Modelling of the Filament-Winding Fabrication Process

by

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(ABSTRACT)

A stress model of the filament-winding fabrication process, previously implemented in a finite element program, was improved. Pre- and post-processing codes were developed to make the program easier and more efficient to use. A program which is used to design filament wound composite rocket motor cases was modified to write a model file for the fabrication stress code in the pre-processing stage. The same code was altered to provide post-processing output in the form of graphic displays. Also, a new code was written to provide additional post-processing capability for the fabrication stress model.

Verification of the model of the filament-winding process was performed by comparing experimental pressure and strain data, for the fabrication of a filament wound bottle, with results of an analytical model. The final analytical results using consecutive models of the filament wound bottle show reasonable agreement with experimental pressure and hoop strain data. The maximum difference in the analytical and experimental values in the pressure data was about 25% for the final winding stage. The difference was smaller during the winding progression. These results also show that the accuracy of the model depends heavily on the assumptions made for input parameters during modelling. The stiffness of the segmented steel mandrel, simulated by an effective modulus (degraded by segmentation), and the instantaneous laydown tension loss parameters significantly affected the results of the model. Including the effective modulus for the segmented mandrel in the model reduced the difference in the experimental and analytical pressure results by about 150%. The inclusion of instantaneous laydown tension loss in the model reduced the analytical-experimental difference by roughly 225%. These two parameters reduced the largest difference in the predicted pressure values from about 400% for the first model to around 25% for the final model.

The fabrication stress model was coupled with the thermo-kinetic cure model to provide more accurate fiber motion tension loss analysis capability. The stress model was modified to use the thermo-kinetic model as a subroutine to calculate fiber motion tension loss using a two-dimensional analysis. The results of the qualitative verification show that fiber motion tension loss is more important in the later stages of winding than in the beginning stages which indicates that it may provide the needed accuracy in the final winding stages.

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1.0 Introduction and Literature Review

1.1 Introduction

The WACSAFE [1,2] (Winding and Curing Stress Analysis Finite Element) program is a finite element code which is used to model the fabrication process of filament wound composite structures. The program predicts the stresses and strains during winding, curing, and after fabrication is complete. These stresses and strains are important because they provide information about the mechanical performance of the final structure. Since WACSAFE is a finite element program, it requires input in the form of geometry and material data, and produces output which can be in printed or plotted form.

The goal of this project is to increase the utility of WACSAFE and improve modelling accuracy for filament wound composites. This can be accomplished in three ways. First, the capability of WACSAFE can be increased by making the program easier and more efficient to use. This may be accomplished by providing a better means of data input and output for the program. To improve the accuracy of and validate the WACSAFE program, experimental results from a verification wind need to be compared with analytical results of different models of the experiment. By evaluating the validity of assumptions and improving the model, WACSAFE will become a more useful tool. Another way to improve the accuracy of the WACSAFE code is to improve the accuracy of the fiber motion tension loss portion of the code (see reference [1] for a description of the fiber motion model). To do this, WACSAFE can be coupled with the thermo-kinetic cure model [3], in the FWCURE [4] program, which provides fiber motion tension loss data as well as cure data to WACSAFE.

The input and output portion of the fabrication analysis must provide more efficient pre- and post-processing for WACSAFE. A program called CDAC [5] (Composite Design and Analysis Code) can serve as a pre-processor by modifying it to write a WACSAFE model file. Modifications to CDAC may also allow reading an output file from WACSAFE and acting as a post-processor by presenting the output in tabulated or graphical form.

Due to the limitations of CDAC graphical output, a separate post-processor, WACPLOT [6], can be developed to provide additional processing of WACSAFE output. The WACPLOT code should display color fill plots which the modifed CDAC code can not and also plot cure and material information which CDAC can not.

Comparing experimental results with analytical results from WACSAFE models of the experiment is the best method of validating WACSAFE and improving the process modelling capabilities for the WACSAFE user. A verification winding experiment, performed by the Thiokol Corporation, made data available for comparison with WACSAFE results. The analytical models for the verification wind may be increased in complexity from a very naive model to a model which includes most of the important process phenomena to establish the importance of various process parameters. Using this modelling approach, the WACSAFE program can be verified and the modelling process improved.

WACSAFE can only perform a one-dimensional analysis to compute the component of tension loss due to fiber motion. To improve the accuracy of the fiber motion tension loss calculations, WACSAFE can be coupled with the FWCURE program. FWCURE is capable of performing a two-dimensional axisymmetric analysis to compute tension loss due to fiber motion. The WACSAFE program needs to be able to write a data file of fiber tension values needed by FWCURE and read a set of fiber tension loss values from FWCURE. Since the changes to the

FWCURE program to make it compatible with WACSAFE are not yet available, the coupled code can be partially verified by examining the data qualitatively.

In chapter 2, the pre- and post-processing of WACSAFE data using the CDAC program are discussed. The code modifications to the CDAC program are presented as well as an overview of how to use the program for creating a WACSAFE model file and processing results. Chapter 3 gives an overview of the structure and capability of the WACPLOT program, which is an alternate post-processor for the WACSAFE program. In chapter 4, a case study is used to verify that the WACSAFE code can be used to provide reasonably accurate solutions when modelling the filament winding process. Experimental stress and strain data are compared with analytical results from a finite element model of the experiment. Also, residual stresses and strains after fabrication are examined. Chapter 5 discusses the efforts to couple the fabrication stress model, WACSAFE, with the thermo-mechanical model, FWCURE, to provide a more accurate estimate of fiber motion tension loss. The programming efforts are presented along with some qualitative verification of the program structure. The final chapter presents some conclusions about the WACSAFE code and the capability for modelling the filament winding process and also suggests some possibilities for future work and improvement.

To provide a better understanding of the topics presented in this thesis, the previous work in related areas is examined next in the literature review.

1.2 Literature Review

Because of the specialized nature of fabrication stress analysis codes for filament wound composites, there is very little work which has been done that relates to the processing of data for codes which are similar to WACSAFE. Also, work related to writing and verifying such code is scarce. The works of Nguyen and Knight [1], and Nguyen, Johnson, and Knight [2] provide the basis for the pre- and post-processing code, the verification of WACSAFE, and the code modifications presented in this thesis. They are discussed in the following paragraphs along with literature related to pre- and post-processing, program verification, and any code modifications.

The works of Nguyen and Knight [1] and Nguyen, Johnson, and Knight [2] are the fabrication stress model, which includes implementation in the form of the WACSAFE code, and the WACSAFE/WACFORM User's Guide, which describes the existing method used for pre-processing of WACSAFE data. The pre-processor described in [2] is called WACFORM. To use the WACFORM pre-processor, several files must be created including a control file which requires a substantial amount of user involvement. The user must have a detailed understanding of the control file which makes the code less accessible to inexperienced users. The available method of post-processing is tabulated output in the form of data files. The output must be sifted by the user to find the important data. The processing of data using WACFORM and the output of WACSAFE is cumbersome.

Also related to pre and post-processing is the United Technologies Incorporated's CDAC [5] and AGCAP [7] User's Guides. The CDAC code uses a menu driven design module that allows a user to design a composite rocket motor case by inputing the basic geometry and layup. The design process for composite cases is made more efficient by automating many of the calculations based on user responses to prompts. After the user has designed the case to the correct specifications, the code creates a file which contains data describing the case design (the file is called PDAxx.NEU).

The CDAC program also includes a module which performs finite element pre-processing, solution, and post-processing with graphic display. It includes pre- and post-processing for codes such as TEXLESP [8], ABAQUS, and PATRAN. The pre-processor has mesh generating capability (by using the file created in the design module). The post-processor also has the capability to plot deformed shape and contour plots of the mesh. The CDAC code is the basis for the new pre- and post-processing for the WACSAFE code.

Because the node numbering produced by CDAC in a finite element mesh is not designed to optimize bandwidth, and produces a large bandwidth, it is necessary to include a bandwidth reduction scheme in WACSAFE. Works related to the bandwidth optimization WACSAFE data are the bandwidth and profile reduction schemes of Cuthill and McKee [9], Gibbs, Poole, and Stockmeyer [10], and Sloan [11]. Although none of the algorithms mentioned above was used precisely, the general idea of numbering nodes for bandwidth reduction applies.

Related to post-processing are the discussion of smoothing of data by Hinton and Campbell [12] and Hinton, Scott, and Ricketts [13]. The CDAC post-processor uses a smoothing function when displaying average values of data. The basic smoothing method, described in the two works mentioned above, multiplies the stresses at the gauss integration points by a smoothing matrix to give smoothed values at the nodes of the element. According to Hinton and Campbell [12], the smoothed values for adjacent elements are then averaged at the element nodes. The authors state that the main advantage of this smoothing technique is that averaged smoothed stresses are consistently good in situations in which averaged conventional stresses are poor.

The work by Nguyen and Knight [1] describes some verification testing of the WACSAFE program. The report discusses two case studies, an overwrap for the space shuttle booster joint and a filament wound bottle. Experimental data are compared with analytical data for the overwrap, but no experimental data are available for the bottle tests. The bottle results are simply compared qualitatively with expected results. The overwrap case study shows that WACSAFE is fairly accurate, but according to Nguyen and Knight [1] the overwrap is a simple geometry which means it probably does not provide enough quantitative information for improving or validating the accuracy of the program. The bottle results shown by Nguyen and Knight [1] agree qualitatively with expected results. This type of experimental and qualitative verification is similar to the verification presented in depth in this thesis.

Nguyen and Knight [1] also provide the foundation for the coupling of their work with a thermo-kinetic cure model created by Tseng and Loos [3]. The fabrication model proposed by Nguyen and Knight [1] includes effects of tension loss due to motion of the composite fibers through the viscous resin flow. The WACSAFE program performs only a one-dimensional analysis to find this tension loss component. The thermo-kinetic model of Tseng and Loos [3], implemememented in a program called FWCURE [4], is capable of performing a two-dimensional analysis to find the fiber motion tension loss. The FWCURE program must be run prior to running WACSAFE, to provide data on temperature, degree of cure, and viscosity for the WACSAFE code to use during the cure portion of a fabrication analysis. Also, the fiber motion tension loss mentioned above must be computed by FWCURE independent of the WACSAFE results. According to Nguyen and Knight [1], the lack of interaction between WACSAFE and FWCURE provides a less accurate model than if the effect of the stresses on the fiber motion was accounted for during the fabrication analysis.

The pre and post-processing for WACSAFE, verification of the WACSAFE code, and coupling of the WACSAFE program with the FWCURE program, presented in this thesis, are based on the literature presented in the previous paragraphs. The code modifications needed to provide the added capability and the verification of the WACSAFE code is presented in the following chapters.

2.0 Pre- and Post-Processing Using CDAC

WACSAFE is a finite element program which performs fabrication stress analysis of filament wound composite structures. The Composite Design and Analysis Code (CDAC) is a menu driven program which provides automatic model generation and finite element analysis of composite rocket motor case designs. Coupling of the two codes yields a method for fabrication stress analysis of filament wound composite rocket motor cases.

The two main components of the CDAC program are the Case Design Module and the Finite Element Analysis Module. The Case Design Module is used by a rocket motor case designer to generate case geometry, materials, composite layup, etc. When the design of a case is completed, the CDAC user writes a file of the design data called PDAxx.NEU (where xx is simply a version number). This file is used as an input file by the Finite Element Analysis Module and is the only means of communication between the Case Design Module and the Finite Element Analysis Module.

Like most finite element codes, the three major stages encountered in the Finite Element Analysis Module are the pre-processing, the solution, and the post-processing. In the pre-processor, the Finite Element Analysis Module creates an axisymmetric finite element model of the rocket motor case from the data in the PDAxx.NEU file. The user can control parameters in the finite element model such as the number of elements along the case, the number of layers per element, etc. The finite element information is written to a file called FEGxx.BIN (where the xx is the same as in the PDAxx.NEU file). After the finite element data has been generated, the pre-processor can be used to create input files for the finite element programs TEXLESP or ABAQUS. In the solution stage, these codes perform the finite element analysis of the composite rocket motor case and write the solution data to an output file. Once the analysis has been performed, the CDAC post-processor displays the solution results in printed or plotted form.

To couple the two codes, the pre-processor of CDAC was modified to produce a WACSAFE model file. WACSAFE then performs a fabrication stress analysis using the model file produced by CDAC and writes an output file in the format which the post-processor of CDAC requires. Post-processing can be done using CDAC. This report presents the code modifications made to the pre-processor and post-processor of the CDAC program and the necessary steps for creating a WACSAFE model file. Further information on both WACSAFE and CDAC can be found in their respective user's guides [2,5].

2.1 CDAC Pre-Processing Code Modifications

CDAC is written as a series of modules, each of which has a different function in the overall CDAC program. The modules which make up the CDAC pre-preprocessor were modified to write a model file for the WACSAFE program. The modifications made to the CDAC pre-processor source code can be grouped into the following four catagories:

1. General CDAC corrections - changes which correct capabilities of the CDAC program which were required for connection with the WACSAFE program.

2. Data gathering code - code which stores data (i.e., material properties, case layup data, etc.) to be used when writing a WACSAFE model file.

3. CDAC/WACSAFE coupling code - code which uses the data gathered from CDAC to write a model file for WACSAFE.

4. Program transfer code - code which guides the flow of the program when a WACSAFE model file is written by CDAC.

Each of the modifications mentioned above is presented in detail in the following sections.

2.1.1 General CDAC Corrections

Two modifications were made to the CDAC pre-processor for the purpose of correcting the code. CDAC was incorrectly plotting and incorrectly assigning node positions for 4 node, linear elements. The problem, modified module, modified subroutine, and changes made to the code are shown in Table 1 on the next page. The CDAC code was changed to assign node coordinates and plot linear elements correctly.

2.1.2 Data Gathering Code

The data in CDAC needed by WACSAFE are contained in several different modules of the CDAC program. Within CDAC these data are assigned to new variables which are separate from the original CDAC variables to distinguish them as data needed for the WACSAFE model file. The reason for assigning new variables to the values in CDAC is to change the original code as little as possible (in other words the modifications made to CDAC to write a WACSAFE model file could be easily deleted to obtain the original code) and also to allow for easier identification of variables needed by WACSAFE for future programming efforts. The variables are then transfered, using common statements, to the module in CDAC which writes the WACSAFE model file

Table 1. General Improvements to the CDAC Code

Problem	Module	Subroutine	Changes
When assigning node numbers, the node counter was being incremented as if all of the elements were quadratic (contained midside nodes). Since the linear elements do not have midside nodes, the node #'s were being improperly assigned and some of the nodes near the end of the dome region of the case were being dropped.	AGFEG2	ASGXY1	The code was changed to increment properly for linear elements (no midside nodes) as well. The nodes are assigned correctly and the end nodes are no longer dropped for 4 node, linear elements.
Plotting was set-up only for 8 node elements. In CDAC, 4 node elements contain zeros for the midside node #'s and midside node coordinates. Because of this, the CDAC plotting routine was connecting all of the elements as if each element had four midside nodes at the origin.	AGPOST	PLTGRD	Added a section that only looked at the first 4 node numbers and coordinates of the elements definition when plotting linear elements. This kept the program from defining all of the midside nodes at the origin and resulted in proper plotting of linear elements.

(AGWAC.FOR). The code used to gather the data within CDAC is discussed in the following pages. The CDAC/WACSAFE coupling code, AGWAC.FOR, is presented in the following section.

The code used to gather the data for the WACSAFE model file is contained in three different CDAC modules. The code modifications are described in the following paragraphs and summarized in tables.

The module AGCAP1 contains material properties and stacking information for the case and mandrel. In the subroutine MATGEN, the properties for both the isotropic and orthotropic materials are stored. The subroutine GEODAT provides the material identification numbers for both hoop ply and polar/helical layers. Each of these material identification numbers has a set of material properties associated with it. Material properties are assigned to elements in WACSAFE by assigning a material identification number to an element depending on the type of material of which the element is comprised. In the subroutines OTSTSQ, INSTSQ, and STQRED, the stacking sequence for the composite case and mandrel are read and stored. Ply identification numbers are stored in arrays in the order that they exist in the case. These identification numbers are associated with a list of numbers which tell the program the orientation of the layer, the thickness of the layer, layer material type, where the layer begins and ends, etc. This information is important for determining orientation angles, off/on numbers, and material set assignments in WACSAFE. These changes are summarized in Table 2.

The module AGCAP2 contains information on the finite element mesh generated by CDAC. It is used to keep track of elements through the thickness of the case, fiber orientations, and transitioning of composite layers in the case. The subroutine INTGRD stores the number of elements through the thickness of both the mandrel and the composite layers. This information is used for determining off/on numbers and number of winding steps in WACSAFE. The subroutine WRTP47 is used to identify the transitioning of elements in the finite element model. The variable "nlayer" counts the number of elements in a given composite case as if none of the layers terminated. This means that there would be the same number of elements through the thickness of the case for each row of elements along the length of the case. For transitioning of elements, an array

Table 2. Code Modifications to the CDAC Module AGCAP1

Module	Subroutine	New CDAC Variables and Arrays	Purpose of Added Code
AGCAP1	MATGEN	Isomax is the number of isotropic materials Iortmax is the number of orthotropic materials Pisowac(10,20) are the isotropic properties needed by WACSAFE (Young's Modulus, Poisson's Ratio, and Alpha*DeltaT) Porthwac(10,20) are the orthotropic properties needed by WACSAFE (Young's moduli, Poisson's ratios, shear moduli, and coefficients of thermal expansion)	The subroutine MATGEN assigns properties to the materials in CDAC. These variables store isotropic and orthotropic material properties for use in creating the WACSAFE.MOD file.
	GEODAT	Matplyw(50) are the material id numbers for ply layers Matiwac(50) are the material id numbers for polar/helical layers	These variables store CDAC material id numbers which correspond to material properties in CDAC. Elements in WACSAFE are assigned this number as the material set number.
	OTSTSQ INSTSQ STQRED	Istype is a flag to determine if outer or inner stacking sequence is being read Ilaywac(50,4) is the ply id number order for the outer stacking sequence (composite case) Ilaybwac(50,4) is the ply id number order for the inner stacking sequence (mandrel)	These variables store ply id number orders from the CDAC stacking sequence to determine the order of layers in the case and mandrel. Each ply id number has a material number, thickness, and fiber orientation associated with it.

is used to flag any elements where a layer has terminated and it is unnecessary to assign an element to the layer at that particular portion of the case. These changes are summarized in Table 3.

AGPOST prints and plots the finite element model data (node coordinates, element connectivity, etc.). Although the node numbers, node coordinates, and element connectivity are not assigned in this module, AGPOST brings all of the model geometry together in one subroutine and was the easiest place to extract the model geometry. Along with the model geometry, the PRTPST subroutine stores values needed for changing the element connectivity as well as a value used in the node renumbering routine (described in the next section). PRTPST stores an array which matches CDAC node numbers with WACSAFE numbers so that the element connectivity in CDAC can be converted to element connectivity in WACSAFE. This is necessary because the CDAC program may skip numbers when numbering nodes, but WACSAFE must number the nodes sequentially. Also, the PRTPST subroutine stores the number of the first node on the inside surface of the midplane of the mandrel. This is used in the bandwidth reduction scheme (explained in the next section). These changes are summarized in Table 4.

2.1.3 CDAC/WACSAFE Coupling

Once all of the data needed by WACSAFE have been initialized in CDAC, the data are called into a single subroutine and written to a WACSAFE model file. Before a model file is written, it is better to renumber the nodes to produce a smaller bandwidth. This is because CDAC numbers the nodes in the composite case proceeding from the inside of the composite to the outside of the case. After all of the nodes in the composite case are numbered, CDAC numbers the nodes in the mandrel. Because of this numbering scheme, the large difference in number between adjacent nodes in the mandrel and composite case creates an unnecessarily large bandwidth. This results in unnecessary computation time and reduced accuracy which is expensive and wasteful.

A subroutine called TRANSW was written which renumbers the nodes in CDAC to produce a smaller bandwidth for the WACSAFE model. The flow chart, in Figure 1, shows the general flow

Table 3. Code Modifications to the CDAC Module AGCAP2

Module	Subroutine	New CDAC Variables and Arrays	Purpose of Added Code
AGCAP2	INTGRD	Lyswac(4) is the number of elements through the thickness of the case Lysbwac(4) is the number of elements through the thickness of the mandrel.	These variables store the number of layers through the thickness for each part of the case and mandrel. This becomes the number of winding load steps in the WACSAFE model file. This information is also used in assigning the off/on numbers in WACSAFE.
	WRTP47	Nlayer is the maximum number of elements that are possible in a case that has a constant number of elements through the case thickness along the entire length of the case.	This counts all of the elements that are possible in a given layup. It tells the program how far to count for assigning fiber angles and off/on numbers to the elements. The variable ilayer (described next) keeps track of transitioning (when a transition occurs, the element for the layer which terminates is dropped).
		Ilayer(elem#) is a flag indicating element existence on a part of the case, a 1 means the layer exists, a 0 means it does not.	This tells whether or not a layer in nlayer exists for an element in a part of the case i.e.: nlayer = 8, (4 polar/helical,4 hoop) For the elements of the hoop layers in the cylinder region: ilayer(elem#) = 1 hoops exist so are assigned to an element. For the elements of the hoop layers in the dome region: ilayer(elem#) = 0 hoops do not exist so are not assigned to an element. This is how the program keeps track of transitioning (i.e., when a hoop layer terminates).
		Ipart(elem#) is an array that describes which section of the case an element is in (FWD, AFT, SKIRT)	Keeps track of which case section an element is in. CDAC has the capability to have a different # of elements through the thickness and even a different layup in the FWD and AFT sections of the case.
		Fibwac(elem#,4) is an array of fiber angles	Fiber angles for use in the WACSAFE model file.

Table 4. Code Modifications to the CDAC Module AGPOST

Module	Subroutine	New CDAC Variables and Arrays	Purpose of Added Code
AGPOST	PRTPST	Nodag(node) is an array containing WACSAFE node numbers where (node) is the CDAC node number	Array which contains corresponding CDAC and WACSAFE node numbers so CDAC element connectivity can be converted to WACSAFE element connectivity. This is necessary because WACSAFE node numbers must be numbered sequentially without ommiting numbers while CDAC may skip numbers.
		Tx(node) are the X nodal coordinates	These are the X and Y node coordinates needed by WACSAFE.
		Ty(node) are the Y nodal coordinates	
		Mst is the number of the first node on the inside surface of the midplane of the mandrel	This value is calculated in this subroutine and used in the renumbering routine (to reduce the bandwidth). as a starting node for renumbering.
		Lyswac(4) is the number of elements through the thickness of the case	Described earlier in table 3.
		Lysbwac(4) is the number of elements through the thickness of the mandrel	Described earlier in table 3.
			NOTE This subroutine calls the routine TRANSW for renumbering the nodes to reduce the bandwidth, and the routine AGWAC for writing a WACSAFE model file. Each of these is described in the following section.

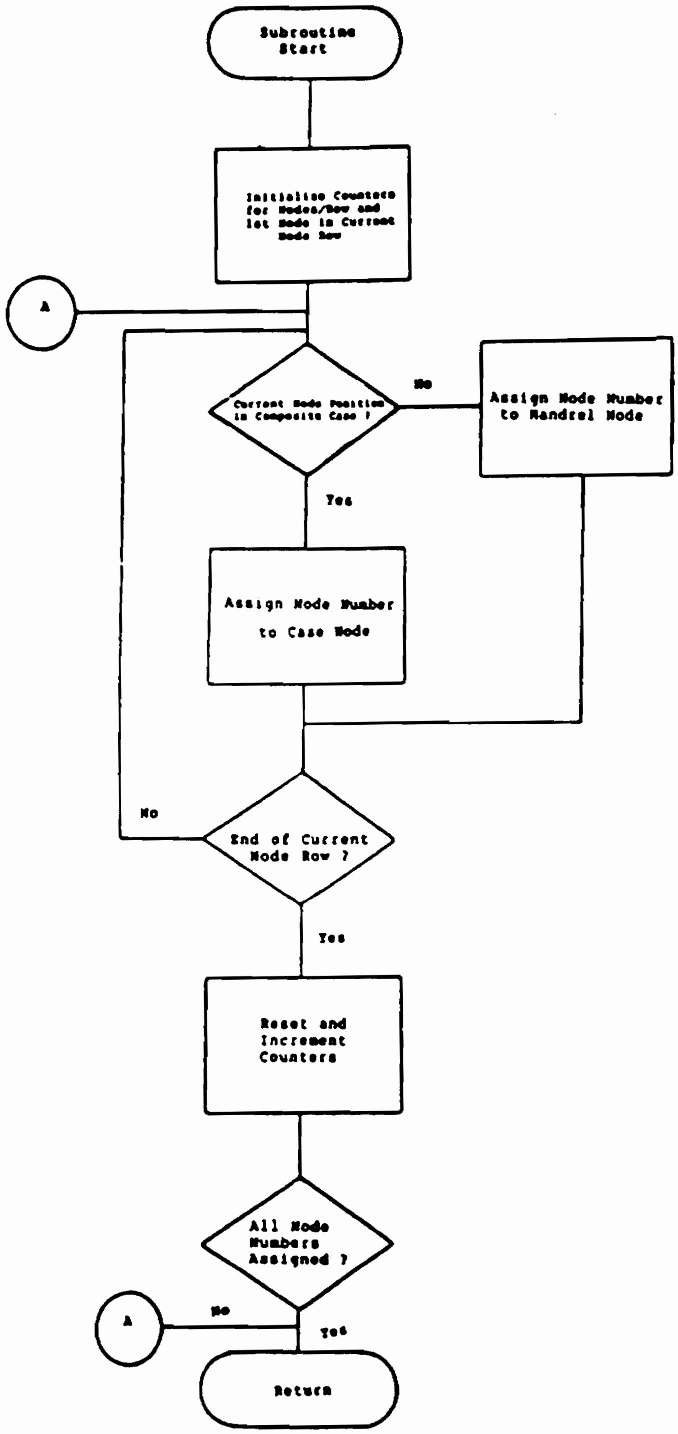

Figure 1. General Flow Chart for CDAC Module TRANSW

of the subroutine. The lower left node position in the mandrel, calculated in the AGPOST module and labelled as point A in Figure 2, is used as the starting point for renumbering the nodes. The routine counts the number of nodes in the current node row (the row that is being renumbered). The routine also assumes that the number of nodes through the thickness of the mandrel is constant over the entire length of the case. This is a valid assumption since there are no composite layers which terminate in the mandrel and there is no need for varying the number of elements through the mandrel thickness. With this information, the routine keeps track of the old node number as well as the new node number so that the element connectivity can be properly modified. The subroutine then numbers the nodes in sequential order proceeding from the inside of the mandrel to the outside of the composite case and then incrementing along the case. The connectivity is preserved although the node numbers have changed. The element numbering remains the same since it is not important for reducing bandwidth. Although the node numbers and element connectivity have been changed, it is not necessary to renumber them for the CDAC post-processor. This is because the new numbering is written in the output file from WACSAFE which is used as input for the CDAC post-processor. The renumbering module is called TRANSW.FOR and is listed in Appendix A.

A new CDAC module AGWAC.FOR provides the link between CDAC and WACSAFE by writing the data from CDAC to a WACSAFE model file. The code contains the common statements used in the data gathering portion of the CDAC modifications. By using the common statements, all of the data needed by WACSAFE that can be retrieved from CDAC are collected in one module (AGWAC). Figure 3 shows a flow chart of the AGWAC module. This module organizes the CDAC data into the format WACSAFE requires and writes it to the WACSAFE model file. First, the user must answer prompts for the number of elements per layer, the number of thermal load steps, and the input winding tension. Then the routine writes the model file using the user input data as well as the data from CDAC. The data are written in the same order they appear in the WACSAFE model file (see reference [2] for a description of this file). The control data are written first followed by the nodal coordinates. Next, the material properties are written. CDAC only supplies the cured material properties, so the cured properties are written in the model

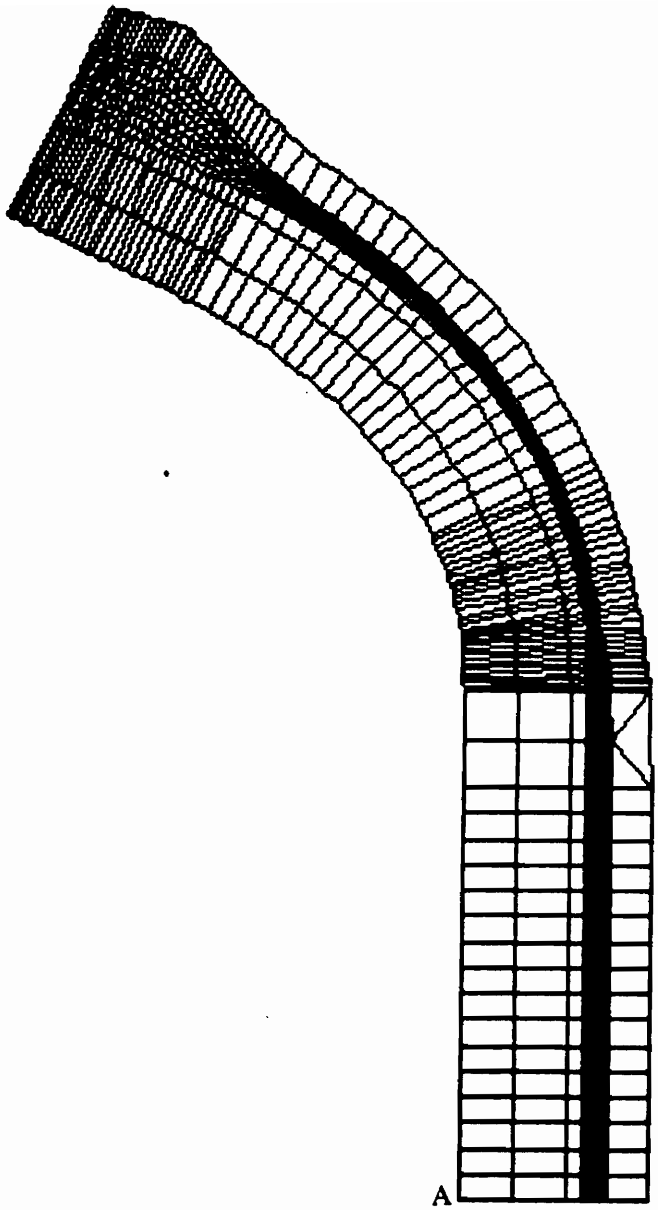

Figure 2. Starting Position for Renumbering Algorithm

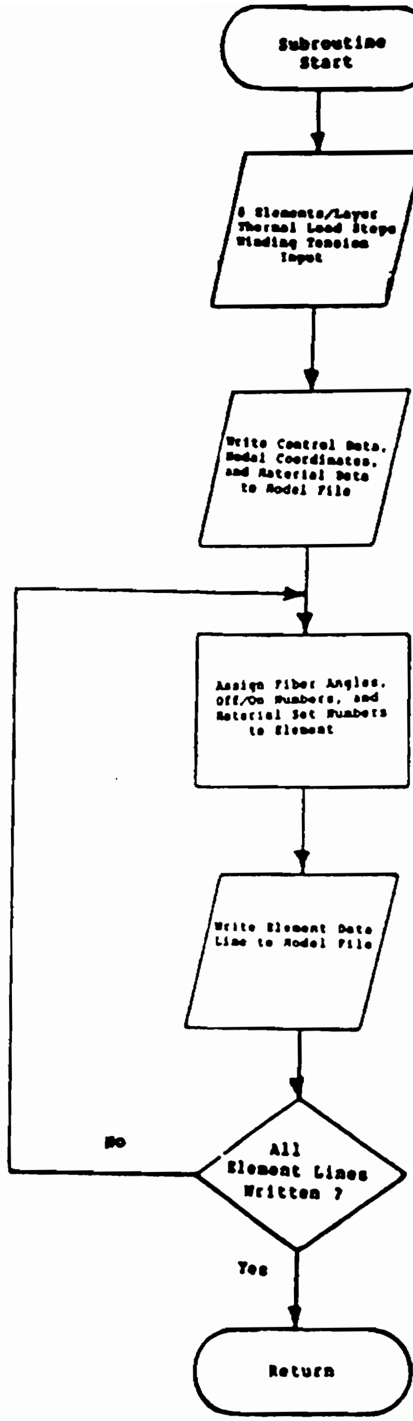

Figure 3. General Flow Chart for CDAC Module AGWAC

file for both the cured and uncured properties. This means that the user must edit the uncured properties to have a correct model. After the properties are written, the AGWAC routine assigns fiber orientation angles, off/on numbers, and material set numbers to each element and writes out the element information. When all of the element data are written, the model file is complete and the routine ends. Appendix B, of this report, contains a complete listing of the module AGWAC.FOR. For a complete description of the WACSAFE model file, refer to the WACSAFE/WACFORM User's Guide [2].

2.1.4 Program Transfer Code

The option to write a WACSAFE model file was inserted into the pre-processing menu of the FEAM (Finite Element Analysis Module) of CDAC. To support this option, three modules were modified to transfer the code properly when writing a WACSAFE model file. The modules which were modified, subroutines which were modified, new CDAC variables, and a description of the modifications of the modules are shown in Table 5 on the following page.

The module DRIVER is the main program of CDAC and contains the pre-processing menu of the FEAM. To avoid large changes in the original CDAC code, the existing flow of the option in the pre-processing menu to print preanalysis data was used for the flow of the option to write a WACSAFE model file (see CDAC User's Guide [5] for a description of the pre-processing menu). A flag was added to the routine to distinguish between the two options. Depending on how the flag is set, CDAC will print preanalysis data or a WACSAFE model file (see Table 5 for the possible flag settings).

The module AGCAP0 directs the program to perform the functions indicated by user input from the menus in the DRIVER module. This module sets certain parameters depending on whether the option to print preanalysis data or to write a WACSAFE model file is selected from the pre-processing menu. The same flag used in the DRIVER module is used in the AGCAP0 module to distinguish between the options. The module AGPOST contains the subroutine which

Table 5. Modifications to the Transfer Code of CDAC

Module	Subroutine	New CDAC Variables and Arrays	Purpose of Added Code
DRIVER	CDAC MAIN	Igrid is a flag which tells whether the option to print preanalysis data or write a WACSAFE model file was selected from the pre-processing menu. If igrid is 1, CDAC model information is written to an output file called PDAxx.NEU. If igrid is 3, a WACSAFE model file called WACSAFE.MOD is written.	A selection was added to the CDAC pre-processing menu to write a WACSAFE model file (added as option 3 - old options 3-7 were shifted down 1). Because option 1 (print preanalysis data) and option 3 (write WACSAFE model file) share the same flow in the program, the igrid flag keeps track of which option has been selected (option 1 or 3).
AGCAP0	PICK3	Igrid is a flag described above	This subroutine sets parameters, used for guiding the program flow, based on the value of igrid.
AGPOST	PRTPST	Igrid is a flag described above	Uses igrid to separate writing CDAC data from writing WACSAFE data. Based on the value of igrid, this subroutine prints CDAC preanalysis data (PDAxx.PST) or a WACSAFE model file (WACSAFE.MOD).

writes either a file containing CDAC preanalysis data or a WACSAFE model file. As in the previous modules, the same flag distinguishes between the two options.

2.2 *Creating a WACSAFE Model File*

An option was added to the CDAC pre-processing menu to write a WACSAFE model file. This option writes a WACSAFE model file with default values for some of the items in the file. In addition to these default settings, there are user prompts from CDAC to retrieve information from the user. The following section discusses the necessary steps for creating a WACSAFE model file using the CDAC pre-processor. While there is some information on the use of CDAC in the following section, it may be helpful to refer to the CDAC User's Guide [5] when reading the section. The reader needs some familiarity with the operation of CDAC to understand this section.

2.2.1 Using the CDAC Pre-Processor

Creating a WACSAFE model file using CDAC is very similar to the existing procedure for creating a TEXLESP or ABAQUS input deck with CDAC. First, in order to use the CDAC pre-processor, a file named PDAxx.NEU must exist (either written using the Case Design Module of CDAC or edited by the user). Once this file is present, the Finite Element Analysis Module of CDAC can be entered and a file called FEGxx.BIN can be written. This file must be present to write a WACSAFE model file. Once the FEGxx.BIN file has been written, a WACSAFE model file can be written.

The option to write a WACSAFE model file was added to the pre-processing menu of CDAC. The new CDAC menu is shown below:

1. Print pre-analysis data

2. Plot pre-analysis data
3. Write WACSAFE model file
4. Write TEXLESP input deck
5. Write ABAQUS input deck
6. Read/Write PATRAN neutral file
7. FEAM Main Menu
8. CDAC Main Menu

To create a WACSAFE model file, the user selects option 3 from the CDAC pre-processing menu. The program then prompts the user for the number of elements to use through the thickness per layer of composite, the number of thermal load steps, and the winding tension for each winding load step.

The number of elements through the thickness per layer of composite refers to the number of elements through the thickness that is to be used to model each individual layer of the composite case. The answer to this prompt must be considered carefully since problems may be caused by an incorrect response. When the PDAxx.NEU file, mentioned earlier, is written, CDAC allows only one element through the thickness for each layer of the composite. In order to have the possibility of obtaining a more refined mesh to obtain more accurate solutions, it was necessary to write the added code so that more than one element per layer could be obtained in the WACSAFE model file written by CDAC. The following example case layup illustrates how the prompt for the number of elements per layer should be answered.

***************************EXAMPLE********************************

Suppose there are eight layers of alternating orientation (1 helical,1 hoop, 1 helical, 1 hoop, etc.) in a composite case. In the PDAxx.NEU file the stacking sequence card would contain eight layers. The same case could be built by halving the thickness of each layer in the case and doubling the number of layers in the stacking sequence. This case would have sixteen total layers (8 sets of two layers oriented in the same direction), but would have the same geometry as the first case which had only eight total layers. CDAC only allows one element through the thickness of a layer of composite so the first case would contain eight elements through the thickness of the case and the second case would contain sixteen elements through the case thickness. To answer the prompt for the number of elements per layer, the number of layers in the case must be considered. In the first case, there can only be one element through the thickness per layer of the case because each layer has a different orientation. In the second case, however, there can be one element through the thickness per layer (resulting in a WACSAFE model with 16 separate winding steps and one element per layer) or two elements through the thickness per layer (resulting in a WACSAFE model with eight separate winding steps and two elements per layer). This is possible because each set of two layers in the stacking sequence contains layers oriented in the same direction.

The answer to the prompt for the number of elements per layer must be considered carefully based on the layup of the case. If the prompt is answered incorrectly, the WACSAFE model file, which is generated by CDAC, will be incorrect. The number of thermal load steps and the winding tension for each winding step are explained in the WACSAFE/WACFORM User's Guide [2]. Once the prompts have been answered, the CDAC program writes a WACSAFE model file using the default values discussed in the following section.

2.2.2 Default Values for WACSAFE Model File

After the prompts have been answered, CDAC writes a WACSAFE model file and returns to the pre-processing menu (previous section). The model file is written with certain default values. A list of the defaults is shown in Table 6 on the following page. After exiting CDAC, the user must edit the model file to change any of the default values. The WACSAFE output flags are set to provide full displacement, stress, and strain results for each load step. It is important to note that the fixed displacement boundary conditions on nodes must be edited by the by the user to prevent rigid body motion or preserve symmetry planes. Also, the degraded material properties for pre-cure

Table 6. Default Values for a WACSAFE Model File Created Using CDAC

Label	Default Value	WACSAFE Variable Name
# of element groups	1	NUMEG
# of external load steps	0	NLCASE
# of excavation load steps	1	NEXCAV
Solution mode	1	MODEX
Equlibrium iteration flag	3	NEQITR
Nodal load print control	0	NVECT
Output suppression control	0	NOUT
Strain output control	1	NSTRAN
Intermediate output control line	# of load steps	INTOUT
Intermediate output data line	# for each load step	IA(INTOUT)
Winding time data line	all 0's Note: This must be edited if fiber motion model is to be active.	WTIME(NLCASE)
r boundary condition code z boundary condition code	0 0 **Note: These must be edited by the user to provide appropriate boundary conditions.**	ID(1,N) ID(2,N)
Fiber motion data line	all 0's Note: This must be edited if fiber motion model is to be active.	VISCOS FFRACT EFIBER FRAD
Material property lines	All properties entered as cured properties obtained from CDAC. **User must edit uncured properties.**	

(winding) analysis must be input by editing. The fiber motion model is deactivated by default. If it is desired to activate the fiber motion model, the winding times and fiber motion data line must be non-zero. Consult the WACFORM/WACSAFE User's Guide [2] for a detailed description of the variables in Table 6.

2.3 CDAC Post-Processor Code Modifications

The modifications made to the CDAC post-processor allow post-processing of four node, linear elements. Although CDAC was supposed to provide post-processing capability for these linear elements, the plotting routines were set-up to support quadratic elements only. Unlike the modifications made to the CDAC pre-processor, no new variables were added to the code to modify the post-processor. Lines were added to perform the correct functions for four node, linear elements using existing data.

There were three modules which were modified to provide CDAC post-processing capability for four node, linear elements. These modules are AGFFLD, AGTXL4, and DRIVER. Tables 7 and 8, on the following pages, show the problem with the code, the modules and subroutines which were modified, and the changes made to the code to correct the problem. The module AGFFLD reads the post-processing data from the WACxx.F13 file. This module was modified to correct an error which occured during reading of the post data. The AGTXL4 module is the main CDAC post-processor. It contains the subroutines necessary to print or plot post-processing data. This module was only operating correctly for eight and nine node, quadratic elements so it was modified to function correctly for four node, linear elements. The DRIVER module is the main CDAC program which also contains the post-processing menu of the Finite Element Analysis Module. This module was modified to provide proper labelling of menus and files during processing of WACSAFE post data.

Table 7. **Code Modifications to the CDAC Post-Processor**

Problem	Module	Subroutine	Changes
When reading the post-processing data from the WACxx.F13 file, the first record was being read twice with read statements of varying length. This created a mismatch between integer and real variables. The second read statement was attempting to read more data than was actually contained in the first record of data. This caused an end-of-data error when running the post-processor.	AGFFLD	RDNTP3	The code was modified to skip the second read statement for the first record. This allowed the first statement to read the first record (as intended) and allowed the second statement to read all the other records (also as intended).
The nodal x and y coordinates were being incorrectly transfered for plotting of 4 node, linear elements. The code was assigning 2 midside nodes (which don't exist for linear elements) to 2 of the element corner nodes. This was placing zeros in for the node coordinates of 2 of the corners of the linear elements so all of the nodes were connected at the origin.	AGTXL4	CONTOU	This problem was corrected by simply skipping the part of the code which assigned midside nodes to the quadratic elements when linear elements were being plotted. This kept the program from assigning midside nodes at the origin and allowed the linear elements to be plotted properly.
The problems with this subroutine are exactly the same as those of the subroutine CONTOU above.	AGTXL4	DEFORM	The code was corrected in the same manner as the code in CONTOU above.

Table 8. Code Modifications to the CDAC Post-Processor

Problem	Module	Subroutine	Changes
This subroutine breaks up quadratic quadrilateral elements into eight sub-triangles in order to better interpolate values within the element for contour plotting. This subroutine only works for 8 and 9 node quadratic elements.	AGTXL4	INTRP1	The routine was modified to exclude the midside nodes when breaking up the 4 node quadrilaterals so the element is divided into 4 sub-triangles if it is a linear element.
In this subroutine the code was again working only for 8 and 9 node quadratic elements. As before, zeros were being assigned for coordinates of 2 of the corner nodes for 4 node, linear elements which caused all of the nodes to be connected at the origin.	AGTXL4	ELMPLT	This problem was corrected by simply skipping the part of the code which assigned midside nodes to the quadratic elements when linear elements were being plotted. This kept the program from assigning midside nodes at the origin and allowed the linear elements to be plotted properly.
Note: The existing flow of the CDAC post-processor was used for WACSAFE post-processing. The CDAC main program was modified to provide proper labelling of menus and files when WACSAFE post data is processed. This was done for user convenience and was not a problem in the original CDAC code.			

2.4 Post-Processing of WACSAFE Post Data

An option was added to the CDAC post-processing menu to perform post-processing for WACSAFE post data. Unlike the pre-processor which is used primarily to write a WACSAFE model file, the post-processor performs many functions. Some of the options which are available for ABAQUS and TEXLESP post-processing (see CDAC User's Guide) are not available, are not useful, or cannot be validated for WACSAFE post-processing. Also, for some of the options which are available for WACSAFE post-processing, the results displayed have a different meaning than the same options for ABAQUS or TEXLESP post-processing. The following sections explain how to use the CDAC post-processor and the options available for WACSAFE post-processing. It may be helpful to consult the CDAC User's Guide when reading these sections.

2.4.1 Using the CDAC Post-Processor

The flow of the CDAC post-processor for processing WACSAFE post data is the same as the flow for processing ABAQUS post data. The two files needed for post-processing WACSAFE data are the FEGxx.BIN file, which is created in the pre-processor, and the WACxx.F13 file, which contains the post data from the WACSAFE program. The output file written by WACSAFE to be used by CDAC is named CDAC.F13. This file must be copied to a file called WACxx.F13 where xx is the current version number. Once the post data file, WACxx.F13, has been obtained, the FEAM of CDAC can be used to perform the desired post-processing of the data.

The option to perform post-processing for WACSAFE was added to the post-processing menu of CDAC. The new CDAC menu is shown below:

1. TEXLESP Post-Processing
2. ABAQUS Post-Processing
3. WACSAFE Post-Processing

4. FEAM Main Menu
5. CDAC Main Menu

To process the WACSAFE post data (contained in the file WACxx.F13), the user selects option 3 from the CDAC post-processing menu. The CDAC menus then prompt the user for the desired post-processing options. Although the menus are the same for WACSAFE post-processing as for TEXLESP and ABAQUS post-processing, not all of the options available for TEXLESP and ABAQUS are available for WACSAFE post-processing. The following section describes the options which are available for post-processing of WACSAFE data.

2.4.2 Post-Processing Options Available for WACSAFE

The following menu shows the options available in the CDAC post-processor:

1. Print Options
2. Plot Options
3. Lamina/Fiber Stress/Strain Analysis Failure Analysis
4. Post-Processing Menu

Under each of these post-processing catagories is a menu which gives specific options within the catagory. Each of the menus is presented here along with a description of the options available for WACSAFE post-processing. Because WACSAFE is a program specifically for fabrication analysis of filament wound composite structures, the results presented by the CDAC post-processor may have a different meaning than the results of a TEXLESP or ABAQUS analysis. The available WACSAFE post-processing options and the meaning of each option are discussed in the following sections.

2.4.2.1 Print Options

When "Print Options" is selected from the CDAC post-postprocessing menu (above), the following menu displays the options available for printing the solution data:

1. Displacement, Unaveraged Stress and Strain, Strain Energy, Von Mises
2. Same as 1, but Stress and Strain Averaged
3. Same as 1, but Stress and Strain at Gauss Points
4. 1 plus Minmax of Stress and Strain
5. 2 plus Minmax of Stress and Strain
6. 3 plus Minmax of Stress and Strain
7. Minmax of Unaveraged Stress and Strain
8. Minmax of Averaged Stress and Strain
9. Minmax of Stress and Strain at the Gauss Points

Each of these print options is available for WACSAFE post-processing. Although some of the options are self explanatory and need no further comment, many of the options produce different or more complex results than the simple menu item proposes. The menu options are explained here.

Option 1 is self explanatory and needs no comment beyond the menu description except that the stresses and strains which are printed are nodal values and are in the fiber coordinate system. This means that sigma-x in CDAC is actually sigma-1, sigma-y is sigma-2, and sigma-z is sigma-3, where 1 is the fiber direction, 2 is the transverse direction, and the 3 direction is through the composite thickness. The second option prints the averaged stresses and strains as indicated, but the print out results must be interpreted carefully. Because composite structures (especially rocket motor cases) often include materials other than the composite material (steel mandrel, rubber lining, etc.) the CDAC post-processor averages stresses and strains only within the same materials, not across material boundaries. For WACSAFE post-processing this was taken one step further and the WACSAFE post data file (CDAC.F13 described earlier) was modified so that CDAC would average stresses and strains only within the same layer of composite material. Therefore, the results from print option 2 will have stress and strain values averaged only within the same material type and the same layer of the composite. For option 3, the printed results are exactly the same as the results of option 1. This is because the centroid values were placed into the Gauss point values so the centroid values of stress and strain would be evenly divided by CDAC between the four node points of each element. Options 4 through 6 print exactly the same data as options 1 through 3 respectively. For some reason CDAC does not print the minmax values as the menu says it should. For options 7 through 9, CDAC prints all of the stresses and strains for the case indicated in the print options menu. Again, the minmax values are not printed.

To summarize the useful print options in CDAC for WACSAFE post-processing, options 1 and 2 provide valid printed data in the form explained above. Also, options 7 and 8 provide stress and strain data without the additional output (displacements, etc.) which is present in options 1 and 2.

2.4.2.2 Plot Options

When "Plot Options" is selected from the main CDAC post-processing menu, the following menu displays the options available for displaying post data in graphic form:

1. Undeformed Grid
2. Deformed Grid
3. 1 Outlined - Material
4. 1 and 2 Outlined - Material
5. 1 and 2 2 Outlined - Material
6. 1 and 2 1 Outlined - Material
7. 1 and 2
8. 1 and 2 Outlined - All
9. 1 and 2 2 Outlined - All
10. 1 and 2 1 Outlined - All
11. Stress/Strain Contours

Each of these plot options is available for WACSAFE post-processing. Options 1, 2, 7, and 11 are straight forward and produce plots which would be expected from the menu description. Example plots of options 7 and 11 are shown on the following pages.

Figure 4 shows a plot of the deformed finite element grid (solid lines) superimposed on the undeformed grid (dashed lines) for a blown up portion of the dome region of a composite case. The distortion of the deformed grid is magnified (by a scale factor for which CDAC prompts the user) for easier viewing so the deformations may appear irregular. A contour plot, in Figure 5, shows the stresses in the fiber direction for the dome region of a composite case. It is important to note that the boundaries on the plot represent the boundaries between materials and layers because the averaged stress and strain values are used for contour plotting. The average stresses and strains are obtained from the file (PDAxx.PST) printed using the print option menu (see the section on "Print Options" for a description of how the stresses and strains are averaged). Unless this file exists, contour plotting is not possible.

Options 3 through 6 and 8 through 10 are related to the plotting of material boundaries. At present the material boundary plots are not working properly. The contour plotting routine shows material boundaries properly and can be used if a material outline plot is desired.

2.4.2.3 Lamina/Fiber Stress/Strain Analysis Failure Analysis

The "Lamina/Fiber" option in the CDAC post-processing menu is supposed to calculate stresses and strains in the fiber direction and perform a failure analysis. Although these options can be selected for WACSAFE post-processing, they currently do not make sense for the WACSAFE data. The CDAC post-processor reads the stresses and strains from the WACSAFE output file as being in the global reference (sigmax, sigmay, etc.). The purpose of the "Lamina/Fiber" portion of the post-processor is to calculate the stresses and strains in the fiber coordinate system and perform a failure analysis if desired. The post data for WACSAFE which is read into the CDAC post-processor is already expressed as the components in the fiber coordinate system. This means

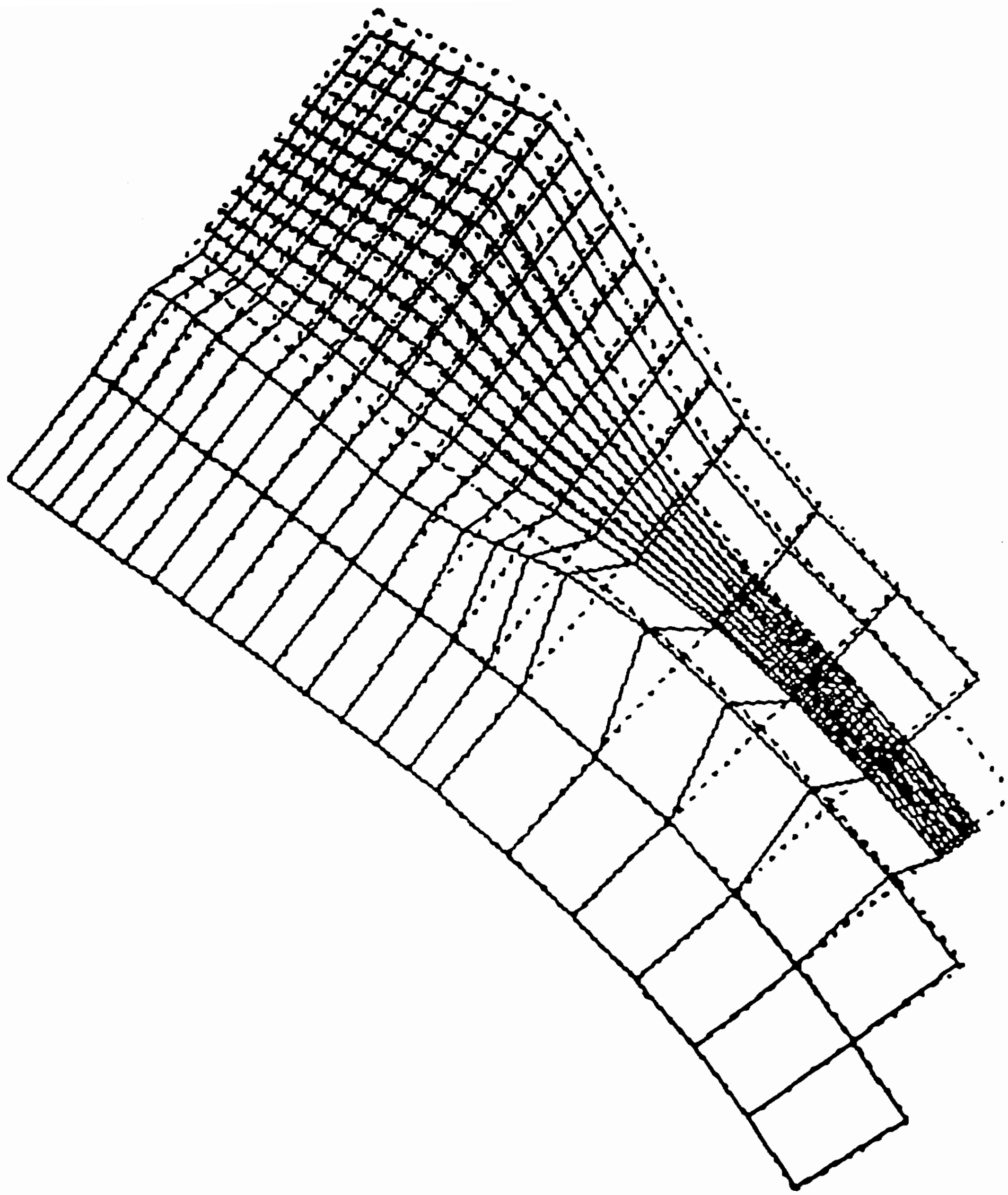

Figure 4. Typical Plot of Deformed Mesh Superimposed on Undeformed Mesh from the CDAC Post-Processor

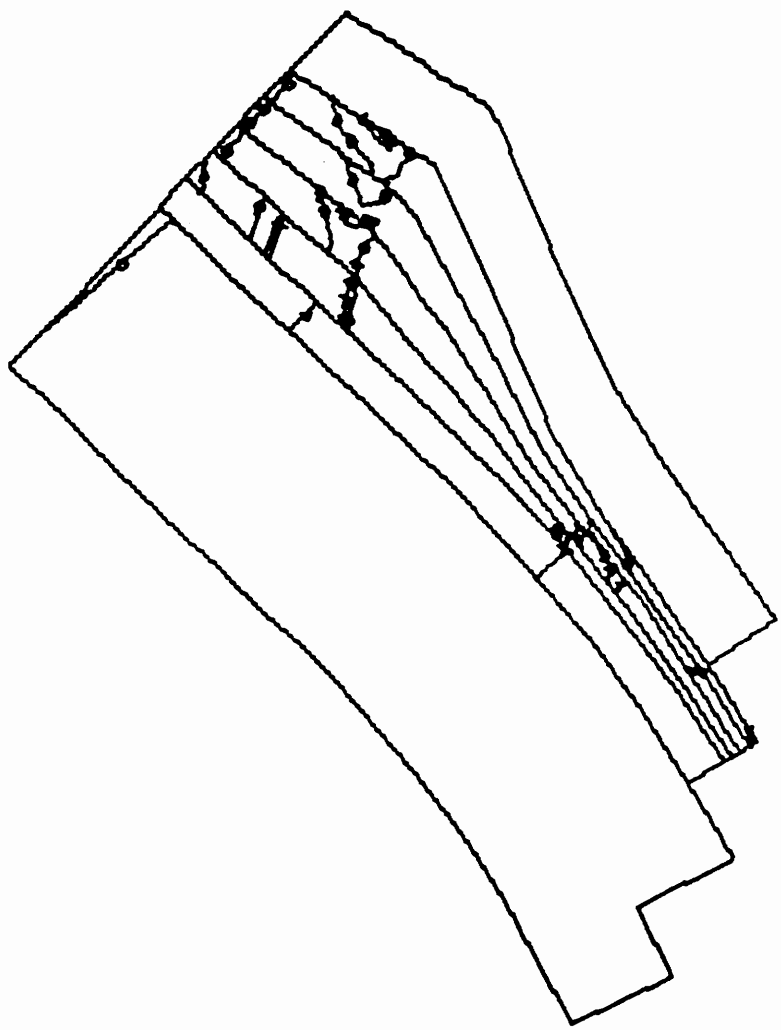

Figure 5. Typical Contour Plot from the CDAC Post-Processor

that the values which CDAC is calculating are incorrect fiber stress and strain values and a failure analysis based on these values would yield an errant conclusion about failure. Also, since WACSAFE calculates stress and strain during the fabrication process, a different definition of failure (rather than simple static failure) should be used. This different definition may include unacceptable levels of residual tension, unacceptable residual intralaminar stresses, and compressive strains at cure. It is not recommended that the "Lamina/Fiber" option be used for WACSAFE post-processing. Instead, an alternate post-processor for WACSAFE, which is discussed in the following chapter, is recommended for determining "failure".

3.0 The WACPLOT Post-Processor

Although post-processing for the WACSAFE program can be done using the CDAC program described in an earlier chapter, a separate post-processing program (WACPLOT) was written to provide additional plotting capability for the post-processing of WACSAFE data. This chapter describes the general program structure and capability. For information on how to use WACPLOT and a complete program listing, refer to the WACPLOT User's Guide [6].

3.1 Program Structure

The WACPLOT program uses the basic input, set-up, and element plotting routines that the WACSAFE pre-processor, WACFORM [2], uses. Figure 6 shows a flow chart of the program structure. The program can be divided into three basic sections: data input from files, user input in response to menu prompts, and plotting of output data. These three parts are decribed below.

For the data input section of the program, WACPLOT uses the WACSAFE model file (see reference [2] for a complete description of this file), the cure data file (see the FWCURE User's Guide [4] for a description of this file), and the WACSAFE plot file (see reference [6] for a de-

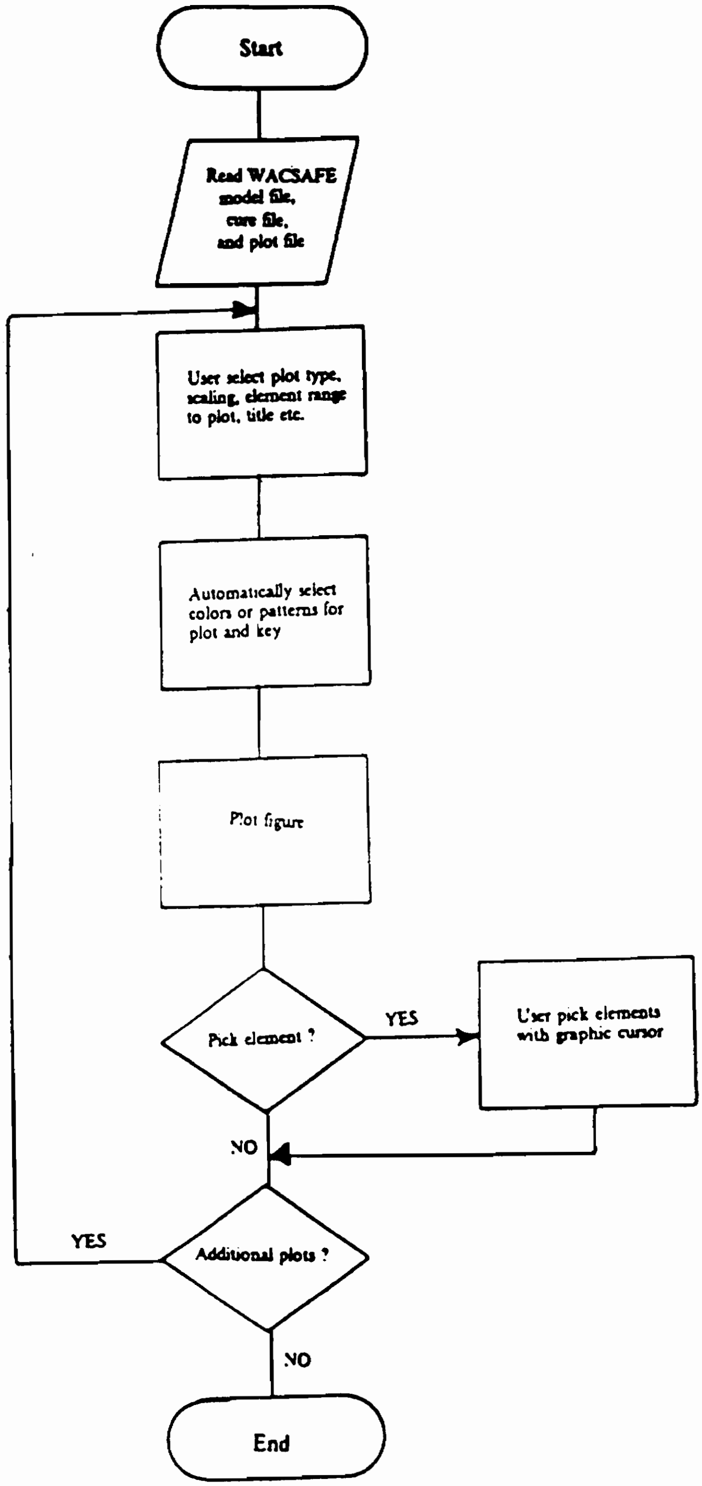

Figure 6. General Flow Chart for the WACPLOT Program

scription of this file). WACPLOT reads the geometry from the model file, the degree of cure, temperature, and viscosity data for each cure step from the cure file, and final displacements, stresses, and strains from the plot file.

After the initial data has been read from the necessary files, the program is completely menu driven. The user must select menu options and answer prompts. Figure 7 shows the four main menus from which the user selects. In the figure, the menu's have boxes around them while the prompts begin with a # symbol. Using the MAIN menu, the user chooses the type of plot from those available.

For stress, strain, degree of cure, and temperature plots, there are two intermediate menu's where the user must answer certain prompts. The user selects the specific data to be plotted from the category selected in the MAIN menu in the TYPE menu. For example, there are six components of stress and one of the six must be selected for plotting. In the SCALE menu, the user instructs the program on how to scale the data (automatically or manually). The DISPLAY menu allows the user to choose from plots with all of the materials, a specific material, or a specific layer. Also, in this menu, the element number range to be plotted is selected. The plot is drawn and control of the program returns to the DISPLAY menu which exits to the MAIN menu. For a thorough explanation of the menus and prompts, consult the WACPLOT User's Guide [6].

3.2 Capability of the WACPLOT Post-Processor

The reason for writing a post-processor code in addition to the CDAC program, is because the CDAC code could not offer all of the needed capability for the post-processing of both WACSAFE and FWCURE data. The WACPLOT post-processor can plot the original geometry, deformed geometry, and a color material type plot in addition to the color element fill plots for stress, strain, degree of cure, and temperature mentioned above. These can be plots of all of the materials, a single material, or a single layer. As the CDAC program is performing at present, it does not have

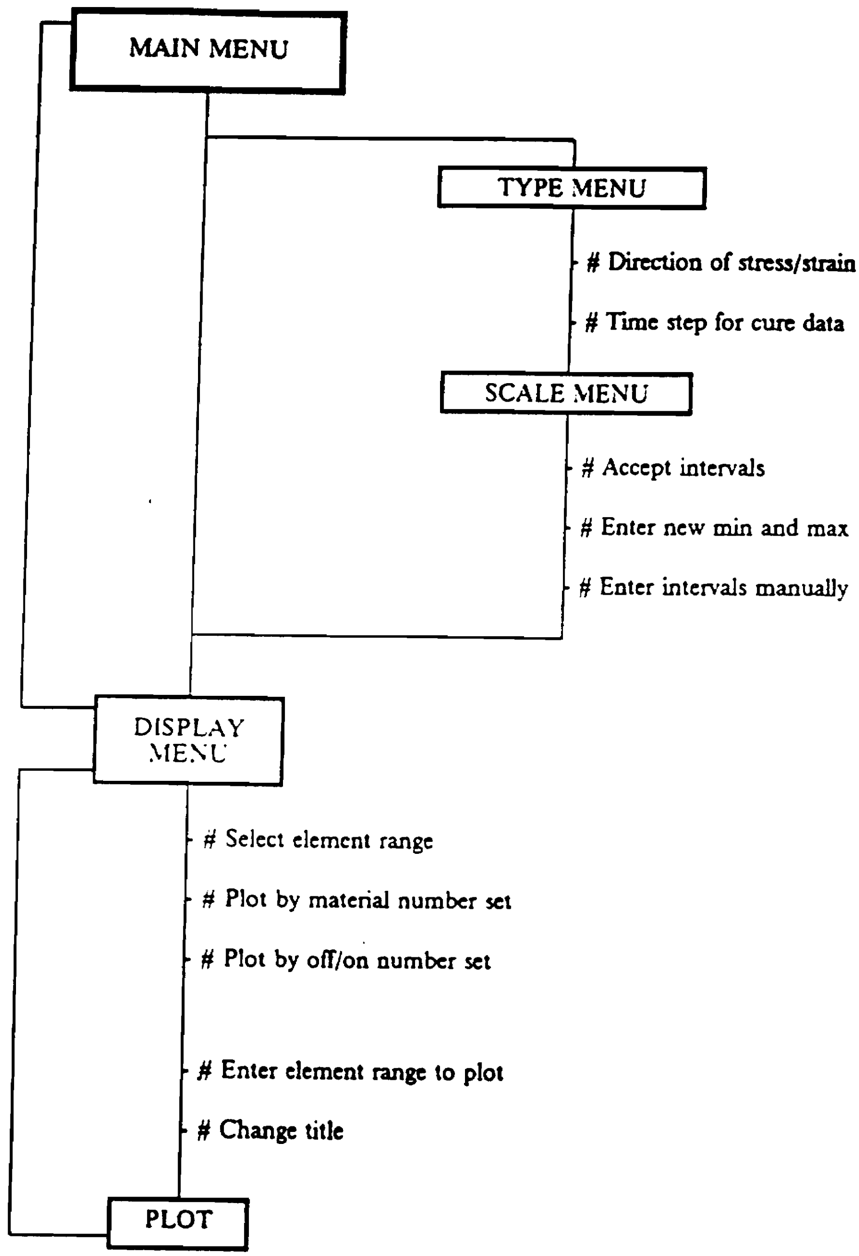

Figure 7. WACPLOT Menu Structure

the capability to plot data by material type or cure data such as degree of cure and temperature. An example of the element fill plots are shown in Figure 8. The plot displays stress in the fiber direction for all of the material groups. Examining the figure, some of the advantages WACPLOT possesses over CDAC become evident. Although a minor advantage, WACPLOT has the capability to plot both color fill plots and black and white pattern fill plots. Also, the WACPLOT program allows the user to input a title for the plot whereas CDAC automatically titles the plot. Although these features are not necessary, they make the program more convenient to use.

Figure 9 displays a plot of only the composite material for the same stress and element range as Figure 8. It is evident that the plot is larger and easier to read properly than the plot in Figure 8. The advantage of plotting only a certain material group is that the unwanted details are filtered out which creates a more readable plot. This capability comes from the base program for WACPLOT which is WACFORM [2].

Another capability of the WACPLOT program is that it allows the user to pick an element with the graphic display cursor and have the value for the element displayed on the plot (the value will be of either stress, strain, degree of cure, or temperature). This way, the user can have more specific information rather than simply the range of numbers into which the value falls. A plot demonstrating this capability is shown in Figure 10. The code for this part of the program was written so that the element whose center is closest to the selected point is the chosen element. This can cause problems if the peripheral area of an element is selected. As shown in the figure, the element number is displayed along with its value so no confusion should result.

As mentioned in the previous chapter, WACPLOT performs a basic type of failure analysis which is appropriate for the filament winding analysis code. The user inputs a value at which "failure" is expected to occur and whether "failure" occurs at values greater than or less than this value. Because the stresses and strains will be processing stresses and strains, the definition of failure is likely to be far different from a mechanical rupture of the material. For example, "failure" may be residual fiber tension which is too high or any residual compressive fiber strains. After the value at which "failure" occurs is defined by the user, WACPLOT plots all elements which "fail" in red

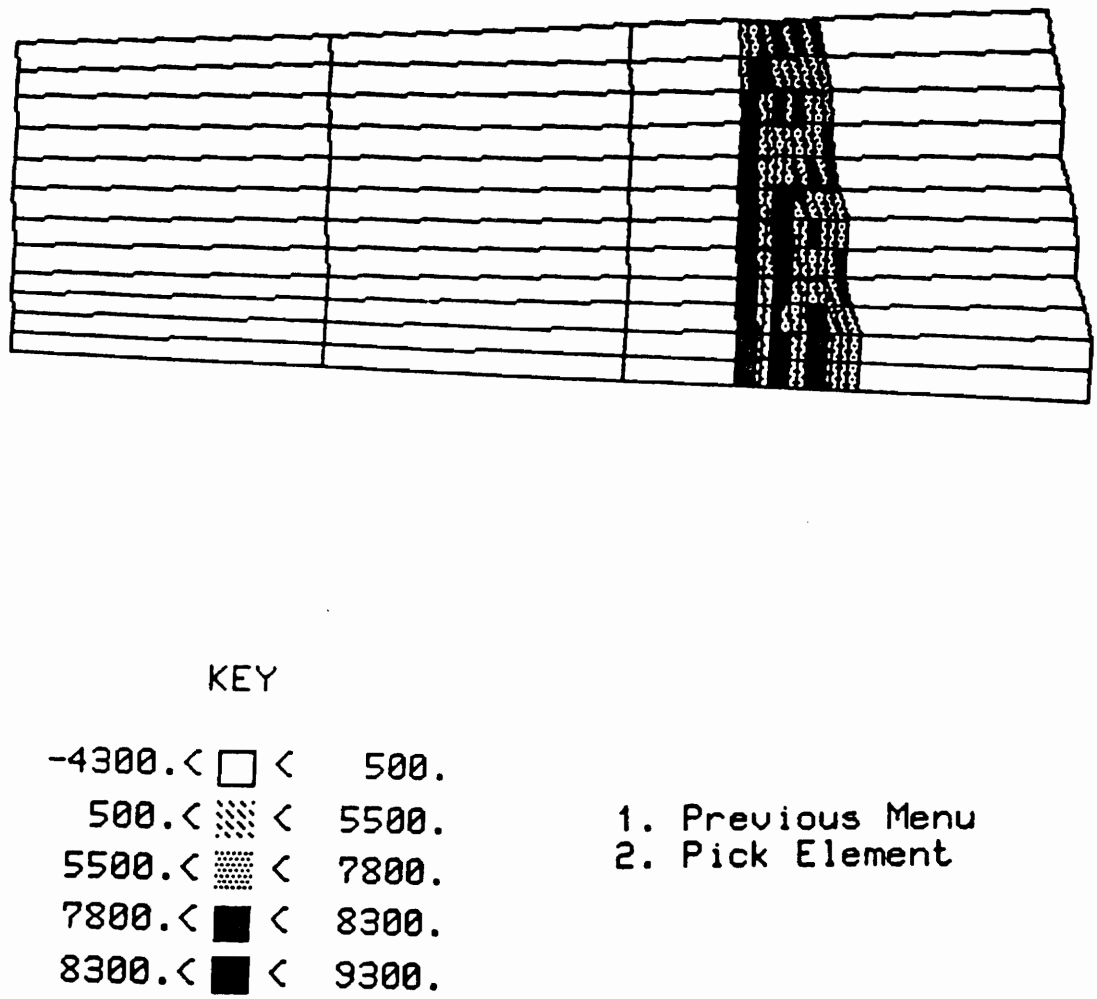

Figure 8. Element Fill Capability of the WACPLOT Program

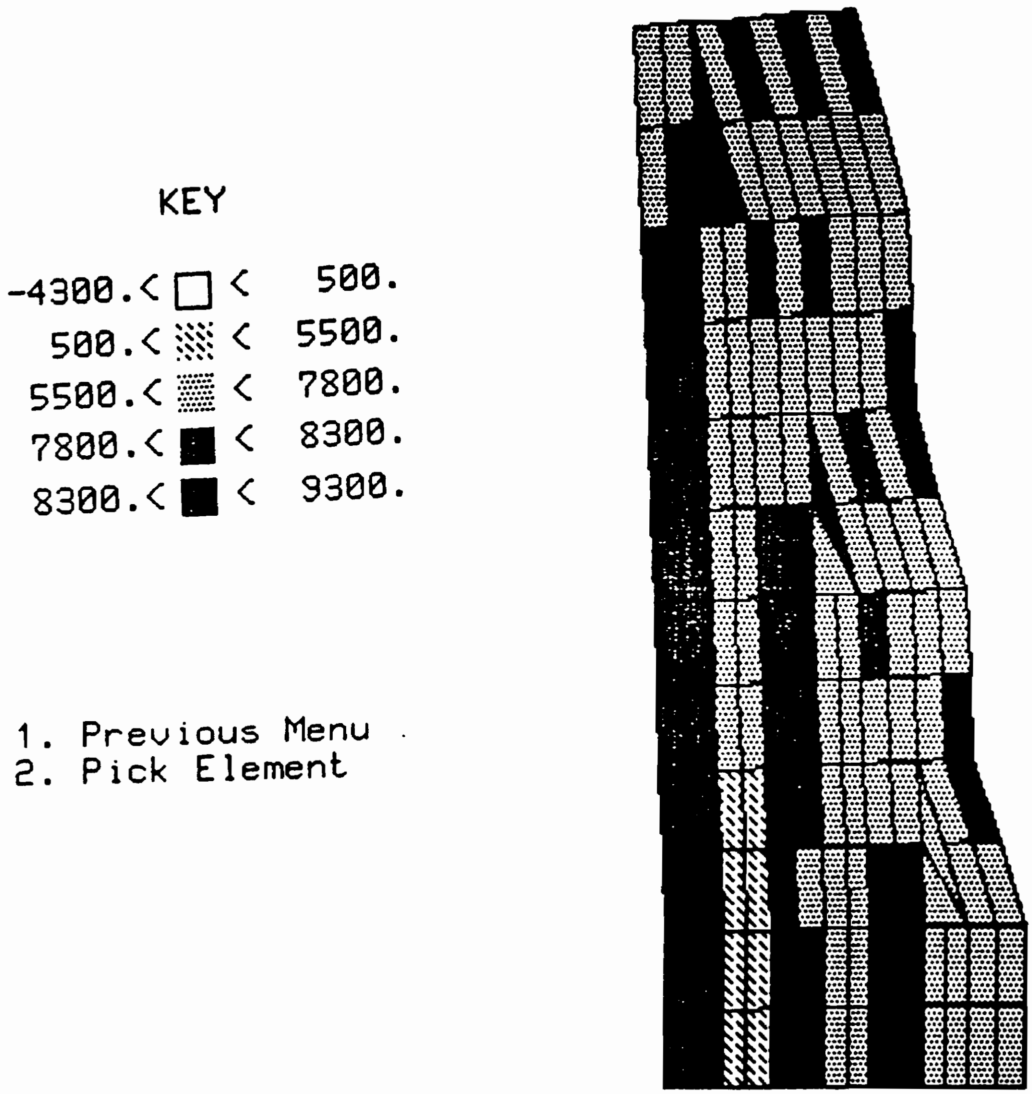

Figure 9. Element Fill Plot by Material Type Using WACPLOT

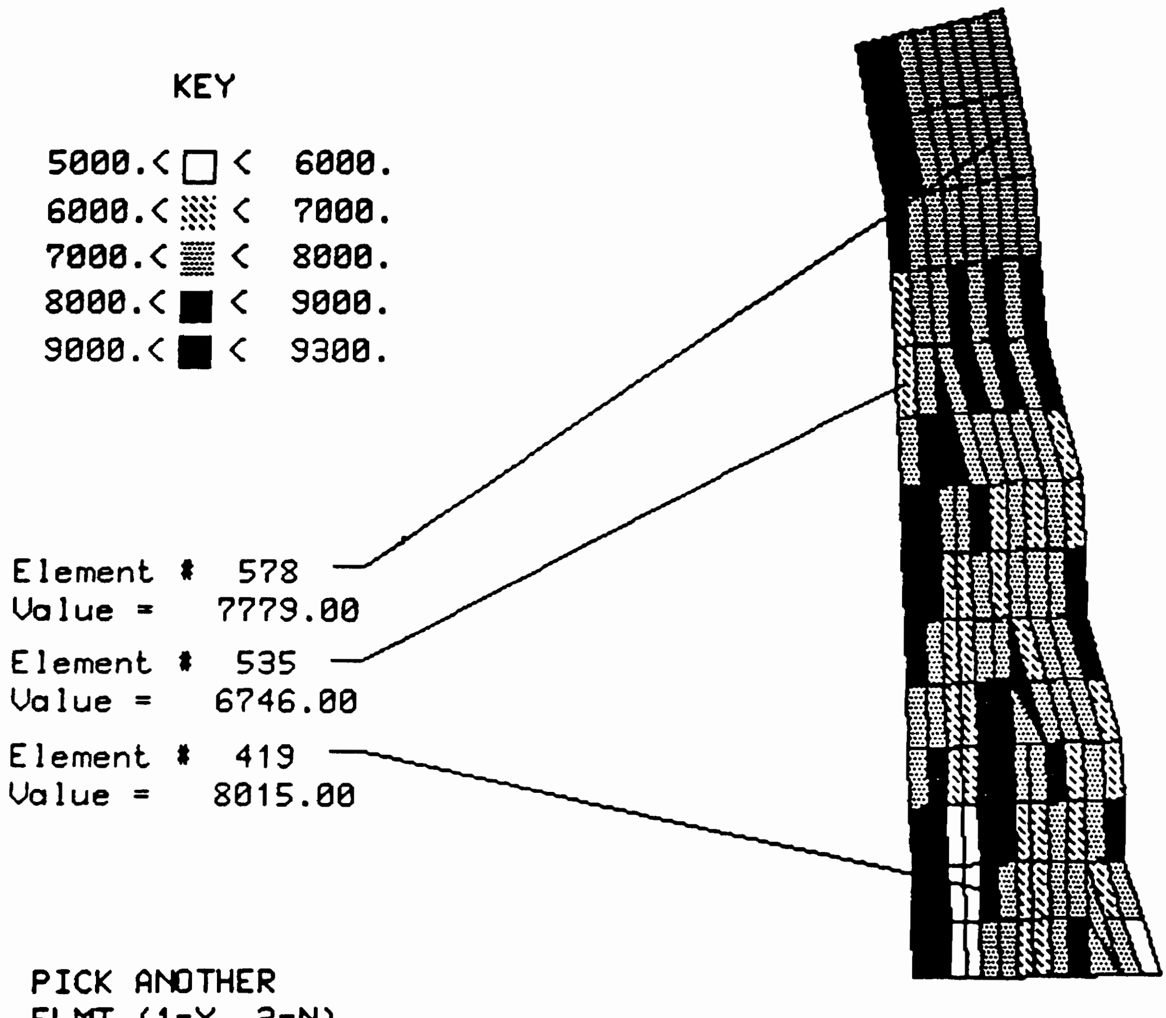

Figure 10. Element Picking Capability of WACPLOT

and all elements which do not "fail" in white. A plot of this type is shown in Figure 11. Consult the WACPLOT User's Guide for more information on how to use these capabilities.

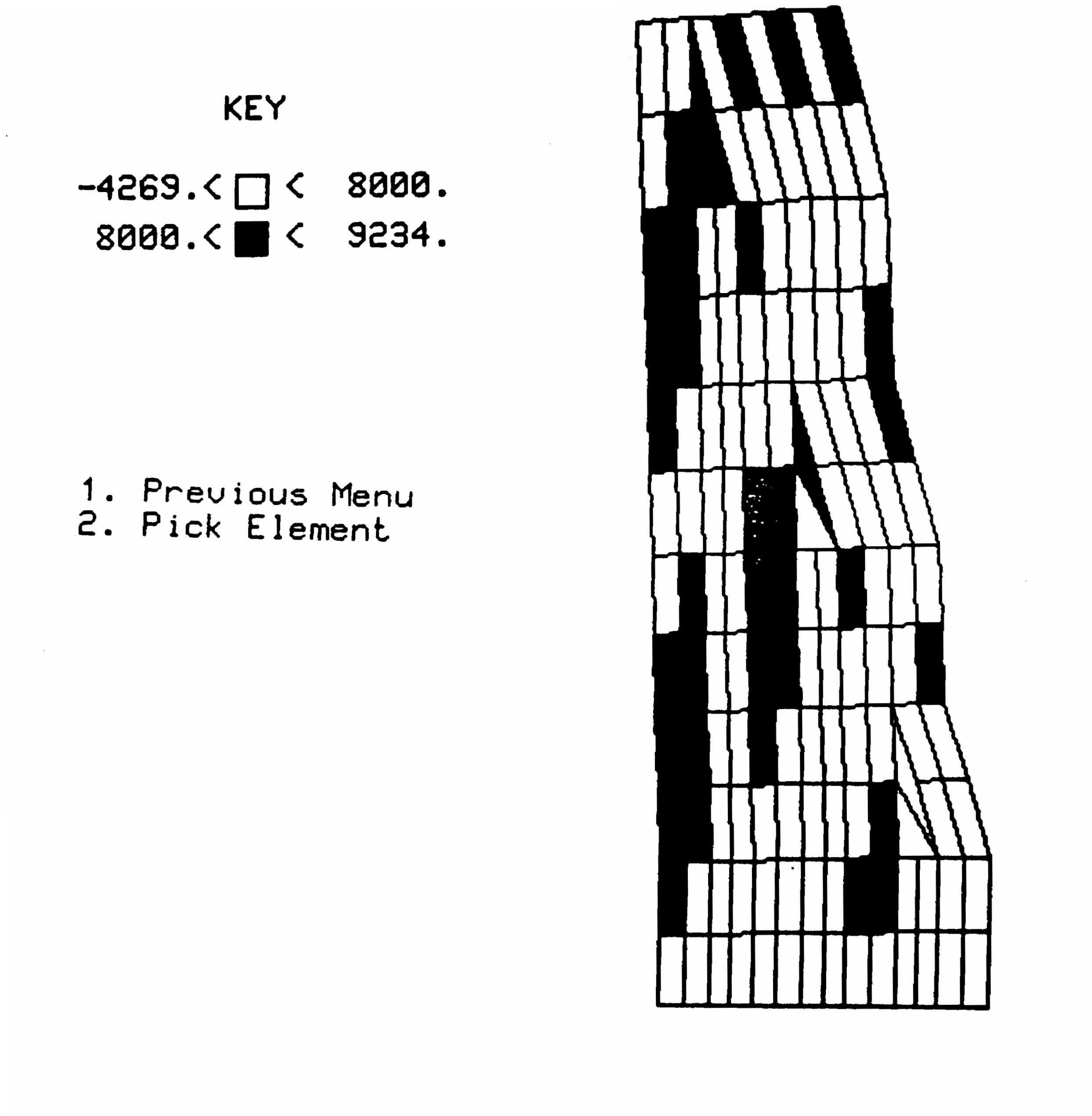

Figure 11. Failure Analysis Capability of WACPLOT.

4.0 Experimental Verification of WACSAFE

WACSAFE [1] is a finite element program which is used to predict the stresses and strains in filament wound composites during winding, curing, and after fabrication is complete. For the program to be useful, it must be verified. An experiment was constructed for the purpose of verifying the WACSAFE program and improving the modelling capabilities for the filament winding and curing processes. The Thiokol Corporation performed the verification wind experiment and provided experimental data for an 18 inch (45.72 cm) test bottle. Comparison of the experimental data with the analytical results of the WACSAFE model provides a method for verifying the validity of the analytical model and improving its accuracy. Using WACSAFE, several models were run to improve the accuracy of the fabrication process model. This chapter presents the experiment set-up, the analytical models, a comparison between analytical and experimental results, and predictions of the residual stresses and strains after fabrication for the verification wind experiment.

4.1 Experiment Set-up

The set-up for the verification winding experiment is shown in Figure 12 below. The bottle consists of a segmented steel mandrel, a rubber insulation layer, the composite case, and a vacuum bag. Four hoop strain gages, a pressure gage, and three polar strain gages were bonded to the outside of the steel mandrel. Hoop strain gage S003 and pressure gage P022 were located at the mid-plane of the mandrel cylinder, hoop strain gages S002 and S004 were located near each tangent line of the cylinder, and hoop strain gage S001 was positioned on the dome. The three polar strain gages S011, S012, and S013 were positioned 120 degrees about the cylinder axis. The data obtained from this experiment were compared with results of the WACSAFE simulations which are presented in the following section.

4.2 WACSAFE Simulations

Several variations of the finite element model were run using the WACSAFE program. After each run, the simplifying assumptions made in forming the model were evaluated and the model was modified to better reflect the experiment. Four cases were run for the verification winding experiment. Each succesive model included a single added factor to provide some idea of the importance of each factor. The four models are summarized below and each is described in detail in the following sections.

1. Case 1 - Solid steel mandrel, full winding tension
2. Case 2 - Effective modulus for steel mandrel, full winding tension
3. Case 3 - Effective modulus for steel mandrel, tension loss from experimental data
4. Case 4 - Effective modulus for steel mandrel, better estimate of tension loss

The input data file for WACSAFE for these cases can be found in reference [14].

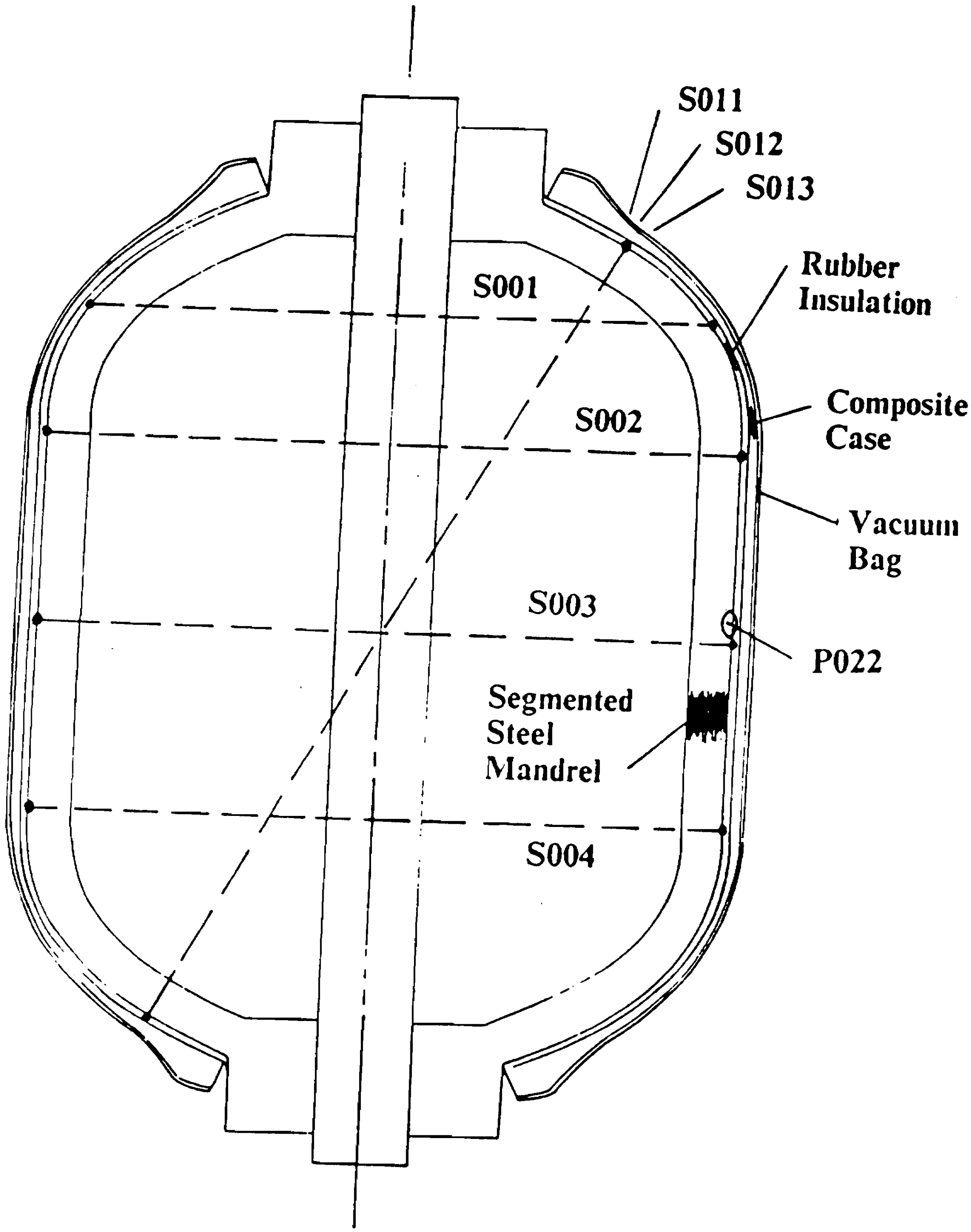

Figure 12. Experiment Set-up for the Verification Wind

4.2.1 Case 1

The first case consisted of the simplest and most naive model of the experiment. The segmented steel mandrel was modelled as solid steel and the fibers were assumed to retain full tension upon laydown. The reason for modeling the segmented mandrel as solid is that it is commonly assumed that the segmented mandrel pieces fit extremely well and therefore are very solid against external winding pressures. The reason for using full tension is that very little data is available at this point on laydown tension loss in prepreg materials (prepreg has the resin injected into the fiber bundles and is staged, i.e., cured slightly).

The results of the first model are shown and discussed on the following pages. In Figures 13 and 14, the analytical and experimental mandrel pressures on the midplane are plotted during winding and cure.

Figure 13, for the winding stage, shows reasonable correlation between the analytical and experimental results because the changes in slope of the experimental curve are predicted by the same changes in slope of the analytical curve. The accuracy of the model is very poor as can be seen by the 400% difference in the cumulative analytical and experimental results for the last winding step. In Figure 14, for the curing stage, the correlation between the experimental and analytical data is not as evident as it was in Figure 13. The upward trend is predicted, but there are no definitive slope changes in the data. Again the accuracy of the model is very poor.

Figures 15 through 19 show the analytical and experimental strains at the midplane, tangent line, and dome locations during winding and cure.

Figure 15 shows the experimental and analytical predictions of strain in the dome of the composite bottle (gage S001). The correlation between the predicted and experimental data is evident in the later winding steps, but the accuracy of the model is again very poor.

The strain results at the bottle tangent lines (gages S002 and S004), in Figure 16, show reasonable correlation throughout the winding process but are less accurate than the data for the dome. Figure 17 shows the hoop strain results at the bottle tangent line (gage S002) during cure. The results for gage S004 are not shown because it failed during cure. The correlation between the experimental and analytical data is very poor as is the accuracy.

Figures 18 and 19 show the experimental and analytical strains at the bottle midplane (gage S003) during winding and curing. The results for the winding stages are very similar to Figures 15 and 16 in that they show the same type of correlation in the slopes of the data and very poor accuracy. Also, the data during cure show very poor correlation and accuracy.

It was suspected that the difference in stiffness between the segmented steel mandrel and solid steel accounted for a large part of the difference between the analytical and experimental results. A lower mandrel stiffness would produce lower analytical pressures and higher analytical strains (which would produce better agreement between the analytical and experimental results). The second analytical model was run to demonstrate the effects of the segmented mandrel.

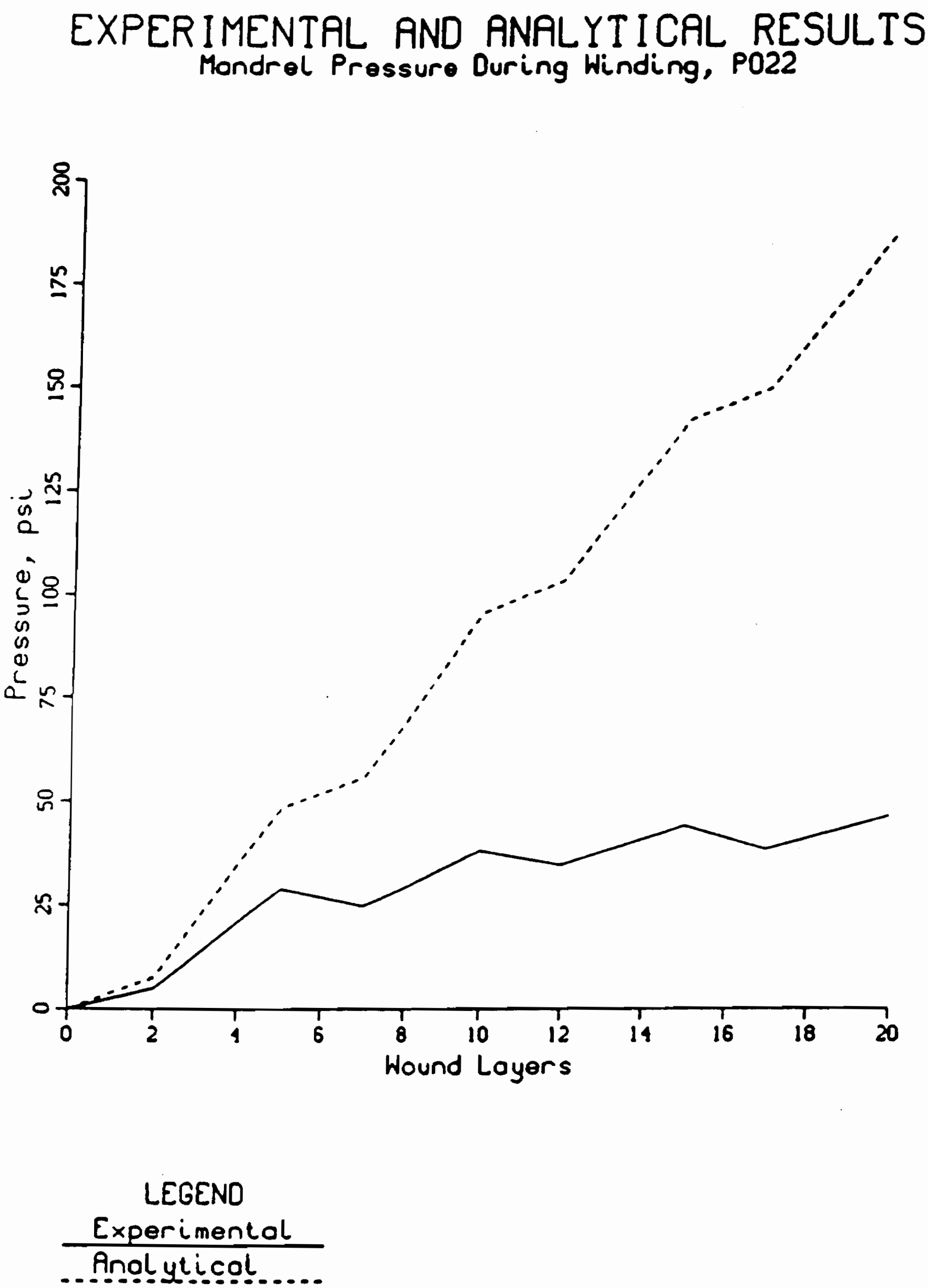

Figure 13. Case 1 Pressure Results

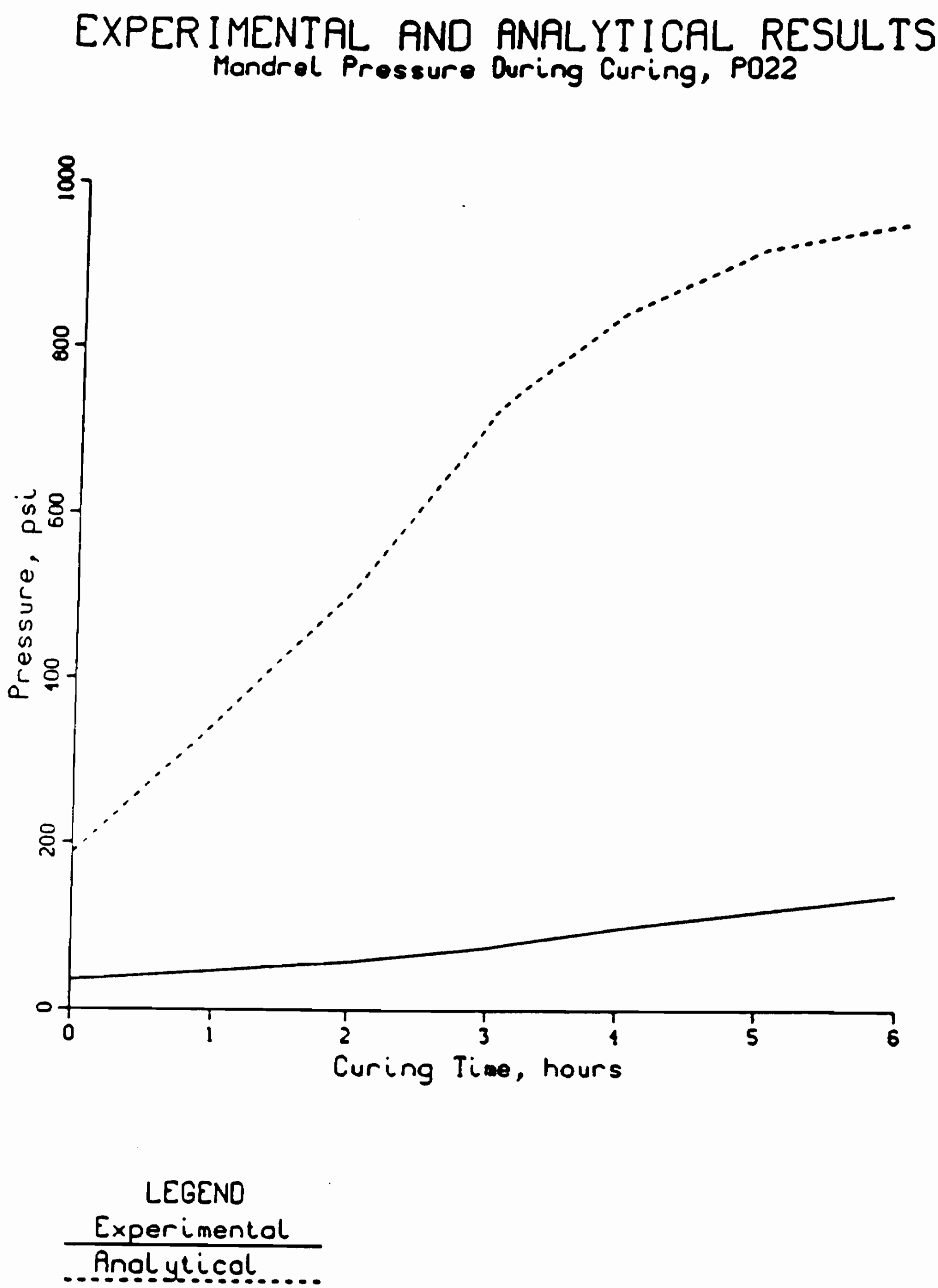

Figure 14. Case 1 Pressure Results

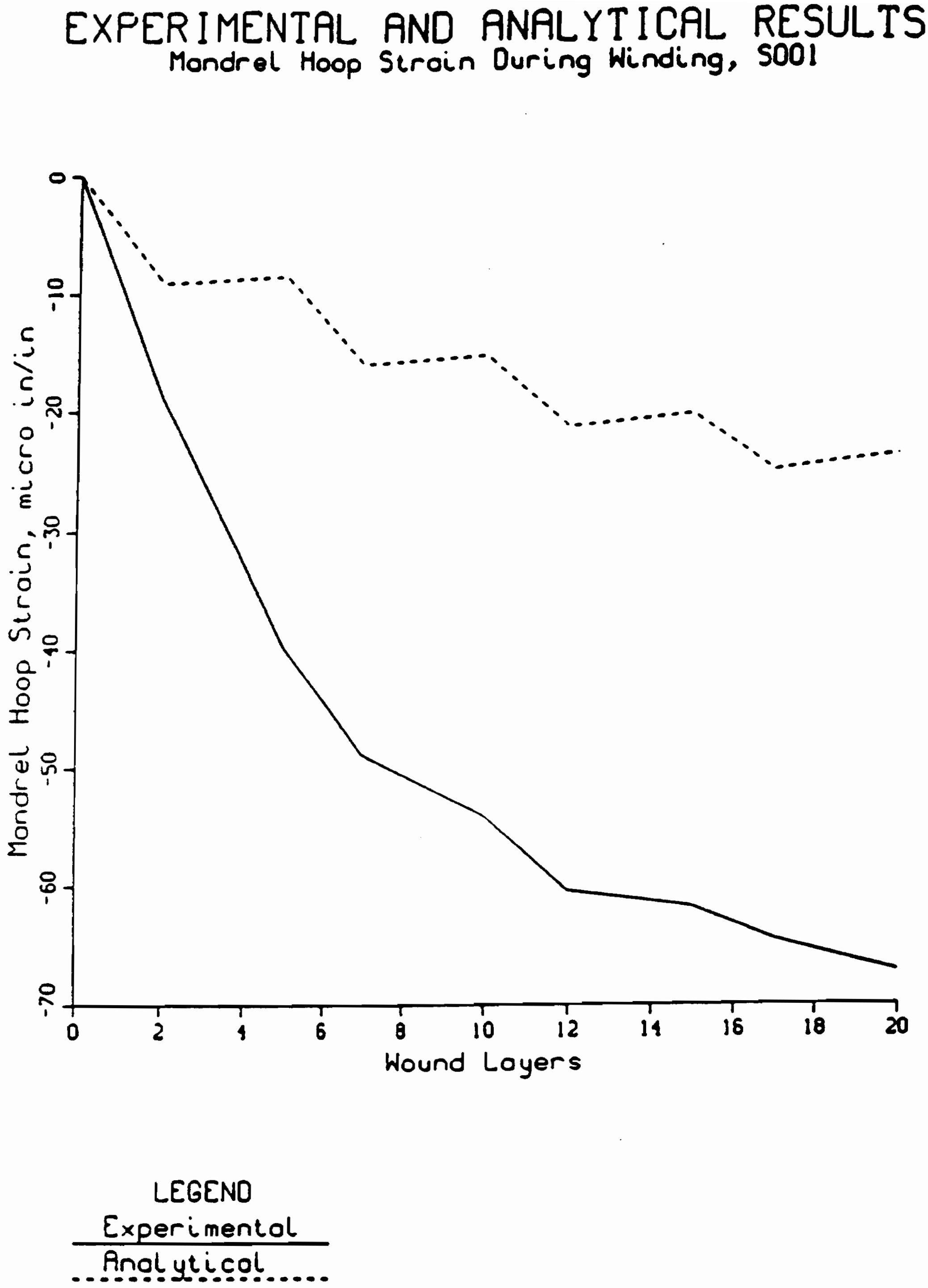

Figure 15. Case 1 Hoop Strain Results

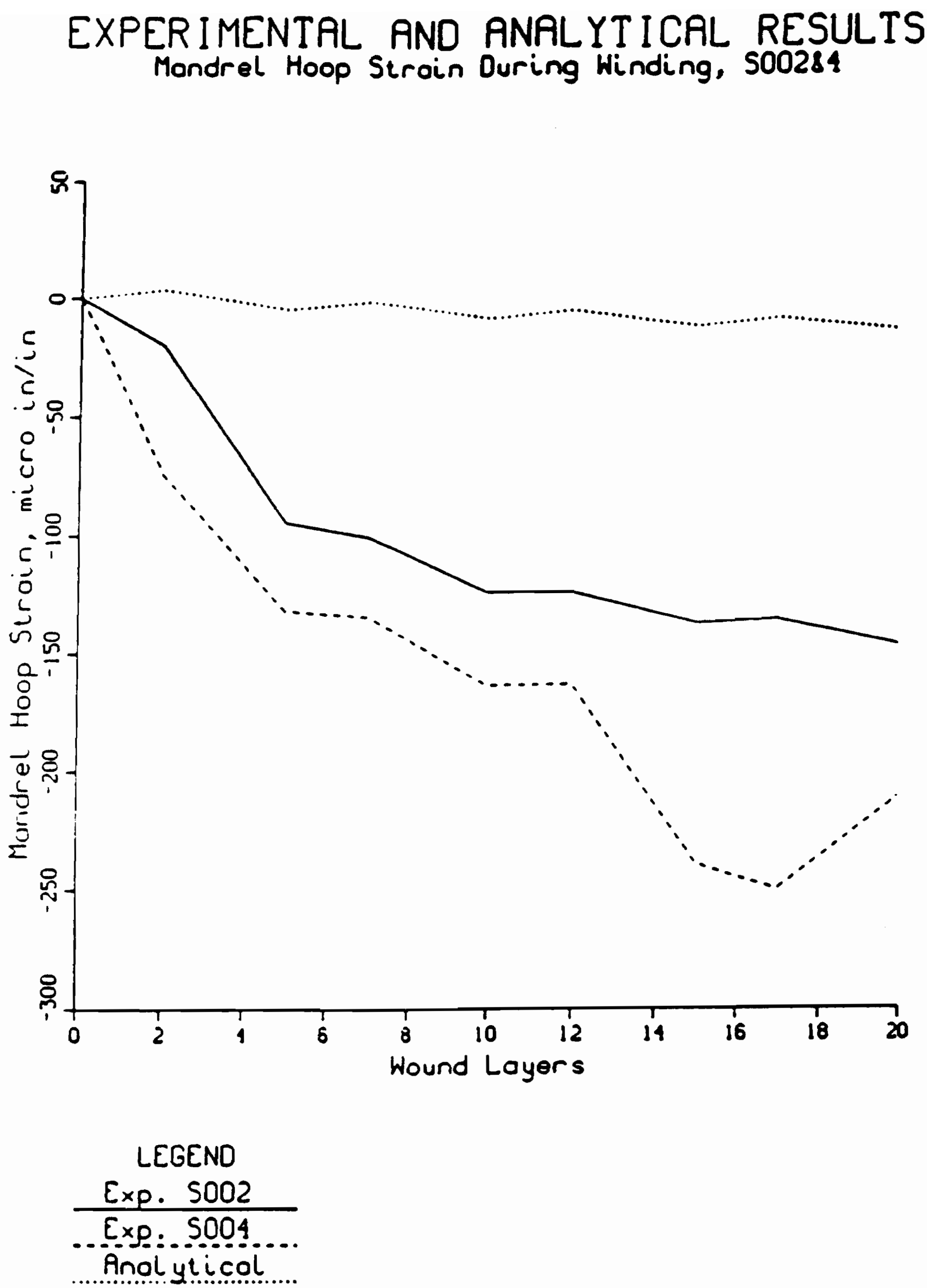

Figure 16. Case 1 Hoop Strain Results

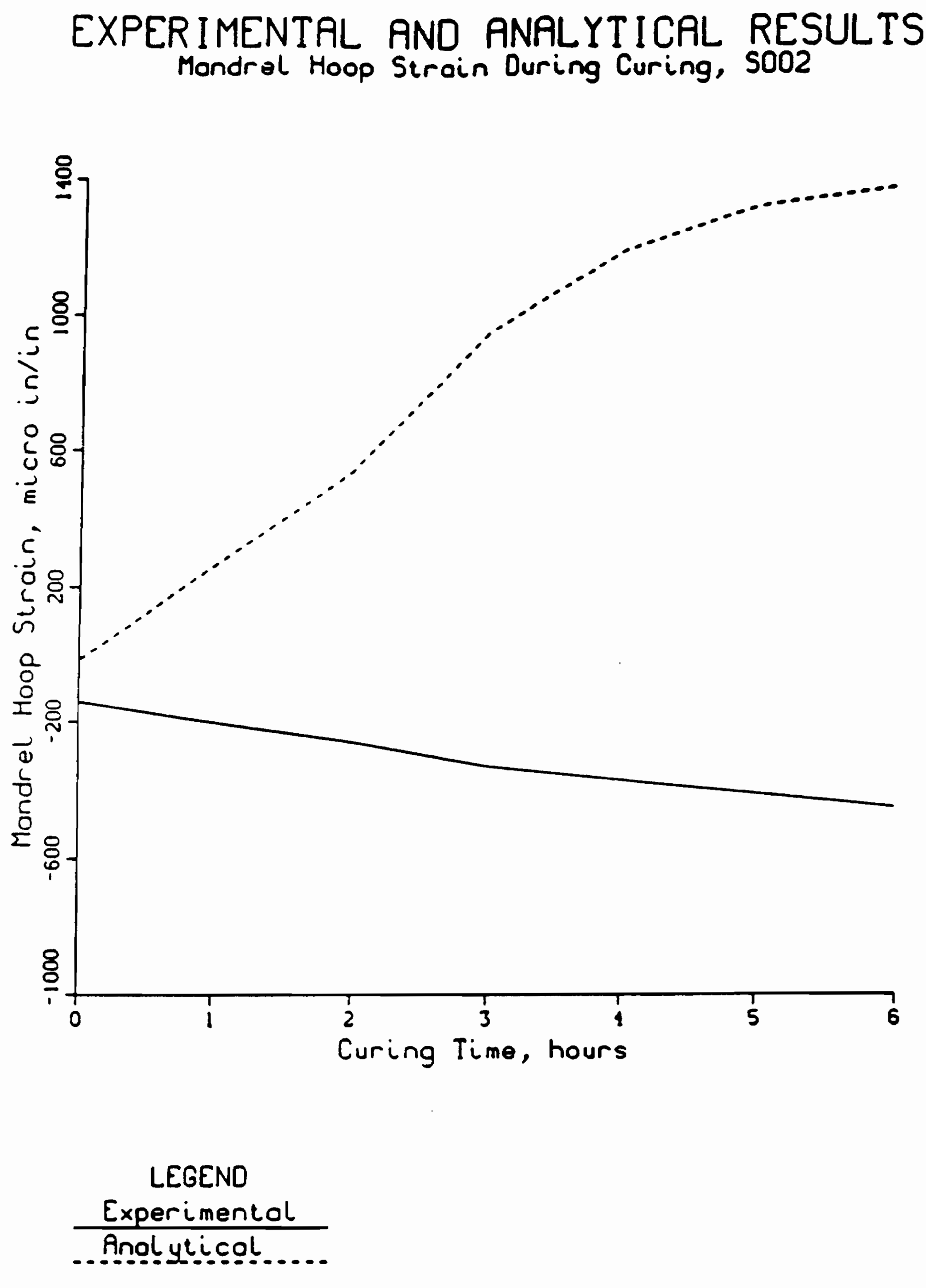

Figure 17. Case 1 Hoop Strain Results

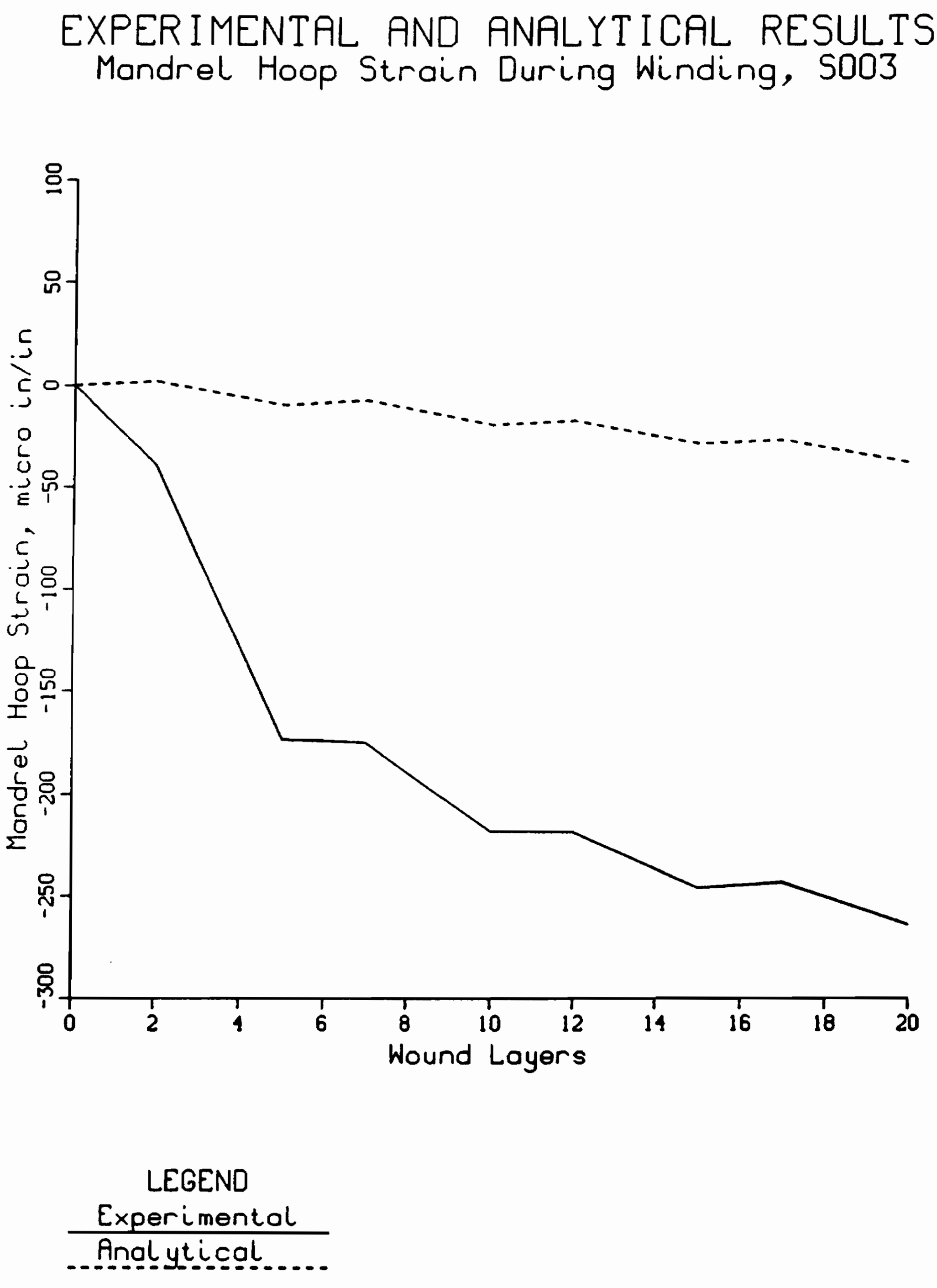

Figure 18. Case 1 Hoop Strain Results

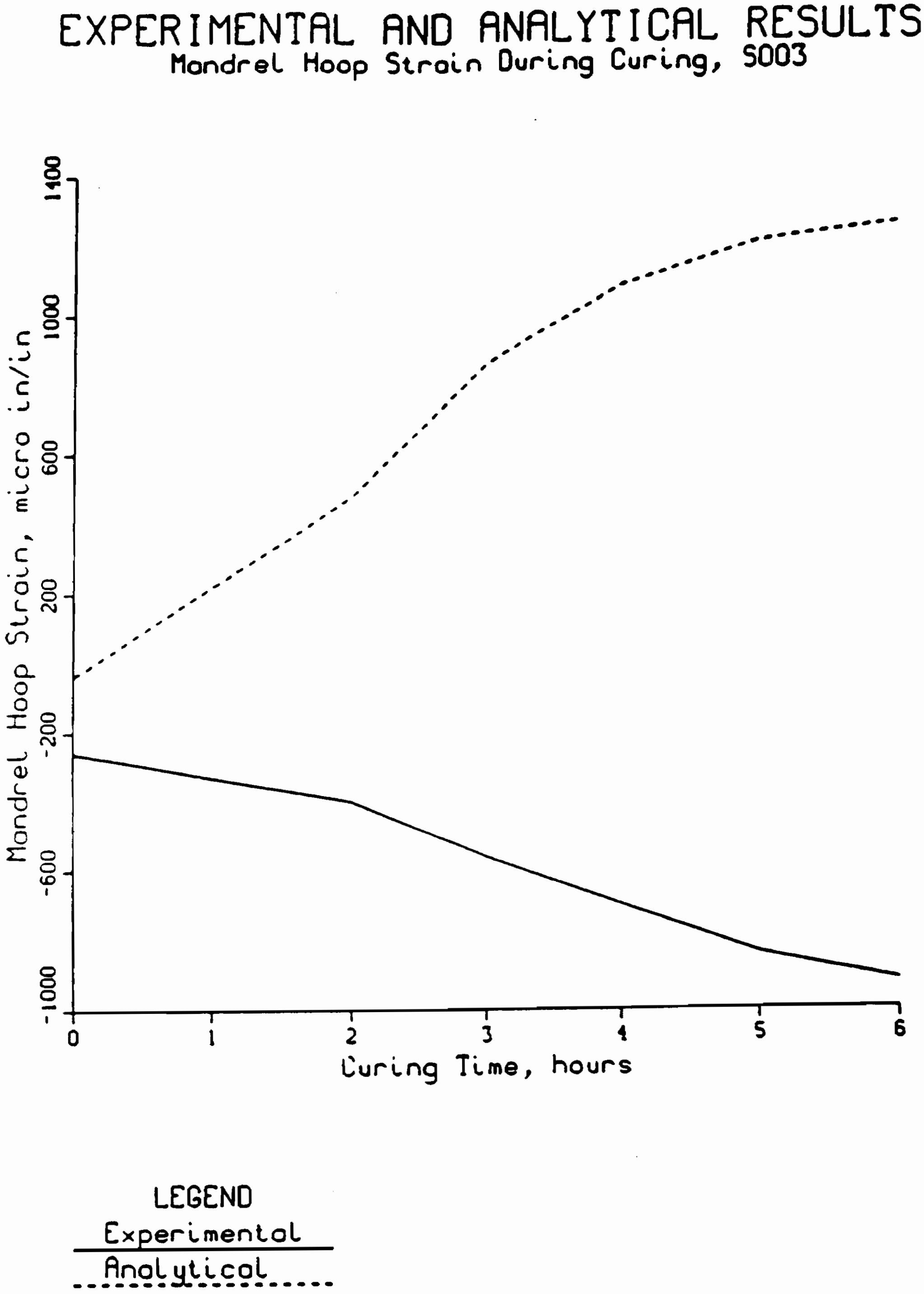

Figure 19. Case 1 Hoop Strain Results

4.2.2 Case 2

The second analytical model was altered to reflect the differences between the solid steel mandrel, used in the first model, and the segmented steel mandrel. An axisymmetric model can not actually model the segmented mandrel, but a simple approach is to reduce the mandrel modulus of elasticity to match the experimental data. An effective modulus for the semented steel mandrel was calculated from the experimental pressures and strains using the following equations and procedure :

$$\varepsilon_h = \frac{\sigma_h}{E} + \nu \frac{\sigma_a}{E}$$

$$\sigma_h = \frac{P d_{avg}}{2t}$$

$$\sigma_a = \frac{\sigma_h}{2}$$

where ε_h is hoop strain in the mandrel (obtained from experimental data), σ_h is hoop stress, σ_a is axial stress, E is Young's modulus for steel (30 Mpsi, 2.07 GPa) , ν is Poisson's ratio for steel (.3), P is the pressure (obtained from experimental data), d_{avg} is the average mandrel diameter (8.97 inches, 22.78 cm), and t is the mandrel thickness (1 inch, 2.54 cm).

The modulus was calculated from the pressure and strain data at the mid-cylinder after 5, 10, 15, and 20 layers of winding were applied. The calculated values did not vary much and were averaged to find an effective modulus for the segmented mandrel of about 0.586 Mpsi (4.04 MPa). This calculated effective modulus for the segmented steel mandrel is over fifty times lower than the modulus of solid steel used in the first model. The new effective modulus for the segmented mandrel was used in the second model.

The analytical results of the second model are shown next.

Figure 20 shows the pressure on the bottle midplane. As expected, the pressures predicted by the WACSAFE program decreased due to the lower stiffness of the segmented mandrel in the model. The reasonable correlation between the experimental and analytical data is still evident and the accuracy, while poor, is much better than the accuracy of the first model.

In Figure 21, the hoop strains in the dome are plotted. The predicted strains are much larger than the experimental strains for the dome location. It is suspected that this large discrepancy in the data may be due to the fact that the hoop strain gage, which was bonded to the dome, may have slipped during the winding process. The predicted strain data for the dome section for subsequent models supports this conclusion. Because of this, the strain data for the dome (gage S001) will be omitted in the results for the last two cases.

The hoop strains at the bottle tangent lines (gages S002 and S004) are plotted in Figure 22. As expected, the analytical strains increased due to the decreased mandrel stiffness. The plot shows reasonable correlation between the analytical and experimental data and much improved accuracy over the first model.

Figure 23 shows the experimental and predicted strains at the bottle midplane during winding. Again the predicted strains increased as a result of the lower mandrel stiffness. The correlation between the data is reasonable, but the accuracy, while much improved over the previous model, is still poor.

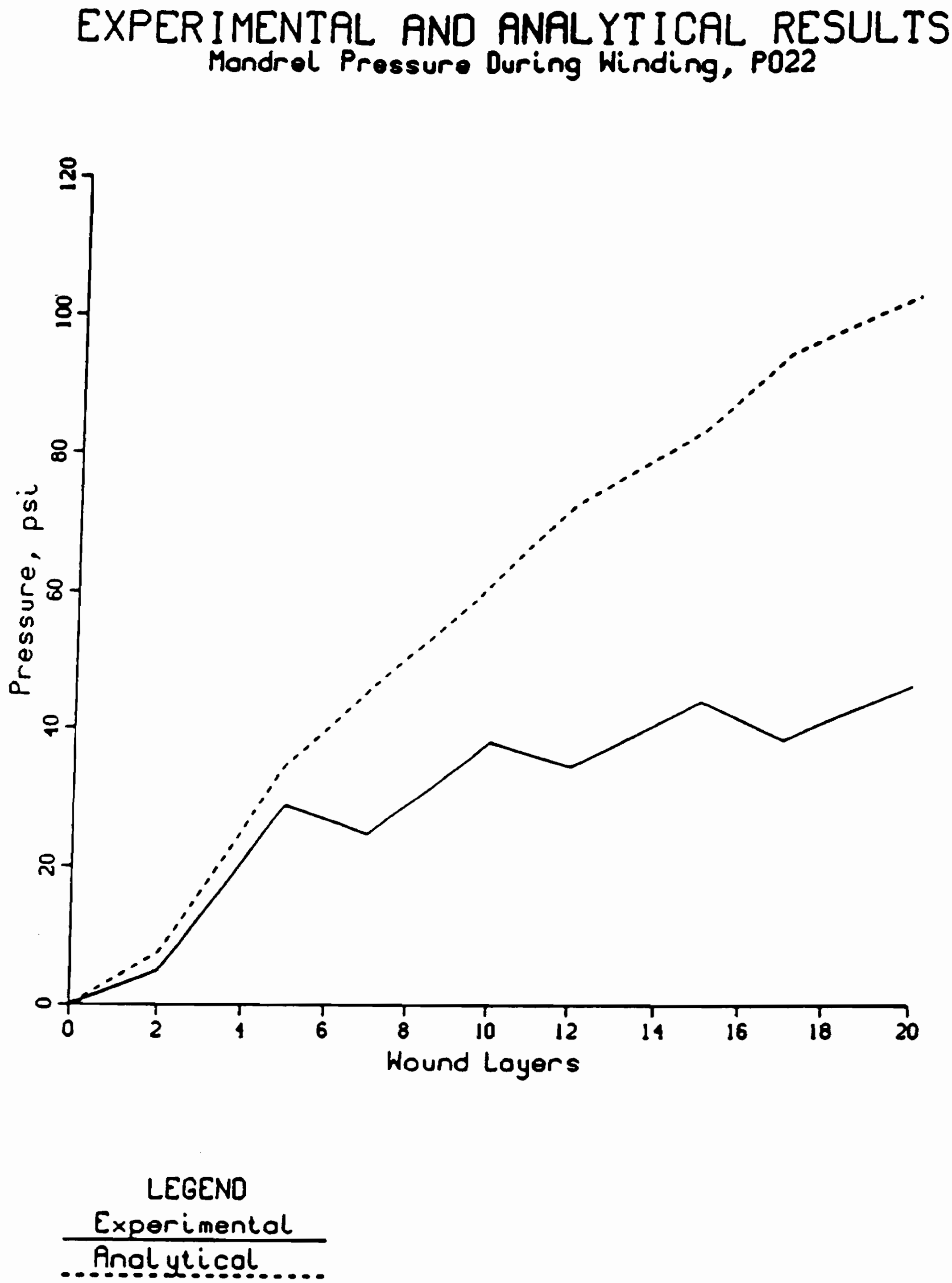

Figure 20. Case 2 Pressure Results

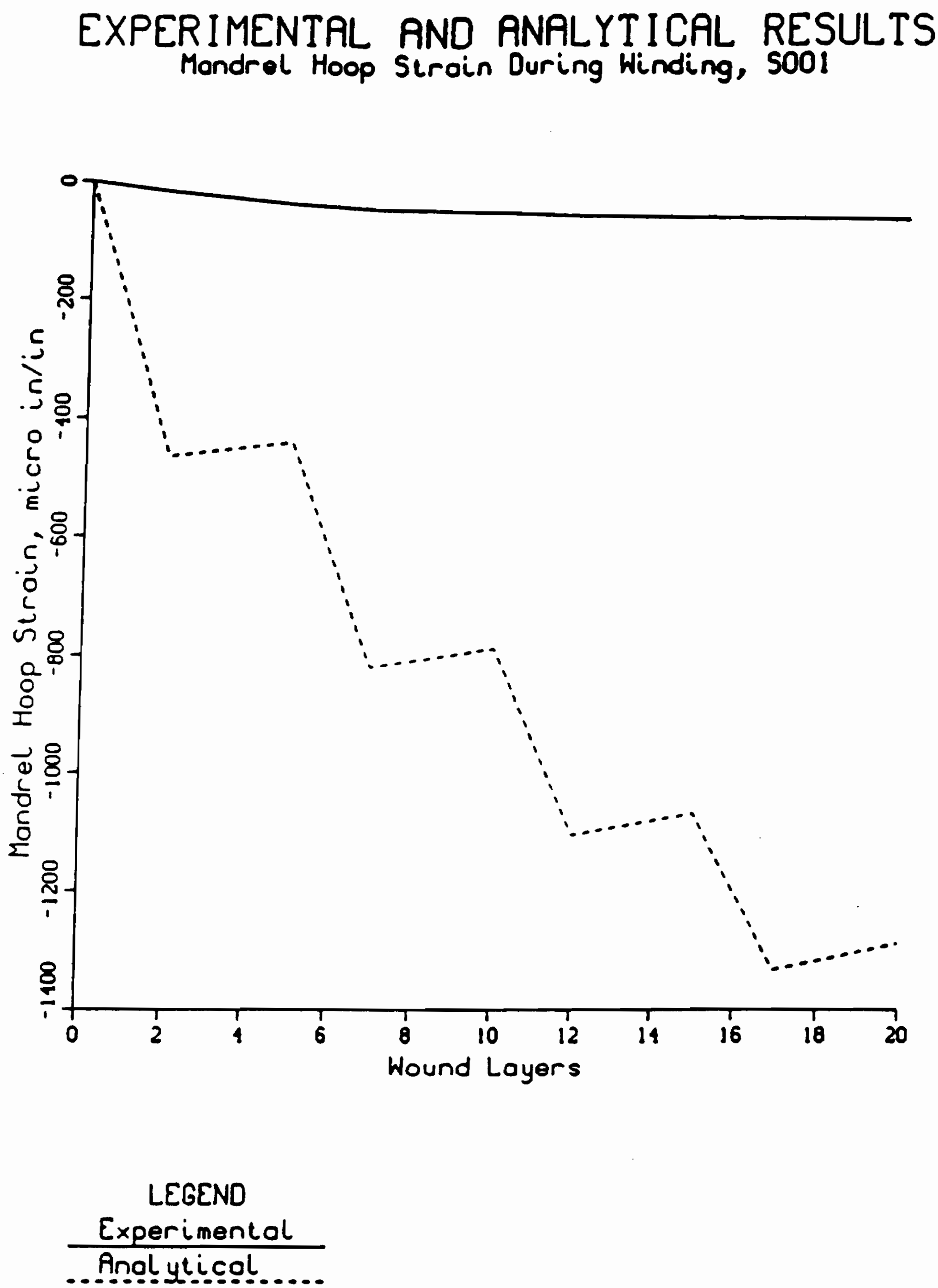

Figure 21. Case 2 Hoop Strain Results

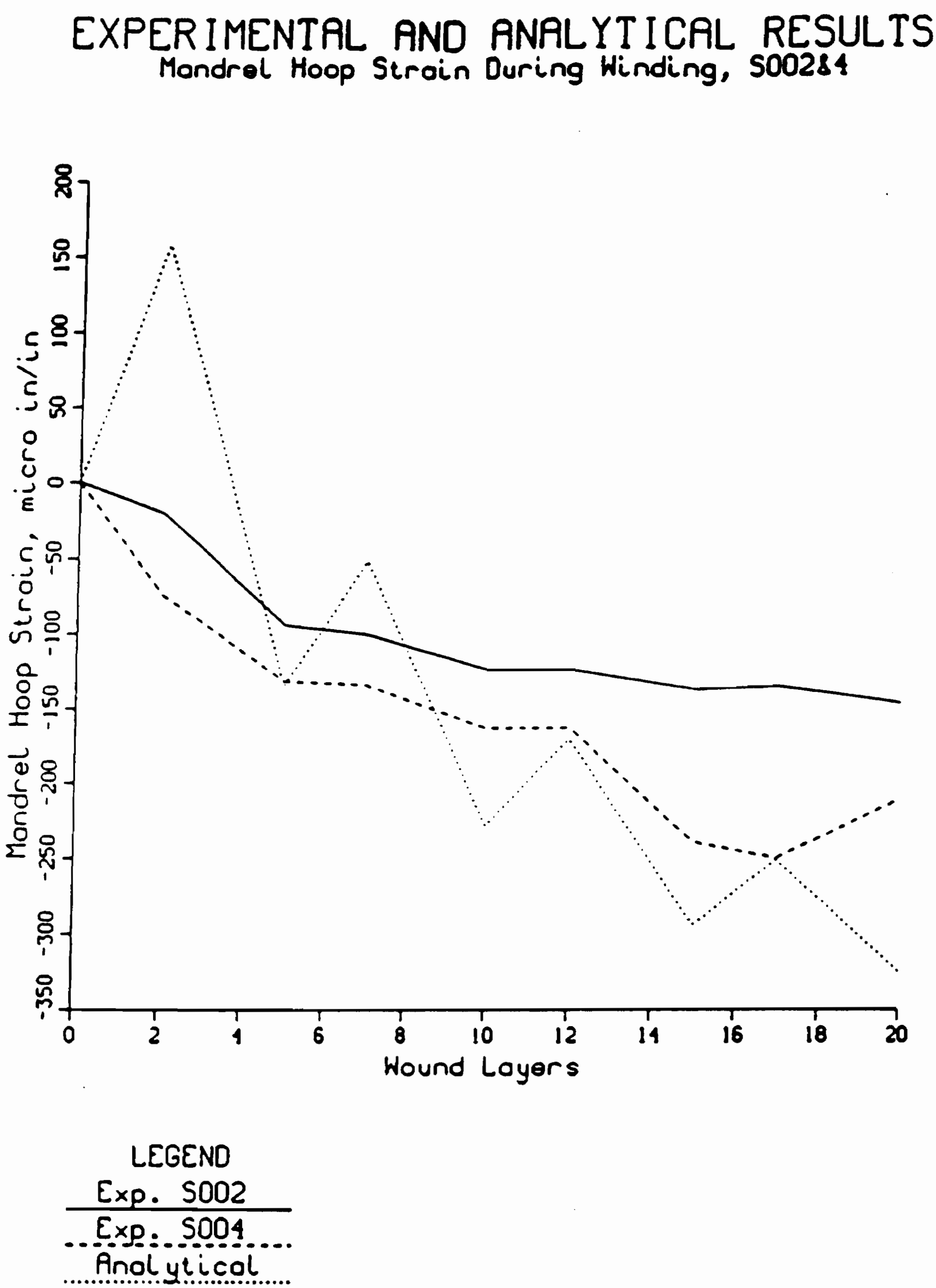

Figure 22. Case 2 Hoop Strain Results

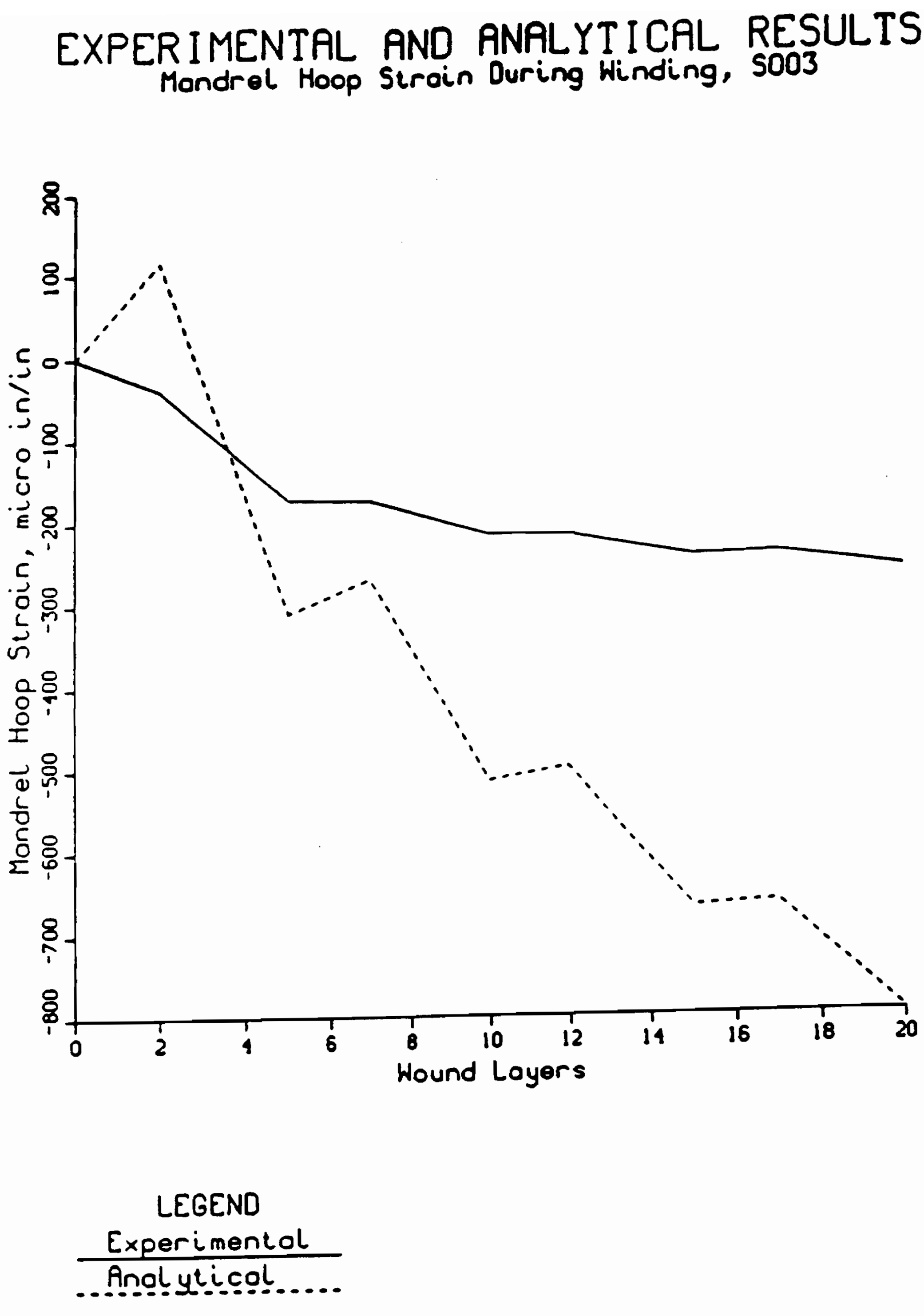

Figure 23. Case 2 Hoop Strain Results

4.2.3 Case 3

The third analytical model included the effects of tension loss in the fibers. Data were obtained (from the Thiokol Corporation - Kent Call) which indicated that the prepreg fibers retain roughly 45% of the spool tension for the tension level used in the verification wind experiment. Using this retention factor and the spool tension level, the tension stress retained in the fibers was calculated to be 6.46 kpsi (44.55 MPa) instead of the 14.35 kpsi (98.97 MPa) used in the first two models. The newly calculated value of tension was used as the winding tension in the third WACSAFE model.

The analytical and experimental pressures on the midplane for case 3 are plotted in Figure 24. As expected, the predicted pressures dropped because of the lower tension level in the fibers. The analytical pressures show reasonable correlation with the experimental results, and the accuracy has improved considerably over the first two models.

Figure 25 shows the strains at the bottle tangent lines. The analytical strains decreased in magnitude compared to the second model. This was expected because the lower tension level in the fibers caused less motion of the mandrel, and of the composite material on the mandrel. The agreement between the experimental and analytical results is difficult to assess because of the large differences in the experimental data. The accuracy seems to be within the variability of the experimental data set.

The analytical and experimental strains at the bottle midplane are plotted in Figure 26. Because of the reduction in tension, the predicted strains are smaller in magnitude than they were in the previous model. The predicted strains show reasonable correlation with the experimental strains. The model also provides the best accuracy for the midplane strains of any of the models considered. This third model shows the importance of laydown tension loss in the model of the filament winding process. The changes in the results are as dramatic as those caused by the segmented steel mandrel.

Although the third model seems to be a fairly accurate representation of the experiment, it appears to overestimate the tension loss in the fibers. The laydown tension loss measured in the experiment can be split into a side-by-side laydown component and an instantaneous laydown tension loss component. Side-by-side tension loss effects are already coded into the WACSAFE program and should not be included in the initial estimate of tension loss of the fibers. The final model separates the instantaneous laydown tension loss from the side-by-side laydown loss to provide a better representation of the retained tension. For a detailed discussion of these components see reference [1].

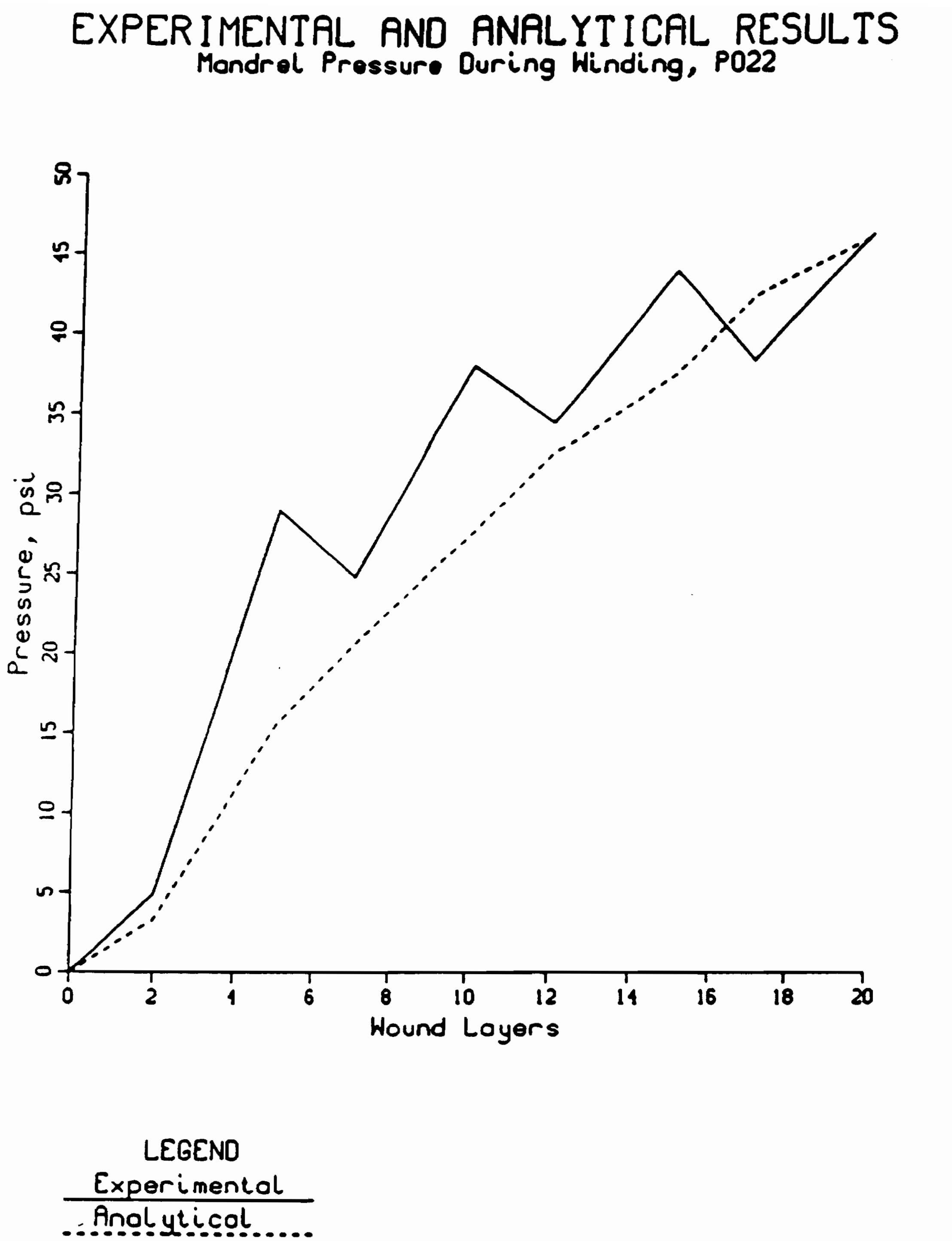

Figure 24. Case 3 Pressure Results

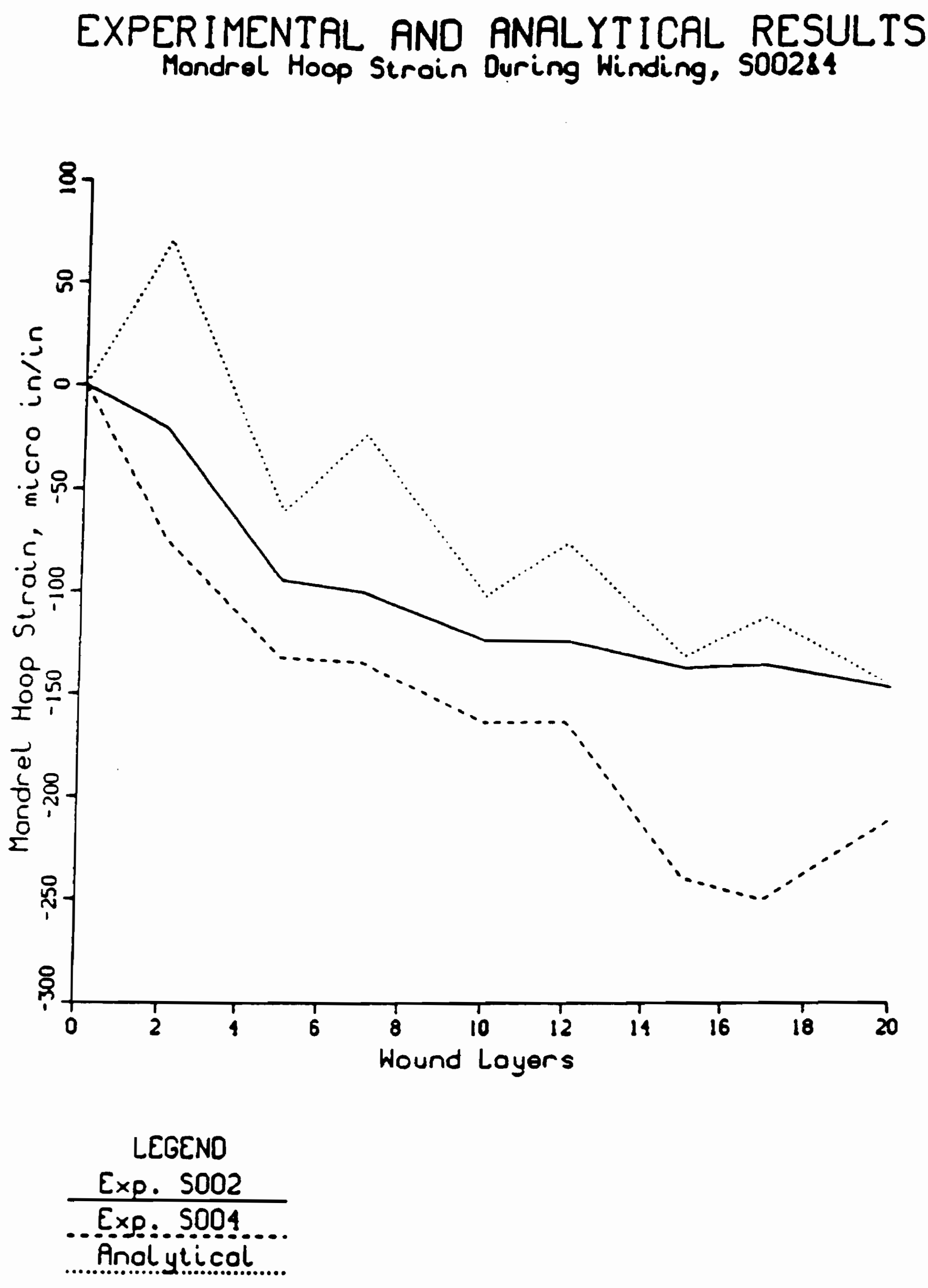

Figure 25. Case 3 Hoop Strain Results

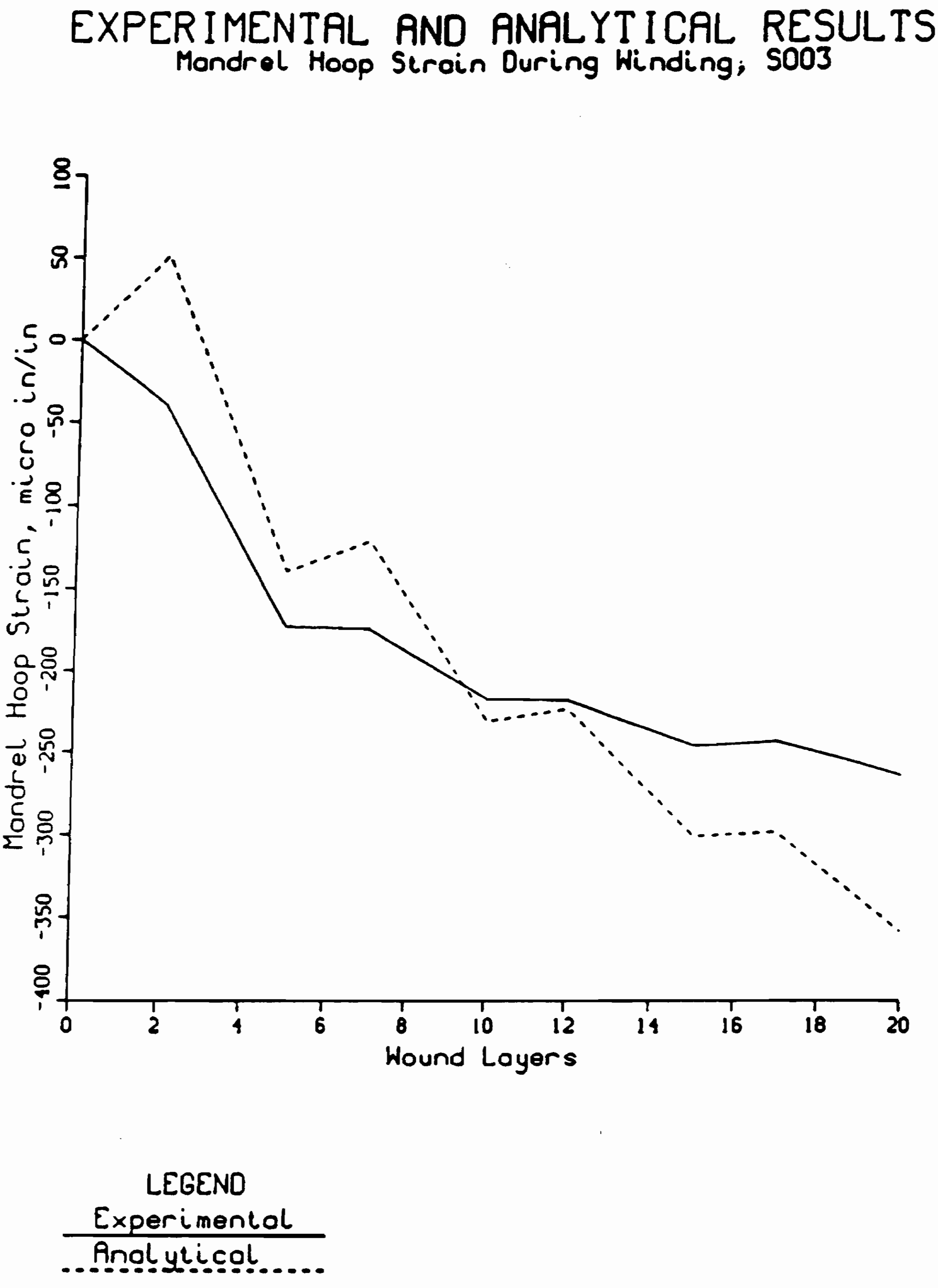

Figure 26. Case 3 Hoop Strain Results

4.2.4 Case 4

The fourth and final analytical model used only the instantaneous laydown tension loss instead of the combined effects of instantaneous and side-by-side losses as measured in the experiment and used in the third model. The instantaneous and side-by-side losses were separated using experimental laydown tension loss data (obtained from Kent Call) and a WACSAFE model of the tension loss experimental data. The tension loss model, a comparison of the analytical and experimental results, and the predicted residual stresses and strains after fabrication are presented in the following paragraphs.

4.2.4.1 Laydown Tension Loss Model

The laydown tension loss in the composite fibers is the result of two effects, an instantaneous laydown component and a side-by-side laydown component. The side-by-side laydown tension loss is included in the coding of the WACSAFE program. The instantaneous laydown tension loss, however, must be accounted for by the WACSAFE user when the initial tension is input into the WACSAFE model file. Since the experimental tension loss data includes both components of the tension loss, and the WACSAFE program already accounts for side-by-side loss, a retention factor was calculated which only included the effects of instantaneous laydown tension loss.

To separate the two effects, a WACSAFE model of the tension loss experiment was created using the full spool tension as the input tension (this means no instantaneous laydown tension loss effects were included in the model). Using the results of this simple WACSAFE model and the experimental data, the actual tension (the tension which should have been used as the input tension to include instantaneous laydown loss in the WACSAFE model) can be found. The relation used to find the actual tension is:

$$\frac{\text{Actual Tension}}{\text{Experimental Pressure}} = \frac{\text{Input Tension}}{\text{Theoretical Pressure}}$$

where the actual tension is the tension in the fibers after instantaneous tension loss, the input tension is the spool tension, the experimental pressure is the interface pressure on the midplane between the mandrel and composite calculated from the experimental data, and the theoretical pressure is the interface pressure on the midplane between the mandrel and composite found from the WACSAFE model. The experimental interface pressure between the mandrel and composite was calculated using the experimental strains and the equation for hoop stress in a cylinder with internal pressure. The experimental pressure was found to be about 10.4 psi (71.72 kPa) for an input tension of 8.86 kpsi (61.10 MPa).

The WACSAFE model of the tension loss experiment is shown in Figure 27. The composite elements were activated one at a time to simulate the side-by-side winding on the mandrel. The final accumulated stress on the mid-plane of the mandrel through the thickness of the mandrel is plotted in Figure 28. The pressure between the mandrel and composite was extrapolated using this stress plot and the theoretical interface pressure was found to be about 18.5 psi (127.6 kPa).

The actual winding tension (due to instantaneous laydown losses only) was calculated from the analytical and experimental pressures and the input tension using the relation presented previously. By dividing the actual tension by the input tension, the retention factor was found to be about 56%. For the final model the winding tension was reduced using a retention factor of 56% which resulted in a winding tension of 8.036 kpsi (55.42 MPa) instead of the 6.46 kpsi (44.55 MPa) used in the third model.

4.2.4.2 Comparison of Analytical and Experimental Results

Plots of the analytical and experimental results are shown in Figures 29 through 34 on the following pages. These results are the best possible (at this time) because of the limited amount of experimental data available. The pressures and strains are shown for each location during both

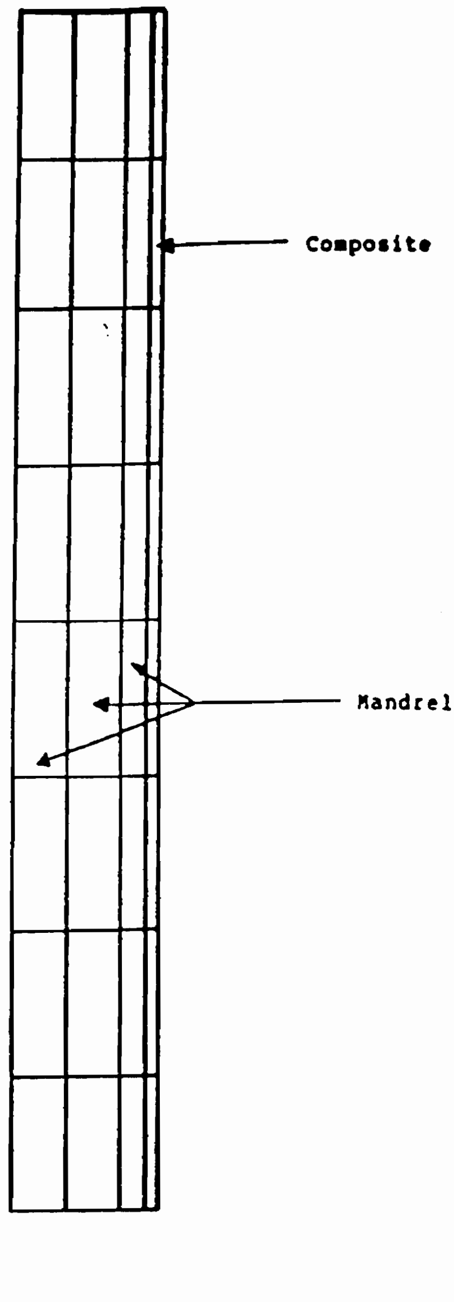

Figure 27. WACSAFE Tension Loss Model

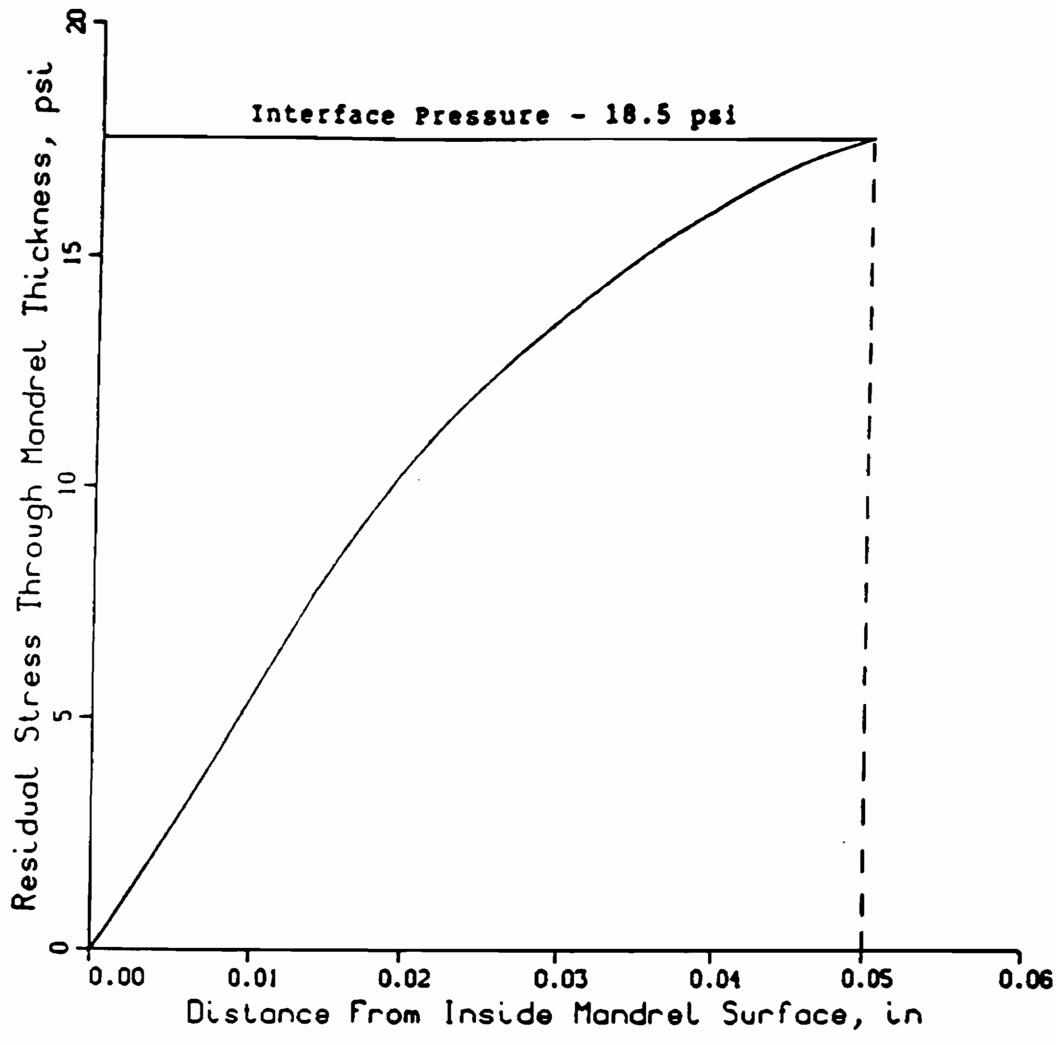

Figure 28. Stress Through the Mandrel Thickness at the Mandrel Midplane

winding and curing. Also, the results for case 1 are superimposed on the case 4 results for easy comparison.

Figures 29 and 30 show the pressure at the midplane of the bottle mandrel during winding and curing. The pressures increased slightly due to the increase in tension caused by separating out the instantaneous laydown tension loss component. The pressures exhibit reasonable correlation between the experimental and analytical results. The predicted pressures during winding are more accurate than the results of the third model for the beginning winding stages, but are less accurate for the last winding steps. The pressures predicted during cure, shown in Figure 30, follow the trend of the experimental data well and the accuracy is far better than the first model.

Figures 31 and 32 show the analytical and experimental strains at the tangent lines of the bottle mandrel during cure. As expected, the predicted strains at the tangent lines of the bottle mandrel increased in magnitude due to the increase in winding tension. The predicted strains, both during winding and curing, correlate well with the experimental data. The strains predicted during winding agree reasonably with the experimental data. Again the accuracy seems to be within the variability of the experimental data set. The strains predicted during cure also agree fairly well with the experimental data. In Figure 32, the experimental results for strain gage S004 are not shown because the gage failed during cure.

It is interesting to note that the predicted strain increases when the first layers are applied while the experimental data decreases. This is explained by poisson effects for the segmented mandrel. In the analytical model, when the first two polar/helical layers are wound, the mandrel is compressed in the axial direction and expands circumferentially causing a positive strain. In the experiment, since the segmentation of the mandrel only occurs in the circumferential direction and the mandrel is bolted to a shaft during processing, the mandrel will actually be much stiffer in the axial direction than the model allows. Because of this, during winding there would be very little compression of the mandrel in the axial direction and there could be compression of the mandrel in the circumferential direction. This difference between the predicted and experimental strains occurs for the gage at the midplane of the bottle as well.

The predicted and experimental strains at the bottle midplane, during winding and curing, are shown in Figures 33 and 34. The correlation is reasonable for the strains during winding. In Figure 33, the accuracy of the predicted strains is better for the beginning winding steps, but drops off in the later winding stages. The predicted strains during cure, in Figure 34, show good correlation between the experimental and analytical data. While the accuracy of the predicted results during cure is poor, it seems as though the data are off by a simple factor since there is an equal spacing between the two curves.

The plots all show the reasonable correlation between the experimental and analytical results that the previous three models exhibited. The accuracy has improved considerably over the first model for the pressures and strains at the bottle midplane and the strains at the bottle tangent lines. Since this model appears to provide a reasonable representation of the experiment, the residual stresses and strains after fabrication can be predicted with some confidence.

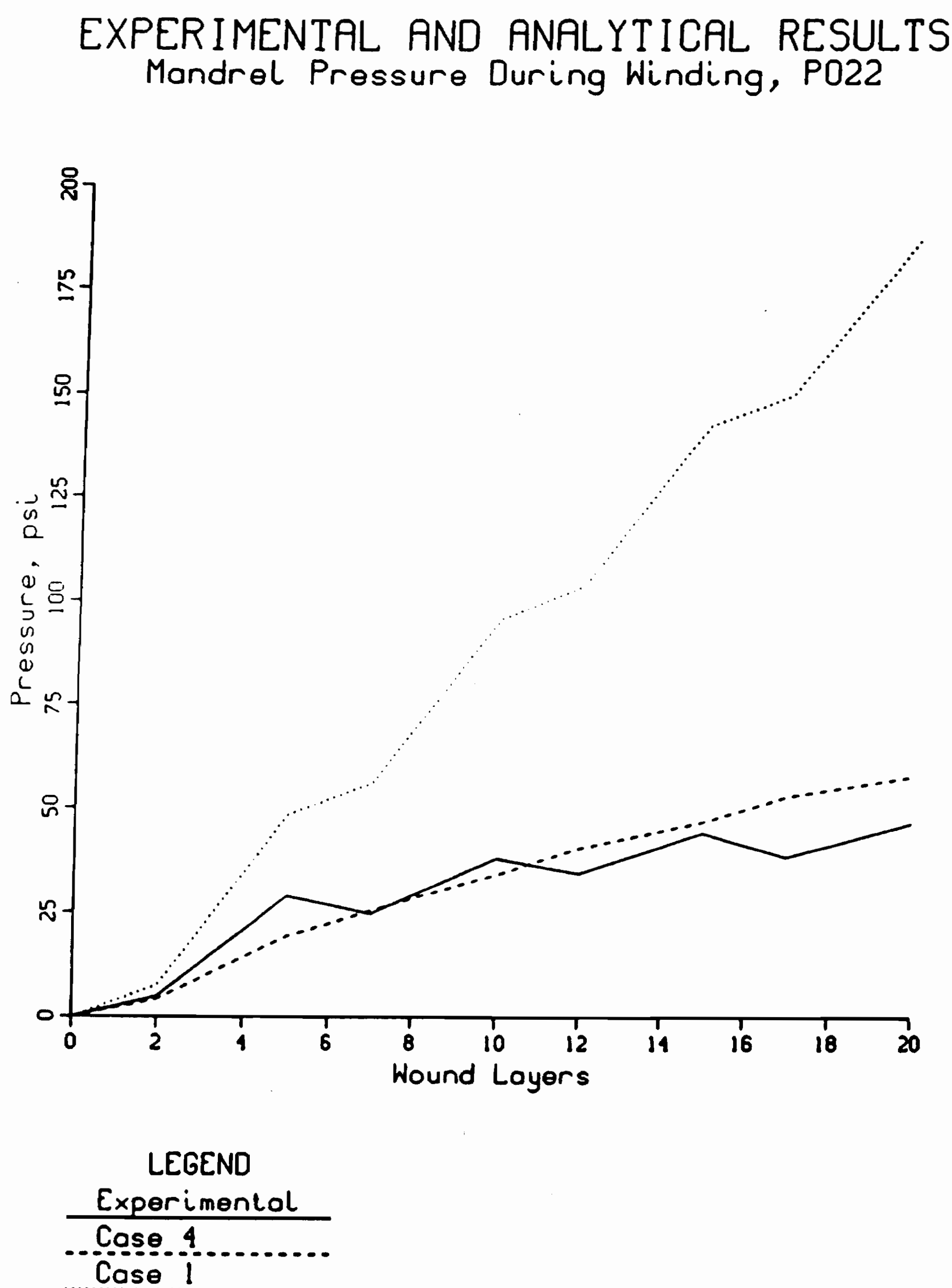

Figure 29. Case 4 Pressure Results

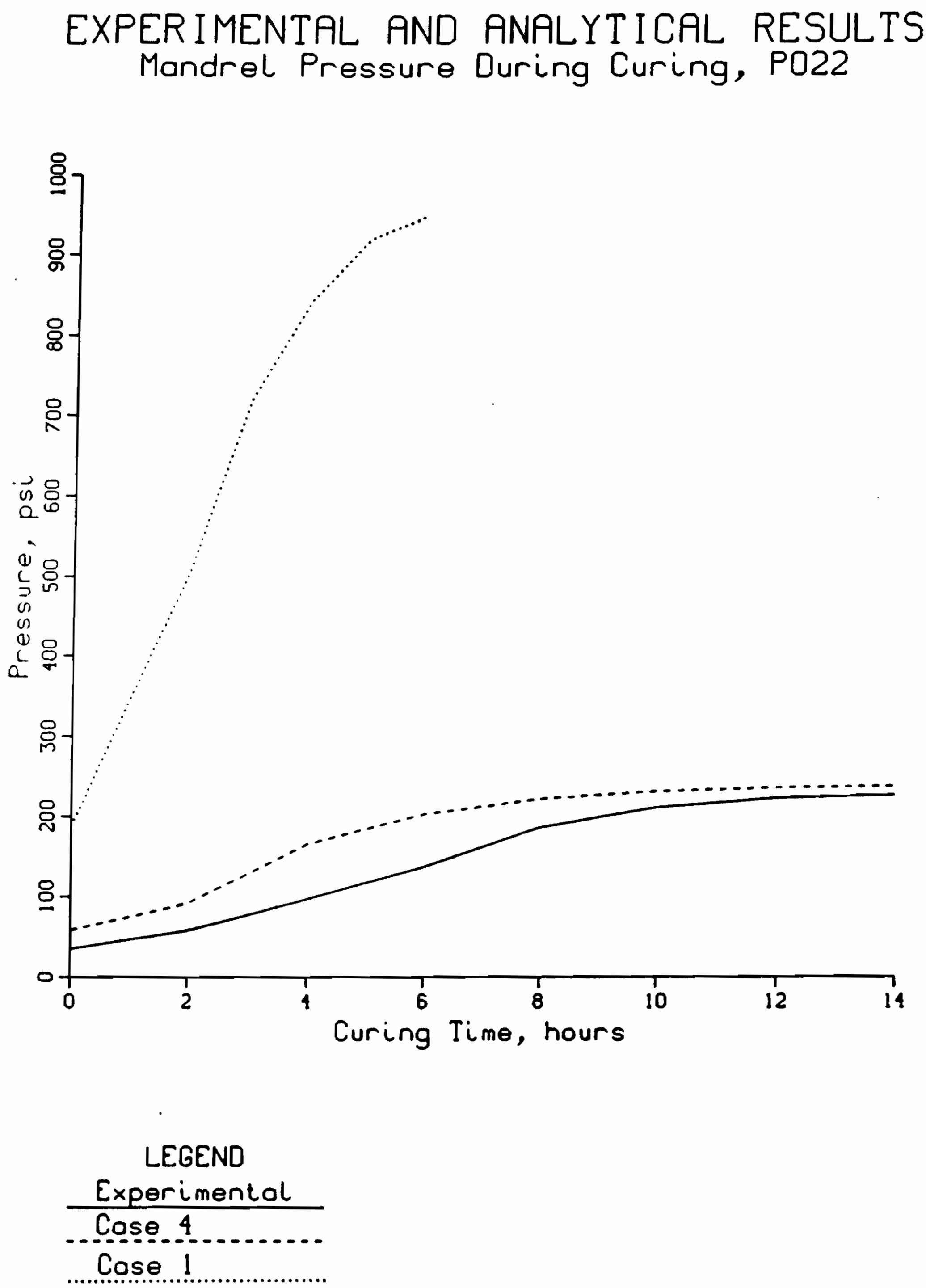

Figure 30. Case 4 Pressure Results

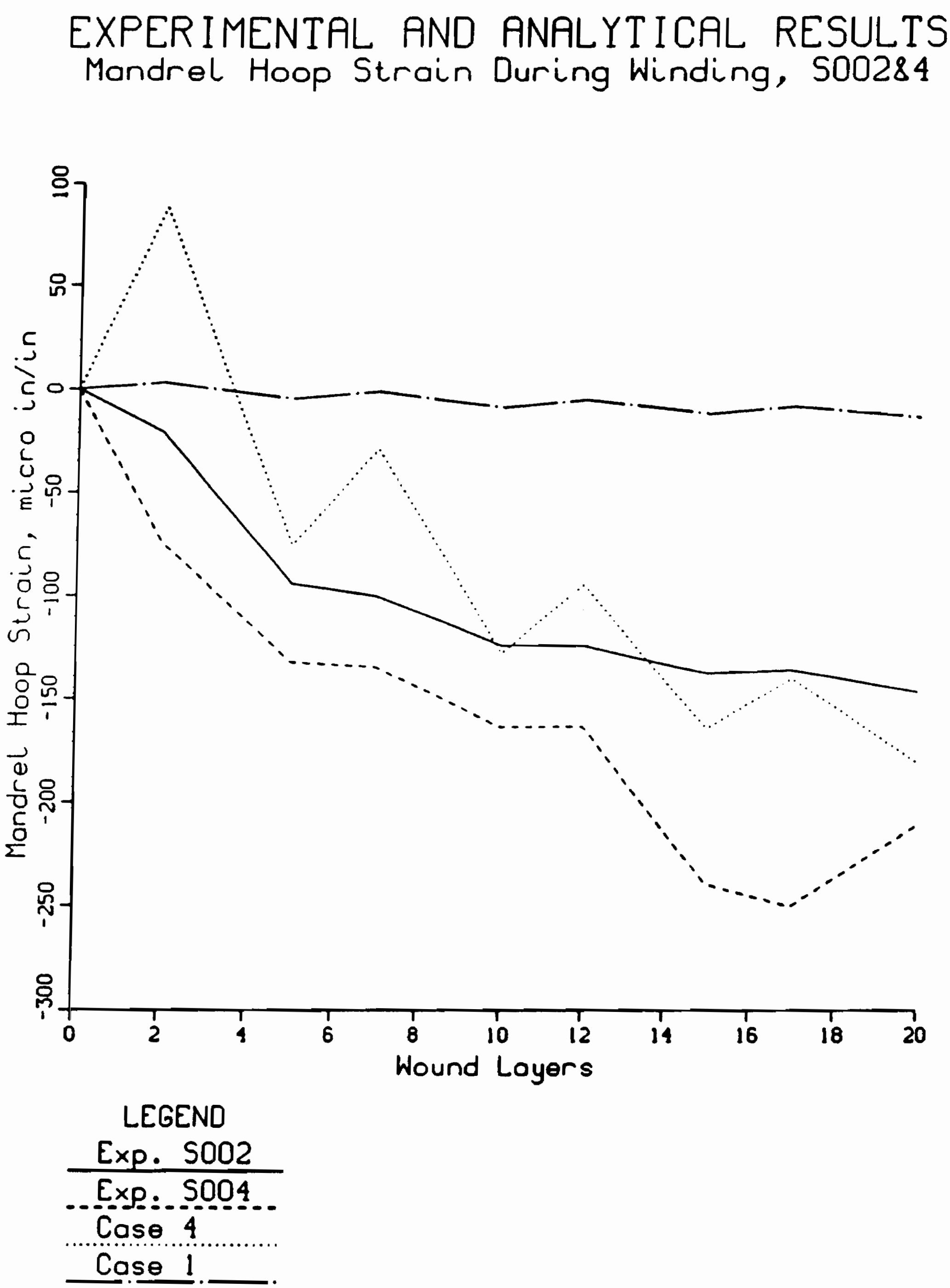

Figure 31. Case 4 Hoop Strain Results

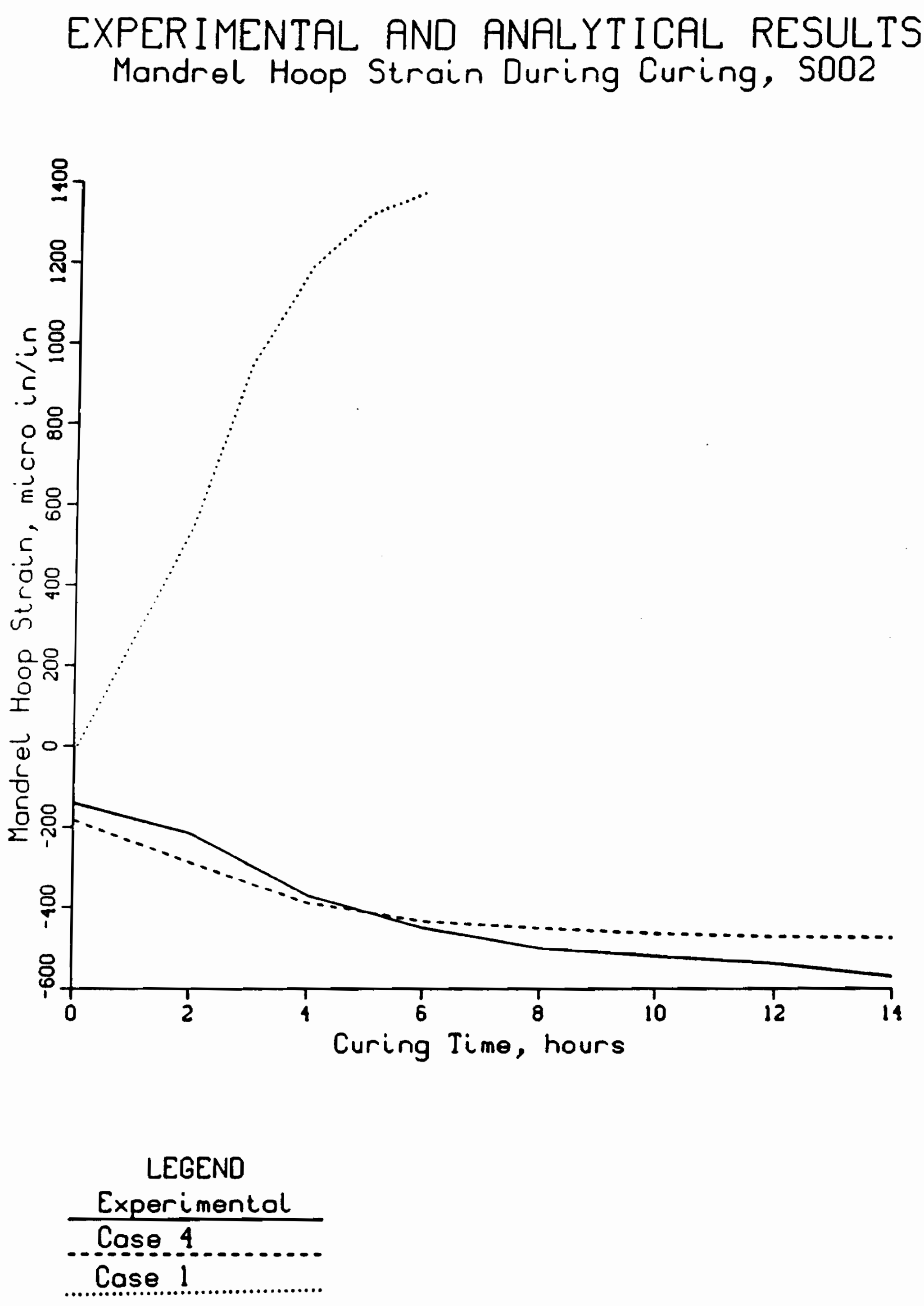

Figure 32. Case 4 Hoop Strain Results

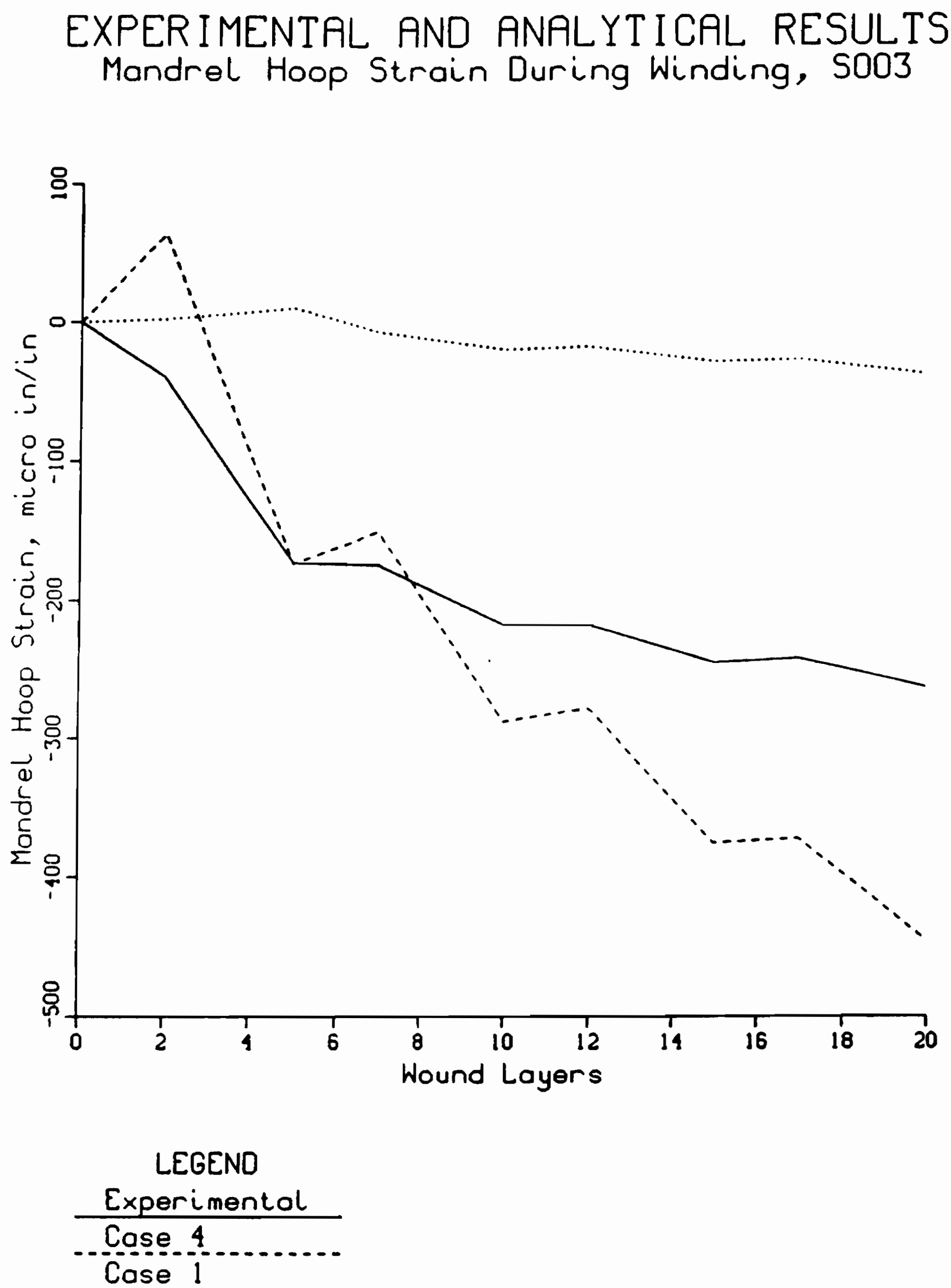

Figure 33. Case 4 Hoop Strain Results

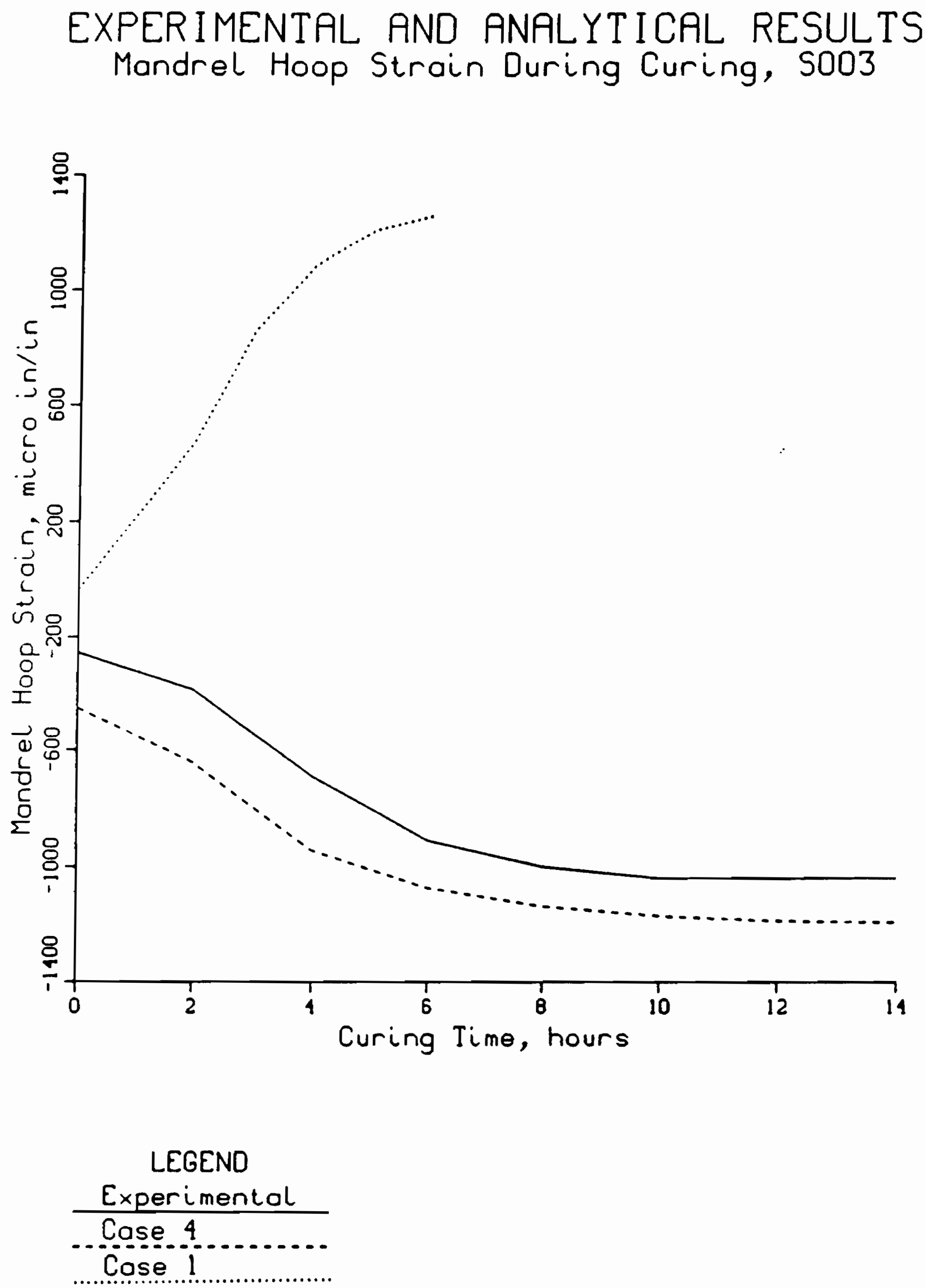

Figure 34. Case 4 Hoop Strain Results

4.2.4.3 Residual Stresses and Strains After Fabrication

The analytical results for the residual stresses and strains provide information on potential problem areas in the composite case. Residual fiber tension, tension through the composite thickness, and compressive fiber strains can cause problems such as delamination and strength degradation of the composite. Each of these potential problems is addressed in the following text.

A plot of the residual fiber stresses in the dome region of the 18 inch (45.72 cm) bottle is shown in Figure 35. The residual fiber stresses were found to be mainly compressive although a few areas of the case contained fibers with tensile stresses of about 5000 psi (34.48 MPa). While this tension is undesirable, the 5000 psi (34.48 MPa) maximum stress is well below the strength of the material in the fiber direction.

Areas of tensile stress acting normal to the thickness of the composite are potential delamination sites for the composite case. Figure 36 shows a plot of the intralaminar normal stresses for the 18 inch (45.72 cm) bottle. The maximum tensile stress was found to be about 400 psi (2.76 MPa). The strength in the normal direction is much higher than this so the model predicts that a delamination is unlikely.

Fibers in a state of compressive strain just prior to resin cure can cause severe degradation of strength of the composite case. The analytical model in this case predicts no residual compressive strains anywhere in the composite case so wrinkles and the resulting strength degradation seem unlikely.

The goal of the WACSAFE model is to predict the residual stresses and strains that exist in the composite after, as well as during, fabrication. Although no experimental data are available for the final stress and strain states in the composite case, the comparison of the analytical pressures and strains with the experimental pressures and strains, during winding and cure, provides a measure of the validity of the final stress and strain predictions of the WACSAFE model. The great improvement in accuracy between the first and final models and the reasonable correlation of analytical and experimental results for each model provide confidence in the results of the WACSAFE

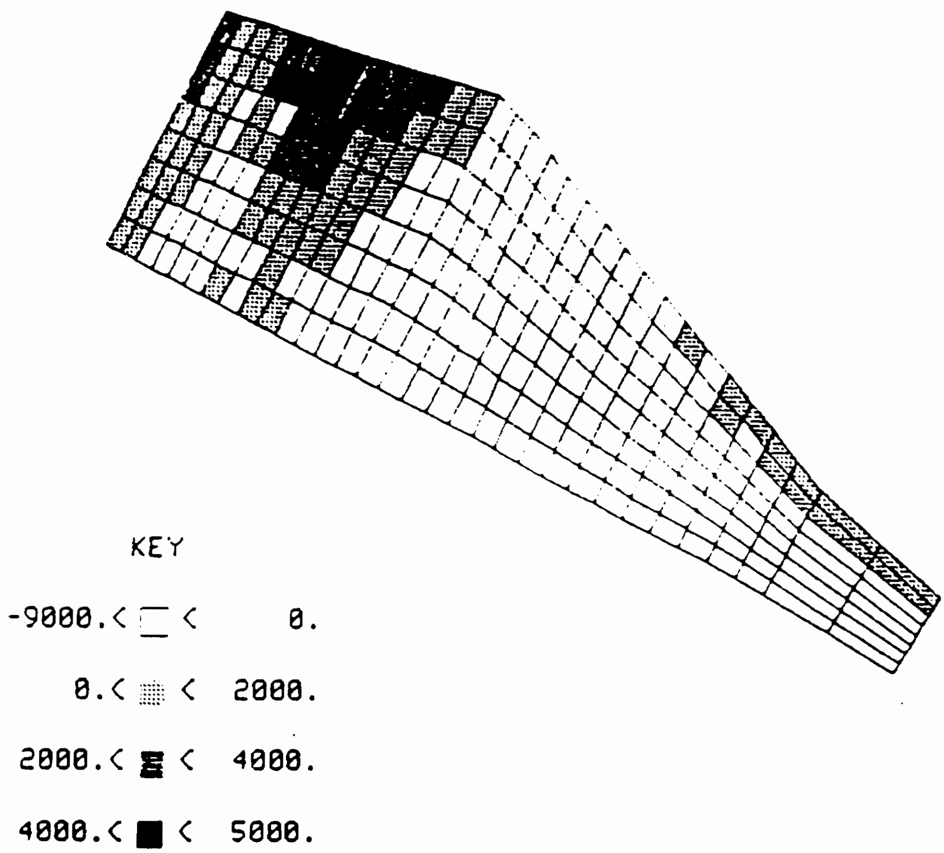

Figure 35. Residual Fiber Stresses - Dome Region

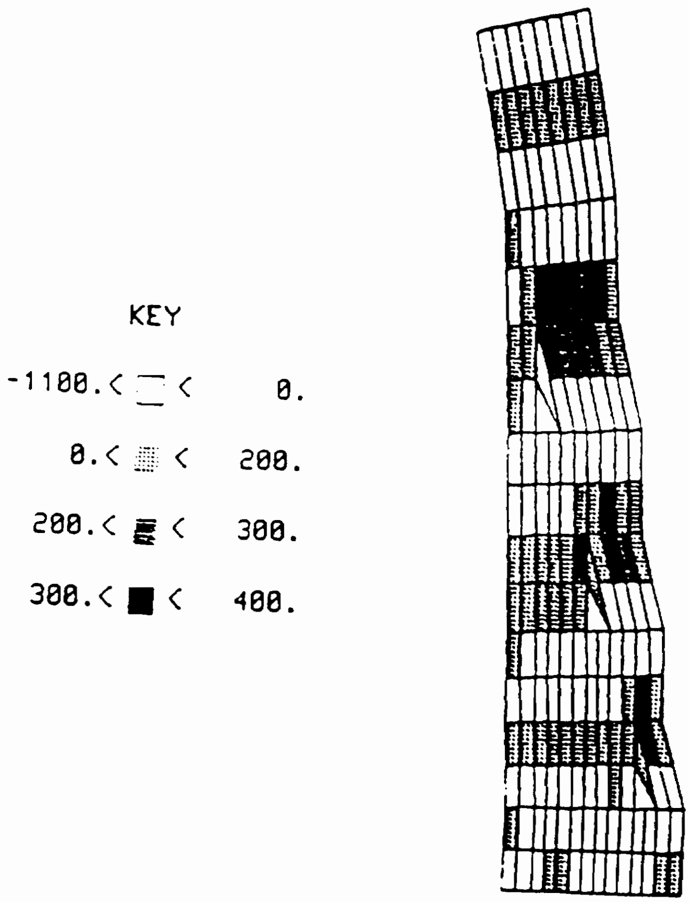

Figure 36. Residual Intralaminar Stresses - Transition Region

program. With more experimental data, the accuracy of the model may be improved by eliminating estimates of material properties and reducing measuring error in the experimental results.

5.0 WACSAFE/FWCURE Coupling

The WACSAFE and FWCURE programs are both used in the fabrication analysis of axisymmetric filament wound structures. Currently, FWCURE performs a separate analysis of the composite during curing to provide WACSAFE with a thermal data file. The data file contains information such as average temperature, degree of cure, and average viscosity for the material of each element in the composite case for discrete time steps during cure. For information on the data file, called WACSAFE.FWC, consult the WACSAFE/WACFORM User's Guide [2].

After the data file of cure information is created using FWCURE, WACSAFE performs a fabrication stress and strain analysis during winding and cure. One of the important features of the WACSAFE program is that it is capable of including the component of tension loss due to fiber motion [1] in the analysis in addition to the two laydown tension loss components discussed in a previous chapter. Presently, WACSAFE can perform a one-dimensional fiber motion tension loss analysis (during both winding and cure) given the viscosity. The viscosity used during winding is obtained from the model file, and is assumed to be constant during the winding stages. During cure, however, WACSAFE uses the information in the thermal data file, obtained from FWCURE, as an approximation to the more rapidly changing viscosities. As mentioned earlier, this thermal data file is created by FWCURE independently, prior to running WACSAFE. In this manner, the two programs, WACSAFE and FWCURE, run separately at present.

A better method for the fabrication analysis involves interaction between the two codes. The main reason for coupling WACSAFE and FWCURE is because FWCURE is programmed to run a two-dimensional resin flow analysis to find the fiber motion tension loss. Currently, this tension loss analysis uses the initial winding fiber tension as an input and calculates the nodal pressure field in the composite from the fiber tension, the case geometry, and material properties of the composite. FWCURE then calculates the tension loss due to the motion of the fibers through the resin using the nodal pressure distribution.

To couple the two codes, WACSAFE will pass the stress in the fiber direction to FWCURE, and FWCURE will pass the fiber tension loss increments due to fiber motion for each load step back to WACSAFE. Using this approach, the stress distribution which is passed from WACSAFE is likely to be more accurate than that calculated by FWCURE.

WACSAFE was modified to provide interaction between the two codes by using FWCURE as a subroutine. The modifications to the WACSAFE program are discussed in this chapter as well as verification and proper use of the new code.

5.1 Fiber Motion Tension Loss Analysis

The WACSAFE program has the capability to include or exclude tension loss due to fiber motion in a fabrication analysis. There are two possible methods of calculating this tension loss in WACSAFE. The first is to perform a one-dimensional analysis. This is discussed thoroughly in reference [1]. The second method uses the FWCURE program to perform a two-dimensional fiber motion analysis and pass the resulting tension loss to WACSAFE for use in the overall fabrication analysis. The WACSAFE code was modified to provide both of these options.

Figures 37 and 38 show the basic flow of the fiber motion portion of the program for the modified WACSAFE code. After initialization of variables, WACSAFE begins the first load step. The flag which describes which type of fiber motion analysis is to be performed is labelled "ITENS".

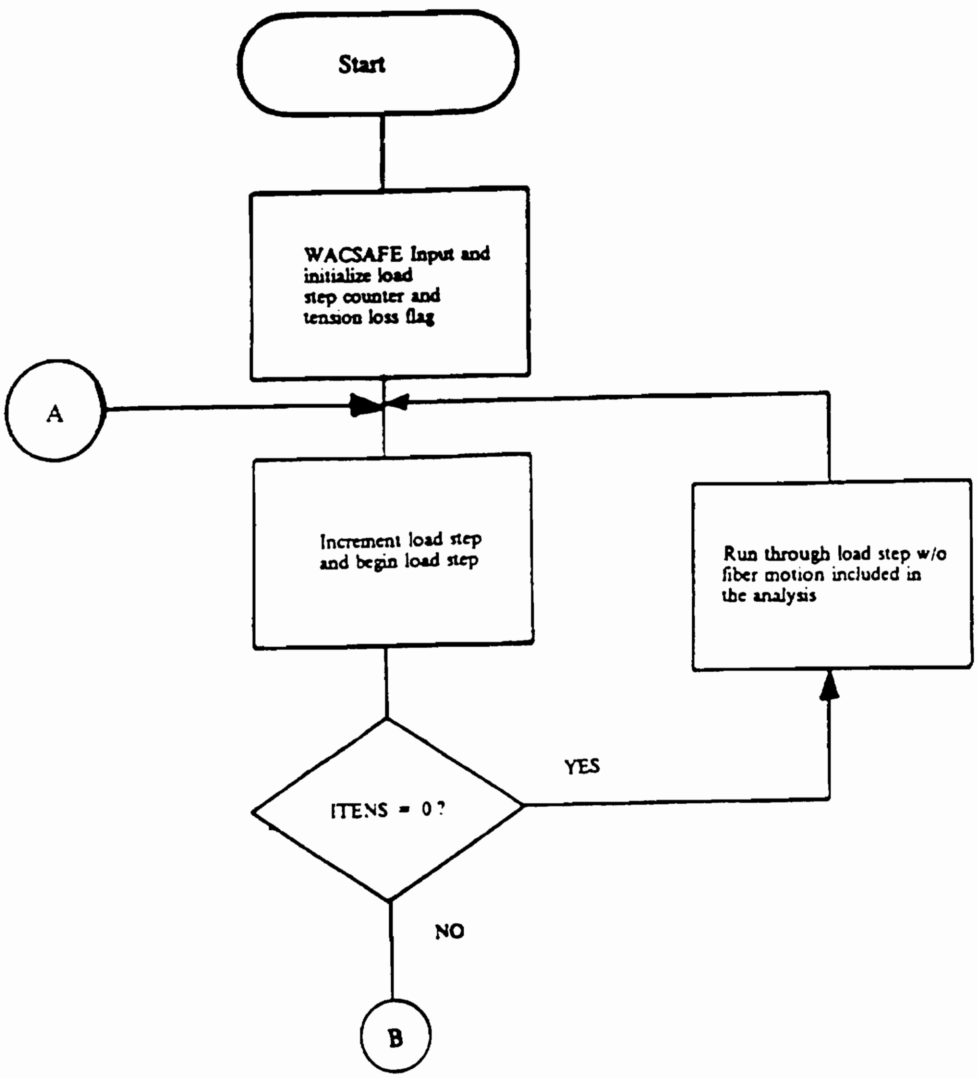

Figure 37. General Flow Chart for the Modified Fiber Motion Portion of the WACSAFE Program

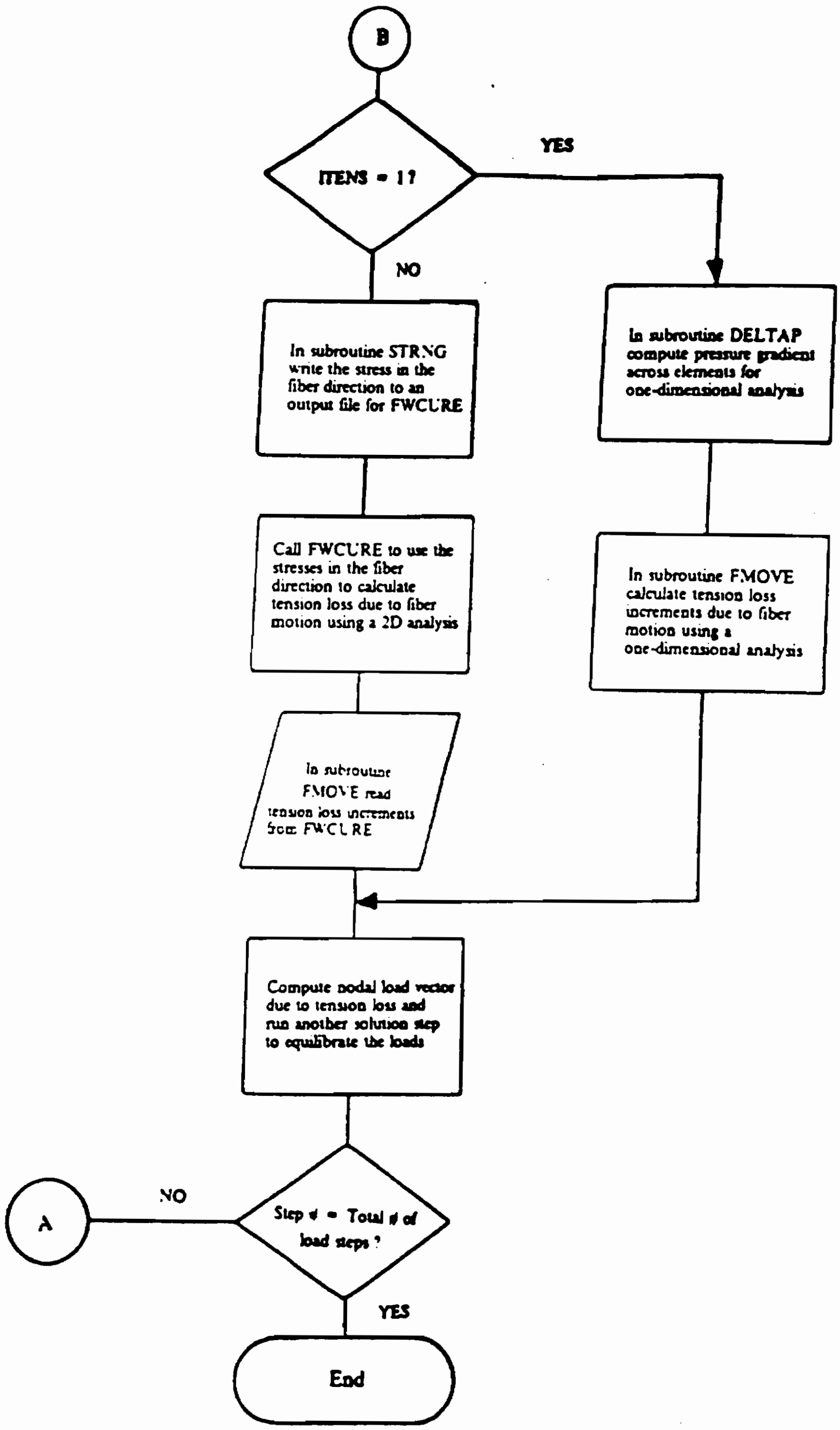

Figure 38. General Flow Chart for the Modified Fiber Motion Portion of the WACSAFE Program

If ITENS equals zero, then the fiber motion model is deactivated, if ITENS is one, a one-dimensional analysis is performed, and if ITENS is two, the tension loss due to fiber motion is computed by FWCURE using a two-dimensional analysis.

The figures also illustrate the difference between the code for the one-dimensional and two-dimensional analyses. In the one-dimensional analysis, WACSAFE computes the pressure gradient for each element and uses this gradient to calculate the tension loss due to fiber motion. For the two-dimensional analysis, WACSAFE does not compute a pressure gradient, but instead writes element stresses in the fiber direction to a file which is used as input by FWCURE. FWCURE then calculates the tension loss increments due to fiber motion for WACSAFE. In either case, the nodal load vector due to these tension loss increments is calculated and a second pass solution is used to update the stresses. The one and two-dimensional analyses follow basically the same program flow except for the manner in which the fiber motion tension loss is computed. The tension loss calculations are discussed in more detail with the code modifications to the WACSAFE program in the following section.

5.2 *WACSAFE Code Modifications*

The WACSAFE code was modified to read a tension loss data file created by FWCURE and to write a file of stresses in the fiber direction for FWCURE. The main program was changed to initialize the fiber motion flag ITENS. The subroutine FMOVE, in the module WACFMOT.FOR, was modified to read the tension loss file. The subroutine STRNG, in the module WACRNG.FOR, was altered to write the stresses in the fiber direction. Also, the module WACRNG.FOR was altered to accept the tension loss values from FWCURE. Table 9 summarizes the modifications made to the WACSAFE program.

The main program, in module WACSAFE.FOR, contains the input code and the load step loop. A place for the fiber motion flag, ITENS, was added to the WACSAFE model file. To read the flag, a statement was added to the main program to initialize ITENS.

Since the STRNG subroutine already contained the array of fiber stresses, it was modified to write the stress values to an output file for the FWCURE program when a two-dimensional fiber motion analysis is run. When fiber motion tension loss is not included in the analysis, or when a one-dimensional fiber motion analysis is performed, the statement to write the fiber direction stresses is skipped. The flag, ITENS, was used to separate the two options as described previously and shown in Table 9.

The subroutine FMOVE calculates the tension loss due to fiber motion when the one-dimensional fiber motion analysis is run in WACSAFE. Because of this, FMOVE was the best and easiest place in the code to read in the tension loss increments from the file created by FWCURE. The subroutine was modified to read the tension loss values. As before, the original code was not altered so the one-dimensional tension loss can be performed by WACSAFE. Again, the flag ITENS is used to determine which type of analysis is to be performed (1D or 2D). If the flag is set for a one-dimensional analysis, the subroutine FMOVE calculates the tension loss using a 1D approximation. If the fiber motion flag is set for a two-dimensional analysis, FMOVE reads the tension loss values from the data file created by FWCURE.

The subroutine STRNG, in module WACRNG.FOR, was modified to call the FWCURE program as a subroutine, and to accomodate the changes in the FMOVE subroutine. When a one-dimensional analysis is performed, STRNG calls the FMOVE subroutine to calculate the tension loss increments due to fiber motion for each element. For a two-dimensional analysis, STRNG first calls FWCURE to calculate the tension loss increments and write them to a file, then calls FMOVE to read the tension loss values from the file. The reason for reading the file of tension loss data using FMOVE instead of directly passing the array between FWCURE and WACSAFE is to avoid a mismatch in the array position counters. This is described next.

The subroutine STRNG only calls the FMOVE subroutine for elements which have compressive values of stress in the 3 direction, positive pressure gradients, non-zero curvature, and

Table 9. Code Modifications to the WACSAFE Program

Module	Subroutine	Modifications
WACSAFE	Main Program	The main program was modified to read the flag ITENS used to determine which type of fiber motion analysis is to be performed. If ITENS = 0 then no fiber motion analysis is to be done, if ITENS = 1 then a 1-D analysis is to be done by WACSAFE, and if ITENS = 2 then a 2-D analysis is to be done by FWCURE.
WACFMOT	DELTAP	Modified to calculate the nodal pressure distribution and to write it to a data file for use by FWCURE when a 2-D analysis is performed.
WACFMOT	FMOVE	Modified to read a data file of values of tension loss due to fiber motion from the FWCURE program when a 2-D analysis is performed.
WACRNG	STRNG	Modified to call the FWCURE program as a subroutine. Also altered to avoid mismatch between the array of tension loss values and the data from the file created by FWCURE (see text for more explanation).

off/on numbers less than the load step number. This means that some elements, which can not have tension loss, are skipped entirely in the fiber motion tension loss calculations. Then the WACSAFE program does not calculate tension loss values for every element in all of the load steps. In order to simplify the coupled analysis, STRNG was modified to read values for all of the elements for each load step. This means for a two-dimensional analysis, WACSAFE expects a value for every element from FWCURE each load step. A dummy read statement discards any unnecesary data while keeping the proper position correlation between the input array and the data file. This avoids the mismatch in array positions mentioned above.

5.3 *Verification of the Coupled Program*

In order for the program to be a useful tool, it must be verified. Since the FWCURE modifications have not yet been completed, quantitative verification of the coupled WACSAFE/FWCURE program is not as straight forward as the verification of WACSAFE. It is possible, however, to estimate tension loss due to fiber motion, which should be provided by FWCURE, and to compare the results qualitatively with the results from the verification of the WACSAFE code. If the results follow the expected trend shown in the verification wind results (i.e., the magnitudes of the pressures and strains drop due to the lower tension levels), the confidence that the code is valid is increased. Also, running the coupled program using the Case 4 model file from the verification wind (discussed in the previous chapter) and zero fiber motion tension should provide the same results as Case 4 from the verification wind. This provides greater confidence in the coupling program. This section compares the results of the coupling code using estimated tension loss values for the FWCURE part of the program with the results from the verification wind, discussed in a previous chapter, and results obtained using zero fiber motion tension loss with the Case 4 results. The two test cases can be compared with the expected trends to give some qualitative verification of the coupled code.

The first model run for verification of the new code was the model file for Case 4 of the verification wind experiment discussed in the previous chapter. The file was changed to include the necessary data for a two-dimensional fiber motion analysis. The file of tension loss increments from FWCURE was filled with zero values. See reference [14] for a list of the Case 4 model file.

As expected, the results from the new coupled WACSAFE/FWCURE program matched the Case 4 results exactly. If the results had not been exact, the program would have been invalidated and would have to be debugged. Since the results obtained were expected, the second verification test was run.

The second model run to verify the modified program was the same as the first model except the tension loss due to fiber motion was estimated to be about 5% of the initial tension. The value used for the tension loss was -400.0 psi (-2.76 MPa). Because this is additional tension loss, the pressures and strains were expected to decrease in magnitude compared to those of Case 4 in the WACSAFE verification.

Figure 39 compares pressure results at the mandrel midsurface from the coupled code with the experimental results and the Case 4 results from the WACSAFE verification (presented in the previous chapter). In the legend, Coup TL=-400 means the coupled code with estimated tension loss of -400 psi (-2.76 MPa). The data follow the expected trend for a constant tension loss in each step. Also, the loss in pressure builds with each wound layer as expected. As with the Case 4 results, the results from the new code correlate well with the experimental data. While the results of the new program can not be considered quantitatively accurate because the tension loss due to fiber motion was estimated, the estimate is assumed to be within a reasonable range. Observing this, it appears that the inclusion of fiber motion tension loss can increase the accuracy of the analytical prediction of the experimental data. This is evident because the overall tension loss builds as the number of wound layers increases which produces a greater effect in the later winding stages where it is needed. These results along with the results of the first case provide evidence that the coupled WACSAFE/FWCURE program is working correctly.

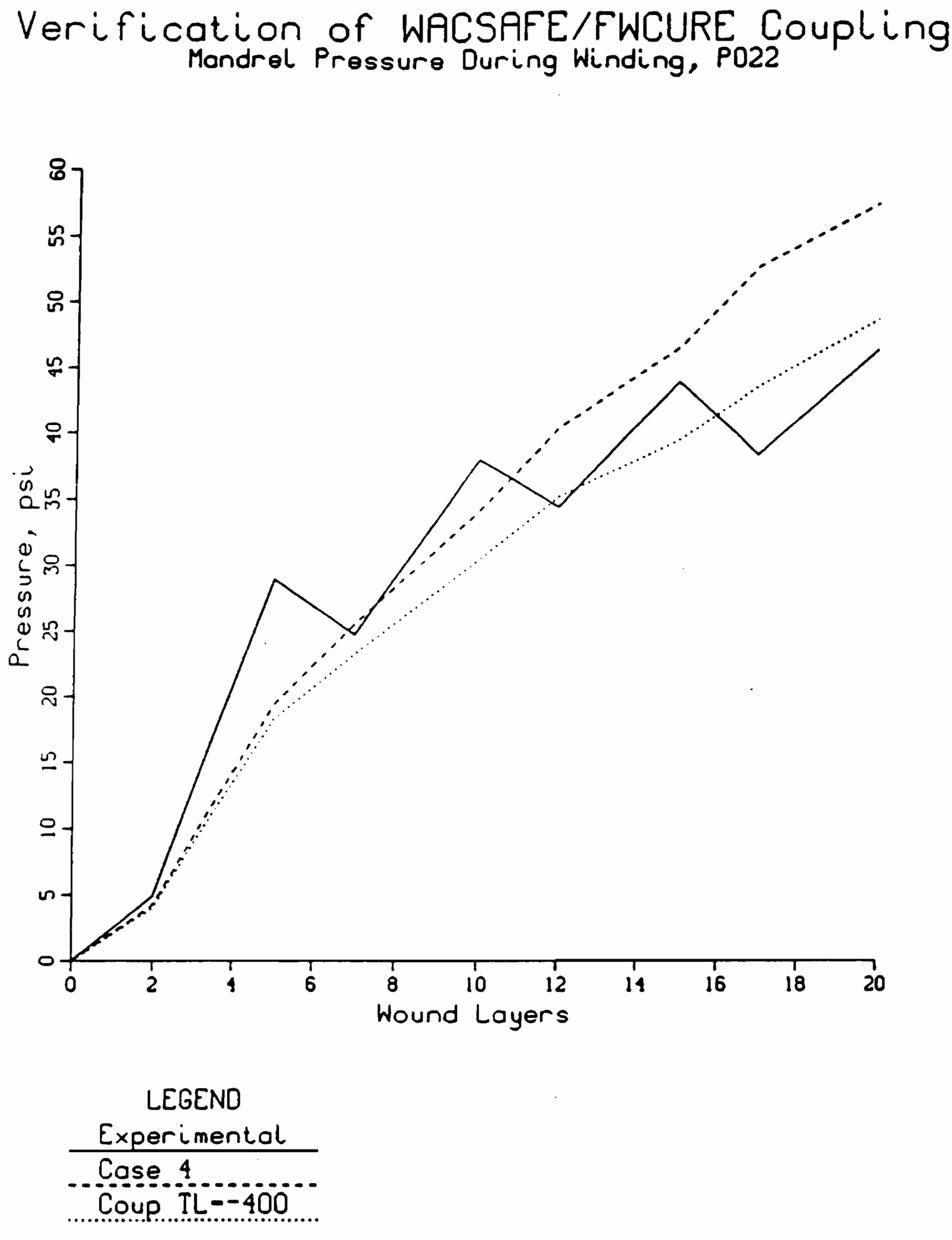

Figure 39. Pressure Results for the Verification of the Coupled WACSAFE/FWCURE Code

6.0 Conclusions and Recommendations

6.1 Conclusions

Several conclusions can be drawn from the comparison of experimental data with analytical results from the WACSAFE program and the coupled WACSAFE/FWCURE program. The first is that the WACSAFE program provides a reasonable model for and can be used to estimate stresses and strains in the composite case during winding, curing, and after fabrication. When any program of this type is used, care must be exercised when assumptions are made about the effect of certain process parameters. The effects of the segmented steel mandrel and the laydown tension loss are quite dramatic. From the results of chapter 5, it can be concluded that the coupled WACSAFE/FWCURE code seems to provide valid results. Also, fiber motion is an important factor and should be included for accurate modelling.

In chapters 4 and 5, both the WACSAFE and coupled WACSAFE/FWCURE codes were shown to predict the fabrication stresses fairly accurately. For the WACSAFE code, comparisons between the analytical predictions of WACSAFE and the experimental data supplied by the Thiokol Corporation provided quantitative evidence that WACSAFE is a viable model. For the coupled WACSAFE/FWCURE code, qualitative comparison between expected results and predicted results was used to verify the program structure. The difference in the analytical and experimental values in the pressure data for the last comparison in the WACSAFE verification was about 25% at the final winding stage. While this seems high, when the fiber motion tension loss was included in the analysis using the coupled program, the difference in the final winding stages dropped to less than 5%. Although the values for the fiber motion tension loss in the verification of the coupled code were only an educated guess, it is expected that the results will follow the trend where more tension loss is evident in the later winding stages as the overall number of wound layers grows. This means that including the fiber motion correctly in the model is very important and may be able to bring the analytical results to within 5-10% of the experimental data. It can be concluded then that not only is the WACSAFE program useful for predicting the stresses and strains at any point in the fabrication process, but the coupled WACSAFE/FWCURE code, which properly includes the fiber motion tension loss is probably more accurate than the WACSAFE program alone.

As expected, the accuracy of the results depends heavily on the assumptions made in the modelling process. The results of chapter 4 indicate that both the modulus of the segmented steel mandrel and the two laydown tension loss components affect the model quite dramatically. The analytical-experimental difference for the pressure results of the model with the effective modulus for the segmented mandrel was about 150% less than for the model where the modulus of solid steel was used. Also, the difference for the pressure results which included the instantaneous laydown tension loss was roughly 225% lower than the results without this factor included. Due to these two factors alone, the largest difference in the predicted pressure values was reduced from about 400% for the first model to around 25% for the final model. In chapter 5, it was demonstrated that the fiber motion tension loss may have a large effect in the later winding stages and a fairly small effect in the earlier winding steps. Although no quantitative measure of this effect has been obtained at this time, from the qualitative evidence available it is expected that this factor will provide the needed accuracy in the final winding stages when the FWCURE program has been properly modified.

As discussed in chapter 4, the results of the WACSAFE program for the bottle verification wind were used to qualitatively predict the mechanical performance of the finished bottle. It was concluded that the bottle was neither in danger of losing strength due to compressive fiber strains just prior to cure nor was it likely that a delamination would occur based on the final stresses through the composite thickness. It was also found that the final residual stresses in the fiber direction were reasonable and the tensile stresses that exist were small compared to the strength of the composite in the fiber direction. From this qualitative evidence, it can be concluded that the mechanical performance of the finished bottle was not degraded by the manufacturing process.

6.2 Recommendations

The following recommendations are suggested to further improve the accuracy of the WACSAFE and coupled WACSAFE/FWCURE programs as well as assumptions made during modelling. Also suggested are methods for increasing the ability of WACSAFE to relate process variables to final performance characteristics of a filament wound structure.

1. Through experimentation, improve the estimates of process variables such as tension loss for pre-preg material (for which only a single experimental data point was available) and material property estimates. This would decrease the error in the major assumptions that have to be made in modelling the process and increase the program accuracy.

2. Provide experimental data on final residual stresses and strains in the composite case. Also possibly try to provide experimental data on wrinkle areas and/or delamination sites to see if the qualitative predictions of these performance characteristics are correct.

3. Create quantitative measures for the mechanical performance of the final structure based on the residual strain state just prior to cure and the stresses after fabrication. Incorpo-

rate this into the WACSAFE code in the form of an automatic failure analysis or as another option in the WACPLOT post-processor.

4. Improve the model by improving the model of the rubber insulation layer that exists between the mandrel and composite. Because the rubber is nearly incompressible, it is very difficult to model properly. A new technique and/or element may be developed to model the rubber layer more accurately, thus improving the accuracy of the overall model.

5. Study the anisotropic nature of the segmented steel mandrel and possibly try to characterize its effect on the performance of the composite during and after fabrication. Possibly perform winding experiments on a solid mandrel for comparison.

7.0 References

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Appendix A. FORTRAN Code Listing for CDAC Module TRANSW

```
*****************************************************************
*  This routine converts the node numbering pattern in CDAC to  *
*  a minimum bandwidth node numbering prefered by WACSAFE.  The *
*  nodes are numbered consecutively from the inside of the      *
*  mandrel to the outside of the case and then sequentially     *
*  along the case from equator to dome to create a smaller      *
*  bandwidth in the WACSAFE model.  After the WACSAFE program   *
*  runs, it is not necessary to revert to the old CDAC          *
*  numbering to use the CDAC post-processor.                    *
*****************************************************************
      SUBROUTINE TRANSW(NUMNP,MST)

      IMPLICIT DOUBLE PRECISION (A-H,O-Z)

      COMMON /ELMTHK/ LYSWAC(4),LYSBWAC(4)
      COMMON /NODAL/ NODWAG(4000),WACX(4000),WACY(4000),NODAG(4000)
      COMMON /FIBANG/ NLAYER,ILAYER(2000),IPART(2000),FIBWAC(2000,4)
      COMMON /FINNOD/ NODW(4000)
      COMMON /PLTNDS/ TX(4000),TY(4000)

C  COUNTERS FOR THE NODE ROW NUMBER, THE CURRENT NODE NUMBER FOR THE
C  COMPOSITE CASE, AND THE NODE COUNTER FOR THE CURRENT NODE ROW

      LCOUNT = 0
      NST = 1
      MCOUNT = 0

      DO 100 I=1,NUMNP

C  COUNTER FOR THE NODE NUMBER AT THE BEGINNING OF THE CURRENT NODE ROW

        NCURR = LCOUNT * LYSWAC(1) + 1
        NROW = 1

        DO 50 NELM=NCURR,NCURR+LYSWAC(1)-1

C  FINDS THE NUMBER OF NODES IN THE CURRENT NODE ROW BY ADDING 1 FOR EACH
C  ELEMENT THAT EXISTS IN THE CASE (TRACKS TRANSITIONING)

          IF(ILAYER(NELM).NE.0) NROW = NROW + 1
   50     CONTINUE

         NROW = NROW + LYSBWAC(1)

C  LINES WHICH WERE TO BE USED FOR RENUMBERING FOR POST-PROCESSING BUT
C  FOUND IT WAS UNNECESSARY

         J=NODWAG(NST)
         K=NODWAG(MST)

C  INCREMENTS CURRENT NODE ROW COUNTER

         MCOUNT = MCOUNT + 1

C  RENUMBERS NODE FOR MANDREL NODES

         IF(MCOUNT.LE.LYSBWAC(1)) THEN
           NODW(K) = I
           WACX(I) = TX(MST)
           WACY(I) = TY(MST)

C  MANDREL NODE NUMBER COUNTER

           MST = MST - 1
         ELSE

C  RENUMBERS NODES FOR COMPOSITE CASE NODES
```

```
            NODW(J) = I
            WACX(I) = TX(NST)
            WACY(I) = TY(NST)

C  COMPOSITE CASE NODE NUMBER COUNTER

            NST = NST + 1
          ENDIF

C  WHEN NUMBERING OF THE CURRENT NODE ROW IS COMPLETE RESET MANDREL NODE
C  COUNTER AND INCREMENT MANDREL NODE NUMBERS AND NODE ROW COUNTER

      IF(MCOUNT.EQ.NROW) THEN
        MCOUNT = 0
        MST = MST + 2*LYSBWAC(1)
        LCOUNT = LCOUNT + 1
      ENDIF

  100   CONTINUE

      END
```

Appendix B. FORTRAN Code Listing for CDAC Module AGWAC

```
****************************************************************
*                                                              *
* MODULE TO CREATE AN INPUT FILE FOR WACSAFE CALLED WACSAFE.MOD *
*                                                              *
****************************************************************
*  VARIABLES: HED      = PROBLEM TITLE                         *
*             WACX     = X COORD. OF WACSAFE NODES             *
*             WACY     = Y COORD. OF WACSAFE NODES             *
*             NODAG    = ARRAY WHICH LINKS AGCAP NODE #'S      *
*                        TO WACSAFE NODE #'S                   *
*             IJK      = ELEMENT CONNECTIONS                   *
*             NOELM    = # OF AGCAP ELEMENTS                   *
*             NTOT     = # OF WACSAFE ELEMENTS                 *
*             ANGL     = SETA (LOCAL ANGLES)                   *
*             NUMNP    = # OF WACSAFE NODES                    *
*             NLAYER   = # OF FIBER ANGLES OBTAINED FROM       *
*                        MODULE AGCAP2.FOR                     *
*             ILAYER   = TELLS WHETHER A LAYER EXISTS FOR EACH *
*                        FIBER ANGLE - FROM AGCAP2.FOR         *
*             FIBER    = FIBER ANGLES WHICH CORRESPOND TO NODE *
*                        ROWS - FROM AGCAP2.FOR                *
*             BETA     = FIBER ANGLES WHICH CORRESPOND TO      *
*                        WACSAFE ELEMENTS                      *
*             IOFFON   = IOFFON NUMBERS FOR WACSAFE            *
*             MTYP     = WACSAFE MATERIAL TYPE                 *
*             LYSWAC   = NUMBER OF ELEMENTS THROUGH THICKNESS  *
*             ILAYWAC  = THE FIRST ROW OF THE STACKING SEQUENCE *
*                        THESE NUMBERS ARE THE PLY ID OR THE   *
*                        POLAR/HELICAL WRAP ID NUMBERS         *
*             MATPLYW  = THE MATERIAL ID'S FOR THE PLY LAYERS  *
*             MATIWAC  = THE MATERIAL ID'S FOR THE POLAR/HELICAL*
*                        LAYERS                                *
*           PISOWAC  = ISOTROPIC MATERIAL PROPERTIES FROM CDAC*
*             PORTHWAC = ORTHOTROPIC MAT'L PROPS FROM CDAC     *
*                                                              *
****************************************************************
      SUBROUTINE AGWAC(NUMNP)

      IMPLICIT DOUBLE PRECISION(A-H,O-Z)
      CHARACTER*15 WACMOD

      COMMON /HEAD/ HED(10)
      COMMON /NODAL/ NODWAG(4000),WACX(4000),WACY(4000),NODAG(4000)
      COMMON /ELMIJK/ IJK(10,2000),NOELM,ANGL(2000)
      COMMON /FIBANG/ NLAYER,ILAYER(2000),IPART(2000),FIBWAC(2000,4)
      COMMON /ELMTHK/ LYSWAC(4),LYSBWAC(2)
      COMMON /LAYWAC/ ILAYWAC(50,4),ILAYBWAC(50,2)
      COMMON /MATWAC/ MATPLYW(50),MATIWAC(50)
      COMMON /PROPWAC/ ISOMAX,IORTMAX,PISOWAC(10,20),PORTHWAC(10,20)
      COMMON /FINNOD/ NODW(4000)

      DIMENSION BETA(2000)
      DIMENSION IOFFON(2000)
      DIMENSION MTYP(2000)
      DIMENSION WTIME(20)
      DIMENSION NODWAC(4000)
      DIMENSION TENSION(25),TENS(2000)

      WACMOD = 'WACSAFE.MOD'

      OPEN(UNIT=15,FILE=WACMOD,STATUS='NEW')

C
C GET NECESSARY USER INPUT DATA - MANDREL OFF/ON #, WINDING TENSION/OFF/ON #
C
      WRITE(*,*)'   **************************************************'
      WRITE(*,*)'   * USER INPUT NEEDED TO CREATE WACSAFE MODEL FILE *'
```

```
      WRITE(*,*)'   *************************************************'
      WRITE(*,*)
      WRITE(*,*)'           ENTER THE NUMBER OF ELEMENTS PER LAYER'
      WRITE(*,*)'           OF THE COMPOSITE CASE'
      READ(*,*) NEPL
      NWSTEP = LYSWAC(1)/NEPL
      WRITE(*,*)
      WRITE(*,*)'           ENTER THE # OF THERMAL LOAD STEPS'
      WRITE(*,*)'           = # OF HEATUP STEPS + 1 COOLDOWN'
      READ(*,*) NTCASE
      MOFFON = -(NTCASE+NWSTEP+1)
      DO 50 N=1,NWSTEP
        WRITE(*,*)
        WRITE(*,500) N
        READ(*,*) TENSION(N)
   50   CONTINUE

C     PROBLEM TITLE

      WRITE(15,1000) HED

C     CONTROL DATA LINE

      WRITE(15,1100) NUMNP,NWSTEP,NTCASE

C     INTERMEDIATE OUTPUT CONTROL LINE

      INTOUT = NTCASE + NWSTEP
      WRITE(15,1200) INTOUT

C     INTERMEDIATE OUTPUT DATA LINE

      WRITE(15,1225) (I,I=1,INTOUT)

C     WINDING TIME DATA LINE

      IF(NWSTEP.EQ.LYSWAC(1)) THEN
        WRITE(15,1250) (WTIME(I),I=1,NWSTEP/2)
        WRITE(15,1250) (WTIME(I),I=NWSTEP/2+1,NWSTEP)
      ELSE
        WRITE(15,1250) (WTIME(I),I=1,NWSTEP)
      ENDIF

C     NODAL POINT DATA LINES

      DO 100 I=1,NUMNP

         WRITE(15,1300) I,WACX(I),WACY(I)

100   CONTINUE


C     TOTAL NUMBER OF ELEMENTS

      NTOT = 0

      DO 200 NEL = 1,NOELM

         IJK9 = IJK(9,NEL)
         IF(IJK9.EQ.99) GO TO 200
         NTOT = NTOT + 1

200   CONTINUE

C     TOTAL NUMBER OF MATERIAL SETS

      NUMMAT = ISOMAX + IORTMAX
```

```
C     ELEMENT CONTROL DATA LINE

      WRITE(15,1400) NTOT,NUMMAT

C     FIBER MOTION DATA LINE

      WRITE(15,1500) VISCOS,FFRACT,EFIBER,FRAD,ALFCUR

C     MATERIAL PROPERTY LINES

      JPROP = 0

  210   CONTINUE

      DO 220 I=1,ISOMAX

         IF(JPROP.EQ.1) THEN
           MCOUNT=I+NUMMAT
         ELSE
           MCOUNT=I
         ENDIF

         WRITE(15,1600) MCOUNT,(PISOWAC(K,I),K=1,10)

  220   CONTINUE

      DO 230 I=ISOMAX+1,ISOMAX+IORTMAX

         IF(JPROP.EQ.1) THEN
           MCOUNT=I+NUMMAT
         ELSE
           MCOUNT=I
         ENDIF

         WRITE(15,1600) MCOUNT,(PORTHWAC(K,I),K=1,10)

  230   CONTINUE

      JPROP = JPROP + 1
      IF(JPROP.EQ.1) GO TO 210

C     ELEMENT DATA LINES

      N=0

      DO 300 NEL=1,NOELM

         IJK9 = IJK(9,NEL)
         IF(IJK9.EQ.99) GO TO 300
         N = N + 1

C     RETRIEVE THE WACSAFE NODE NUMBERS WHICH CORRESPOND TO THE
C     AGCAP NODE NUMBERS (NODE1 - NODE4 IS THE ELEMENT
C     CONNECTIVITY ORDER)

         X1 = IJK(1,NEL)
         X2 = IJK(2,NEL)
         X3 = IJK(3,NEL)
         X4 = IJK(4,NEL)

         NODE1 = NODW(X1)
         NODE2 = NODW(X2)
         NODE3 = NODW(X3)
         NODE4 = NODW(X4)
```

```
C   FIBER ANGLE, IOFFON NUMBER, AND MATERIAL SET NUMBER ASSIGNMENT
C   TO EACH ELEMENT

      IF(NEL.EQ.1) THEN

         DO 275 I = 1,NLAYER

C   IF THE LAYER HAS TERMINATED FOR A PART OF THE CASE, THE FIBER
C   ANGLE, IOFFON NUMBER, AND MATERIAL SET NUMBER ASSIGNMENTS ARE
C   SKIPPED FOR THAT PARTICULAR LAYER AT THAT PART OF THE CASE.

      IF(ILAYER(I).EQ.0) GO TO 250

           NELMT1 = I + LYSWAC(1)
           NELMT2 = I + LYSWAC(2)
           NELMT3 = I + LYSWAC(3)
           NELMT4 = I + LYSWAC(4)

           INELMT1 = I + LYSBWAC(1)
           INELMT2 = I + LYSBWAC(2)

C   FIBER ANGLE ASSIGNMENT

C     FORWARD CHAMBER

      IF(IPART(I).EQ.1.AND.IPART(NELMT1).EQ.1)
     *     CALL FIASGN(I,LYSWAC(1),IPART(I),BETA)

C     AFT CHAMBER

      IF(IPART(I).EQ.2.AND.IPART(NELMT2).EQ.2)
     *     CALL FIASGN(I,LYSWAC(2),IPART(I),BETA)

C     FORWARD AND AFT SKIRTS

C     IF(IPART(I).EQ.3.AND.IPART(NELMT3).EQ.3)
C     *     CALL FIASGN(I,LYSWAC(3),IPART(I),BETA)
C     IF(IPART(I).EQ.4.AND.IPART(NELMT4).EQ.4)
C     *     CALL FIASGN(I,LYSWAC(4),IPART(I),BETA)

250   CONTINUE

C   IOFFON AND MATERIAL SET NUMBER ASSIGNMENT

C     FORWARD CHAMBER

        IF(IPART(I).EQ.1.AND.IPART(NELMT1).EQ.1)
     *     CALL INASGN(I,LYSWAC(1),IPART(I),ILAYER(I),IOFFON,MTYP,
     *     MOFFON,NEPL)

C     AFT CHAMBER

      IF(IPART(I).EQ.2.AND.IPART(NELMT2).EQ.2)
     *     CALL INASGN(I,LYSWAC(2),IPART(I),ILAYER(I),IOFFON,MTYP,
     *     MOFFON,NEPL)

C     FORWARD AND AFT SKIRTS

C     IF(IPART(I).EQ.3.AND.IPART(NELMT3).EQ.3)
C     *     CALL INASGN(I,LYSWAC(3),IPART(I),ILAYER(I),IOFFON,MTYP,
C     *     MOFFON,NEPL)
C     IF(IPART(I).EQ.4.AND.IPART(NELMT4).EQ.4)
C     *     CALL INASGN(I,LYSWAC(4),IPART(I),ILAYER(I),IOFFON,MTYP,
C     *     MOFFON,NEPL)

C      FORWARD CHAMBER - INNER ELEMENTS (MANDREL, RUBBER, ETC.)
```

```
      IF(IPART(I).EQ.-1.AND.IPART(INELMT1).EQ.-1)
     *      CALL INASGN(I,LYSBWAC(1),IPART(I),ILAYER(I),IOFFON,MTYP,
     *      MOFFON,1)

C       AFT CHAMBER - INNER ELEMENTS (MANDREL, RUBBER, ETC.)

      IF(IPART(I).EQ.-2.AND.IPART(INELMT2).EQ.-2)
     *      CALL INASGN(I,LYSBWAC(2),IPART(I),ILAYER(I),IOFFON,MTYP,
     *      MOFFON,1)

275     CONTINUE

      ENDIF

C   CONNECT TRIANGULAR ELEMENTS AS NEEDED BY WACSAFE

         IF(NODE1.EQ.NODE2) THEN
            NODE1 = NODE3
            NODE3 = NODE2
            NODE2 = NODE4
            NODE4 = NODE3
         ENDIF

         IF(NODE2.EQ.NODE3) THEN
            NODE2 = NODE1
            NODE1 = NODE4
            NODE4 = NODE3
         ENDIF

C    STORE WINDING TENSION DATA

      IF(IOFFON(N).GT.0.AND.IOFFON(N).LT.NWSTEP) THEN
         NDUM=IOFFON(N)
         TENS(N)=TENSION(NDUM)
      ENDIF
C
C    WRITE ELEMENT LINES TO WACSAFE.MOD FILE
C
      WRITE(15,2000) N,NODE1,NODE2,NODE3,NODE4,MTYP(N),IOFFON(N),
     *                 TENS(N),BETA(N),ANGL(NEL)
300   CONTINUE

C    FORMAT STATEMENTS

 500    FORMAT(7X,'ENTER THE WINDING TENSION FOR WINDING STEP',I3)
1000  FORMAT(10A8)
1100  FORMAT(I6,1X,' 1',1X,I3,1X,' 0',I3,1X,' 1  1  3  0  0  1')
1200  FORMAT(I2)
1225    FORMAT(40(I3))
1250  FORMAT(20D12.4)
1300  FORMAT(I6,1X,'  0   0  ',1X,2(E14.5,2X),2x,'0')
1400  FORMAT(I6,I6,'  0')
1500  FORMAT(D12.4,2X,F6.2,2X,D12.4,2X,D12.4,2X,F5.2)
1600    FORMAT(I6,10E9.2E2)
2000    FORMAT(I5,2X,4(I6,2X),I3,2X,'1',2X,I3,2X,
     *         E10.3,2X,2(F5.2,2X))

      RETURN
      END
*****************************************************************
*                                                               *
*    SUBROUTINE ASSIGNS FIBER ANGLES TO ELEMENTS                *
*                                                               *
*****************************************************************
      SUBROUTINE FIASGN(I,NELMTH,NWD,BETA)

      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
```

```
      COMMON /FIBANG/ NLAYER,ILAYER(2000),IPART(2000),FIBWAC(2000,4)

      DIMENSION BETA(1)

C    KEEPS TRACK OF ELEMENT NUMBER

      NELM = NELM + 1

C    I KEEPS TRACK OF THE ELEMENT POSITION IN THE PRESENT NODE ROW
C    WHILE NROW KEEPS TRACK OF THE ELEMENT POSITION IN THE
C    FOLLOWING NODE ROW - THIS IS DONE SO INTERPOLATION CAN
C    BE DONE BETWEEN NODE ROWS TO OBTAIN ELEMENT VALUES

      NROW = I + NELMTH

C    THIS LOOP ASSIGNS FIBER ANGLES TO TRIANGULAR ELEMENTS

      IF(ILAYER(NROW).EQ.0) THEN

         BETA(NELM) = 90.0 - FIBWAC(I,NWD)
         GO TO 100

      ENDIF

C    ASSIGNS FIBER ANGLES TO FOUR SIDED ELEMENTS

      ANGLE   = (FIBWAC(I,NWD) + FIBWAC(NROW,NWD))/2.0
      BETA(NELM) = 90.0 - ANGLE

100     RETURN

      END
*****************************************************************
*                                                               *
*    SUBROUTINE ASSIGNS IOFFON NUMBERS TO ELEMENTS              *
*                                                               *
*****************************************************************
      SUBROUTINE INASGN(I,NELMTH,NWD,LAYEXT,IOFFON,MTYP,MOFFON,NEPL)

      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      INTEGER*2 MATID

      COMMON /LAYWAC/ ILAYWAC(50,4),ILAYBWAC(50,2)
      COMMON /MATWAC/ MATPLYW(50),MATIWAC(50)

      DIMENSION IOFFON(1)
      DIMENSION MTYP(1)

C    RESETS LAYER TO ZERO WHEN THE PART OF THE CASE CHANGES

      IF(I.EQ.1) LAYER = 1
      IF(NWD.NE.NWDP) LAYER = 1
      NWDP = NWD

C    KEEPS TRACK OF LAYER

      IF(NWD.GT.0.AND.NECT.EQ.NEPL) THEN
        LAYER = LAYER + 1
        NECT = 0
      ENDIF
        NECT = NECT + 1

C    LCOUNT COUNTS ELEMENTS THROUGH THE THICKNESS

      LCOUNT = LCOUNT + 1
```

```
C    RESETS LAYER VALUE IF LCOUNT IS LARGER THAN THE MAXIMUM
C    NUMBER OF ELEMENTS THROUGH THE THICKNESS

      IF(LCOUNT.GT.NELMTH) THEN
        LAYER = 1
        LCOUNT = 1
      ENDIF

C    IF THE LAYER DOES NOT EXIST FOR A PARTICULAR PART OF THE
C    CASE THE PROGRAM CONTINUES

      IF(LAYEXT.EQ.0) GO TO 100

C    KEEPS TRACK OF ELEMENT NUMBERS

      NELM = NELM + 1

C    IOFFON NUMBER ASSIGNMENT FOR OUTER CASE COMPOSITE ELEMENTS

      IF(NWD.GT.0) IOFFON(NELM) = LAYER

C    IOFFON NUMBER ASSIGNMENT FOR INNER CASE LAYERS

      IF(NWD.LT.0.AND.LAYER.EQ.1) THEN
        IOFFON(NELM) = 0
        LAYER = LAYER + 1
      ELSE IF(NWD.LT.0) THEN
        IOFFON(NELM) = MOFFON
        LAYER = LAYER + 1
      ENDIF

C    MATERIAL SET NUMBER ASSIGNMENT FOR OUTER COMPOSITE ELEMENTS

      IF(NWD.GT.0) MATID = ILAYWAC(LCOUNT,NWD)

C    MATERIAL SET NUMBER ASSIGNMENT FOR INNER CASE LAYERS

      NWP = IABS(NWD)
      IF(NWD.LT.0) MATID = ILAYBWAC(LCOUNT,NWP)

C    RETRIEVES MATERIAL ID NUMBERS FOR POLAR/HELICAL WRAPS

      IF(MATID.LT.0) THEN
         MATID = IIABS(MATID)
         MTYP(NELM) = MATIWAC(MATID)
         GO TO 100
      ENDIF

C    RETRIEVES MATERIAL ID NUMBERS FOR PLY WRAPS

      MTYP(NELM) = MATPLYW(MATID)

100   RETURN
      END
```

Vita

Steven Craig Stein was born in Lancaster, Pennsylvania, on August 30, 1966. He grew up in Strasburg, Pennsylvania, and graduated from Lampeter Strasburg High School. Steve entered the engineering program at Virginia Polytechnic Institute and State University and graduated with a B.S. in Mechanical Engineering in 1989. He then went on to graduate school at VPI&SU where he received a M.S. in Mechnical Engineering in August of 1990. Steve is currently pursuing his doctorate in Mechanical Engineering at VPI&SU.

Steven C. Stein