requested (normalized wrt a total cylinder with radius 1).

```
ENTER NUMBER OF FIBER LAYERS -> 2
ENTER RELATIVE FIBER CORE RADIUS -> .5
ENTER RELATIVE OUTER RADIUS OF FIBER LAYER 2 -> .632
```

Note: Next, enter the number of interfacial layers for the concentric cylinder assemblage, followed by the relative thickness of each of the interfacial layers, entered as the ratio of the thickness of the layer to the outer radius of the fiber.

```
ENTER THE NUMBER OF INTERFACE LAYERS -> 3
t/a RATIO OF INTERFACE 1: .03333
t/a RATIO OF INTERFACE 2: .03333
t/a RATIO OF INTERFACE 3: .03334
```

CONCENTRIC CYLINDER CONFIGURATION

SHELL	MATERIAL	OUTER RADIUS	VOLUME FRACTION
1	FIBER	0.50000	0.2500
2	FIBER	0.63200	0.1494
3	INTERFACE 1	0.65306	0.0271
4	INTERFACE 2	0.67413	0.0280
5	INTERFACE 3	0.69520	0.0289
6	MATRIX	0.75616	0.0885
7	MATRIX	0.81712	0.0959
8	MATRIX	0.87808	0.1033
9	MATRIX	0.93904	0.1108
10	MATRIX	1.00000	0.1182

```
FIBER VOLUME FRACTION =   0.3994
MATRIX VOLUME FRACTION =  0.5167

  IS INFORMATION CORRECT? <Y/N> y
```

Note: If the information supplied in the summary is correct, enter Y. If the information is incorrect and needs to

be changed, enter N.

```
                ***FIBER MATERIAL PROPERTY SELECTION***

         AVAILABLE FIBERS            AVAILABLE CONSTITUTIVE MODELS
     1    SiC  (SCS-6)  (psi)                  1  ELASTIC
     2    Al2O3 (psi)                          2  PLASTIC
     3    ENTER NEW MATERIAL
```

Note: Select the materials that describe the fiber structure. The fiber core must be an isotropic material. If a material other than isotropic is selected, an error message will result. For subsequent fiber layers, enter fiber material and constitutive model as prompted. If the material you wish is not available, select the option ENTER NEW MATERIAL and follow the instructions given. You will then be presented with a new material menu including the material just entered. You may now select that material.

```
   ENTER MATERIAL FOR FIBER LAYER 1 -> 1
   ENTER MATERIAL FOR FIBER LAYER 2 -> 1
   ENTER CONSTITUTIVE MODEL FOR FIBER LAYER 2 -> 1
```

Note: Enter the material for the matrix, and the constitutive model as prompted. If the material you wish is not available, select ENTER NEW MATERIAL and follow the instructions given. You will then be presented with a new material menu including the material just entered. You may now select that material.

```
                ***MATRIX MATERIAL PROPERTY SELECTION***

     AVAILABLE MATRIX MATERIALS     AVAILABLE CONSTITUTIVE MODELS
      1    Ti-24Al-11Nb  (psi)                 1  ELASTIC
      2    NiCrAlY1 (psi)                      2  PLASTIC
      3    NiCrAlY2 (psi)
      4    NiAl (psi)
      5    ENTER NEW MATERIAL

   ENTER MATERIAL FOR MATRIX -> 1
   ENTER CONSTITUTIVE MODEL FOR MATRIX -> 2
```

Note: Enter the reference material for each of the interfacial layers, and the constitutive model. If the material you wish is not available, select ENTER NEW MATERIAL and follow the instructions given. You will then be presented with a new material menu including the material just entered. You may then select that material.

```
                ***INTERFACIAL LAYER REFERENCE MATERIALS***

       AVAILABLE MATERIALS            AVAILABLE CONSTITUTIVE MODELS
      1    SiC  (SCS-6)  (psi)                 1  ELASTIC
      2    Ti-24Al-11Nb  (psi)                 2  PLASTIC
      3    Al2O3 (psi)
      4    NiCrAlY1 (psi)
      5    NiCrAlY2 (psi)
      6    NiAl (psi)
      7    ENTER NEW MATERIAL

   ENTER REFERENCE MATERIAL FOR INTERFACE  1 -> 2
   ENTER CONSTITUTIVE MODEL FOR INTERFACE 1 -> 2
   ENTER REFERENCE MATERIAL FOR INTERFACE  2 -> 2
   ENTER CONSTITUTIVE MODEL FOR INTERFACE 2 -> 2
   ENTER REFERENCE MATERIAL FOR INTERFACE  3 -> 2
   ENTER CONSTITUTIVE MODEL FOR INTERFACE 3 -> 2
```

Note: Enter the inital design for each of the interfacial layers in terms of the ratios of the interface properties to those of the reference materials.

```
   ENTER INITIAL DESIGN: Ei/Er, Yi/Yr, CTEi/CTEr, Hi/Hr

   INTERFACE  1 : .5 .5 2 .5
```

```
INTERFACE  2 : .5 .5 2 .5
INTERFACE  3 : .5 .5 2 .5
```

CONCENTRIC CYLINDER MATERIAL SPECIFICATION

	SHELL	MATERIAL	CONSTITUTIVE MODEL
1	FIBER	SiC (SCS-6) (psi)	ELASTIC
2	FIBER	SiC (SCS-6) (psi)	ELASTIC
3	INTERFACE	TBD	INELASTIC
4	INTERFACE	TBD	INELASTIC
5	INTERFACE	TBD	INELASTIC
6	MATRIX	Ti-24Al-11Nb (psi)	INELASTIC
7	MATRIX	Ti-24Al-11Nb (psi)	INELASTIC
8	MATRIX	Ti-24Al-11Nb (psi)	INELASTIC
9	MATRIX	Ti-24Al-11Nb (psi)	INELASTIC
10	MATRIX	Ti-24Al-11Nb (psi)	INELASTIC

INTERFACE REFERENCE MATERIALS

INTERFACE	MATERIAL	CONSTITUTIVE MODEL
1	Ti-24Al-11Nb (psi)	INELASTIC
2	Ti-24Al-11Nb (psi)	INELASTIC
3	Ti-24Al-11Nb (psi)	INELASTIC

INTERFACIAL LAYER INITIAL DESIGN

LAYER	Ei/Er	Yi/Yr	CTEi/CTEr	Hi/Hr
1	.500	.500	2.000	.500
2	.500	.500	2.000	.500
3	.500	.500	2.000	.500

```
IS INFORMATION CORRECT? <Y/N> y
```

**********************************BLOCK 2**********************************

DEFINE OPTIMIZATION PROBLEM

DESIGN VARIABLE MENU

I.D.	DESIGN VARIABLE
1	INTERFACIAL LAYER(S) CTE
2	INTERFACIAL LAYER(S) ELASTIC MODULUS
3	INTERFACIAL LAYER(S) HARDENING SLOPE
4	INTERFACIAL LAYER(S) YIELD STRESS
5	THICKNESS OF INTERFACIAL LAYER(S)

Note: Enter the number of design variables (1-5), followed by the identification number for each design variable. By selecting any combination of the design variables in any order, those variables will become activated for each interfacial layer.

```
ENTER NUMBER OF SELECTIONS -> 1
ENTER I.D. CHOICE(S) -> 1
```

Note: Enter the lower and upper bounds for each design variable and for each layer.

```
ENTER LOWER & UPPER BOUNDS OF CTE RATIO FOR INTERFACE  1 -> 0 4
ENTER LOWER & UPPER BOUNDS OF CTE RATIO FOR INTERFACE  2 -> 0 4
ENTER LOWER & UPPER BOUNDS OF CTE RATIO FOR INTERFACE  3 -> 0 4
```

```
                ***DESIGN VARIABLE SUMMARY***

               INTERFACE LAYER C.T.E. RATIO(S)
          LAYER   LOWER BOUND         UPPER BOUND
            1         .000               4.000
            2         .000               4.000
            3         .000               4.000

IS INFORMATION CORRECT? <Y/N> y
```

Note: Select an objective function from the menu below, or choose the User Defined Objective Function (15) that has been entered by the user into the EXTOBJ subroutine residing in the file objective.f

```
           CHOOSE AN OBJECTIVE FUNCTION:

ITEM#          FUNCTION

               FIBER FUNCTIONS
  1. RADIAL STRESS (INTERFACE)

            INTERFACIAL LAYER FUNCTIONS
  2. HOOP STRESS (FIBER/I.L.)
  3. HOOP STRESS (AVERAGE)
  4. RADIAL STRESS (FIBER/I.L.)
  5. RADIAL STRESS (I.L./MATRIX)
  6. HYDROSTATIC PRESSURE (I.L./MATRIX)
  7. LONGITUDINAL STRESS (AVERAGE)

               MATRIX FUNCTIONS
  8. HOOP STRESS (INTERFACE)
  9. RADIAL STRESS (INTERFACE)
 10. RADIAL STRAIN (INTERFACE)
 11. HYDROSTATIC PRESSURE (INTERFACE)
 12. LONGITUDINAL STRESS (INTERFACE)
 13. LONGITUDINAL STRESS (AVERAGE)

             MISCELLANEOUS FUNCTIONS
 14. LONGITUDINAL STRAIN (ASSEMBLAGE)
 15. USER DEFINED OBJECTIVE FUNCTION
ENTER CHOICE -> 8
```

Note: Specify whether the objective function selected is to be minimized or maximized.

```
               OBJECTIVE FUNCTION IS TO BE:
                     1.  MINIMIZED
                     2.  MAXIMIZED
               ENTER CHOICE -> 1


               OBJECTIVE FUNCTION:

               MINIMIZATION OF THE
               MATRIX HOOP STRESS (INTERFACE)

               IS INFORMATION CORRECT? <Y/N> y
```

Note: Enter total number of constraints. Each inequality constraint counts as one. Create equality constraints by selecting both greater than and less than constraints. Enter 0 for an unconstrained problem.

```
              CHOOSE DESIRED CONSTRAINTS:

ITEM#           FUNCTION                          CONSTRAINT

          INTERFACIAL LAYER FUNCTIONS
```

```
 1.  HOOP STRESS (FIBER/I.L.)           1.  >  (NOT TO BE LESS THAN)
 2.  HOOP STRESS (I.L./MATRIX)          2.  <  (NOT TO EXCEED)
 3.  RADIAL STRESS (I.L./MATRIX)
 4.  RADIAL STRESS (FIBER/I.L.)
 5.  LONGITUDINAL STRESS (AVERAGE)

     MATRIX FUNCTIONS
 6.  HOOP STRESS (INTERFACE)
 7.  RADIAL STRESS (INTERFACE)
 8.  HYDROSTATIC PRESSURE (INTERFACE)
 9.  LONGITUDINAL STRESS (INTERFACE)
10.  LONGITUDINAL STRESS (AVERAGE)

      MISCELLANEOUS FUNCTIONS
11.  LONGITUDINAL STRAIN (ASSEMBLAGE)
12.  USER DEFINED CONSTRAINT FUNCTION

ENTER NUMBER OF SELECTIONS (ENTER 0 FOR NO CONSTRAINTS) -> 0

       CONSTRAINTS:

       NO CONSTRAINTS

       IS INFORMATION CORRECT? <Y/N> y


**********************************BLOCK 3**********************************
                    DEFINE LOAD HISTORY, INCREMENT,
                           AND ITERATIONS


                             ***CAUTION***
THE APPLIED TEMPERATURE LOAD MUST REMAIN BETWEEN   75.00 deg AND 1500.00 deg
                             *************
```

Note: The data for the materials chosen have been internally analyzed and the applied thermal load cannot exceed the stated limits due to the temperature range of the supplied data.

Note: Enter total number of loading segments (i.e. 1 for monotonic cooling), the initial temperature, the initial external pressure, and the initial axial load (force). Then, enter the number of increments that this load segment will be divided into, followed by the final temperature, the final external pressure and the final axial load for each of the specified loading segments. In this example, 570 increments will produce temperature increments of -2.5°F.

```
NO. OF LOAD SEGMENTS, INITIAL TEMP., INITIAL PRESSURE, INITIAL AXIAL LOAD
-> 1 1500 0 0
NO. OF INCREMENTS, ENDING TEMP., ENDING PRESSURE, ENDING AXIAL LOAD
-> 570 75 0 0
```

Note: Choose the maximum number of iterations and the error tolerance allowed for convergence. Iteration will be terminated after reaching this limit.

```
CHANGE MAXIMUM NUMBER OF ITERATIONS (DEFAULT=10)? <Y/N> y
MAXIMUM NUMBER OF ITERATIONS -> 15

CHANGE CONVERGENCE ERROR TOLERANCE (DEFAULT=0.01)? <Y/N> n
```

Note: Indicate whether to suppress or write convergence messages to the optcomp.conv file.

```
WRITE CONVERGENCE INFORMATION TO optcomp.conv FILE? <Y/N> y
```

Note: Indicate whether to suppress or write optimization iterations to the screen.

```
WRITE OPTIMIZATION ITERATIONS TO SCREEN? <Y/N> y

                              LOAD HISTORY

STEP      INCREMENTS      TEMPERATURE      AXIAL      PRESSURE
  1                         1500.00         0.00        0.00
             570
  2                           75.00         0.00        0.00

          MAXIMUM NUMBER OF ITERATIONS =     15
          CONVERGENCE ERROR TOLERANCE = 0.01000
          CONVERGENCE INFORMATION WRITTEN TO optcomp.conv
          OPTIMIZATION ITERATIONS WRITTEN TO SCREEN

IS INFORMATION CORRECT? <Y/N> y


WOULD YOU LIKE TO SEE A PROBLEM REVIEW? <Y/N> y
```

Note: The problem review information is written to the file optcomp.review.

```
*******************************PROBLEM REVIEW******************************

              ***CONCENTRIC CYLINDER CONFIGURATION**

 SHELL          MATERIAL              OUTER RADIUS  CONSTITUTIVE MODEL

 1  FIBER      SiC  (SCS-6)  (psi)      0.50000        ELASTIC
 2  FIBER      SiC  (SCS-6)  (psi)      0.63200        ELASTIC
 3  INTERFACE     TBD                   0.65306        INELASTIC
 4  INTERFACE     TBD                   0.67413        INELASTIC
 5  INTERFACE     TBD                   0.69520        INELASTIC
 6  MATRIX     Ti-24Al-11Nb  (psi)      0.75616        INELASTIC
 7  MATRIX     Ti-24Al-11Nb  (psi)      0.81712        INELASTIC
 8  MATRIX     Ti-24Al-11Nb  (psi)      0.87808        INELASTIC
 9  MATRIX     Ti-24Al-11Nb  (psi)      0.93904        INELASTIC
10  MATRIX     Ti-24Al-11Nb  (psi)      1.00000        INELASTIC

 FIBER VOLUME FRACTION =    0.3994
 MATRIX VOLUME FRACTION =   0.5167

HIT RETURN TO CONTINUE ->

             ***INTERFACE REFERENCE MATERIALS***

       INTERFACE       MATERIAL          CONSTITUTIVE MODEL
           1      Ti-24Al-11Nb  (psi)       INELASTIC
           2      Ti-24Al-11Nb  (psi)       INELASTIC
           3      Ti-24Al-11Nb  (psi)       INELASTIC

             ***INTERFACIAL LAYER INITIAL DESIGN***

          LAYER      Ei/Er     Yi/Yr    CTEi/CTEr   Hi/Hr
            1        0.500     0.500      2.000     0.500
            2        0.500     0.500      2.000     0.500
            3        0.500     0.500      2.000     0.500


HIT RETURN TO CONTINUE ->
```

```
                    DESIGN VARIABLE

            INTERFACE LAYER C.T.E. RATIO(S)
        LAYER     LOWER BOUND          UPPER BOUND
          1          0.000                4.000
          2          0.000                4.000
          3          0.000                4.000

HIT RETURN TO CONTINUE ->

         OBJECTIVE FUNCTION:
         MINIMIZATION OF THE MATRIX HOOP STRESS (INTERFACE)

         CONSTRAINTS:
         NO CONSTRAINTS

HIT RETURN TO CONTINUE ->

                          ***LOAD HISTORY***

  STEP      INCREMENTS       TEMPERATURE      AXIAL        PRESSURE
   1                           1500.00         0.00          0.00
                570
   2                             75.00         0.00          0.00

             MAXIMUM NUMBER OF ITERATIONS =    15
             CONVERGENCE ERROR TOLERANCE = 0.01000
             CONVERGENCE INFORMATION WRITTEN TO optcomp.conv
             OPTIMIZATION ITERATIONS WRITTEN TO SCREEN

HIT RETURN TO CONTINUE ->

         ******MAIN MENU******

       1.  CREATE NEW DATA FILE
       2.  RUN EXISTING DATA FILE
       3.  ENTER NEW MATERIALS INTO DATABANK
       4.  EXIT SHELL
      ENTER CHOICE -> 4
```

8.2.2 Execution of the optcomp.datafile

The execution of the data file **optcomp.data**, whose contruction has been outlined in Section 8.2.1, is presented below as it is written to the screen during the actual optimization run. The information presented, excluding the header and the initial menu, is written independently to the file **optcomp.history**.

```
NASA-LEWIS RESEARCH CENTER, STRUCTURES DIVISION, CLEVELAND OHIO
          *********************************************
          ***                OPTCOMP                ***
          ***                                       ***
          ***    CONCENTRIC CYLINDER OPTIMIZATION   ***
          ***   PROGRAM FOR THE DETERMINATION OF    ***
          *** IDEALIZED INTERFACIAL LAYER PROPERTIES***
          ***              WRITTEN BY               ***
          ***                                       ***
          ***          ROBERT SCOTT SALZAR          ***
          ***         TODD OAKHILL WILLIAMS         ***
          ***          MAREK-JERZY PINDERA          ***
          ***                                       ***
          ***                  OF                   ***
          ***       THE UNIVERSITY OF VIRGINIA      ***
          ***            SEPTEMBER, 1993            ***
          ***                                       ***
          *** DEVELOPED FOR THE FATIGUE AND FRACTURE***
          ***  BRANCH OF NASA-LEWIS RESEARCH CENTER ***
          ***        UNDER CONTRACT NAS3-26571      ***
          ***  DR. S. M. ARNOLD (CONTRACT MONITOR)  ***
          *********************************************

 HIT RETURN TO CONTINUE ->

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b.  assumes any liabilities with respect to the use of, or for damages
    resulting from use of this software.

------------------------------------------------------------------------------

 HIT RETURN TO CONTINUE ->

          ******MAIN MENU******

        1.  CREATE NEW DATA FILE
        2.  RUN EXISTING DATA FILE
        3.  ENTER NEW MATERIALS INTO DATABANK
        4.  EXIT SHELL
       ENTER CHOICE -> 2
```

```
**************LEGEND FOR DESIGN VARIABLES***********
 X 1= CTE RATIO FOR INTERFACE  1
 X 2= CTE RATIO FOR INTERFACE  2
 X 3= CTE RATIO FOR INTERFACE  3
****************************************************

  ITERATION #:     1
DESIGN VARIABLE  LOWER BOUND  CURRENT VALUE  UPPER BOUND   OBJECTIVE FN
      X 1           0.0000        2.0000        4.0000
      X 2           0.0000        2.0000        4.0000
      X 3           0.0000        2.0000        4.0000
                                                             36656.05078
  ITERATION #:     2
DESIGN VARIABLE  LOWER BOUND  CURRENT VALUE  UPPER BOUND   OBJECTIVE FN
      X 1           0.0000        2.0000        4.0000
      X 2           0.0000        2.0000        4.0000
      X 3           0.0000        2.0000        4.0000
                                                             36656.01172
  ITERATION #:     3
DESIGN VARIABLE  LOWER BOUND  CURRENT VALUE  UPPER BOUND   OBJECTIVE FN
      X 1           0.0000        2.0020        4.0000
      X 2           0.0000        2.0000        4.0000
      X 3           0.0000        2.0000        4.0000
                                                             36648.22266
  ITERATION #:     4
DESIGN VARIABLE  LOWER BOUND  CURRENT VALUE  UPPER BOUND   OBJECTIVE FN
      X 1           0.0000        2.0000        4.0000
      X 2           0.0000        2.0020        4.0000
      X 3           0.0000        2.0000        4.0000
                                                             36648.02344
  ITERATION #:     5
DESIGN VARIABLE  LOWER BOUND  CURRENT VALUE  UPPER BOUND   OBJECTIVE FN
      X 1           0.0000        2.0000        4.0000
      X 2           0.0000        2.0000        4.0000
      X 3           0.0000        2.0020        4.0000
                                                             36647.75000
  ITERATION #:     6
DESIGN VARIABLE  LOWER BOUND  CURRENT VALUE  UPPER BOUND   OBJECTIVE FN
      X 1           0.0000        2.2963        4.0000
      X 2           0.0000        2.3039        4.0000
      X 3           0.0000        2.3143        4.0000
                                                             32546.26758
  ITERATION #:     7
DESIGN VARIABLE  LOWER BOUND  CURRENT VALUE  UPPER BOUND   OBJECTIVE FN
      X 1           0.0000        2.7757        4.0000
      X 2           0.0000        2.7955        4.0000
      X 3           0.0000        2.8227        4.0000
                                                             23592.54492
  ITERATION #:     8
DESIGN VARIABLE  LOWER BOUND  CURRENT VALUE  UPPER BOUND   OBJECTIVE FN
      X 1           0.0000        4.0000        4.0000
      X 2           0.0000        4.0000        4.0000
      X 3           0.0000        4.0000        4.0000
                                                             -5868.93896
  ITERATION #:     9
DESIGN VARIABLE  LOWER BOUND  CURRENT VALUE  UPPER BOUND   OBJECTIVE FN
      X 1           0.0000        3.9960        4.0000
      X 2           0.0000        4.0000        4.0000
      X 3           0.0000        4.0000        4.0000
                                                             -5838.97900
  ITERATION #:    10
DESIGN VARIABLE  LOWER BOUND  CURRENT VALUE  UPPER BOUND   OBJECTIVE FN
      X 1           0.0000        4.0000        4.0000
      X 2           0.0000        3.9960        4.0000
```

```
      X 3            0.0000        4.0000        4.0000
                                                             -5838.14209

  ITERATION #:    11
DESIGN VARIABLE   LOWER BOUND   CURRENT VALUE   UPPER BOUND   OBJECTIVE FN
      X 1            0.0000        4.0000        4.0000
      X 2            0.0000        4.0000        4.0000
      X 3            0.0000        3.9960        4.0000
                                                             -5837.01172

THE PROBLEM REVIEW FILE IS optcomp.review
THE INITIAL AND FINAL DESIGNS ARE LOCATED
IN FILE optcomp.out
```

8.2.3 Results of the unconstrained optimization process

The file **optcomp.out**, containing information on the initial and final (optimum) values of the interfacial material properties, geometry, stresses and inelastic strains, for the data file **optcomp.data** constructed in Section 8.2.1, is given below.

```
*********************************************
***               OPTCOMP               ***
***                                     ***
***   CONCENTRIC CYLINDER OPTIMIZATION  ***
***   PROGRAM FOR THE DETERMINATION OF  ***
*** IDEALIZED INTERFACIAL LAYER PROPERTIES***
***             WRITTEN BY              ***
***                                     ***
***          ROBERT SCOTT SALZAR        ***
***         TODD OAKHILL WILLIAMS       ***
***          MAREK-JERZY PINDERA        ***
***                                     ***
***                 OF                  ***
***      THE UNIVERSITY OF VIRGINIA     ***
***           SEPTEMBER, 1993           ***
***                                     ***
*** DEVELOPED FOR THE FATIGUE AND FRACTURE***
***  BRANCH OF NASA-LEWIS RESEARCH CENTER ***
***       UNDER CONTRACT NAS3-26571     ***
***  DR. S. M. ARNOLD (CONTRACT MONITOR) ***
*********************************************
```

Note: The initial concentric cylinder configuration and material specifications, including the resulting stresses and inelastic strains, are given below. Starting with the fiber core, the materials listed below the initial concentric cylinder configuration are the properties of each specified cylinder. Following the fiber core and the coating are the properties of the matrix. Provided next are the initial properties of the interfacial layers. The stress and strain distributions based on the initial concentric cylinder design are given last.

```
          ***INITIAL CONCENTRIC CYLINDER CONFIGURATION***

 RING    MATERIAL                    OUTER RADIUS    CONSTITUTIVE MODEL

  1      FIBER LAYER 1 (CORE)            .500        ISOTROPIC ELASTIC
  2      FIBER LAYER 2                   .632        ISOTROPIC ELASTIC
  3      INTERFACE LAYER 1               .653        ISOTROPIC INELASTIC
  4      INTERFACE LAYER 2               .674        ISOTROPIC INELASTIC
  5      INTERFACE LAYER 3               .695        ISOTROPIC INELASTIC
  6      MATRIX                          .756        ISOTROPIC INELASTIC
  7      MATRIX                          .817        ISOTROPIC INELASTIC
  8      MATRIX                          .878        ISOTROPIC INELASTIC
  9      MATRIX                          .939        ISOTROPIC INELASTIC
 10      MATRIX                         1.000        ISOTROPIC INELASTIC

 ***FIBER LAYER  1 PROPERTIES (CORE)***

 TEMPERATURE =    .1500E+04

  .5800E+08   .5800E+08   .5800E+08           EXX    ETT    ERR
  .2500E+00   .2500E+00   .2500E+00           VXR    VXT    VRT
  .2500E-05   .2500E-05   .2500E-05           ALFXX  ALFTT  ALFRR
  .1000E+08   .5800E+08                       Y      HS
```

```
TEMPERATURE =    .1342E+04

 .5800E+08   .5800E+08   .5800E+08
 .2500E+00   .2500E+00   .2500E+00
 .2440E-05   .2440E-05   .2440E-05
 .1000E+08   .5800E+08

TEMPERATURE =    .1183E+04

 .5800E+08   .5800E+08   .5800E+08
 .2500E+00   .2500E+00   .2500E+00
 .2370E-05   .2370E-05   .2370E-05
 .1000E+08   .5800E+08

TEMPERATURE =    .1025E+04

 .5800E+08   .5800E+08   .5800E+08
 .2500E+00   .2500E+00   .2500E+00
 .2278E-05   .2278E-05   .2278E-05
 .1000E+08   .5800E+08

TEMPERATURE =    .8667E+03

 .5800E+08   .5800E+08   .5800E+08
 .2500E+00   .2500E+00   .2500E+00
 .2187E-05   .2187E-05   .2187E-05
 .1000E+08   .5800E+08

TEMPERATURE =    .7083E+03

 .5800E+08   .5800E+08   .5800E+08
 .2500E+00   .2500E+00   .2500E+00
 .2109E-05   .2109E-05   .2109E-05
 .1000E+08   .5800E+08

TEMPERATURE =    .5500E+03

 .5800E+08   .5800E+08   .5800E+08
 .2500E+00   .2500E+00   .2500E+00
 .2051E-05   .2051E-05   .2051E-05
 .1000E+08   .5800E+08

TEMPERATURE =    .3917E+03

 .5800E+08   .5800E+08   .5800E+08
 .2500E+00   .2500E+00   .2500E+00
 .2010E-05   .2010E-05   .2010E-05
 .1000E+08   .5800E+08

TEMPERATURE =    .2333E+03

 .5800E+08   .5800E+08   .5800E+08
 .2500E+00   .2500E+00   .2500E+00
 .1983E-05   .1983E-05   .1983E-05
 .1000E+08   .5800E+08

TEMPERATURE =    .7500E+02

 .5800E+08   .5800E+08   .5800E+08
 .2500E+00   .2500E+00   .2500E+00
 .1960E-05   .1960E-05   .1960E-05
 .1000E+08   .5800E+08

***FIBER LAYER  2 PROPERTIES***
```

TEMPERATURE = .1500E+04

.5800E+08	.5800E+08	.5800E+08	**EXX ETT ERR**
.2500E+00	.2500E+00	.2500E+00	**VXR VXT VRT**
.2500E-05	.2500E-05	.2500E-05	**ALFXX ALFTT ALFRR**
.1000E+08	.5800E+08		**Y HS**

TEMPERATURE = .1342E+04

.5800E+08	.5800E+08	.5800E+08
.2500E+00	.2500E+00	.2500E+00
.2440E-05	.2440E-05	.2440E-05
.1000E+08	.5800E+08	

TEMPERATURE = .1183E+04

.5800E+08	.5800E+08	.5800E+08
.2500E+00	.2500E+00	.2500E+00
.2370E-05	.2370E-05	.2370E-05
.1000E+08	.5800E+08	

TEMPERATURE = .1025E+04

.5800E+08	.5800E+08	.5800E+08
.2500E+00	.2500E+00	.2500E+00
.2278E-05	.2278E-05	.2278E-05
.1000E+08	.5800E+08	

TEMPERATURE = .8667E+03

.5800E+08	.5800E+08	.5800E+08
.2500E+00	.2500E+00	.2500E+00
.2187E-05	.2187E-05	.2187E-05
.1000E+08	.5800E+08	

TEMPERATURE = .7083E+03

.5800E+08	.5800E+08	.5800E+08
.2500E+00	.2500E+00	.2500E+00
.2109E-05	.2109E-05	.2109E-05
.1000E+08	.5800E+08	

TEMPERATURE = .5500E+03

.5800E+08	.5800E+08	.5800E+08
.2500E+00	.2500E+00	.2500E+00
.2051E-05	.2051E-05	.2051E-05
.1000E+08	.5800E+08	

TEMPERATURE = .3917E+03

.5800E+08	.5800E+08	.5800E+08
.2500E+00	.2500E+00	.2500E+00
.2010E-05	.2010E-05	.2010E-05
.1000E+08	.5800E+08	

TEMPERATURE = .2333E+03

.5800E+08	.5800E+08	.5800E+08
.2500E+00	.2500E+00	.2500E+00
.1983E-05	.1983E-05	.1983E-05
.1000E+08	.5800E+08	

TEMPERATURE = .7500E+02

```
 .5800E+08   .5800E+08   .5800E+08
 .2500E+00   .2500E+00   .2500E+00
 .1960E-05   .1960E-05   .1960E-05
 .1000E+08   .5800E+08

***MATRIX PROPERTIES***

TEMPERATURE =    .1500E+04

 .6200E+07   .6200E+07   .6200E+07             EXX   ETT   ERR
 .2600E+00   .2600E+00   .2600E+00             VXR   VXT   VRT
 .6150E-05   .6150E-05   .6150E-05             ALFXX ALFTT ALFRR
 .2400E+05   .1000E+04                         Y     HS

TEMPERATURE =    .1342E+04

 .7554E+07   .7554E+07   .7554E+07
 .2600E+00   .2600E+00   .2600E+00
 .6010E-05   .6010E-05   .6010E-05
 .3251E+05   .3306E+05

TEMPERATURE =    .1183E+04

 .1044E+08   .1044E+08   .1044E+08
 .2600E+00   .2600E+00   .2600E+00
 .5888E-05   .5888E-05   .5888E-05
 .3979E+05   .1130E+06

TEMPERATURE =    .1025E+04

 .1335E+08   .1335E+08   .1335E+08
 .2600E+00   .2600E+00   .2600E+00
 .5816E-05   .5816E-05   .5816E-05
 .4535E+05   .2793E+06

TEMPERATURE =    .8667E+03

 .1174E+08   .1174E+08   .1174E+08
 .2600E+00   .2600E+00   .2600E+00
 .5750E-05   .5750E-05   .5750E-05
 .5134E+05   .3591E+06

TEMPERATURE =    .7083E+03

 .1092E+08   .1092E+08   .1092E+08
 .2600E+00   .2600E+00   .2600E+00
 .5606E-05   .5606E-05   .5606E-05
 .5616E+05   .2007E+06

TEMPERATURE =    .5500E+03

 .1249E+08   .1249E+08   .1249E+08
 .2600E+00   .2600E+00   .2600E+00
 .5394E-05   .5394E-05   .5394E-05
 .5882E+05   .3999E+05

TEMPERATURE =    .3917E+03

 .1450E+08   .1450E+08   .1450E+08
 .2600E+00   .2600E+00   .2600E+00
 .5200E-05   .5200E-05   .5200E-05
 .5900E+05   .4428E+06
```

TEMPERATURE =   .2333E+03

.1545E+08	.1545E+08	.1545E+08
.2600E+00	.2600E+00	.2600E+00
.5086E-05	.5086E-05	.5086E-05
.5679E+05	.1746E+07	

TEMPERATURE =   .7500E+02

.1600E+08	.1600E+08	.1600E+08
.2600E+00	.2600E+00	.2600E+00
.5000E-05	.5000E-05	.5000E-05
.5389E+05	.3333E+07	

*********INITIAL INTERFACE PROPERTIES*********

INTERFACE LAYER 1

TEMPERATURE =   .1500E+04

.3100E+07	.3100E+07	.3100E+07
.2600E+00	.2600E+00	.2600E+00
.1230E-04	.1230E-04	.1230E-04
.1200E+05	.5000E+03	

TEMPERATURE =   .1342E+04

.3777E+07	.3777E+07	.3777E+07
.2600E+00	.2600E+00	.2600E+00
.1202E-04	.1202E-04	.1202E-04
.1625E+05	.1653E+05	

TEMPERATURE =   .1183E+04

.5219E+07	.5219E+07	.5219E+07
.2600E+00	.2600E+00	.2600E+00
.1178E-04	.1178E-04	.1178E-04
.1990E+05	.5652E+05	

TEMPERATURE =   .1025E+04

.6675E+07	.6675E+07	.6675E+07
.2600E+00	.2600E+00	.2600E+00
.1163E-04	.1163E-04	.1163E-04
.2267E+05	.1397E+06	

TEMPERATURE =   .8667E+03

.5869E+07	.5869E+07	.5869E+07
.2600E+00	.2600E+00	.2600E+00
.1150E-04	.1150E-04	.1150E-04
.2567E+05	.1796E+06	

TEMPERATURE =   .7083E+03

.5458E+07	.5458E+07	.5458E+07
.2600E+00	.2600E+00	.2600E+00
.1121E-04	.1121E-04	.1121E-04
.2808E+05	.1004E+06	

TEMPERATURE =   .5500E+03

.6243E+07	.6243E+07	.6243E+07
.2600E+00	.2600E+00	.2600E+00
.1079E-04	.1079E-04	.1079E-04
.2941E+05	.1999E+05	

TEMPERATURE = .3917E+03

.7252E+07	.7252E+07	.7252E+07
.2600E+00	.2600E+00	.2600E+00
.1040E-04	.1040E-04	.1040E-04
.2950E+05	.2214E+06	

TEMPERATURE = .2333E+03

.7726E+07	.7726E+07	.7726E+07
.2600E+00	.2600E+00	.2600E+00
.1017E-04	.1017E-04	.1017E-04
.2840E+05	.8730E+06	

TEMPERATURE = .7500E+02

.8000E+07	.8000E+07	.8000E+07
.2600E+00	.2600E+00	.2600E+00
.1000E-04	.1000E-04	.1000E-04
.2694E+05	.1666E+07	

INTERFACE LAYER 2

TEMPERATURE = .1500E+04

.3100E+07	.3100E+07	.3100E+07
.2600E+00	.2600E+00	.2600E+00
.1230E-04	.1230E-04	.1230E-04
.1200E+05	.5000E+03	

TEMPERATURE = .1342E+04

.3777E+07	.3777E+07	.3777E+07
.2600E+00	.2600E+00	.2600E+00
.1202E-04	.1202E-04	.1202E-04
.1625E+05	.1653E+05	

TEMPERATURE = .1183E+04

.5219E+07	.5219E+07	.5219E+07
.2600E+00	.2600E+00	.2600E+00
.1178E-04	.1178E-04	.1178E-04
.1990E+05	.5652E+05	

TEMPERATURE = .1025E+04

.6675E+07	.6675E+07	.6675E+07
.2600E+00	.2600E+00	.2600E+00
.1163E-04	.1163E-04	.1163E-04
.2267E+05	.1397E+06	

TEMPERATURE = .8667E+03

.5869E+07	.5869E+07	.5869E+07
.2600E+00	.2600E+00	.2600E+00
.1150E-04	.1150E-04	.1150E-04
.2567E+05	.1796E+06	

```
TEMPERATURE =    .7083E+03

 .5458E+07   .5458E+07   .5458E+07
 .2600E+00   .2600E+00   .2600E+00
 .1121E-04   .1121E-04   .1121E-04
 .2808E+05   .1004E+06

TEMPERATURE =    .5500E+03

 .6243E+07   .6243E+07   .6243E+07
 .2600E+00   .2600E+00   .2600E+00
 .1079E-04   .1079E-04   .1079E-04
 .2941E+05   .1999E+05

TEMPERATURE =    .3917E+03

 .7252E+07   .7252E+07   .7252E+07
 .2600E+00   .2600E+00   .2600E+00
 .1040E-04   .1040E-04   .1040E-04
 .2950E+05   .2214E+06

TEMPERATURE =    .2333E+03

 .7726E+07   .7726E+07   .7726E+07
 .2600E+00   .2600E+00   .2600E+00
 .1017E-04   .1017E-04   .1017E-04
 .2840E+05   .8730E+06

TEMPERATURE =    .7500E+02

 .8000E+07   .8000E+07   .8000E+07
 .2600E+00   .2600E+00   .2600E+00
 .1000E-04   .1000E-04   .1000E-04
 .2694E+05   .1666E+07


***INTERFACE LAYER  3***

TEMPERATURE =    .1500E+04

 .3100E+07   .3100E+07   .3100E+07
 .2600E+00   .2600E+00   .2600E+00
 .1230E-04   .1230E-04   .1230E-04
 .1200E+05   .5000E+03

TEMPERATURE =    .1342E+04

 .3777E+07   .3777E+07   .3777E+07
 .2600E+00   .2600E+00   .2600E+00
 .1202E-04   .1202E-04   .1202E-04
 .1625E+05   .1653E+05

TEMPERATURE =    .1183E+04

 .5219E+07   .5219E+07   .5219E+07
 .2600E+00   .2600E+00   .2600E+00
 .1178E-04   .1178E-04   .1178E-04
 .1990E+05   .5652E+05

TEMPERATURE =    .1025E+04

 .6675E+07   .6675E+07   .6675E+07
 .2600E+00   .2600E+00   .2600E+00
 .1163E-04   .1163E-04   .1163E-04
```

```
 .2267E+05    .1397E+06

TEMPERATURE =    .8667E+03

 .5869E+07    .5869E+07    .5869E+07
 .2600E+00    .2600E+00    .2600E+00
 .1150E-04    .1150E-04    .1150E-04
 .2567E+05    .1796E+06

TEMPERATURE =    .7083E+03

 .5458E+07    .5458E+07    .5458E+07
 .2600E+00    .2600E+00    .2600E+00
 .1121E-04    .1121E-04    .1121E-04
 .2808E+05    .1004E+06

TEMPERATURE =    .5500E+03

 .6243E+07    .6243E+07    .6243E+07
 .2600E+00    .2600E+00    .2600E+00
 .1079E-04    .1079E-04    .1079E-04
 .2941E+05    .1999E+05

TEMPERATURE =    .3917E+03

 .7252E+07    .7252E+07    .7252E+07
 .2600E+00    .2600E+00    .2600E+00
 .1040E-04    .1040E-04    .1040E-04
 .2950E+05    .2214E+06

TEMPERATURE =    .2333E+03

 .7726E+07    .7726E+07    .7726E+07
 .2600E+00    .2600E+00    .2600E+00
 .1017E-04    .1017E-04    .1017E-04
 .2840E+05    .8730E+06

TEMPERATURE =    .7500E+02

 .8000E+07    .8000E+07    .8000E+07
 .2600E+00    .2600E+00    .2600E+00
 .1000E-04    .1000E-04    .1000E-04
 .2694E+05    .1666E+07
```

INITIAL STRESSES AND INELASTIC STRAINS

RING NO.	INTER RADIUS	STRXX	STRRR	STRTT	W(I)
1	0.0000E+00	-0.8383E+05	-0.1959E+05	-0.1959E+05	0.0000E+00
1	0.5000E+00	-0.8383E+05	-0.1959E+05	-0.1959E+05	-0.1502E-02
2	0.5000E+00	-0.8383E+05	-0.1959E+05	-0.1959E+05	-0.1502E-02
2	0.6320E+00	-0.8383E+05	-0.1959E+05	-0.1959E+05	-0.1899E-02
3	0.6320E+00	0.3855E+05	-0.1959E+05	0.4157E+05	-0.1899E-02
3	0.6531E+00	0.3968E+05	-0.1762E+05	0.4075E+05	-0.2662E-02
4	0.6531E+00	0.3968E+05	-0.1762E+05	0.4075E+05	-0.2662E-02
4	0.6741E+00	0.4072E+05	-0.1582E+05	0.3997E+05	-0.3397E-02
5	0.6741E+00	0.4072E+05	-0.1582E+05	0.3997E+05	-0.3397E-02
5	0.6952E+00	0.4168E+05	-0.1414E+05	0.3921E+05	-0.4115E-02
6	0.6952E+00	0.5034E+05	-0.1414E+05	0.3666E+05	-0.4115E-02
6	0.7562E+00	0.5430E+05	-0.1011E+05	0.3493E+05	-0.4791E-02
7	0.7562E+00	0.5430E+05	-0.1011E+05	0.3493E+05	-0.4791E-02

7	0.8171E+00	0.5736E+05	-0.6817E+04	0.3310E+05	-0.5435E-02
8	0.8171E+00	0.5736E+05	-0.6817E+04	0.3310E+05	-0.5435E-02
8	0.8781E+00	0.5968E+05	-0.4108E+04	0.3128E+05	-0.6056E-02
9	0.8781E+00	0.5968E+05	-0.4108E+04	0.3128E+05	-0.6056E-02
9	0.9390E+00	0.6142E+05	-0.1869E+04	0.2957E+05	-0.6657E-02
10	0.9390E+00	0.6142E+05	-0.1869E+04	0.2957E+05	-0.6657E-02
10	0.1000E+01	0.6272E+05	0.7276E-10	0.2800E+05	-0.7246E-02

RING NO.	EPXXP	EPRRP	EPTTP	STREFF	SIGEFF
1	0.0000E+00	0.0000E+00	0.0000E+00	0.6424E+05	0.1000E+08
1	0.0000E+00	0.0000E+00	0.0000E+00	0.6424E+05	0.1000E+08
2	0.0000E+00	0.0000E+00	0.0000E+00	0.6424E+05	0.1000E+08
2	0.0000E+00	0.0000E+00	0.0000E+00	0.6424E+05	0.1000E+08
3	0.7443E-02	-0.1580E-01	0.8352E-02	0.5970E+05	0.6021E+05
3	0.7339E-02	-0.1482E-01	0.7484E-02	0.5784E+05	0.5814E+05
4	0.7339E-02	-0.1482E-01	0.7484E-02	0.5784E+05	0.5814E+05
4	0.7242E-02	-0.1395E-01	0.6710E-02	0.5616E+05	0.5632E+05
5	0.7242E-02	-0.1395E-01	0.6710E-02	0.5616E+05	0.5632E+05
5	0.7152E-02	-0.1316E-01	0.6011E-02	0.5462E+05	0.5468E+05
6	0.7989E-03	-0.1146E-02	0.3470E-03	0.5884E+05	0.5884E+05
6	0.5890E-03	-0.7559E-03	0.1669E-03	0.5723E+05	0.5723E+05
7	0.5890E-03	-0.7559E-03	0.1669E-03	0.5723E+05	0.5723E+05
7	0.4214E-03	-0.4905E-03	0.6909E-04	0.5613E+05	0.5613E+05
8	0.4214E-03	-0.4905E-03	0.6909E-04	0.5613E+05	0.5613E+05
8	0.2906E-03	-0.3105E-03	0.1985E-04	0.5535E+05	0.5535E+05
9	0.2906E-03	-0.3105E-03	0.1985E-04	0.5535E+05	0.5535E+05
9	0.1904E-03	-0.1887E-03	-0.1639E-05	0.5481E+05	0.5481E+05
10	0.1904E-03	-0.1887E-03	-0.1639E-05	0.5481E+05	0.5481E+05
10	0.1139E-03	-0.1057E-03	-0.8108E-05	0.5443E+05	0.5442E+05

LONGITUDINAL STRAIN = -0.4389E-02

LONGITUDINAL FORCE = -0.5093E-10

Note: The results of the optimization are given below. First, the final geometry of the concentric cylinder configuration is given. Next, the final material properties are given for each interfacial layer, followed by the final stresses and inelastic strains based on the optimum values of the design variables.

FINAL CONCENTRIC CYLINDER CONFIGURATION

RING	MATERIAL	OUTER RADIUS	CONSTITUTIVE MODEL
1	FIBER LAYER 1 (CORE)	.500	ISOTROPIC ELASTIC
2	FIBER LAYER 2	.632	ISOTROPIC ELASTIC
3	INTERFACE LAYER 1	.653	ISOTROPIC INELASTIC
4	INTERFACE LAYER 2	.674	ISOTROPIC INELASTIC
5	INTERFACE LAYER 3	.695	ISOTROPIC INELASTIC
6	MATRIX	.756	ISOTROPIC INELASTIC
7	MATRIX	.817	ISOTROPIC INELASTIC
8	MATRIX	.878	ISOTROPIC INELASTIC
9	MATRIX	.939	ISOTROPIC INELASTIC
10	MATRIX	1.000	ISOTROPIC INELASTIC

**********FINAL INTERFACE PROPERTIES**********

```
***INTERFACE LAYER  1***

TEMPERATURE =  0.1500E+04

0.3100E+07  0.3100E+07  0.3100E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.2460E-04  0.2460E-04  0.2460E-04
0.1200E+05  0.5000E+03

TEMPERATURE =  0.1342E+04

0.3777E+07  0.3777E+07  0.3777E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.2404E-04  0.2404E-04  0.2404E-04
0.1625E+05  0.1653E+05

TEMPERATURE =  0.1183E+04

0.5219E+07  0.5219E+07  0.5219E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.2355E-04  0.2355E-04  0.2355E-04
0.1990E+05  0.5652E+05

TEMPERATURE =  0.1025E+04

0.6675E+07  0.6675E+07  0.6675E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.2326E-04  0.2326E-04  0.2326E-04
0.2267E+05  0.1397E+06

TEMPERATURE =  0.8667E+03

0.5869E+07  0.5869E+07  0.5869E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.2300E-04  0.2300E-04  0.2300E-04
0.2567E+05  0.1796E+06

TEMPERATURE =  0.7083E+03

0.5458E+07  0.5458E+07  0.5458E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.2242E-04  0.2242E-04  0.2242E-04
0.2808E+05  0.1004E+06

TEMPERATURE =  0.5500E+03

0.6243E+07  0.6243E+07  0.6243E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.2158E-04  0.2158E-04  0.2158E-04
0.2941E+05  0.1999E+05

TEMPERATURE =  0.3917E+03

0.7252E+07  0.7252E+07  0.7252E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.2080E-04  0.2080E-04  0.2080E-04
0.2950E+05  0.2214E+06

TEMPERATURE =  0.2333E+03

0.7726E+07  0.7726E+07  0.7726E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.2034E-04  0.2034E-04  0.2034E-04
0.2840E+05  0.8730E+06
```

```
TEMPERATURE =  0.7500E+02

0.8000E+07  0.8000E+07  0.8000E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.2000E-04  0.2000E-04  0.2000E-04
0.2695E+05  0.1666E+07


***INTERFACE LAYER  2***

TEMPERATURE =  0.1500E+04

0.3100E+07  0.3100E+07  0.3100E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.2460E-04  0.2460E-04  0.2460E-04
0.1200E+05  0.5000E+03

TEMPERATURE =  0.1342E+04

0.3777E+07  0.3777E+07  0.3777E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.2404E-04  0.2404E-04  0.2404E-04
0.1625E+05  0.1653E+05

TEMPERATURE =  0.1183E+04

0.5219E+07  0.5219E+07  0.5219E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.2355E-04  0.2355E-04  0.2355E-04
0.1990E+05  0.5652E+05

TEMPERATURE =  0.1025E+04

0.6675E+07  0.6675E+07  0.6675E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.2326E-04  0.2326E-04  0.2326E-04
0.2267E+05  0.1397E+06

TEMPERATURE =  0.8667E+03

0.5869E+07  0.5869E+07  0.5869E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.2300E-04  0.2300E-04  0.2300E-04
0.2567E+05  0.1796E+06

TEMPERATURE =  0.7083E+03

0.5458E+07  0.5458E+07  0.5458E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.2242E-04  0.2242E-04  0.2242E-04
0.2808E+05  0.1004E+06

TEMPERATURE =  0.5500E+03

0.6243E+07  0.6243E+07  0.6243E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.2158E-04  0.2158E-04  0.2158E-04
0.2941E+05  0.1999E+05

TEMPERATURE =  0.3917E+03

0.7252E+07  0.7252E+07  0.7252E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.2080E-04  0.2080E-04  0.2080E-04
```

0.2950E+05	0.2214E+06	

TEMPERATURE = 0.2333E+03

0.7726E+07	0.7726E+07	0.7726E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.2034E-04	0.2034E-04	0.2034E-04
0.2840E+05	0.8730E+06	

TEMPERATURE = 0.7500E+02

0.8000E+07	0.8000E+07	0.8000E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.2000E-04	0.2000E-04	0.2000E-04
0.2695E+05	0.1666E+07	

INTERFACE LAYER 3

TEMPERATURE = 0.1500E+04

0.3100E+07	0.3100E+07	0.3100E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.2460E-04	0.2460E-04	0.2460E-04
0.1200E+05	0.5000E+03	

TEMPERATURE = 0.1342E+04

0.3777E+07	0.3777E+07	0.3777E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.2404E-04	0.2404E-04	0.2404E-04
0.1625E+05	0.1653E+05	

TEMPERATURE = 0.1183E+04

0.5219E+07	0.5219E+07	0.5219E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.2355E-04	0.2355E-04	0.2355E-04
0.1990E+05	0.5652E+05	

TEMPERATURE = 0.1025E+04

0.6675E+07	0.6675E+07	0.6675E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.2326E-04	0.2326E-04	0.2326E-04
0.2267E+05	0.1397E+06	

TEMPERATURE = 0.8667E+03

0.5869E+07	0.5869E+07	0.5869E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.2300E-04	0.2300E-04	0.2300E-04
0.2567E+05	0.1796E+06	

TEMPERATURE = 0.7083E+03

0.5458E+07	0.5458E+07	0.5458E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.2242E-04	0.2242E-04	0.2242E-04
0.2808E+05	0.1004E+06	

TEMPERATURE = 0.5500E+03

0.6243E+07	0.6243E+07	0.6243E+07

```
0.2600E+00  0.2600E+00  0.2600E+00
0.2158E-04  0.2158E-04  0.2158E-04
0.2941E+05  0.1999E+05

TEMPERATURE =   0.3917E+03

0.7252E+07  0.7252E+07  0.7252E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.2080E-04  0.2080E-04  0.2080E-04
0.2950E+05  0.2214E+06

TEMPERATURE =   0.2333E+03

0.7726E+07  0.7726E+07  0.7726E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.2034E-04  0.2034E-04  0.2034E-04
0.2840E+05  0.8730E+06

TEMPERATURE =   0.7500E+02

0.8000E+07  0.8000E+07  0.8000E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.2000E-04  0.2000E-04  0.2000E-04
0.2695E+05  0.1666E+07
```

FINAL STRESSES AND INELASTIC STRAINS

RING NO.	INTER RADIUS	STRXX	STRRR	STRTT	W(I)
1	0.0000E+00	-0.8720E+05	-0.7040E+04	-0.7040E+04	0.0000E+00
1	0.5000E+00	-0.8720E+05	-0.7040E+04	-0.7040E+04	-0.1414E-02
2	0.5000E+00	-0.8720E+05	-0.7040E+04	-0.7040E+04	-0.1414E-02
2	0.6320E+00	-0.8720E+05	-0.7040E+04	-0.7040E+04	-0.1787E-02
3	0.6320E+00	0.9219E+05	-0.7040E+04	0.9602E+05	-0.1787E-02
3	0.6531E+00	0.9346E+05	-0.3744E+04	0.9400E+05	-0.3392E-02
4	0.6531E+00	0.9346E+05	-0.3744E+04	0.9400E+05	-0.3392E-02
4	0.6741E+00	0.9466E+05	-0.7278E+03	0.9216E+05	-0.4940E-02
5	0.6741E+00	0.9466E+05	-0.7278E+03	0.9216E+05	-0.4940E-02
5	0.6952E+00	0.9580E+05	0.2065E+04	0.9045E+05	-0.6449E-02
6	0.6952E+00	0.5199E+05	0.2065E+04	-0.5869E+04	-0.6449E-02
6	0.7562E+00	0.5207E+05	0.1449E+04	-0.5287E+04	-0.6977E-02
7	0.7562E+00	0.5207E+05	0.1449E+04	-0.5287E+04	-0.6977E-02
7	0.8171E+00	0.5212E+05	0.9653E+03	-0.4824E+04	-0.7506E-02
8	0.8171E+00	0.5212E+05	0.9653E+03	-0.4824E+04	-0.7506E-02
8	0.8781E+00	0.5216E+05	0.5765E+03	-0.4450E+04	-0.8039E-02
9	0.8781E+00	0.5216E+05	0.5765E+03	-0.4450E+04	-0.8039E-02
9	0.9390E+00	0.5219E+05	0.2607E+03	-0.4144E+04	-0.8572E-02
10	0.9390E+00	0.5219E+05	0.2607E+03	-0.4144E+04	-0.8572E-02
10	0.1000E+01	0.5221E+05	0.2547E-10	-0.3891E+04	-0.9108E-02

RING NO.	EPXXP	EPRRP	EPTTP	STREFF	SIGEFF
1	0.0000E+00	0.0000E+00	0.0000E+00	0.8016E+05	0.1000E+08
1	0.0000E+00	0.0000E+00	0.0000E+00	0.8016E+05	0.1000E+08
2	0.0000E+00	0.0000E+00	0.0000E+00	0.8016E+05	0.1000E+08
2	0.0000E+00	0.0000E+00	0.0000E+00	0.8016E+05	0.1000E+08
3	0.1869E-01	-0.3849E-01	0.1981E-01	0.1012E+06	0.1080E+06
3	0.1857E-01	-0.3641E-01	0.1784E-01	0.9747E+05	0.1036E+06
4	0.1857E-01	-0.3641E-01	0.1784E-01	0.9747E+05	0.1036E+06
4	0.1846E-01	-0.3453E-01	0.1608E-01	0.9416E+05	0.9967E+05
5	0.1846E-01	-0.3453E-01	0.1608E-01	0.9416E+05	0.9967E+05
5	0.1835E-01	-0.3282E-01	0.1447E-01	0.9118E+05	0.9617E+05
6	0.1020E-03	-0.3900E-04	-0.6303E-04	0.5432E+05	0.5432E+05

6	0.9646E-04	-0.3865E-04	-0.5781E-04	0.5430E+05	0.5430E+05
7	0.9646E-04	-0.3865E-04	-0.5781E-04	0.5430E+05	0.5430E+05
7	0.9269E-04	-0.3847E-04	-0.5422E-04	0.5428E+05	0.5428E+05
8	0.9269E-04	-0.3847E-04	-0.5422E-04	0.5428E+05	0.5428E+05
8	0.9005E-04	-0.3840E-04	-0.5165E-04	0.5427E+05	0.5427E+05
9	0.9005E-04	-0.3840E-04	-0.5165E-04	0.5427E+05	0.5427E+05
9	0.8818E-04	-0.3842E-04	-0.4976E-04	0.5426E+05	0.5426E+05
10	0.8818E-04	-0.3842E-04	-0.4976E-04	0.5426E+05	0.5426E+05
10	0.8681E-04	-0.3848E-04	-0.4833E-04	0.5426E+05	0.5426E+05

```
LONGITUDINAL STRAIN = -0.4555E-02

LONGITUDINAL FORCE  = -0.2037E-09
```

The file **optcomp.conv**, containing convergence messages at each optimization iteration, is given below.

```
OPTIMIZATION ITERATION #   1
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #   2
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #   3
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #   4
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #   5
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #   6
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #   7
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #   8
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #   9
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #  10
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #  11
ALL POINTS REACHED CONVERGENCE
```

8.3 Appendix III: Example 2 - Constrained Optimization Problem

8.3.1 Construction and execution of the optcomp.data file

The construction of the **optcomp.data** file for the constrained optimization problem of Example 2, menu-driven by the user-friendly interface **shell.f**, is illustrated below. The text that appears in Courier-type capital letters is written to the screen at each step in the construction of the **optcomp.data** file. User's responses to the menu-driven commands are shown in bold Courier-type letters. The text in bold italics preceded by the word ***Note:*** represents manually inserted comments that explain in more detail certain options available to the user that have not been explained in the unconstrained optimization problem of Example 1 in Section 8.2.1.

```
        NASA-LEWIS RESEARCH CENTER, STRUCTURES DIVISION, CLEVELAND OHIO
                  ***********************************************
                  ***                OPTCOMP                  ***
                  ***                                         ***
                  ***    CONCENTRIC CYLINDER OPTIMIZATION     ***
                  ***    PROGRAM FOR THE DETERMINATION OF     ***
                  *** IDEALIZED INTERFACIAL LAYER PROPERTIES***
                  ***               WRITTEN BY                ***
                  ***                                         ***
                  ***           ROBERT SCOTT SALZAR           ***
                  ***          TODD OAKHILL WILLIAMS          ***
                  ***           MAREK-JERZY PINDERA           ***
                  ***                                         ***
                  ***                   OF                    ***
                  ***       THE UNIVERSITY OF VIRGINIA        ***
                  ***             SEPTEMBER, 1993             ***
                  ***                                         ***
                  *** DEVELOPED FOR THE FATIGUE AND FRACTURE***
                  ***  BRANCH OF NASA-LEWIS RESEARCH CENTER ***
                  ***        UNDER CONTRACT NAS3-26571        ***
                  ***  DR. S. M. ARNOLD (CONTRACT MONITOR)    ***
                  ***********************************************

 HIT RETURN TO CONTINUE ->

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b.   assumes any liabilities with respect to the use of, or for damages
     resulting from use of this software.

-------------------------------------------------------------------------------

 HIT RETURN TO CONTINUE ->
```

```
******MAIN MENU******

 1.  CREATE NEW DATA FILE
 2.  RUN EXISTING DATA FILE
 3.  ENTER NEW MATERIALS INTO DATABANK
 4.  EXIT SHELL
ENTER CHOICE -> 1

**********************************BLOCK 1**********************************
          SPECIFY CONCENTRIC CYLINDER GEOMETRY, MATERIALS
                      INCLUDING PROPERTIES


 IF FIBER IS HOMOGENEOUS, ENTER: 1
 IF FIBER IS LAYERED, ENTER: 2
 CHOICE -> 2

ENTER NUMBER OF FIBER LAYERS -> 2
ENTER RELATIVE FIBER CORE RADIUS -> .5
ENTER RELATIVE OUTER RADIUS OF FIBER LAYER 2 -> .632
ENTER THE NUMBER OF INTERFACE LAYERS -> 3
t/a RATIO OF INTERFACE 1: .03333
t/a RATIO OF INTERFACE 2: .03333
t/a RATIO OF INTERFACE 3: .03334


          ***CONCENTRIC CYLINDER CONFIGURATION***

SHELL         MATERIAL       OUTER RADIUS     VOLUME FRACTION

  1            FIBER           0.50000            0.2500
  2            FIBER           0.63200            0.1494
  3         INTERFACE 1        0.65306            0.0271
  4         INTERFACE 2        0.67413            0.0280
  5         INTERFACE 3        0.69520            0.0289
  6            MATRIX          0.75616            0.0885
  7            MATRIX          0.81712            0.0959
  8            MATRIX          0.87808            0.1033
  9            MATRIX          0.93904            0.1108
 10            MATRIX          1.00000            0.1182

FIBER VOLUME FRACTION =    0.3994
MATRIX VOLUME FRACTION =   0.5167

  IS INFORMATION CORRECT? <Y/N> y


          ***FIBER MATERIAL PROPERTY SELECTION***

    AVAILABLE FIBERS            AVAILABLE CONSTITUTIVE MODELS
  1  SiC  (SCS-6)  (psi)                1  ELASTIC
  2  Al2O3 (psi)                        2  PLASTIC
  3  ENTER NEW MATERIAL

ENTER MATERIAL FOR FIBER LAYER 1 -> 1

ENTER MATERIAL FOR FIBER LAYER 2 -> 1
ENTER CONSTITUTIVE MODEL FOR FIBER LAYER 2 -> 1


          ***MATRIX MATERIAL PROPERTY SELECTION***
```

```
 AVAILABLE MATRIX MATERIALS    AVAILABLE CONSTITUTIVE MODELS
  1   Ti-24Al-11Nb  (psi)                1  ELASTIC
  2   NiCrAlY1 (psi)                     2  PLASTIC
  3   NiCrAlY2 (psi)
  4   NiAl (psi)
  5   ENTER NEW MATERIAL

ENTER MATERIAL FOR MATRIX -> 1
ENTER CONSTITUTIVE MODEL FOR MATRIX -> 2

           ***INTERFACIAL LAYER REFERENCE MATERIALS***

   AVAILABLE MATERIALS           AVAILABLE CONSTITUTIVE MODELS
  1   SiC  (SCS-6)  (psi)                1  ELASTIC
  2   Ti-24Al-11Nb  (psi)                2  PLASTIC
  3   Al2O3 (psi)
  4   NiCrAlY1 (psi)
  5   NiCrAlY2 (psi)
  6   NiAl (psi)
  7   ENTER NEW MATERIAL

ENTER REFERENCE MATERIAL FOR INTERFACE  1 -> 2
ENTER CONSTITUTIVE MODEL FOR INTERFACE 1 -> 2
ENTER REFERENCE MATERIAL FOR INTERFACE  2 -> 2
ENTER CONSTITUTIVE MODEL FOR INTERFACE 2 -> 2
ENTER REFERENCE MATERIAL FOR INTERFACE  3 -> 2
ENTER CONSTITUTIVE MODEL FOR INTERFACE 3 -> 2


ENTER INITIAL DESIGN: Ei/Er, Yi/Yr, CTEi/CTEr, Hi/Hr

INTERFACE  1 : .5 .5 1 .5
INTERFACE  2 : .5 .5 3 .5
INTERFACE  3 : .5 .5 1 .5

    ***CONCENTRIC CYLINDER MATERIAL SPECIFICATION***

    SHELL          MATERIAL              CONSTITUTIVE MODEL

 1  FIBER       SiC  (SCS-6)  (psi)           ELASTIC
 2  FIBER       SiC  (SCS-6)  (psi)           ELASTIC
 3  INTERFACE     TBD                         INELASTIC
 4  INTERFACE     TBD                         INELASTIC
 5  INTERFACE     TBD                         INELASTIC
 6  MATRIX      Ti-24Al-11Nb  (psi)           INELASTIC
 7  MATRIX      Ti-24Al-11Nb  (psi)           INELASTIC
 8  MATRIX      Ti-24Al-11Nb  (psi)           INELASTIC
 9  MATRIX      Ti-24Al-11Nb  (psi)           INELASTIC
10  MATRIX      Ti-24Al-11Nb  (psi)           INELASTIC
           ***INTERFACE REFERENCE MATERIALS***

       INTERFACE     MATERIAL          CONSTITUTIVE MODEL
           1      Ti-24Al-11Nb  (psi)      INELASTIC
           2      Ti-24Al-11Nb  (psi)      INELASTIC
           3      Ti-24Al-11Nb  (psi)      INELASTIC

          ***INTERFACIAL LAYER INITIAL DESIGN***

    LAYER      Ei/Er       Yi/Yr      CTEi/CTEr      Hi/Hr
      1        0.500       0.500        1.000        0.500
      2        0.500       0.500        3.000        0.500
```

```
       3        0.500      0.500       1.000        0.500

        IS INFORMATION CORRECT? <Y/N> y

**********************************BLOCK 2**********************************
                            DEFINE OPTIMIZATION PROBLEM


                   ***DESIGN VARIABLE MENU***

         I.D.    DESIGN VARIABLE
          1    INTERFACIAL LAYER(S) CTE
          2    INTERFACIAL LAYER(S) ELASTIC MODULUS
          3    INTERFACIAL LAYER(S) HARDENING SLOPE
          4    INTERFACIAL LAYER(S) YIELD STRESS
          5    THICKNESS OF INTERFACIAL LAYER(S)

            ENTER NUMBER OF SELECTIONS -> 1
            ENTER I.D. CHOICE(S) -> 1


ENTER LOWER & UPPER BOUNDS OF CTE RATIO FOR INTERFACE  1 -> 0 4
ENTER LOWER & UPPER BOUNDS OF CTE RATIO FOR INTERFACE  2 -> 0 4
ENTER LOWER & UPPER BOUNDS OF CTE RATIO FOR INTERFACE  3 -> 0 4

                  ***DESIGN VARIABLE SUMMARY***

                   INTERFACE LAYER C.T.E. RATIO(S)
                LAYER   LOWER BOUND        UPPER BOUND
                  1        0.000              4.000
                  2        0.000              4.000
                  3        0.000              4.000

 IS INFORMATION CORRECT? <Y/N> y


          CHOOSE AN OBJECTIVE FUNCTION:

 ITEM#         FUNCTION

           FIBER FUNCTIONS
   1. RADIAL STRESS (INTERFACE)

       INTERFACIAL LAYER FUNCTIONS
   2. HOOP STRESS (FIBER/I.L.)
   3. HOOP STRESS (AVERAGE)
   4. RADIAL STRESS (FIBER/I.L.)
   5. RADIAL STRESS (I.L./MATRIX)
   6. HYDROSTATIC PRESSURE (I.L./MATRIX)
   7. LONGITUDINAL STRESS (AVERAGE)

           MATRIX FUNCTIONS
   8. HOOP STRESS (INTERFACE)
   9. RADIAL STRESS (INTERFACE)
  10. RADIAL STRAIN (INTERFACE)
  11. HYDROSTATIC PRESSURE (INTERFACE)
  12. LONGITUDINAL STRESS (INTERFACE)
  13. LONGITUDINAL STRESS (AVERAGE)

          MISCELLANEOUS FUNCTIONS
  14. LONGITUDINAL STRAIN (ASSEMBLAGE)
  15. USER DEFINED OBJECTIVE FUNCTION
ENTER CHOICE -> 8
```

```
OBJECTIVE FUNCTION IS TO BE:
      1.  MINIMIZED
      2.  MAXIMIZED
ENTER CHOICE -> 1


OBJECTIVE FUNCTION:

MINIMIZATION OF THE
MATRIX HOOP STRESS (INTERFACE)

IS INFORMATION CORRECT? <Y/N> y
```

Note: Select constraint functions from the menu below, or choose the User Defined Constraint Function (12) that has been entered by the user into the EXTCONST subroutine residing in the file constraint.f

```
            CHOOSE DESIRED CONSTRAINTS:

ITEM#            FUNCTION                          CONSTRAINT

      INTERFACIAL LAYER FUNCTIONS
  1.  HOOP STRESS (FIBER/I.L.)            1.  >  (NOT TO BE LESS THAN)
  2.  HOOP STRESS (I.L./MATRIX)           2.  <  (NOT TO EXCEED)
  3.  RADIAL STRESS (I.L./MATRIX)
  4.  RADIAL STRESS (FIBER/I.L.)
  5.  LONGITUDINAL STRESS (AVERAGE)

      MATRIX FUNCTIONS
  6.  HOOP STRESS (INTERFACE)
  7.  RADIAL STRESS (INTERFACE)
  8.  HYDROSTATIC PRESSURE (INTERFACE)
  9.  LONGITUDINAL STRESS (INTERFACE)
 10.  LONGITUDINAL STRESS (AVERAGE)

       MISCELLANEOUS FUNCTIONS
 11.  LONGITUDINAL STRAIN (ASSEMBLAGE)
 12.  USER DEFINED CONSTRAINT FUNCTION

 ENTER NUMBER OF SELECTIONS (ENTER 0 FOR NO CONSTRAINTS) -> 3
 ENTER FUNCTION  1 -> 1
 ENTER CONSTRAINT  1 -> 2
 ENTER FUNCTION  2 -> 2
 ENTER CONSTRAINT  2 -> 2
 ENTER FUNCTION  3 -> 12


 I.L. HOOP STRESS (FIBER/I.L.) NOT TO EXCEED -> 40000


 I.L. HOOP STRESS (I.L./MATRIX) NOT TO EXCEED -> 40000

 ****************************************************
 TO USE CONSTRAINT(S) IN SUBROUTINE EXTCONST: ENTER 1

 TO CHANGE CONSTRAINTS, EXIT SHELL PROGRAM, EDIT, COMPILE
 AND LINK SUBROUTINE EXTCONST TO INCLUDE YOUR
 CHOICE OF CONSTRAINT FUNCTION(S): ENTER 2
 ****************************************************

 ENTER CHOICE -> 1

 ENTER NUMBER OF CONSTRAINTS IN SUBROUTINE -> 1
```

CONSTRAINTS:

I.L. HOOP STRESS (FIBER/I.L.)
NOT TO EXCEED 40000.00

I.L. HOOP STRESS (I.L./MATRIX)
NOT TO EXCEED 40000.00

USER DEFINED CONSTRAINT FUNCTION(S)

IS INFORMATION CORRECT? <Y/N> **y**

**********************************BLOCK 3**********************************

DEFINE LOAD HISTORY, INCREMENT,
AND ITERATIONS

CAUTION
THE APPLIED TEMPERATURE LOAD MUST REMAIN BETWEEN 75.00 deg AND 1500.00 deg
****

NO. OF LOAD SEGMENTS, INITIAL TEMP., INITIAL PRESSURE, INITIAL AXIAL LOAD
-> **1 1500 0 0**
NO. OF INCREMENTS, ENDING TEMP., ENDING PRESSURE, ENDING AXIAL LOAD
-> **570 75 0 0**

CHANGE MAXIMUM NUMBER OF ITERATIONS (DEFAULT=10)? <Y/N> **y**
MAXIMUM NUMBER OF ITERATIONS -> **15**

CHANGE CONVERGENCE ERROR TOLERANCE (DEFAULT=0.01)? <Y/N> **n**

WRITE CONVERGENCE INFORMATION TO optcomp.conv FILE? <Y/N> **y**

WRITE OPTIMIZATION ITERATIONS TO SCREEN? <Y/N> **y**

LOAD HISTORY

STEP	INCREMENTS	TEMPERATURE	AXIAL	PRESSURE
1		1500.00	0.00	0.00
	570			
2		75.00	0.00	0.00

MAXIMUM NUMBER OF ITERATIONS = 15
CONVERGENCE ERROR TOLERANCE = 0.01000
CONVERGENCE INFORMATION WRITTEN TO optcomp.conv
OPTIMIZATION ITERATIONS WRITTEN TO SCREEN

IS INFORMATION CORRECT? <Y/N> **y**

WOULD YOU LIKE TO SEE A PROBLEM REVIEW? <Y/N> **y**

******************************PROBLEM REVIEW******************************

***CONCENTRIC CYLINDER CONFIGURATION**

```
  SHELL           MATERIAL              OUTER RADIUS  CONSTITUTIVE MODEL

 1  FIBER      SiC  (SCS-6)  (psi)        0.50000        ELASTIC
 2  FIBER      SiC  (SCS-6)  (psi)        0.63200        ELASTIC
 3  INTERFACE     TBD                     0.65306        INELASTIC
 4  INTERFACE     TBD                     0.67413        INELASTIC
 5  INTERFACE     TBD                     0.69520        INELASTIC
 6  MATRIX     Ti-24Al-11Nb  (psi)        0.75616        INELASTIC
 7  MATRIX     Ti-24Al-11Nb  (psi)        0.81712        INELASTIC
 8  MATRIX     Ti-24Al-11Nb  (psi)        0.87808        INELASTIC
 9  MATRIX     Ti-24Al-11Nb  (psi)        0.93904        INELASTIC
10  MATRIX     Ti-24Al-11Nb  (psi)        1.00000        INELASTIC

  FIBER VOLUME FRACTION =   0.3994
  MATRIX VOLUME FRACTION =  0.5167


HIT RETURN TO CONTINUE ->

              ***INTERFACE REFERENCE MATERIALS***

        INTERFACE      MATERIAL         CONSTITUTIVE MODEL
            1      Ti-24Al-11Nb  (psi)      INELASTIC
            2      Ti-24Al-11Nb  (psi)      INELASTIC
            3      Ti-24Al-11Nb  (psi)      INELASTIC


              ***INTERFACIAL LAYER INITIAL DESIGN***

           LAYER     Ei/Er     Yi/Yr    CTEi/CTEr  Hi/Hr
             1       0.500     0.500      1.000    0.500
             2       0.500     0.500      3.000    0.500
             3       0.500     0.500      1.000    0.500


HIT RETURN TO CONTINUE ->

                      DESIGN VARIABLE

              INTERFACE LAYER C.T.E. RATIO(S)
          LAYER     LOWER BOUND        UPPER BOUND
            1          0.000              4.000
            2          0.000              4.000
            3          0.000              4.000


HIT RETURN TO CONTINUE ->

         OBJECTIVE FUNCTION:
         MINIMIZATION OF THE MATRIX HOOP STRESS (INTERFACE)

         CONSTRAINTS:
         I.L HOOP STRESS (FIBER/I.L.)
         NOT TO EXCEED  40000.00

         I.L. HOOP STRESS (I.L./MATRIX)
         NOT TO EXCEED  40000.00

         USER DEFINED CONSTRAINT FUNCTION(S)


HIT RETURN TO CONTINUE ->
```

LOAD HISTORY

STEP	INCREMENTS	TEMPERATURE	AXIAL	PRESSURE
1		1500.00	0.00	0.00
	570			
2		75.00	0.00	0.00

```
MAXIMUM NUMBER OF ITERATIONS =    15
CONVERGENCE ERROR TOLERANCE = 0.01000
CONVERGENCE INFORMATION WRITTEN TO optcomp.conv
OPTIMIZATION ITERATIONS WRITTEN TO SCREEN

HIT RETURN TO CONTINUE ->

******MAIN MENU******

1.  CREATE NEW DATA FILE
2.  RUN EXISTING DATA FILE
3.  ENTER NEW MATERIALS INTO DATABANK
4.  EXIT SHELL
ENTER CHOICE -> 2


**************LEGEND FOR DESIGN VARIABLES***********
 X 1= CTE RATIO FOR INTERFACE  1
 X 2= CTE RATIO FOR INTERFACE  2
 X 3= CTE RATIO FOR INTERFACE  3
****************************************************
```

ITERATION #: 1

DESIGN VARIABLE	LOWER BOUND	CURRENT VALUE	UPPER BOUND	OBJECTIVE FN
X 1	0.0000	1.0000	4.0000	
X 2	0.0000	3.0000	4.0000	
X 3	0.0000	1.0000	4.0000	
				40182.75781

CONSTRAINT	VALUE	LIMIT
1	17231.0547	40000.0000
2	13842.7637	40000.0000
3	USER DEFINED CONSTRAINT	

ITERATION #: 2

DESIGN VARIABLE	LOWER BOUND	CURRENT VALUE	UPPER BOUND	OBJECTIVE FN
X 1	0.0000	1.0000	4.0000	
X 2	0.0000	3.0000	4.0000	
X 3	0.0000	1.0000	4.0000	
				40182.75391

CONSTRAINT	VALUE	LIMIT
1	17231.0957	40000.0000
2	13842.7812	40000.0000
3	USER DEFINED CONSTRAINT	

ITERATION #: 3

DESIGN VARIABLE	LOWER BOUND	CURRENT VALUE	UPPER BOUND	OBJECTIVE FN
X 1	0.0000	1.0010	4.0000	
X 2	0.0000	3.0000	4.0000	
X 3	0.0000	1.0000	4.0000	
				40179.64844

CONSTRAINT	VALUE	LIMIT
1	17254.7871	40000.0000
2	13842.1436	40000.0000
3	USER DEFINED CONSTRAINT	

ITERATION #: 4

DESIGN VARIABLE	LOWER BOUND	CURRENT VALUE	UPPER BOUND	OBJECTIVE FN

X 1	0.0000	1.0000	4.0000	
X 2	0.0000	3.0030	4.0000	
X 3	0.0000	1.0000	4.0000	
				40172.91797

CONSTRAINT	VALUE	LIMIT
1	17234.3301	40000.0000
2	13840.7520	40000.0000
3	USER DEFINED CONSTRAINT	

ITERATION #: 5

DESIGN VARIABLE	LOWER BOUND	CURRENT VALUE	UPPER BOUND	OBJECTIVE FN
X 1	0.0000	1.0000	4.0000	
X 2	0.0000	3.0000	4.0000	
X 3	0.0000	1.0010	4.0000	
				40179.42578

CONSTRAINT	VALUE	LIMIT
1	17232.0039	40000.0000
2	13870.5625	40000.0000
3	USER DEFINED CONSTRAINT	

ITERATION #: 6

DESIGN VARIABLE	LOWER BOUND	CURRENT VALUE	UPPER BOUND	OBJECTIVE FN
X 1	0.0000	1.0577	4.0000	
X 2	0.0000	2.0519	4.0000	
X 3	0.0000	1.0518	4.0000	
				42749.44141

CONSTRAINT	VALUE	LIMIT
1	17716.9844	40000.0000
2	15714.0479	40000.0000
3	USER DEFINED CONSTRAINT	

ITERATION #: 7

DESIGN VARIABLE	LOWER BOUND	CURRENT VALUE	UPPER BOUND	OBJECTIVE FN
X 1	0.0000	1.0115	4.0000	
X 2	0.0000	2.8104	4.0000	
X 3	0.0000	1.0104	4.0000	
				40725.58594

CONSTRAINT	VALUE	LIMIT
1	17313.5938	40000.0000
2	14242.8086	40000.0000
3	USER DEFINED CONSTRAINT	

ITERATION #: 8

DESIGN VARIABLE	LOWER BOUND	CURRENT VALUE	UPPER BOUND	OBJECTIVE FN
X 1	0.0000	1.0588	4.0000	
X 2	0.0000	2.0519	4.0000	
X 3	0.0000	1.0518	4.0000	
				42746.57031

CONSTRAINT	VALUE	LIMIT
1	17742.2305	40000.0000
2	15713.5459	40000.0000
3	USER DEFINED CONSTRAINT	

ITERATION #: 9

DESIGN VARIABLE	LOWER BOUND	CURRENT VALUE	UPPER BOUND	OBJECTIVE FN
X 1	0.0000	1.0577	4.0000	
X 2	0.0000	2.0539	4.0000	
X 3	0.0000	1.0518	4.0000	
				42743.59375

CONSTRAINT	VALUE	LIMIT
1	17718.7891	40000.0000
2	15713.0176	40000.0000
3	USER DEFINED CONSTRAINT	

```
  ITERATION #:    10
DESIGN VARIABLE   LOWER BOUND  CURRENT VALUE  UPPER BOUND   OBJECTIVE FN
      X 1           0.0000        1.0577         4.0000
      X 2           0.0000        2.0519         4.0000
      X 3           0.0000        1.0529         4.0000
                                                             42746.39453
  CONSTRAINT          VALUE          LIMIT
       1           17717.8125     40000.0000
       2           15740.3799     40000.0000
       3         USER DEFINED CONSTRAINT

  ITERATION #:    11
DESIGN VARIABLE   LOWER BOUND  CURRENT VALUE  UPPER BOUND   OBJECTIVE FN
      X 1           0.0000        1.5997         4.0000
      X 2           0.0000        2.0217         4.0000
      X 3           0.0000        1.6088         4.0000
                                                             39478.32422
  CONSTRAINT          VALUE          LIMIT
       1           31468.2871     40000.0000
       2           29457.8438     40000.0000
       3         USER DEFINED CONSTRAINT

  ITERATION #:    12
DESIGN VARIABLE   LOWER BOUND  CURRENT VALUE  UPPER BOUND   OBJECTIVE FN
      X 1           0.0000        2.4766         4.0000
      X 2           0.0000        1.9729         4.0000
      X 3           0.0000        2.5099         4.0000
                                                             32298.29883
  CONSTRAINT          VALUE          LIMIT
       1           53432.3047     40000.0000
       2           51542.0156     40000.0000
       3         USER DEFINED CONSTRAINT

  ITERATION #:    13
DESIGN VARIABLE   LOWER BOUND  CURRENT VALUE  UPPER BOUND   OBJECTIVE FN
      X 1           0.0000        2.4765         4.0000
      X 2           0.0000        1.9396         4.0000
      X 3           0.0000        2.5095         4.0000
                                                             32467.79297
  CONSTRAINT          VALUE          LIMIT
       1           53369.2969     40000.0000
       2           51497.3672     40000.0000
       3         USER DEFINED CONSTRAINT

  ITERATION #:    14
DESIGN VARIABLE   LOWER BOUND  CURRENT VALUE  UPPER BOUND   OBJECTIVE FN
      X 1           0.0000        1.9392         4.0000
      X 2           0.0000        2.0028         4.0000
      X 3           0.0000        1.9577         4.0000
                                                             37051.10938
  CONSTRAINT          VALUE          LIMIT
       1           40077.4102     40000.0000
       2           38160.8438     40000.0000
       3         USER DEFINED CONSTRAINT

  ITERATION #:    15
DESIGN VARIABLE   LOWER BOUND  CURRENT VALUE  UPPER BOUND   OBJECTIVE FN
      X 1           0.0000        1.9392         4.0000
      X 2           0.0000        1.9879         4.0000
      X 3           0.0000        1.9575         4.0000
                                                             37110.14062
  CONSTRAINT          VALUE          LIMIT
       1           40055.9727     40000.0000
       2           38149.5625     40000.0000
```

```
       3           USER DEFINED CONSTRAINT

  ITERATION #:    16
DESIGN VARIABLE   LOWER BOUND  CURRENT VALUE  UPPER BOUND   OBJECTIVE FN
      X 1           0.0000        1.9411        4.0000
      X 2           0.0000        1.9879        4.0000
      X 3           0.0000        1.9575        4.0000
                                                             37102.80078
  CONSTRAINT          VALUE          LIMIT
       1            40101.8086     40000.0000
       2            38150.3594     40000.0000
       3           USER DEFINED CONSTRAINT

  ITERATION #:    17
DESIGN VARIABLE   LOWER BOUND  CURRENT VALUE  UPPER BOUND   OBJECTIVE FN
      X 1           0.0000        1.9392        4.0000
      X 2           0.0000        1.9899        4.0000
      X 3           0.0000        1.9575        4.0000
                                                             37102.41016
  CONSTRAINT          VALUE          LIMIT
       1            40058.6719     40000.0000
       2            38150.4102     40000.0000
       3           USER DEFINED CONSTRAINT

  ITERATION #:    18
DESIGN VARIABLE   LOWER BOUND  CURRENT VALUE  UPPER BOUND   OBJECTIVE FN
      X 1           0.0000        1.9392        4.0000
      X 2           0.0000        1.9879        4.0000
      X 3           0.0000        1.9595        4.0000
                                                             37102.28125
  CONSTRAINT          VALUE          LIMIT
       1            40058.6914     40000.0000
       2            38197.2500     40000.0000
       3           USER DEFINED CONSTRAINT

  ITERATION #:    19
DESIGN VARIABLE   LOWER BOUND  CURRENT VALUE  UPPER BOUND   OBJECTIVE FN
      X 1           0.0000        1.8997        4.0000
      X 2           0.0000        1.9479        4.0000
      X 3           0.0000        2.6674        4.0000
                                                             34328.69141
  CONSTRAINT          VALUE          LIMIT
       1            40112.4062     40000.0000
       2            54530.1445     40000.0000
       3           USER DEFINED CONSTRAINT

  ITERATION #:    20
DESIGN VARIABLE   LOWER BOUND  CURRENT VALUE  UPPER BOUND   OBJECTIVE FN
      X 1           0.0000        1.9347        4.0000
      X 2           0.0000        1.9834        4.0000
      X 3           0.0000        2.0377        4.0000
                                                             36819.55469
  CONSTRAINT          VALUE          LIMIT
       1            40056.5508     40000.0000
       2            40083.9805     40000.0000
       3           USER DEFINED CONSTRAINT

  ITERATION #:    21
DESIGN VARIABLE   LOWER BOUND  CURRENT VALUE  UPPER BOUND   OBJECTIVE FN
      X 1           0.0000        1.9367        4.0000
      X 2           0.0000        1.9834        4.0000
      X 3           0.0000        2.0377        4.0000
                                                             36812.10938
  CONSTRAINT          VALUE          LIMIT
```

1	40102.4062	40000.0000
2	40084.9219	40000.0000
3	USER DEFINED CONSTRAINT	

ITERATION #: 22

DESIGN VARIABLE	LOWER BOUND	CURRENT VALUE	UPPER BOUND	OBJECTIVE FN
X 1	0.0000	1.9347	4.0000	
X 2	0.0000	1.9854	4.0000	
X 3	0.0000	2.0377	4.0000	
				36811.71094

CONSTRAINT	VALUE	LIMIT
1	40059.2656	40000.0000
2	40084.9766	40000.0000
3	USER DEFINED CONSTRAINT	

ITERATION #: 23

DESIGN VARIABLE	LOWER BOUND	CURRENT VALUE	UPPER BOUND	OBJECTIVE FN
X 1	0.0000	1.9347	4.0000	
X 2	0.0000	1.9834	4.0000	
X 3	0.0000	2.0397	4.0000	
				36811.20703

CONSTRAINT	VALUE	LIMIT
1	40059.4297	40000.0000
2	40132.8164	40000.0000
3	USER DEFINED CONSTRAINT	

THE PROBLEM REVIEW FILE IS optcomp.review
THE INITIAL AND FINAL DESIGNS ARE LOCATED
IN FILE optcomp.out

8.3.2 Results of the constrained optimization process

The file **optcomp.out**, containing information on the initial and final (optimum) values of the interfacial material properties, geometry, stresses and inelastic strains, for the data file **optcomp.data** constructed in Section 8.3.1, is given below.

```
NASA-LEWIS RESEARCH CENTER, STRUCTURES DIVISION, CLEVELAND OHIO
         *********************************************
         ***               OPTCOMP                 ***
         ***                                       ***
         ***    CONCENTRIC CYLINDER OPTIMIZATION   ***
         ***   PROGRAM FOR THE DETERMINATION OF    ***
         *** IDEALIZED INTERFACIAL LAYER PROPERTIES***
         ***              WRITTEN BY               ***
         ***                                       ***
         ***          ROBERT SCOTT SALZAR          ***
         ***         TODD OAKHILL WILLIAMS         ***
         ***          MAREK-JERZY PINDERA          ***
         ***                                       ***
         ***                  OF                   ***
         ***       THE UNIVERSITY OF VIRGINIA      ***
         ***            SEPTEMBER, 1993            ***
         ***                                       ***
         *** DEVELOPED FOR THE FATIGUE AND FRACTURE***
         ***  BRANCH OF NASA-LEWIS RESEARCH CENTER ***
         ***        UNDER CONTRACT NAS3-26571      ***
         ***  DR. S. M. ARNOLD (CONTRACT MONITOR)  ***
         *********************************************

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b.  assumes any liabilities with respect to the use of, or for damages
    resulting from use of this software.

------------------------------------------------------------------------------


           ***INITIAL CONCENTRIC CYLINDER CONFIGURATION***

 RING     MATERIAL                 OUTER RADIUS    CONSTITUTIVE MODEL

  1       FIBER LAYER 1 (CORE)        0.500        ISOTROPIC ELASTIC
  2       FIBER LAYER 2               0.632        ISOTROPIC ELASTIC
  3       INTERFACE LAYER 1           0.653        ISOTROPIC INELASTIC
  4       INTERFACE LAYER 2           0.674        ISOTROPIC INELASTIC
  5       INTERFACE LAYER 3           0.695        ISOTROPIC INELASTIC
  6       MATRIX                      0.756        ISOTROPIC INELASTIC
  7       MATRIX                      0.817        ISOTROPIC INELASTIC
  8       MATRIX                      0.878        ISOTROPIC INELASTIC
```

```
 9      MATRIX                          0.939       ISOTROPIC INELASTIC
10      MATRIX                          1.000       ISOTROPIC INELASTIC

***FIBER LAYER  1 PROPERTIES (CORE)***

TEMPERATURE =  0.1500E+04

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2500E-05  0.2500E-05  0.2500E-05
0.1000E+08  0.5800E+08

TEMPERATURE =  0.1342E+04

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2440E-05  0.2440E-05  0.2440E-05
0.1000E+08  0.5800E+08

TEMPERATURE =  0.1183E+04

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2370E-05  0.2370E-05  0.2370E-05
0.1000E+08  0.5800E+08

TEMPERATURE =  0.1025E+04

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2278E-05  0.2278E-05  0.2278E-05
0.1000E+08  0.5800E+08

TEMPERATURE =  0.8667E+03

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2187E-05  0.2187E-05  0.2187E-05
0.1000E+08  0.5800E+08

TEMPERATURE =  0.7083E+03

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2109E-05  0.2109E-05  0.2109E-05
0.1000E+08  0.5800E+08

TEMPERATURE =  0.5500E+03

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2051E-05  0.2051E-05  0.2051E-05
0.1000E+08  0.5800E+08

TEMPERATURE =  0.3917E+03

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2010E-05  0.2010E-05  0.2010E-05
0.1000E+08  0.5800E+08

TEMPERATURE =  0.2333E+03

0.5800E+08  0.5800E+08  0.5800E+08
```

```
0.2500E+00  0.2500E+00  0.2500E+00
0.1983E-05  0.1983E-05  0.1983E-05
0.1000E+08  0.5800E+08

TEMPERATURE =  0.7500E+02

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.1960E-05  0.1960E-05  0.1960E-05
0.1000E+08  0.5800E+08

***FIBER LAYER  2 PROPERTIES***

TEMPERATURE =  0.1500E+04

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2500E-05  0.2500E-05  0.2500E-05
0.1000E+08  0.5800E+08

TEMPERATURE =  0.1342E+04

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2440E-05  0.2440E-05  0.2440E-05
0.1000E+08  0.5800E+08

TEMPERATURE =  0.1183E+04

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2370E-05  0.2370E-05  0.2370E-05
0.1000E+08  0.5800E+08

TEMPERATURE =  0.1025E+04

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2278E-05  0.2278E-05  0.2278E-05
0.1000E+08  0.5800E+08

TEMPERATURE =  0.8667E+03

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2187E-05  0.2187E-05  0.2187E-05
0.1000E+08  0.5800E+08

TEMPERATURE =  0.7083E+03

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2109E-05  0.2109E-05  0.2109E-05
0.1000E+08  0.5800E+08

TEMPERATURE =  0.5500E+03

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2051E-05  0.2051E-05  0.2051E-05
0.1000E+08  0.5800E+08

TEMPERATURE =  0.3917E+03
```

```
  0.5800E+08  0.5800E+08  0.5800E+08
  0.2500E+00  0.2500E+00  0.2500E+00
  0.2010E-05  0.2010E-05  0.2010E-05
  0.1000E+08  0.5800E+08

  TEMPERATURE =   0.2333E+03

  0.5800E+08  0.5800E+08  0.5800E+08
  0.2500E+00  0.2500E+00  0.2500E+00
  0.1983E-05  0.1983E-05  0.1983E-05
  0.1000E+08  0.5800E+08

  TEMPERATURE =   0.7500E+02

  0.5800E+08  0.5800E+08  0.5800E+08
  0.2500E+00  0.2500E+00  0.2500E+00
  0.1960E-05  0.1960E-05  0.1960E-05
  0.1000E+08  0.5800E+08


***MATRIX PROPERTIES***

  TEMPERATURE =   0.1500E+04

  0.6200E+07  0.6200E+07  0.6200E+07
  0.2600E+00  0.2600E+00  0.2600E+00
  0.6150E-05  0.6150E-05  0.6150E-05
  0.2400E+05  0.1000E+04

  TEMPERATURE =   0.1342E+04

  0.7554E+07  0.7554E+07  0.7554E+07
  0.2600E+00  0.2600E+00  0.2600E+00
  0.6010E-05  0.6010E-05  0.6010E-05
  0.3251E+05  0.3306E+05

  TEMPERATURE =   0.1183E+04

  0.1044E+08  0.1044E+08  0.1044E+08
  0.2600E+00  0.2600E+00  0.2600E+00
  0.5888E-05  0.5888E-05  0.5888E-05
  0.3979E+05  0.1130E+06

  TEMPERATURE =   0.1025E+04

  0.1335E+08  0.1335E+08  0.1335E+08
  0.2600E+00  0.2600E+00  0.2600E+00
  0.5816E-05  0.5816E-05  0.5816E-05
  0.4535E+05  0.2793E+06

  TEMPERATURE =   0.8667E+03

  0.1174E+08  0.1174E+08  0.1174E+08
  0.2600E+00  0.2600E+00  0.2600E+00
  0.5750E-05  0.5750E-05  0.5750E-05
  0.5134E+05  0.3591E+06

  TEMPERATURE =   0.7083E+03

  0.1092E+08  0.1092E+08  0.1092E+08
  0.2600E+00  0.2600E+00  0.2600E+00
  0.5606E-05  0.5606E-05  0.5606E-05
  0.5616E+05  0.2007E+06
```

TEMPERATURE = 0.5500E+03

0.1249E+08	0.1249E+08	0.1249E+08
0.2600E+00	0.2600E+00	0.2600E+00
0.5394E-05	0.5394E-05	0.5394E-05
0.5882E+05	0.3999E+05	

TEMPERATURE = 0.3917E+03

0.1450E+08	0.1450E+08	0.1450E+08
0.2600E+00	0.2600E+00	0.2600E+00
0.5200E-05	0.5200E-05	0.5200E-05
0.5900E+05	0.4428E+06	

TEMPERATURE = 0.2333E+03

0.1545E+08	0.1545E+08	0.1545E+08
0.2600E+00	0.2600E+00	0.2600E+00
0.5086E-05	0.5086E-05	0.5086E-05
0.5679E+05	0.1746E+07	

TEMPERATURE = 0.7500E+02

0.1600E+08	0.1600E+08	0.1600E+08
0.2600E+00	0.2600E+00	0.2600E+00
0.5000E-05	0.5000E-05	0.5000E-05
0.5389E+05	0.3333E+07	

*********INITIAL INTERFACE PROPERTIES*********

INTERFACE LAYER 1

TEMPERATURE = 0.1500E+04

0.3100E+07	0.3100E+07	0.3100E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.6150E-05	0.6150E-05	0.6150E-05
0.1200E+05	0.5000E+03	

TEMPERATURE = 0.1342E+04

0.3777E+07	0.3777E+07	0.3777E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.6010E-05	0.6010E-05	0.6010E-05
0.1625E+05	0.1653E+05	

TEMPERATURE = 0.1183E+04

0.5219E+07	0.5219E+07	0.5219E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.5888E-05	0.5888E-05	0.5888E-05
0.1990E+05	0.5652E+05	

TEMPERATURE = 0.1025E+04

0.6675E+07	0.6675E+07	0.6675E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.5816E-05	0.5816E-05	0.5816E-05
0.2267E+05	0.1397E+06	

TEMPERATURE = 0.8667E+03

```
0.5869E+07  0.5869E+07  0.5869E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.5750E-05  0.5750E-05  0.5750E-05
0.2567E+05  0.1796E+06

TEMPERATURE =  0.7083E+03

0.5458E+07  0.5458E+07  0.5458E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.5606E-05  0.5606E-05  0.5606E-05
0.2808E+05  0.1004E+06

TEMPERATURE =  0.5500E+03

0.6243E+07  0.6243E+07  0.6243E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.5394E-05  0.5394E-05  0.5394E-05
0.2941E+05  0.1999E+05

TEMPERATURE =  0.3917E+03

0.7252E+07  0.7252E+07  0.7252E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.5200E-05  0.5200E-05  0.5200E-05
0.2950E+05  0.2214E+06

TEMPERATURE =  0.2333E+03

0.7726E+07  0.7726E+07  0.7726E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.5086E-05  0.5086E-05  0.5086E-05
0.2840E+05  0.8730E+06

TEMPERATURE =  0.7500E+02

0.8000E+07  0.8000E+07  0.8000E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.5000E-05  0.5000E-05  0.5000E-05
0.2695E+05  0.1666E+07


***INTERFACE LAYER  2***

TEMPERATURE =  0.1500E+04

0.3100E+07  0.3100E+07  0.3100E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1845E-04  0.1845E-04  0.1845E-04
0.1200E+05  0.5000E+03

TEMPERATURE =  0.1342E+04

0.3777E+07  0.3777E+07  0.3777E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1803E-04  0.1803E-04  0.1803E-04
0.1625E+05  0.1653E+05

TEMPERATURE =  0.1183E+04

0.5219E+07  0.5219E+07  0.5219E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1766E-04  0.1766E-04  0.1766E-04
0.1990E+05  0.5652E+05
```

TEMPERATURE = 0.1025E+04

0.6675E+07	0.6675E+07	0.6675E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1745E-04	0.1745E-04	0.1745E-04
0.2267E+05	0.1397E+06	

TEMPERATURE = 0.8667E+03

0.5869E+07	0.5869E+07	0.5869E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1725E-04	0.1725E-04	0.1725E-04
0.2567E+05	0.1796E+06	

TEMPERATURE = 0.7083E+03

0.5458E+07	0.5458E+07	0.5458E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1682E-04	0.1682E-04	0.1682E-04
0.2808E+05	0.1004E+06	

TEMPERATURE = 0.5500E+03

0.6243E+07	0.6243E+07	0.6243E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1618E-04	0.1618E-04	0.1618E-04
0.2941E+05	0.1999E+05	

TEMPERATURE = 0.3917E+03

0.7252E+07	0.7252E+07	0.7252E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1560E-04	0.1560E-04	0.1560E-04
0.2950E+05	0.2214E+06	

TEMPERATURE = 0.2333E+03

0.7726E+07	0.7726E+07	0.7726E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1526E-04	0.1526E-04	0.1526E-04
0.2840E+05	0.8730E+06	

TEMPERATURE = 0.7500E+02

0.8000E+07	0.8000E+07	0.8000E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1500E-04	0.1500E-04	0.1500E-04
0.2695E+05	0.1666E+07	

INTERFACE LAYER 3

TEMPERATURE = 0.1500E+04

0.3100E+07	0.3100E+07	0.3100E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.6150E-05	0.6150E-05	0.6150E-05
0.1200E+05	0.5000E+03	

TEMPERATURE = 0.1342E+04

0.3777E+07	0.3777E+07	0.3777E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.6010E-05	0.6010E-05	0.6010E-05

0.1625E+05 0.1653E+05

TEMPERATURE = 0.1183E+04

0.5219E+07	0.5219E+07	0.5219E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.5888E-05	0.5888E-05	0.5888E-05
0.1990E+05	0.5652E+05	

TEMPERATURE = 0.1025E+04

0.6675E+07	0.6675E+07	0.6675E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.5816E-05	0.5816E-05	0.5816E-05
0.2267E+05	0.1397E+06	

TEMPERATURE = 0.8667E+03

0.5869E+07	0.5869E+07	0.5869E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.5750E-05	0.5750E-05	0.5750E-05
0.2567E+05	0.1796E+06	

TEMPERATURE = 0.7083E+03

0.5458E+07	0.5458E+07	0.5458E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.5606E-05	0.5606E-05	0.5606E-05
0.2808E+05	0.1004E+06	

TEMPERATURE = 0.5500E+03

0.6243E+07	0.6243E+07	0.6243E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.5394E-05	0.5394E-05	0.5394E-05
0.2941E+05	0.1999E+05	

TEMPERATURE = 0.3917E+03

0.7252E+07	0.7252E+07	0.7252E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.5200E-05	0.5200E-05	0.5200E-05
0.2950E+05	0.2214E+06	

TEMPERATURE = 0.2333E+03

0.7726E+07	0.7726E+07	0.7726E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.5086E-05	0.5086E-05	0.5086E-05
0.2840E+05	0.8730E+06	

TEMPERATURE = 0.7500E+02

0.8000E+07	0.8000E+07	0.8000E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.5000E-05	0.5000E-05	0.5000E-05
0.2695E+05	0.1666E+07	

INITIAL STRESSES AND INELASTIC STRAINS

RING NO.	INTER RADIUS	STRXX	STRRR	STRTT	W(I)
1	0.0000E+00	-0.8115E+05	-0.2065E+05	-0.2065E+05	0.0000E+00

1	0.5000E+00	-0.8115E+05	-0.2065E+05	-0.2065E+05	-0.1515E-02
2	0.5000E+00	-0.8115E+05	-0.2065E+05	-0.2065E+05	-0.1515E-02
2	0.6320E+00	-0.8115E+05	-0.2065E+05	-0.2065E+05	-0.1915E-02
3	0.6320E+00	0.1360E+05	-0.2065E+05	0.1723E+05	-0.1915E-02
3	0.6531E+00	0.1458E+05	-0.1943E+05	0.1709E+05	-0.2245E-02
4	0.6531E+00	0.5976E+05	-0.1943E+05	0.6136E+05	-0.2245E-02
4	0.6741E+00	0.6095E+05	-0.1693E+05	0.6006E+05	-0.3441E-02
5	0.6741E+00	0.1663E+05	-0.1693E+05	0.1405E+05	-0.3441E-02
5	0.6952E+00	0.1751E+05	-0.1600E+05	0.1384E+05	-0.3725E-02
6	0.6952E+00	0.4852E+05	-0.1600E+05	0.4018E+05	-0.3725E-02
6	0.7562E+00	0.5293E+05	-0.1152E+05	0.3890E+05	-0.4435E-02
7	0.7562E+00	0.5293E+05	-0.1152E+05	0.3890E+05	-0.4435E-02
7	0.8171E+00	0.5653E+05	-0.7814E+04	0.3738E+05	-0.5105E-02
8	0.8171E+00	0.5653E+05	-0.7814E+04	0.3738E+05	-0.5105E-02
8	0.8781E+00	0.5940E+05	-0.4731E+04	0.3573E+05	-0.5747E-02
9	0.8781E+00	0.5940E+05	-0.4731E+04	0.3573E+05	-0.5747E-02
9	0.9390E+00	0.6164E+05	-0.2161E+04	0.3407E+05	-0.6365E-02
10	0.9390E+00	0.6164E+05	-0.2161E+04	0.3407E+05	-0.6365E-02
10	0.1000E+01	0.6336E+05	0.3020E-09	0.3247E+05	-0.6966E-02

RING NO.	EPXXP	EPRRP	EPTTP	STREFF	SIGEFF
1	0.0000E+00	0.0000E+00	0.0000E+00	0.6050E+05	0.1000E+08
1	0.0000E+00	0.0000E+00	0.0000E+00	0.6050E+05	0.1000E+08
2	0.0000E+00	0.0000E+00	0.0000E+00	0.6050E+05	0.1000E+08
2	0.0000E+00	0.0000E+00	0.0000E+00	0.6050E+05	0.1000E+08
3	0.1823E-02	-0.4378E-02	0.2555E-02	0.3621E+05	0.3621E+05
3	0.1736E-02	-0.3973E-02	0.2237E-02	0.3533E+05	0.3533E+05
4	0.1346E-01	-0.2757E-01	0.1411E-01	0.8000E+05	0.8497E+05
4	0.1335E-01	-0.2608E-01	0.1272E-01	0.7744E+05	0.8183E+05
5	0.1461E-02	-0.2560E-02	0.1098E-02	0.3235E+05	0.3235E+05
5	0.1376E-02	-0.2305E-02	0.9291E-03	0.3183E+05	0.3183E+05
6	0.9950E-03	-0.1622E-02	0.6275E-03	0.6078E+05	0.6078E+05
6	0.7711E-03	-0.1116E-02	0.3452E-03	0.5870E+05	0.5870E+05
7	0.7711E-03	-0.1116E-02	0.3452E-03	0.5870E+05	0.5870E+05
7	0.5816E-03	-0.7570E-03	0.1754E-03	0.5723E+05	0.5723E+05
8	0.5816E-03	-0.7570E-03	0.1754E-03	0.5723E+05	0.5723E+05
8	0.4255E-03	-0.5040E-03	0.7847E-04	0.5617E+05	0.5617E+05
9	0.4255E-03	-0.5040E-03	0.7847E-04	0.5617E+05	0.5617E+05
9	0.3006E-03	-0.3277E-03	0.2711E-04	0.5542E+05	0.5542E+05
10	0.3006E-03	-0.3277E-03	0.2711E-04	0.5542E+05	0.5542E+05
10	0.2020E-03	-0.2047E-03	0.2772E-05	0.5488E+05	0.5488E+05

LONGITUDINAL STRAIN = -0.4334E-02

LONGITUDINAL FORCE = 0.4002E-10

FINAL CONCENTRIC CYLINDER CONFIGURATION

RING	MATERIAL	OUTER RADIUS	CONSTITUTIVE MODEL
1	FIBER LAYER 1 (CORE)	0.500	ISOTROPIC ELASTIC
2	FIBER LAYER 2	0.632	ISOTROPIC ELASTIC
3	INTERFACE LAYER 1	0.653	ISOTROPIC INELASTIC
4	INTERFACE LAYER 2	0.674	ISOTROPIC INELASTIC
5	INTERFACE LAYER 3	0.695	ISOTROPIC INELASTIC
6	MATRIX	0.756	ISOTROPIC INELASTIC
7	MATRIX	0.817	ISOTROPIC INELASTIC
8	MATRIX	0.878	ISOTROPIC INELASTIC
9	MATRIX	0.939	ISOTROPIC INELASTIC
10	MATRIX	1.000	ISOTROPIC INELASTIC

```
**********FINAL INTERFACE PROPERTIES**********


  ***INTERFACE LAYER  1***

  TEMPERATURE =  0.1500E+04

  0.3100E+07  0.3100E+07  0.3100E+07
  0.2600E+00  0.2600E+00  0.2600E+00
  0.1190E-04  0.1190E-04  0.1190E-04
  0.1200E+05  0.5000E+03

  TEMPERATURE =  0.1342E+04

  0.3777E+07  0.3777E+07  0.3777E+07
  0.2600E+00  0.2600E+00  0.2600E+00
  0.1163E-04  0.1163E-04  0.1163E-04
  0.1625E+05  0.1653E+05

  TEMPERATURE =  0.1183E+04

  0.5219E+07  0.5219E+07  0.5219E+07
  0.2600E+00  0.2600E+00  0.2600E+00
  0.1139E-04  0.1139E-04  0.1139E-04
  0.1990E+05  0.5652E+05

  TEMPERATURE =  0.1025E+04

  0.6675E+07  0.6675E+07  0.6675E+07
  0.2600E+00  0.2600E+00  0.2600E+00
  0.1125E-04  0.1125E-04  0.1125E-04
  0.2267E+05  0.1397E+06

  TEMPERATURE =  0.8667E+03

  0.5869E+07  0.5869E+07  0.5869E+07
  0.2600E+00  0.2600E+00  0.2600E+00
  0.1112E-04  0.1112E-04  0.1112E-04
  0.2567E+05  0.1796E+06

  TEMPERATURE =  0.7083E+03

  0.5458E+07  0.5458E+07  0.5458E+07
  0.2600E+00  0.2600E+00  0.2600E+00
  0.1085E-04  0.1085E-04  0.1085E-04
  0.2808E+05  0.1004E+06

  TEMPERATURE =  0.5500E+03

  0.6243E+07  0.6243E+07  0.6243E+07
  0.2600E+00  0.2600E+00  0.2600E+00
  0.1044E-04  0.1044E-04  0.1044E-04
  0.2941E+05  0.1999E+05

  TEMPERATURE =  0.3917E+03

  0.7252E+07  0.7252E+07  0.7252E+07
  0.2600E+00  0.2600E+00  0.2600E+00
  0.1006E-04  0.1006E-04  0.1006E-04
  0.2950E+05  0.2214E+06

  TEMPERATURE =  0.2333E+03
```

```
0.7726E+07  0.7726E+07  0.7726E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.9840E-05  0.9840E-05  0.9840E-05
0.2840E+05  0.8730E+06

TEMPERATURE =  0.7500E+02

0.8000E+07  0.8000E+07  0.8000E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.9674E-05  0.9674E-05  0.9674E-05
0.2695E+05  0.1666E+07


***INTERFACE LAYER  2***

TEMPERATURE =  0.1500E+04

0.3100E+07  0.3100E+07  0.3100E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1220E-04  0.1220E-04  0.1220E-04
0.1200E+05  0.5000E+03

TEMPERATURE =  0.1342E+04

0.3777E+07  0.3777E+07  0.3777E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1192E-04  0.1192E-04  0.1192E-04
0.1625E+05  0.1653E+05

TEMPERATURE =  0.1183E+04

0.5219E+07  0.5219E+07  0.5219E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1168E-04  0.1168E-04  0.1168E-04
0.1990E+05  0.5652E+05

TEMPERATURE =  0.1025E+04

0.6675E+07  0.6675E+07  0.6675E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1154E-04  0.1154E-04  0.1154E-04
0.2267E+05  0.1397E+06

TEMPERATURE =  0.8667E+03

0.5869E+07  0.5869E+07  0.5869E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1140E-04  0.1140E-04  0.1140E-04
0.2567E+05  0.1796E+06

TEMPERATURE =  0.7083E+03

0.5458E+07  0.5458E+07  0.5458E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1112E-04  0.1112E-04  0.1112E-04
0.2808E+05  0.1004E+06

TEMPERATURE =  0.5500E+03

0.6243E+07  0.6243E+07  0.6243E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1070E-04  0.1070E-04  0.1070E-04
0.2941E+05  0.1999E+05
```

TEMPERATURE = 0.3917E+03

0.7252E+07	0.7252E+07	0.7252E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1031E-04	0.1031E-04	0.1031E-04
0.2950E+05	0.2214E+06	

TEMPERATURE = 0.2333E+03

0.7726E+07	0.7726E+07	0.7726E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1009E-04	0.1009E-04	0.1009E-04
0.2840E+05	0.8730E+06	

TEMPERATURE = 0.7500E+02

0.8000E+07	0.8000E+07	0.8000E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.9917E-05	0.9917E-05	0.9917E-05
0.2695E+05	0.1666E+07	

INTERFACE LAYER 3

TEMPERATURE = 0.1500E+04

0.3100E+07	0.3100E+07	0.3100E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1253E-04	0.1253E-04	0.1253E-04
0.1200E+05	0.5000E+03	

TEMPERATURE = 0.1342E+04

0.3777E+07	0.3777E+07	0.3777E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1225E-04	0.1225E-04	0.1225E-04
0.1625E+05	0.1653E+05	

TEMPERATURE = 0.1183E+04

0.5219E+07	0.5219E+07	0.5219E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1200E-04	0.1200E-04	0.1200E-04
0.1990E+05	0.5652E+05	

TEMPERATURE = 0.1025E+04

0.6675E+07	0.6675E+07	0.6675E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1185E-04	0.1185E-04	0.1185E-04
0.2267E+05	0.1397E+06	

TEMPERATURE = 0.8667E+03

0.5869E+07	0.5869E+07	0.5869E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1172E-04	0.1172E-04	0.1172E-04
0.2567E+05	0.1796E+06	

TEMPERATURE = 0.7083E+03

0.5458E+07	0.5458E+07	0.5458E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1142E-04	0.1142E-04	0.1142E-04

0.2808E+05 0.1004E+06

TEMPERATURE = 0.5500E+03

0.6243E+07	0.6243E+07	0.6243E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1099E-04	0.1099E-04	0.1099E-04
0.2941E+05	0.1999E+05	

TEMPERATURE = 0.3917E+03

0.7252E+07	0.7252E+07	0.7252E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1060E-04	0.1060E-04	0.1060E-04
0.2950E+05	0.2214E+06	

TEMPERATURE = 0.2333E+03

0.7726E+07	0.7726E+07	0.7726E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1036E-04	0.1036E-04	0.1036E-04
0.2840E+05	0.8730E+06	

TEMPERATURE = 0.7500E+02

0.8000E+07	0.8000E+07	0.8000E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1019E-04	0.1019E-04	0.1019E-04
0.2695E+05	0.1666E+07	

FINAL STRESSES AND INELASTIC STRAINS

RING NO.	INTER RADIUS	STRXX	STRRR	STRTT	W(I)
1	0.0000E+00	-0.8373E+05	-0.1964E+05	-0.1964E+05	0.0000E+00
1	0.5000E+00	-0.8373E+05	-0.1964E+05	-0.1964E+05	-0.1503E-02
2	0.5000E+00	-0.8373E+05	-0.1964E+05	-0.1964E+05	-0.1503E-02
2	0.6320E+00	-0.8373E+05	-0.1964E+05	-0.1964E+05	-0.1900E-02
3	0.6320E+00	0.3703E+05	-0.1964E+05	0.4006E+05	-0.1900E-02
3	0.6531E+00	0.3814E+05	-0.1773E+05	0.3926E+05	-0.2634E-02
4	0.6531E+00	0.3925E+05	-0.1773E+05	0.4037E+05	-0.2634E-02
4	0.6741E+00	0.4029E+05	-0.1593E+05	0.3959E+05	-0.3364E-02
5	0.6741E+00	0.4152E+05	-0.1593E+05	0.4085E+05	-0.3364E-02
5	0.6952E+00	0.4250E+05	-0.1422E+05	0.4008E+05	-0.4098E-02
6	0.6952E+00	0.5026E+05	-0.1422E+05	0.3682E+05	-0.4098E-02
6	0.7562E+00	0.5424E+05	-0.1017E+05	0.3512E+05	-0.4776E-02
7	0.7562E+00	0.5424E+05	-0.1017E+05	0.3512E+05	-0.4776E-02
7	0.8171E+00	0.5733E+05	-0.6861E+04	0.3329E+05	-0.5421E-02
8	0.8171E+00	0.5733E+05	-0.6861E+04	0.3329E+05	-0.5421E-02
8	0.8781E+00	0.5967E+05	-0.4135E+04	0.3148E+05	-0.6043E-02
9	0.8781E+00	0.5967E+05	-0.4135E+04	0.3148E+05	-0.6043E-02
9	0.9390E+00	0.6144E+05	-0.1882E+04	0.2976E+05	-0.6645E-02
10	0.9390E+00	0.6144E+05	-0.1882E+04	0.2976E+05	-0.6645E-02
10	0.1000E+01	0.6276E+05	0.6439E-09	0.2819E+05	-0.7234E-02

RING NO.	EPXXP	EPRRP	EPTTP	STREFF	SIGEFF
1	0.0000E+00	0.0000E+00	0.0000E+00	0.6409E+05	0.1000E+08
1	0.0000E+00	0.0000E+00	0.0000E+00	0.6409E+05	0.1000E+08
2	0.0000E+00	0.0000E+00	0.0000E+00	0.6409E+05	0.1000E+08
2	0.0000E+00	0.0000E+00	0.0000E+00	0.6409E+05	0.1000E+08
3	0.7064E-02	-0.1503E-01	0.7969E-02	0.5825E+05	0.5860E+05
3	0.6961E-02	-0.1410E-01	0.7139E-02	0.5644E+05	0.5662E+05

4	0.7247E-02	-0.1467E-01	0.7424E-02	0.5754E+05	0.5782E+05
4	0.7151E-02	-0.1381E-01	0.6656E-02	0.5587E+05	0.5601E+05
5	0.7470E-02	-0.1444E-01	0.6973E-02	0.5712E+05	0.5735E+05
5	0.7378E-02	-0.1363E-01	0.6250E-02	0.5555E+05	0.5566E+05
6	0.8077E-03	-0.1165E-02	0.3572E-03	0.5892E+05	0.5892E+05
6	0.5968E-03	-0.7699E-03	0.1731E-03	0.5729E+05	0.5729E+05
7	0.5968E-03	-0.7699E-03	0.1731E-03	0.5729E+05	0.5729E+05
7	0.4281E-03	-0.5006E-03	0.7256E-04	0.5617E+05	0.5617E+05
8	0.4281E-03	-0.5006E-03	0.7256E-04	0.5617E+05	0.5617E+05
8	0.2960E-03	-0.3176E-03	0.2161E-04	0.5538E+05	0.5538E+05
9	0.2960E-03	-0.3176E-03	0.2161E-04	0.5538E+05	0.5538E+05
9	0.1947E-03	-0.1938E-03	-0.8914E-06	0.5483E+05	0.5483E+05
10	0.1947E-03	-0.1938E-03	-0.8914E-06	0.5483E+05	0.5483E+05
10	0.1172E-03	-0.1093E-03	-0.7940E-05	0.5444E+05	0.5444E+05

```
LONGITUDINAL STRAIN = -0.4387E-02

LONGITUDINAL FORCE  =  0.3638E-11
```

The file **optcomp.conv**, containing convergence messages at each optimization iteration, is given below.

```
OPTIMIZATION ITERATION #   1
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #   2
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #   3
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #   4
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #   5
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #   6
NON-CONVERGENCE AT FOLLOWING LOADING STATES

Temperature =    200.000
Radial traction =      0.000
Average axial stress =     -0.031


OPTIMIZATION ITERATION #   7
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #   8
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #   9
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #  10
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #  11
ALL POINTS REACHED CONVERGENCE
```

```
OPTIMIZATION ITERATION #  12
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #  13
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #  14
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #  15
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #  16
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #  17
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #  18
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #  19
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #  20
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #  21
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #  22
ALL POINTS REACHED CONVERGENCE

OPTIMIZATION ITERATION #  23
ALL POINTS REACHED CONVERGENCE
```

8.4 Appendix IV: Example 3 - Construction of a Material Property Databank

An example illustrating the construction of the fiber material property data bank **fiber.data** for the SiC SCS-6 fiber of Example 3, menu-driven by the user-friendly interface **shell.f**, is provided below. The text that appears in Courier-type capital letters is written to the screen at each step in the construction of the **fiber.data** file. User's responses to the menu-driven commands are shown in bold Courier-type letters. The text in bold italics preceded by the word ***Note:*** represents manually inserted comments that explain in more detail certain options available to the user.

```
NASA-LEWIS RESEARCH CENTER, STRUCTURES DIVISION, CLEVELAND OHIO
         *********************************************
         ***              OPTCOMP                  ***
         ***                                       ***
         ***   CONCENTRIC CYLINDER OPTIMIZATION    ***
         ***   PROGRAM FOR THE DETERMINATION OF    ***
         *** IDEALIZED INTERFACIAL LAYER PROPERTIES***
         ***             WRITTEN BY                ***
         ***                                       ***
         ***          ROBERT SCOTT SALZAR          ***
         ***         TODD OAKHILL WILLIAMS         ***
         ***          MAREK-JERZY PINDERA          ***
         ***                                       ***
         ***                 OF                    ***
         ***       THE UNIVERSITY OF VIRGINIA      ***
         ***            SEPTEMBER, 1993            ***
         ***                                       ***
         *** DEVELOPED FOR THE FATIGUE AND FRACTURE***
         ***  BRANCH OF NASA-LEWIS RESEARCH CENTER ***
         ***        UNDER CONTRACT NAS3-26571      ***
         ***  DR. S. M. ARNOLD (CONTRACT MONITOR)  ***
         *********************************************

 HIT RETURN TO CONTINUE ->

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b.  assumes any liabilities with respect to the use of, or for damages
    resulting from use of this software.

------------------------------------------------------------------------------

 HIT RETURN TO CONTINUE ->
```

```
        ******MAIN MENU******

      1.  CREATE NEW DATA FILE
      2.  RUN EXISTING DATA FILE
      3.  ENTER NEW MATERIALS INTO DATABANK
      4.  EXIT SHELL
     ENTER CHOICE -> 3
```

Note: Select choice 3 in order to add additional material properties into the material selection menus.

```
            ***MATERIAL INPUT MENU***

   1.  ENTER NEW FIBER MATERIALS
   2.  ENTER NEW MATRIX MATERIALS
   3.  ENTER NEW REFERENCE MATERIALS FOR INTERFACE LAYERS
   4.  RETURN TO MAIN MENU

   ENTER CHOICE -> 1
```

Note: Select which databank to update (in this case the fiber databank).

```
         ***FIBER MATERIAL DATABANK***

         AVAILABLE FIBERS
       NONE
   1.  ENTER NEW MATERIAL
   2.  RETURN TO MATERIAL MENU

   ENTER CHOICE -> 1
```

Note: At this point, there are no fibers in the databank. Select 1 to add a fiber or 2 to return one menu back.

```
*******************SPECIFY NEW MATERIAL PROPERTIES*******************
```

Note: Enter the material name string (including units for future reference), and the number of temperatures at which material properties are specified.

```
ENTER NEW MATERIAL NAME -> SiC  (psi)
ENTER NUMBER OF TEMPERATURES AT WHICH PROPERTIES
WILL BE ENTERED (3 OR GREATER) -> 6
```

Note: Enter whether your material is isotropic, transversely isotropic, or orthotropic.

```
IF MATERIAL IS ISOTROPIC, ENTER 1
IF MATERIAL IS TRANSVERSELY ISOTROPIC, ENTER 2
IF MATERIAL IS ORTHOTROPIC, ENTER 3
ENTER CHOICE -> 1
```

Note: Review of material name and input information.

```
MATERIAL NAME IS SiC  (psi)
NUMBER OF TEMPERATURES IS   6
MATERIAL IS ISOTROPIC

IS INFORMATION CORRECT? <Y/N> y
```

Note: Properties can be entered with either ascending or descending temperature. Enter properties at prompt. At review, check properties for correctness.

```
***ENTER PROPERTIES WITH EITHER ASCENDING OR***
         ***DESCENDING TEMPERATURES***

ENTER TEMPERATURE -> 1500
ENTER ELASTIC MODULUS (EXX) -> 58.0D+06
```

```
ENTER POISSON'S RATIO (VXR) -> .25
ENTER C.T.E. (ALFXX) -> 2.5D-06
ENTER YIELD POINT (Y) -> 10.0D+06
ENTER HARDENING SLOPE (HS) -> 58.0D+06

TEMP =                      1500.0000
EXX, ETT, ERR  =            .5800D+08   .5800D+08   .5800D+08
VXR, VXT, VRT  =                .2500       .2500       .2500
ALFXX, ALFTT, ALFRR =       .2500D-05   .2500D-05   .2500D-05
Y, HS =                     .1000D+08   .5800D+08

IS INFORMATION CORRECT? <Y/N> Y

ENTER TEMPERATURE -> 1202
ENTER ELASTIC MODULUS (EXX) -> 58.0D+06
ENTER POISSON'S RATIO (VXR) -> .25
ENTER C.T.E. (ALFXX) -> 2.38D-06
ENTER YIELD POINT (Y) -> 10.0D+06
ENTER HARDENING SLOPE (HS) -> 58.0D+06

TEMP =                      1202.0000
EXX, ETT, ERR  =            .5800D+08   .5800D+08   .5800D+08
VXR, VXT, VRT  =                .2500       .2500       .2500
ALFXX, ALFTT, ALFRR =       .2380D-05   .2380D-05   .2380D-05
Y, HS =                     .1000D+08   .5800D+08

IS INFORMATION CORRECT? <Y/N> Y

ENTER TEMPERATURE -> 1112
ENTER ELASTIC MODULUS (EXX) -> 58.0D+06
ENTER POISSON'S RATIO (VXR) -> .25
ENTER C.T.E. (ALFXX) -> 2.33D-06
ENTER YIELD POINT (Y) -> 10.0D+06
ENTER HARDENING SLOPE (HS) -> 58.0D+06

TEMP =                      1112.0000
EXX, ETT, ERR  =            .5800D+08   .5800D+08   .5800D+08
VXR, VXT, VRT  =                .2500       .2500       .2500
ALFXX, ALFTT, ALFRR =       .2330D-05   .2330D-05   .2330D-05
Y, HS =                     .1000D+08   .5800D+08

IS INFORMATION CORRECT? <Y/N> Y

ENTER TEMPERATURE -> 797
ENTER ELASTIC MODULUS (EXX) -> 58.0D+06
ENTER POISSON'S RATIO (VXR) -> .25
ENTER C.T.E. (ALFXX) -> 2.15D-06
ENTER YIELD POINT (Y) -> 10.0D+06
ENTER HARDENING SLOPE (HS) -> 58.0D+06

TEMP =                       797.0000
EXX, ETT, ERR  =            .5800D+08   .5800D+08   .5800D+08
VXR, VXT, VRT  =                .2500       .2500       .2500
ALFXX, ALFTT, ALFRR =       .2150D-05   .2150D-05   .2150D-05
Y, HS =                     .1000D+08   .5800D+08

IS INFORMATION CORRECT? <Y/N> Y

ENTER TEMPERATURE -> 392
ENTER ELASTIC MODULUS (EXX) -> 58.0D+06
ENTER POISSON'S RATIO (VXR) -> .25
ENTER C.T.E. (ALFXX) -> 2.01D-06
ENTER YIELD POINT (Y) -> 10.0D+06
ENTER HARDENING SLOPE (HS) -> 58.0D+06
```

```
TEMP =                       392.0000
EXX, ETT, ERR   =            .5800D+08    .5800D+08    .5800D+08
VXR, VXT, VRT   =                .2500        .2500        .2500
ALFXX, ALFTT, ALFRR =        .2010D-05    .2010D-05    .2010D-05
Y, HS =                      .1000D+08    .5800D+08

IS INFORMATION CORRECT? <Y/N> Y

ENTER TEMPERATURE -> 75
ENTER ELASTIC MODULUS (EXX) -> 58.0D+06
ENTER POISSON'S RATIO (VXR) -> .25
ENTER C.T.E. (ALFXX) -> 1.96D-06
ENTER YIELD POINT (Y) -> 10.0D+06
ENTER HARDENING SLOPE (HS) -> 58.0D+06

TEMP =                        75.0000
EXX, ETT, ERR   =            .5800D+08    .5800D+08    .5800D+08
VXR, VXT, VRT   =                .2500        .2500        .2500
ALFXX, ALFTT, ALFRR =        .1960D-05    .1960D-05    .1960D-05
Y, HS =                      .1000D+08    .5800D+08

IS INFORMATION CORRECT? <Y/N> Y
```

Note: At the end of the material property input, the information will be processed by cubic spline interpolation to be either expanded or contracted into ten (10) data points to be stored in the files fiber.out, matrix.out, or refer.out. Any material placed in either fiber.out or matrix.out will be automatically entered into refer.out. It is possible to enter materials into refer.out separately.

```
          ***FIBER MATERIAL DATABANK***

          AVAILABLE FIBERS
        SiC  (psi)
    1.  ENTER NEW MATERIAL
    2.  RETURN TO MATERIAL MENU

    ENTER CHOICE -> 2
```

Note: The new material is now shown in the material databank. The user can now enter additional materials into this databank or return back one menu.

```
           ***MATERIAL INPUT MENU***

    1.  ENTER NEW FIBER MATERIALS
    2.  ENTER NEW MATRIX MATERIALS
    3.  ENTER NEW REFERENCE MATERIALS FOR INTERFACE LAYERS
    4.  RETURN TO MAIN MENU

    ENTER CHOICE -> 4
```

Note: The user can now enter materials into other databanks or return back one menu.

```
          ******MAIN MENU******

       1.  CREATE NEW DATA FILE
       2.  RUN EXISTING DATA FILE
       3.  ENTER NEW MATERIALS INTO DATABANK
       4.  EXIT SHELL
      ENTER CHOICE -> 4
```

Note: Back at the main menu, the user can run a data file created earlier, create a new data file taking advantage of the new materials in the databank, continue to enter more materials in the databank, or exit the program.

8.5 Appendix V: Example 3 - Fiber.data and Matrix.data File Format

The material properties in the files **fiber.data, matrix.data** and **ref.data** are stored vertically for reasons of internal bookkeeping. For each set of material properties entered at a number of different temperatures, the program automatically re-evaluates these properties at ten equally spaced temperatures using cubic splines. Thus if properties at six temperatures were entered by the user for a fiber, matrix or reference material, these properties would subsequently be re-valuated at ten temperatures and stored vertically, as illustrated below for the SiC SCS-6 fiber properties stored in the file **fiber.data**. The user can edit these properties using any text editor, making sure that the logical organization of the file is not re-arranged. To delete a material, the entire block (all ten temperature points) must be deleted, leaving no blank lines between material sets.

```
SiC-SCS6   (psi)      Fiber name
1                     Internal flag indicating orthotropy of the material
     1500.00000       Temperature # 1
 .580000D+08          EXX
 .580000D+08          ETT
 .580000D+08          ERR
 .250000D+00          VXR
 .250000D+00          VXT
 .250000D+00          VRT
 .250000D-05          ALFXX
 .250000D-05          ALFTT
 .250000D-05          ALFRR
 .100000D+08          Y
 .580000D+08          HS
     1341.66667       Temperature # 2
 .580000D+08          e
 .580000D+08          t
 .580000D+08          c
 .250000D+00          .
 .250000D+00          .
 .250000D+00          .
 .244042D-05
 .244042D-05
 .244042D-05
 .100000D+08
 .580000D+08
     1183.33333
 .580000D+08
 .580000D+08
 .580000D+08
 .250000D+00
 .250000D+00
 .250000D+00
 .237027D-05
 .237027D-05
 .237027D-05
 .100000D+08
 .580000D+08
     1025.00000
 .580000D+08
 .580000D+08
```

```
.580000D+08
.250000D+00
.250000D+00
.250000D+00
.227839D-05
.227839D-05
.227839D-05
.100000D+08
.580000D+08
      866.66667
.580000D+08
.580000D+08
.580000D+08
.250000D+00
.250000D+00
.250000D+00
.218659D-05
.218659D-05
.218659D-05
.100000D+08
.580000D+08
      708.33333
.580000D+08
.580000D+08
.580000D+08
.250000D+00
.250000D+00
.250000D+00
.210894D-05
.210894D-05
.210894D-05
.100000D+08
.580000D+08
      550.00000
.580000D+08
.580000D+08
.580000D+08
.250000D+00
.250000D+00
.250000D+00
.205067D-05
.205067D-05
.205067D-05
.100000D+08
.580000D+08
      391.66667
.580000D+08
.580000D+08
.580000D+08
.250000D+00
.250000D+00
.250000D+00
.200993D-05
.200993D-05
.200993D-05
.100000D+08
.580000D+08
      233.33333
.580000D+08
.580000D+08
.580000D+08
.250000D+00
.250000D+00
.250000D+00
```

```
 .198304D-05
 .198304D-05
 .198304D-05
 .100000D+08
 .580000D+08
        75.00000
 .580000D+08
 .580000D+08
 .580000D+08
 .250000D+00
 .250000D+00
 .250000D+00
 .196000D-05
 .196000D-05
 .196000D-05
 .100000D+08
 .580000D+08
```

The properties of the Ti-24Al-11Nb matrix stored in the **matrix.data** file in the same order as the SiC SCS-6 fiber properties given above follow.

```
Ti-24Al-11Nb  (psi)
1
      1500.00000
 .620000D+07
 .620000D+07
 .620000D+07
 .260000D+00
 .260000D+00
 .260000D+00
 .615000D-05
 .615000D-05
 .615000D-05
 .240000D+05
 .100000D+04
      1341.66667
 .755441D+07
 .755441D+07
 .755441D+07
 .260000D+00
 .260000D+00
 .260000D+00
 .601014D-05
 .601014D-05
 .601014D-05
 .325064D+05
 .330626D+05
      1183.33333
 .104376D+08
 .104376D+08
 .104376D+08
 .260000D+00
 .260000D+00
 .260000D+00
 .588808D-05
 .588808D-05
 .588808D-05
 .397910D+05
 .113031D+06
      1025.00000
```

.133491D+08
.133491D+08
.133491D+08
.260000D+00
.260000D+00
.260000D+00
.581649D-05
.581649D-05
.581649D-05
.453463D+05
.279321D+06
866.66667
.117389D+08
.117389D+08
.117389D+08
.260000D+00
.260000D+00
.260000D+00
.575014D-05
.575014D-05
.575014D-05
.513392D+05
.359116D+06
708.33333
.109163D+08
.109163D+08
.109163D+08
.260000D+00
.260000D+00
.260000D+00
.560627D-05
.560627D-05
.560627D-05
.561634D+05
.200717D+06
550.00000
.124868D+08
.124868D+08
.124868D+08
.260000D+00
.260000D+00
.260000D+00
.539352D-05
.539352D-05
.539352D-05
.588226D+05
.399888D+05
391.66667
.145033D+08
.145033D+08
.145033D+08
.260000D+00
.260000D+00
.260000D+00
.519967D-05
.519967D-05
.519967D-05
.589976D+05
.442843D+06
233.33333
.154524D+08
.154524D+08
.154524D+08
.260000D+00

```
.260000D+00
.260000D+00
.508625D-05
.508625D-05
.508625D-05
.567903D+05
.174601D+07
       75.00000
.160000D+08
.160000D+08
.160000D+08
.260000D+00
.260000D+00
.260000D+00
.500000D-05
.500000D-05
.500000D-05
.538900D+05
.333300D+07
```

8.6 Appendix VI: RTSHELL Example

8.6.1 Construction and execution of the rtshell.data file

The construction and subsequent execution of the **rtshell.data** file, menu-driven by the user-friendly interface **shell.f**, is illustrated below. The input data is identical to that provided in Example 1, excluding the specification of optimization parameters. The text that appears in Courier-type capital letters is written to the screen at each step in the construction of the **fiber.data** file. User's responses to the menu-driven commands are shown in bold Courier-type letters. The text in bold italics preceded by the word ***Note:*** represents manually inserted comments that explain in more detail certain options available to the user.

```
NASA-LEWIS RESEARCH CENTER, STRUCTURES DIVISION, CLEVELAND OHIO
             *********************************************
             ***              RTSTRESS                 ***
             ***                                       ***
             ***   DETERMINATION OF THE ELASTOPLASTIC  ***
             *** RESPONSE OF A MULTI-LAYERED COMPOSITE ***
             ***   CYLINDER SUBJECTED TO AXISYMMETRIC  ***
             ***        THERMO-MECHANICAL LOADING      ***
             ***                                       ***
             ***              WRITTEN BY               ***
             ***                                       ***
             ***          ROBERT SCOTT SALZAR          ***
             ***         TODD OAKHILL WILLIAMS         ***
             ***          MAREK-JERZY PINDERA          ***
             ***                                       ***
             ***       THE UNIVERSITY OF VIRGINIA      ***
             ***            SEPTEMBER, 1993            ***
             ***                                       ***
             *** DEVELOPED FOR THE FATIGUE AND FRACTURE***
             ***  BRANCH OF NASA-LEWIS RESEARCH CENTER ***
             ***        UNDER CONTRACT NAS3-26571      ***
             ***  DR. S. M. ARNOLD (CONTRACT MONITOR)  ***
             *********************************************

 HIT RETURN TO CONTINUE ->

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b.  assumes any liabilities with respect to the use of, or for damages
    resulting from use of this software.

==============================================================================

 HIT RETURN TO CONTINUE ->
```

C-2

```
******MAIN MENU******

 1.  CREATE NEW DATA FILE
 2.  RUN EXISTING DATA FILE
 3.  ENTER NEW MATERIALS INTO DATABANK
 4.  EXIT SHELL
ENTER CHOICE -> 1

**********************************BLOCK 1**********************************
        SPECIFY CONCENTRIC CYLINDER GEOMETRY, MATERIALS
                    INCLUDING PROPERTIES


 IF FIBER IS HOMOGENEOUS, ENTER: 1
 IF FIBER IS LAYERED, ENTER: 2
 CHOICE -> 2

ENTER NUMBER OF FIBER LAYERS -> 2
ENTER RELATIVE FIBER CORE RADIUS -> .5
ENTER RELATIVE OUTER RADIUS OF FIBER LAYER 2 -> .632
ENTER THE NUMBER OF INTERFACE LAYERS -> 3
t/a RATIO OF INTERFACE 1: .03333
t/a RATIO OF INTERFACE 2: .03333
t/a RATIO OF INTERFACE 3: .03334


        ***CONCENTRIC CYLINDER CONFIGURATION***

SHELL        MATERIAL       OUTER RADIUS     VOLUME FRACTION

  1           FIBER           0.50000           0.2500
  2           FIBER           0.63200           0.1494
  3        INTERFACE 1        0.65306           0.0271
  4        INTERFACE 2        0.67413           0.0280
  5        INTERFACE 3        0.69520           0.0289
  6           MATRIX          0.75616           0.0885
  7           MATRIX          0.81712           0.0959
  8           MATRIX          0.87808           0.1033
  9           MATRIX          0.93904           0.1108
 10           MATRIX          1.00000           0.1182

FIBER VOLUME FRACTION =   0.3994
MATRIX VOLUME FRACTION =  0.5167

  IS INFORMATION CORRECT? <Y/N> y


        ***FIBER MATERIAL PROPERTY SELECTION***

     AVAILABLE FIBERS           AVAILABLE CONSTITUTIVE MODELS
  1   SiC  (SCS-6)  (psi)                1  ELASTIC
  2   Al2O3 (psi)                        2  PLASTIC
  3   ENTER NEW MATERIAL

ENTER MATERIAL FOR FIBER LAYER 1 -> 1

ENTER MATERIAL FOR FIBER LAYER 2 -> 1
ENTER CONSTITUTIVE MODEL FOR FIBER LAYER 2 -> 1


        ***MATRIX MATERIAL PROPERTY SELECTION***
```

```
  AVAILABLE MATRIX MATERIALS    AVAILABLE CONSTITUTIVE MODELS
   1   Ti-24Al-11Nb  (psi)              1  ELASTIC
   2   NiCrAlY1 (psi)                   2  PLASTIC
   3   NiCrAlY2 (psi)
   4   NiAl (psi)
   5   ENTER NEW MATERIAL

ENTER MATERIAL FOR MATRIX -> 1
ENTER CONSTITUTIVE MODEL FOR MATRIX -> 2

            ***INTERFACIAL LAYER REFERENCE MATERIALS***

    AVAILABLE MATERIALS            AVAILABLE CONSTITUTIVE MODELS
   1   SiC  (SCS-6)  (psi)                  1  ELASTIC
   2   Ti-24Al-11Nb  (psi)                  2  PLASTIC
   3   Al2O3 (psi)
   4   NiCrAlY1 (psi)
   5   NiCrAlY2 (psi)
   6   NiAl (psi)
   7   ENTER NEW MATERIAL

ENTER MATERIAL FOR INTERFACE  1 -> 2
ENTER CONSTITUTIVE MODEL FOR INTERFACE 1 -> 2
ENTER MATERIAL FOR INTERFACE  2 -> 2
ENTER CONSTITUTIVE MODEL FOR INTERFACE 2 -> 2
ENTER MATERIAL FOR INTERFACE  3 -> 2
ENTER CONSTITUTIVE MODEL FOR INTERFACE 3 -> 2


ENTER INTERFACE LAYER DESIGN: Ei/Er, Yi/Yr, CTEi/CTEr, Hi/Hr

INTERFACE  1 : .5 .5 2 .5
INTERFACE  2 : .5 .5 2 .5
INTERFACE  3 : .5 .5 2 .5


    ***CONCENTRIC CYLINDER MATERIAL SPECIFICATION***

    SHELL          MATERIAL              CONSTITUTIVE MODEL

 1  FIBER      SiC  (SCS-6)  (psi)             ELASTIC
 2  FIBER      SiC  (SCS-6)  (psi)             ELASTIC
 3  INTERFACE                                  INELASTIC
 4  INTERFACE                                  INELASTIC
 5  INTERFACE                                  INELASTIC
 6  MATRIX     Ti-24Al-11Nb  (psi)             INELASTIC
 7  MATRIX     Ti-24Al-11Nb  (psi)             INELASTIC
 8  MATRIX     Ti-24Al-11Nb  (psi)             INELASTIC
 9  MATRIX     Ti-24Al-11Nb  (psi)             INELASTIC
10  MATRIX     Ti-24Al-11Nb  (psi)             INELASTIC
           ***INTERFACE REFERENCE MATERIALS***

       INTERFACE      MATERIAL           CONSTITUTIVE MODEL
           1      Ti-24Al-11Nb  (psi)       INELASTIC
           2      Ti-24Al-11Nb  (psi)       INELASTIC
           3      Ti-24Al-11Nb  (psi)       INELASTIC


             ***INTERFACIAL LAYER DESIGN***

    LAYER      Ei/Er       Yi/Yr       CTEi/CTEr       Hi/Hr
      1        0.500       0.500         2.000         0.500
      2        0.500       0.500         2.000         0.500
```

```
     3          0.500       0.500       2.000       0.500

     IS INFORMATION CORRECT? <Y/N> y

**********************************BLOCK 2*********************************
                    DEFINE LOAD HISTORY, INCREMENT,
                           AND ITERATIONS

                             ***CAUTION***
THE APPLIED TEMPERATURE LOAD MUST REMAIN BETWEEN   75.00 deg AND 1500.00 deg
                             *************

NO. OF LOAD SEGMENTS, INITIAL TEMP., INITIAL PRESSURE, INITAL AXIAL LOAD
-> 1 1500 0 0
NO. OF INCREMENTS, ENDING TEMP., ENDING PRESSURE, ENDING AXIAL
-> 570 75 0 0

   CHANGE MAXIMUM NUMBER OF ITERATIONS (DEFAULT=10)? <Y/N> y
   MAXIMUM NUMBER OF ITERATIONS -> 15

   CHANGE CONVERGENCE ERROR TOLERANCE (DEFAULT=0.01)? <Y/N> n

   WRITE CONVERGENCE INFORMATION TO rtshell.conv FILE? <Y/N> y

                              LOAD HISTORY

  STEP      INCREMENTS       TEMPERATURE      AXIAL         PRESSURE
   1                           1500.00         0.00           0.00
               570
   2                             75.00         0.00           0.00

           MAXIMUM NUMBER OF ITERATIONS =    15
           CONVERGENCE ERROR TOLERANCE = 0.01000
           CONVERGENCE INFORMATION WRITTEN TO rtshell.conv

  IS INFORMATION CORRECT? <Y/N> y


  WOULD YOU LIKE TO SEE A PROBLEM REVIEW? <Y/N> y


*******************************PROBLEM REVIEW******************************

                ***CONCENTRIC CYLINDER CONFIGURATION**

  SHELL          MATERIAL              OUTER RADIUS  CONSTITUTIVE MODEL

 1  FIBER      SiC  (SCS-6)  (psi)       0.50000         ELASTIC
 2  FIBER      SiC  (SCS-6)  (psi)       0.63200         ELASTIC
 3  INTERFACE                            0.65306         INELASTIC
 4  INTERFACE                            0.67413         INELASTIC
 5  INTERFACE                            0.69520         INELASTIC
 6  MATRIX     Ti-24Al-11Nb  (psi)       0.75616         INELASTIC
 7  MATRIX     Ti-24Al-11Nb  (psi)       0.81712         INELASTIC
 8  MATRIX     Ti-24Al-11Nb  (psi)       0.87808         INELASTIC
 9  MATRIX     Ti-24Al-11Nb  (psi)       0.93904         INELASTIC
10  MATRIX     Ti-24Al-11Nb  (psi)       1.00000         INELASTIC
```

```
FIBER VOLUME FRACTION =    0.3994
MATRIX VOLUME FRACTION =   0.5167


HIT RETURN TO CONTINUE ->

              ***INTERFACE REFERENCE MATERIALS***

        INTERFACE       MATERIAL          CONSTITUTIVE MODEL
            1      Ti-24Al-11Nb  (psi)        INELASTIC
            2      Ti-24Al-11Nb  (psi)        INELASTIC
            3      Ti-24Al-11Nb  (psi)        INELASTIC

              ***INTERFACIAL LAYER DESIGN***

           LAYER       Ei/Er     Yi/Yr    CTEi/CTEr   Hi/Hr
             1         0.500     0.500      2.000     0.500
             2         0.500     0.500      2.000     0.500
             3         0.500     0.500      2.000     0.500

HIT RETURN TO CONTINUE ->

                              ***LOAD HISTORY***

   STEP        INCREMENTS        TEMPERATURE       AXIAL          PRESSURE
     1                             1500.00          0.00            0.00
                   570
     2                               75.00          0.00            0.00

             MAXIMUM NUMBER OF ITERATIONS =     15
             CONVERGENCE ERROR TOLERANCE = 0.01000
             CONVERGENCE INFORMATION WRITTEN TO rtshell.conv

HIT RETURN TO CONTINUE ->

         ******MAIN MENU******

       1.  CREATE NEW DATA FILE
       2.  RUN EXISTING DATA FILE
       3.  ENTER NEW MATERIALS INTO DATABANK
       4.  EXIT SHELL
      ENTER CHOICE -> 2
```

8.6.2 Results

The file **rtshell.out**, containing information on the geometry, material properties, stresses and inelastic strains in each layer of the specified concentric cylinder assemblage, for the data file **rtshell.data** constructed in Section 8.6.1, is given below.

```
NASA-LEWIS RESEARCH CENTER, STRUCTURES DIVISION, CLEVELAND OHIO

          ********************************************
          ***                RTSTRESS              ***
          ***                                      ***
          ***   DETERMINATION OF THE ELASTOPLASTIC ***
          *** RESPONSE OF A MULTI-LAYERED COMPOSITE ***
          ***   CYLINDER SUBJECTED TO AXISYMMETRIC ***
          ***        THERMO-MECHANICAL LOADING     ***
          ***                                      ***
          ***               WRITTEN BY             ***
          ***                                      ***
          ***          ROBERT SCOTT SALZAR         ***
          ***         TODD OAKHILL WILLIAMS        ***
          ***          MAREK-JERZY PINDERA         ***
          ***                                      ***
          ***                   OF                 ***
          ***        THE UNIVERSITY OF VIRGINIA    ***
          ***            SEPTEMBER, 1993           ***
          ***                                      ***
          *** DEVELOPED FOR THE FATIGUE AND FRACTURE***
          ***  BRANCH OF NASA-LEWIS RESEARCH CENTER ***
          ***        UNDER CONTRACT NAS3-26571     ***
          ***  DR. S. M. ARNOLD (CONTRACT MONITOR) ***
          ********************************************

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    resulting from use of this software.

================================================================================


              ***CONCENTRIC CYLINDER CONFIGURATION***

 RING    MATERIAL                      OUTER RADIUS    CONSTITUTIVE MODEL

  1      FIBER LAYER 1 (CORE)             0.500        ISOTROPIC ELASTIC
  2      FIBER LAYER 2                    0.632        ISOTROPIC ELASTIC
  3      INTERFACE LAYER 1                0.653        ISOTROPIC INELASTIC
  4      INTERFACE LAYER 2                0.674        ISOTROPIC INELASTIC
  5      INTERFACE LAYER 3                0.695        ISOTROPIC INELASTIC
```

6	MATRIX	0.756	ISOTROPIC INELASTIC
7	MATRIX	0.817	ISOTROPIC INELASTIC
8	MATRIX	0.878	ISOTROPIC INELASTIC
9	MATRIX	0.939	ISOTROPIC INELASTIC
10	MATRIX	1.000	ISOTROPIC INELASTIC

FIBER LAYER 1 PROPERTIES (CORE)

TEMPERATURE = 0.1500E+04

```
0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2500E-05  0.2500E-05  0.2500E-05
0.1000E+08  0.5800E+08
```

TEMPERATURE = 0.1342E+04

```
0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2440E-05  0.2440E-05  0.2440E-05
0.1000E+08  0.5800E+08
```

TEMPERATURE = 0.1183E+04

```
0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2370E-05  0.2370E-05  0.2370E-05
0.1000E+08  0.5800E+08
```

TEMPERATURE = 0.1025E+04

```
0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2278E-05  0.2278E-05  0.2278E-05
0.1000E+08  0.5800E+08
```

TEMPERATURE = 0.8667E+03

```
0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2187E-05  0.2187E-05  0.2187E-05
0.1000E+08  0.5800E+08
```

TEMPERATURE = 0.7083E+03

```
0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2109E-05  0.2109E-05  0.2109E-05
0.1000E+08  0.5800E+08
```

TEMPERATURE = 0.5500E+03

```
0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2051E-05  0.2051E-05  0.2051E-05
0.1000E+08  0.5800E+08
```

TEMPERATURE = 0.3917E+03

```
0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2010E-05  0.2010E-05  0.2010E-05
0.1000E+08  0.5800E+08
```

```
TEMPERATURE =  0.2333E+03

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.1983E-05  0.1983E-05  0.1983E-05
0.1000E+08  0.5800E+08

TEMPERATURE =  0.7500E+02

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.1960E-05  0.1960E-05  0.1960E-05
0.1000E+08  0.5800E+08

***FIBER LAYER  2 PROPERTIES***

TEMPERATURE =  0.1500E+04

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2500E-05  0.2500E-05  0.2500E-05
0.1000E+08  0.5800E+08

TEMPERATURE =  0.1342E+04

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2440E-05  0.2440E-05  0.2440E-05
0.1000E+08  0.5800E+08

TEMPERATURE =  0.1183E+04

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2370E-05  0.2370E-05  0.2370E-05
0.1000E+08  0.5800E+08

TEMPERATURE =  0.1025E+04

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2278E-05  0.2278E-05  0.2278E-05
0.1000E+08  0.5800E+08

TEMPERATURE =  0.8667E+03

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2187E-05  0.2187E-05  0.2187E-05
0.1000E+08  0.5800E+08

TEMPERATURE =  0.7083E+03

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2109E-05  0.2109E-05  0.2109E-05
0.1000E+08  0.5800E+08

TEMPERATURE =  0.5500E+03

0.5800E+08  0.5800E+08  0.5800E+08
0.2500E+00  0.2500E+00  0.2500E+00
0.2051E-05  0.2051E-05  0.2051E-05
0.1000E+08  0.5800E+08
```

TEMPERATURE = 0.3917E+03

0.5800E+08	0.5800E+08	0.5800E+08
0.2500E+00	0.2500E+00	0.2500E+00
0.2010E-05	0.2010E-05	0.2010E-05
0.1000E+08	0.5800E+08	

TEMPERATURE = 0.2333E+03

0.5800E+08	0.5800E+08	0.5800E+08
0.2500E+00	0.2500E+00	0.2500E+00
0.1983E-05	0.1983E-05	0.1983E-05
0.1000E+08	0.5800E+08	

TEMPERATURE = 0.7500E+02

0.5800E+08	0.5800E+08	0.5800E+08
0.2500E+00	0.2500E+00	0.2500E+00
0.1960E-05	0.1960E-05	0.1960E-05
0.1000E+08	0.5800E+08	

INTERFACE LAYER 1

TEMPERATURE = 0.1500E+04

0.3100E+07	0.3100E+07	0.3100E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1230E-04	0.1230E-04	0.1230E-04
0.1200E+05	0.5000E+03	

TEMPERATURE = 0.1342E+04

0.3777E+07	0.3777E+07	0.3777E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1202E-04	0.1202E-04	0.1202E-04
0.1625E+05	0.1653E+05	

TEMPERATURE = 0.1183E+04

0.5219E+07	0.5219E+07	0.5219E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1178E-04	0.1178E-04	0.1178E-04
0.1990E+05	0.5652E+05	

TEMPERATURE = 0.1025E+04

0.6675E+07	0.6675E+07	0.6675E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1163E-04	0.1163E-04	0.1163E-04
0.2267E+05	0.1397E+06	

TEMPERATURE = 0.8667E+03

0.5869E+07	0.5869E+07	0.5869E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1150E-04	0.1150E-04	0.1150E-04
0.2567E+05	0.1796E+06	

TEMPERATURE = 0.7083E+03

0.5458E+07	0.5458E+07	0.5458E+07
0.2600E+00	0.2600E+00	0.2600E+00
0.1121E-04	0.1121E-04	0.1121E-04

```
0.2808E+05  0.1004E+06

TEMPERATURE =  0.5500E+03

0.6243E+07  0.6243E+07  0.6243E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1079E-04  0.1079E-04  0.1079E-04
0.2941E+05  0.1999E+05

TEMPERATURE =  0.3917E+03

0.7252E+07  0.7252E+07  0.7252E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1040E-04  0.1040E-04  0.1040E-04
0.2950E+05  0.2214E+06

TEMPERATURE =  0.2333E+03

0.7726E+07  0.7726E+07  0.7726E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1017E-04  0.1017E-04  0.1017E-04
0.2840E+05  0.8730E+06

TEMPERATURE =  0.7500E+02

0.8000E+07  0.8000E+07  0.8000E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1000E-04  0.1000E-04  0.1000E-04
0.2695E+05  0.1666E+07


***INTERFACE LAYER  2***

TEMPERATURE =  0.1500E+04

0.3100E+07  0.3100E+07  0.3100E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1230E-04  0.1230E-04  0.1230E-04
0.1200E+05  0.5000E+03

TEMPERATURE =  0.1342E+04

0.3777E+07  0.3777E+07  0.3777E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1202E-04  0.1202E-04  0.1202E-04
0.1625E+05  0.1653E+05

TEMPERATURE =  0.1183E+04

0.5219E+07  0.5219E+07  0.5219E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1178E-04  0.1178E-04  0.1178E-04
0.1990E+05  0.5652E+05

TEMPERATURE =  0.1025E+04

0.6675E+07  0.6675E+07  0.6675E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1163E-04  0.1163E-04  0.1163E-04
0.2267E+05  0.1397E+06

TEMPERATURE =  0.8667E+03

0.5869E+07  0.5869E+07  0.5869E+07
```

```
0.2600E+00  0.2600E+00  0.2600E+00
0.1150E-04  0.1150E-04  0.1150E-04
0.2567E+05  0.1796E+06

TEMPERATURE =  0.7083E+03

0.5458E+07  0.5458E+07  0.5458E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1121E-04  0.1121E-04  0.1121E-04
0.2808E+05  0.1004E+06

TEMPERATURE =  0.5500E+03

0.6243E+07  0.6243E+07  0.6243E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1079E-04  0.1079E-04  0.1079E-04
0.2941E+05  0.1999E+05

TEMPERATURE =  0.3917E+03

0.7252E+07  0.7252E+07  0.7252E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1040E-04  0.1040E-04  0.1040E-04
0.2950E+05  0.2214E+06

TEMPERATURE =  0.2333E+03

0.7726E+07  0.7726E+07  0.7726E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1017E-04  0.1017E-04  0.1017E-04
0.2840E+05  0.8730E+06

TEMPERATURE =  0.7500E+02

0.8000E+07  0.8000E+07  0.8000E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1000E-04  0.1000E-04  0.1000E-04
0.2695E+05  0.1666E+07


***INTERFACE LAYER  3***

TEMPERATURE =  0.1500E+04

0.3100E+07  0.3100E+07  0.3100E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1230E-04  0.1230E-04  0.1230E-04
0.1200E+05  0.5000E+03

TEMPERATURE =  0.1342E+04

0.3777E+07  0.3777E+07  0.3777E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1202E-04  0.1202E-04  0.1202E-04
0.1625E+05  0.1653E+05

TEMPERATURE =  0.1183E+04

0.5219E+07  0.5219E+07  0.5219E+07
0.2600E+00  0.2600E+00  0.2600E+00
0.1178E-04  0.1178E-04  0.1178E-04
0.1990E+05  0.5652E+05

TEMPERATURE =  0.1025E+04
```

```
 0.6675E+07  0.6675E+07  0.6675E+07
 0.2600E+00  0.2600E+00  0.2600E+00
 0.1163E-04  0.1163E-04  0.1163E-04
 0.2267E+05  0.1397E+06

 TEMPERATURE =  0.8667E+03

 0.5869E+07  0.5869E+07  0.5869E+07
 0.2600E+00  0.2600E+00  0.2600E+00
 0.1150E-04  0.1150E-04  0.1150E-04
 0.2567E+05  0.1796E+06

 TEMPERATURE =  0.7083E+03

 0.5458E+07  0.5458E+07  0.5458E+07
 0.2600E+00  0.2600E+00  0.2600E+00
 0.1121E-04  0.1121E-04  0.1121E-04
 0.2808E+05  0.1004E+06

 TEMPERATURE =  0.5500E+03

 0.6243E+07  0.6243E+07  0.6243E+07
 0.2600E+00  0.2600E+00  0.2600E+00
 0.1079E-04  0.1079E-04  0.1079E-04
 0.2941E+05  0.1999E+05

 TEMPERATURE =  0.3917E+03

 0.7252E+07  0.7252E+07  0.7252E+07
 0.2600E+00  0.2600E+00  0.2600E+00
 0.1040E-04  0.1040E-04  0.1040E-04
 0.2950E+05  0.2214E+06

 TEMPERATURE =  0.2333E+03

 0.7726E+07  0.7726E+07  0.7726E+07
 0.2600E+00  0.2600E+00  0.2600E+00
 0.1017E-04  0.1017E-04  0.1017E-04
 0.2840E+05  0.8730E+06

 TEMPERATURE =  0.7500E+02

 0.8000E+07  0.8000E+07  0.8000E+07
 0.2600E+00  0.2600E+00  0.2600E+00
 0.1000E-04  0.1000E-04  0.1000E-04
 0.2695E+05  0.1666E+07


***MATRIX PROPERTIES***

 TEMPERATURE =  0.1500E+04

 0.6200E+07  0.6200E+07  0.6200E+07
 0.2600E+00  0.2600E+00  0.2600E+00
 0.6150E-05  0.6150E-05  0.6150E-05
 0.2400E+05  0.1000E+04

 TEMPERATURE =  0.1342E+04

 0.7554E+07  0.7554E+07  0.7554E+07
 0.2600E+00  0.2600E+00  0.2600E+00
 0.6010E-05  0.6010E-05  0.6010E-05
 0.3251E+05  0.3306E+05
```

TEMPERATURE = 0.1183E+04

0.1044E+08	0.1044E+08	0.1044E+08
0.2600E+00	0.2600E+00	0.2600E+00
0.5888E-05	0.5888E-05	0.5888E-05
0.3979E+05	0.1130E+06	

TEMPERATURE = 0.1025E+04

0.1335E+08	0.1335E+08	0.1335E+08
0.2600E+00	0.2600E+00	0.2600E+00
0.5816E-05	0.5816E-05	0.5816E-05
0.4535E+05	0.2793E+06	

TEMPERATURE = 0.8667E+03

0.1174E+08	0.1174E+08	0.1174E+08
0.2600E+00	0.2600E+00	0.2600E+00
0.5750E-05	0.5750E-05	0.5750E-05
0.5134E+05	0.3591E+06	

TEMPERATURE = 0.7083E+03

0.1092E+08	0.1092E+08	0.1092E+08
0.2600E+00	0.2600E+00	0.2600E+00
0.5606E-05	0.5606E-05	0.5606E-05
0.5616E+05	0.2007E+06	

TEMPERATURE = 0.5500E+03

0.1249E+08	0.1249E+08	0.1249E+08
0.2600E+00	0.2600E+00	0.2600E+00
0.5394E-05	0.5394E-05	0.5394E-05
0.5882E+05	0.3999E+05	

TEMPERATURE = 0.3917E+03

0.1450E+08	0.1450E+08	0.1450E+08
0.2600E+00	0.2600E+00	0.2600E+00
0.5200E-05	0.5200E-05	0.5200E-05
0.5900E+05	0.4428E+06	

TEMPERATURE = 0.2333E+03

0.1545E+08	0.1545E+08	0.1545E+08
0.2600E+00	0.2600E+00	0.2600E+00
0.5086E-05	0.5086E-05	0.5086E-05
0.5679E+05	0.1746E+07	

TEMPERATURE = 0.7500E+02

0.1600E+08	0.1600E+08	0.1600E+08
0.2600E+00	0.2600E+00	0.2600E+00
0.5000E-05	0.5000E-05	0.5000E-05
0.5389E+05	0.3333E+07	

STRESSES AND INELASTIC STRAINS

RING NO.	INTER RADIUS	STRXX	STRRR	STRTT	W(I)
1	0.0000E+00	-0.8383E+05	-0.1959E+05	-0.1959E+05	0.0000E+00
1	0.5000E+00	-0.8383E+05	-0.1959E+05	-0.1959E+05	-0.1502E-02
2	0.5000E+00	-0.8383E+05	-0.1959E+05	-0.1959E+05	-0.1502E-02

2	0.6320E+00	-0.8383E+05	-0.1959E+05	-0.1959E+05	-0.1899E-02
3	0.6320E+00	0.3855E+05	-0.1959E+05	0.4157E+05	-0.1899E-02
3	0.6531E+00	0.3968E+05	-0.1762E+05	0.4075E+05	-0.2662E-02
4	0.6531E+00	0.3968E+05	-0.1762E+05	0.4075E+05	-0.2662E-02
4	0.6741E+00	0.4072E+05	-0.1582E+05	0.3997E+05	-0.3397E-02
5	0.6741E+00	0.4072E+05	-0.1582E+05	0.3997E+05	-0.3397E-02
5	0.6952E+00	0.4168E+05	-0.1414E+05	0.3921E+05	-0.4115E-02
6	0.6952E+00	0.5034E+05	-0.1414E+05	0.3666E+05	-0.4115E-02
6	0.7562E+00	0.5430E+05	-0.1011E+05	0.3493E+05	-0.4791E-02
7	0.7562E+00	0.5430E+05	-0.1011E+05	0.3493E+05	-0.4791E-02
7	0.8171E+00	0.5736E+05	-0.6817E+04	0.3310E+05	-0.5435E-02
8	0.8171E+00	0.5736E+05	-0.6817E+04	0.3310E+05	-0.5435E-02
8	0.8781E+00	0.5968E+05	-0.4108E+04	0.3128E+05	-0.6056E-02
9	0.8781E+00	0.5968E+05	-0.4108E+04	0.3128E+05	-0.6056E-02
9	0.9390E+00	0.6142E+05	-0.1869E+04	0.2957E+05	-0.6657E-02
10	0.9390E+00	0.6142E+05	-0.1869E+04	0.2957E+05	-0.6657E-02
10	0.1000E+01	0.6272E+05	0.4402E-09	0.2800E+05	-0.7246E-02

RING NO.	EPXXP	EPRRP	EPTTP	STREFF	SIGEFF
1	0.0000E+00	0.0000E+00	0.0000E+00	0.6424E+05	0.1000E+08
1	0.0000E+00	0.0000E+00	0.0000E+00	0.6424E+05	0.1000E+08
2	0.0000E+00	0.0000E+00	0.0000E+00	0.6424E+05	0.1000E+08
2	0.0000E+00	0.0000E+00	0.0000E+00	0.6424E+05	0.1000E+08
3	0.7443E-02	-0.1580E-01	0.8352E-02	0.5970E+05	0.6021E+05
3	0.7339E-02	-0.1482E-01	0.7484E-02	0.5784E+05	0.5814E+05
4	0.7339E-02	-0.1482E-01	0.7484E-02	0.5784E+05	0.5814E+05
4	0.7242E-02	-0.1395E-01	0.6710E-02	0.5616E+05	0.5632E+05
5	0.7242E-02	-0.1395E-01	0.6710E-02	0.5616E+05	0.5632E+05
5	0.7152E-02	-0.1316E-01	0.6011E-02	0.5462E+05	0.5468E+05
6	0.7989E-03	-0.1146E-02	0.3470E-03	0.5884E+05	0.5884E+05
6	0.5890E-03	-0.7559E-03	0.1669E-03	0.5723E+05	0.5723E+05
7	0.5890E-03	-0.7559E-03	0.1669E-03	0.5723E+05	0.5723E+05
7	0.4214E-03	-0.4905E-03	0.6909E-04	0.5613E+05	0.5613E+05
8	0.4214E-03	-0.4905E-03	0.6909E-04	0.5613E+05	0.5613E+05
8	0.2906E-03	-0.3105E-03	0.1985E-04	0.5535E+05	0.5535E+05
9	0.2906E-03	-0.3105E-03	0.1985E-04	0.5535E+05	0.5535E+05
9	0.1904E-03	-0.1887E-03	-0.1639E-05	0.5481E+05	0.5481E+05
10	0.1904E-03	-0.1887E-03	-0.1639E-05	0.5481E+05	0.5481E+05
10	0.1139E-03	-0.1057E-03	-0.8108E-05	0.5443E+05	0.5442E+05

LONGITUDINAL STRAIN = -0.4389E-02

LONGITUDINAL FORCE = 0.9823E-10

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Marek-Jerzy Pindera, Robert S. Salzar, and Todd O. Williams

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University of Virginia
Charlottesville, Virginia 22903

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

A user's guide for the computer program **OPTCOMP** is presented in this report. This program provides a capability to optimize the fabrication or service-induced residual stresses in uni-directional metal matrix composites subjected to combined thermo-mechanical axisymmetric loading using compensating or compliant layers at the fiber/matrix interface. The user specifies the architecture and the initial material parameters of the interfacial region, which can be either elastic or elastoplastic, and defines the design variables, together with the objective function, the associated constraints and the loading history through a user-friendly data input interface. The optimization procedure is based on an efficient solution methodology for the elastoplastic response of an arbitrarily layered multiple concentric cylinder model that is coupled to the commercial optimization package **DOT**. The solution methodology for the arbitrarily layered cylinder is based on the *local-global stiffness matrix formulation* and Mendelson's iterative technique of *successive elastic solutions* developed for elastoplastic boundary-value problems. The optimization algorithm employed in **DOT** is based on the *method of feasible directions*.

14. SUBJECT TERMS
Concentric cylinder model; Optimization; Elastic/plastic; Residual stresses

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