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OMC Compressor Case

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1.0 INTRODUCTION

This report summarizes efforts expended in the development of an all-composite compressor case. Two pre-production units have been built, one utilizing V-CAP and one utilizing AFR-700B resin systems. Both units have been rig tested at elevated temperatures well above design limit loads. This report discusses the manufacturing processes, test results, and Finite Element Analysis performed.

The V-CAP unit was funded by NASA-Lewis Research Center in 1994 under contract number NAS3-27442 for Development of an All-Composite OMC Compressor Case. This contract was followed by an Air Force study in 1996 to build an identical unit using the AFR-700B resin system in place of the V-CAP system. The second compressor case was funded under U.S. Air Force contract F33615-93-D-5326, Advanced Materials for Aerospace Structures Special Studies (AMAS3), Delivery Order 0021 entitled "Advanced Polymeric Composite Materials and Structures Technology for Advanced High Temperature Gas Turbine Engines."

Initial studies using the V-CAP resin system were undertaken in 1993 under a NASA-Lewis contract (NAS3-26829). A first prototype unit was developed in a joint program between Textron-Lycoming (now Allied Signal) and Brunswick (now Lincoln Composites). This unit included composite end closures using low density, high temperature molded end closures. The units was similar in size and shape to a titanium case currently used on the PT-210 engine and was funded as part of the Integrated High Performance Turbine Engine Technology (IHPTET) initiative of DOD and NASA. Table 1-1 summarizes the history of these developments.

1.1 Objectives

The primary objective of this development was to demonstrate the suitability of composite structures at 450°F for high temperature environments typical of jet engine usage. Hopefully, the composite OMC Compressor Case could replace a titanium counterpart at a lower weight, affordable cost, equivalent stiffness, and maintain tolerance control.

A second objective of the study was to utilize Finite Element Analysis (FEA) to predict the response of the unit to the expected thermal and structural loading. Then determine through analysis which properties and features are critical to maximize the units' performance.

A third objective was to test the performance of the unit under static loading at elevated temperatures to validate the FEA analysis performed.

A fourth goal of this effort was performance of actual engine testing using an OMC Compressor Case. This objective was not accomplished due to scheduling problems and the unavailability of engine testing facilities at the time the units were actually delivered.

A final objective of the two programs was a possible head-to-head comparison of the two different high temperature resin systems.

Table 1-1. History

- NAS3-36829 (NASA 1993)
  - Develop processing methods and demonstrate sandwich skin construction using V-CAP resin system.

- CC-19152 (Lycoming 1993/94)
  - Develop prototype compressor case. Demonstrate molded end closures using high temperature molding compound.

- NAS3-27442 (NASA-Lewis 1994/96)
  - Fabricate V-CAP unit on segmented mandrel with improved wind patterns and precise internal interface. Statically test at elevated temperature.

- F33615-93-D-5326 (WPAFB 1996)
  - Fabricate an identical compressor case except using AFR-700B resin system. Statically test at elevated temperature.

2.0 SUMMARY

This report summarizes recent efforts expended in the development and validation of an All-Composite Compressor Case. Much of the emphasis in developing high temperature composite material structures for use in aircraft engines has been focused on material development. Structural analyses and testing have been performed as a part of these material demonstration programs. Improvements in the areas of low-cost, high-speed computers and the increased availability of quality finite element codes has increased the ability to predict the behavior of these complex composite structures. This report also addresses both material development and FEA analysis of the tested units.

The V-CAP unit pioneered the development process. By the time the AFR-700B unit was started most of the significant lessons had been learned. Therefore, the second program benefited and the work progressed smoothly and efficiently.

The configuration selected was an axisymmetric sandwich construction consisting of an inner and outer filament wound skin separated by a light weight honeycomb core. The inner skin, which contacts the hot gases (450°F), utilized the high temperature resin systems while the outer skin employed a high temperature epoxy resin system.

The final manufacturing process evolved over time and several processing and tooling changes were required during the program. Appendix A, taken from the bi-monthly progress reports, addresses these issues in more details. During the development of the OMC Compressor Case several changes in scope were made, which include:

1. Use of Wet Winding

   Prepreg roving offered several potential advantages; however, the problems with batch-to-batch variations in handlability, tack, and non-uniform solvent contents were determined to be insurmountable and the process was returned to wet winding.

2. Molding of Internal Contour

   The original plan of providing ample machining stock to the I.D. for machining to the precise dimensions required for sealing was abandoned when it became apparent that the laminate was too porous and non-uniform. A far superior laminate was produced by net molding the internal surfaces. This required a new segmented wind mandrel that could be removed internally following cure.

3. Vacuum Bag Procedure

   Maintaining vacuum bag integrity at 700°F proved to the most challenging due to the complexity of the wind mandrel and the severity of the temperature. The process was changed with the ARF-700B unit to apply the full autoclave pressure (200 psig) earlier (550°F) in the cure cycle. This was successful and a better, lower void content on the inner skin was produced for the AFR-700B unit.

Both compressor cases were statically tested at Allied Signal. The engine tests were not performed, primarily due to the late delivery of the units. This was also complicated by the transfer of responsibility from

Textron Lycoming to Allied Signal. The window for performing the low cost engine tests had passed when the unit(s) were available.

The V-CAP unit withstood one and half (1.5) times the limit load at 450°F without any obvious defects or permanent damage. It was not possible to take the part to failure due to limited test capabilities at that time.

The AFR-700B unit was tested to failure (in a revised test fixture) at eight (8) times the limit load. Failure was at the inner skin as analysis had predicted.

Finite Element Analysis (FEA) was performed and compared against the actual test results. The analysis conservatively predicted the response to both structural and thermal loads.

This study has shown that organic matrix composites are suitable for high temperature (+450°F) environments typical of jet engine applications. Both resin systems (V-CAP and AFR-700B) were successful and validated that high margins of safety are inherent with the two skinned honeycomb structure. However, a direct comparison between the two resin systems was not fulfilled. To do this would require sectioning the inner skin and performing specimen testing in compression at elevated temperatures.

3.0 CONFIGURATION

The titanium compressor case from the PT-210 engine that was selected for demonstration using all-composite is shown in Figure 3-1. The OMC Compressor Case was designed to match the same geometry and is shown in Figure 3-2. The titanium unit was reported to weight 6.6 pounds and part of the challenge was to beat this weight by 20 percent.

The composite compressor case used an axisymmetric sandwich construction consisting of filament wound composite inner and outer skins separated by a light-weight composite core. Figure 3-3 shows the construction and Table 3-1 tabulates the materials and wind patterns used. The inner skin was constructed of ±80° S-2 glass/V-CAP winding which exhibit good machinability characteristics and adds toughness to the structure, and three layers [±20°, ±80°, ±20°] of T650-35/V-CAP for strength and stiffness. The outer skin comprised of two layers [±20°, 90°] of T650-35/LRF-543 epoxy. The core used a fiberglass reinforced polyimide honeycomb construction. The forward and aft ends of the compressor casing were constructed of QC-126-54-4 molding compound. The skins, core, and end fittings were bonded together with a modified bismaleimide film adhesive (EA 9673) at the inner skin and a high temperature (350°F) epoxy film adhesive (FM 350) at the outer skin.

The sandwich construction provided a structure with high dimensional stability, established repair procedures, and good damage tolerance making it the best choice for producing a reliable engine component. The inner skin used both glass and graphite fibers with the high temperature V-CAP resin system. Glass fibers were used on the inside surface to serve as machining stock for the internal sealing interface. The graphite fibers carry the majority of the axial and torsional loads for both inner and outer skins. Threaded inserts were installed at the end fittings to provide the attachment interfaces to the adjacent jet engine structure.

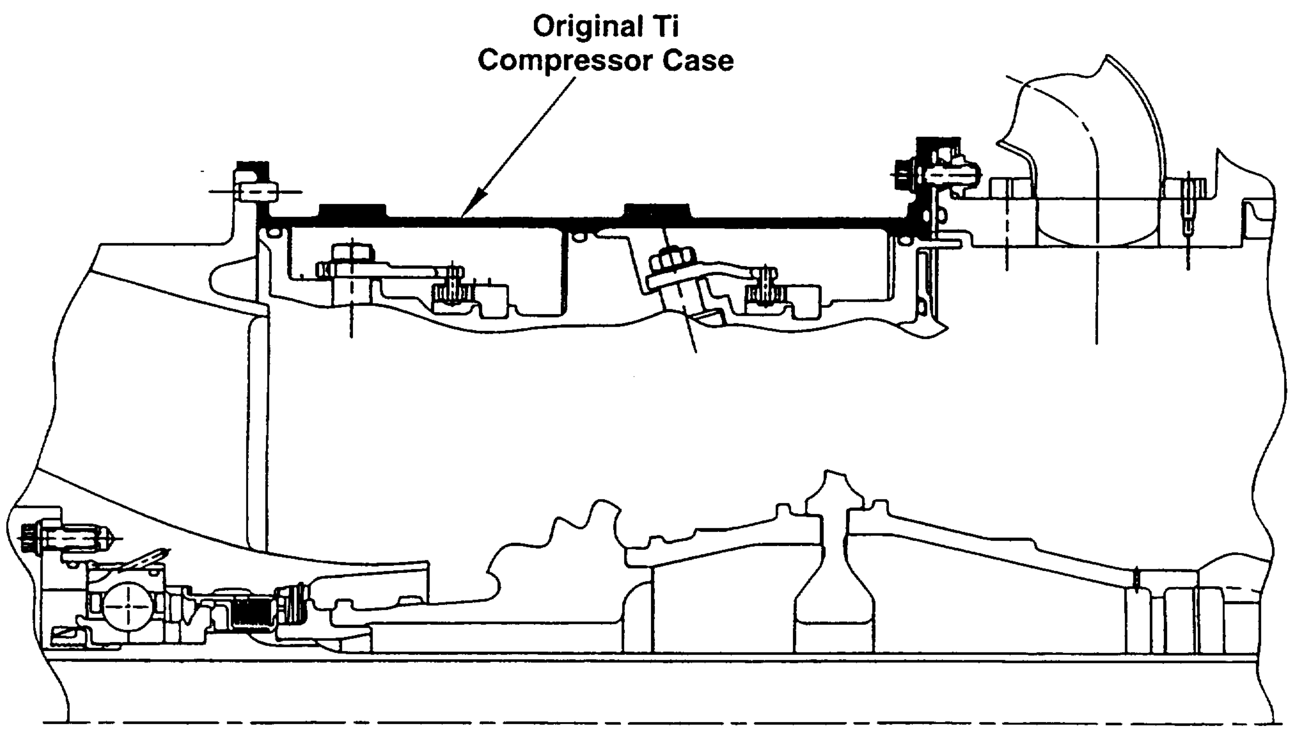

Figure 3-1. JTAGG I Compressor with Original Titanium Compressor Case

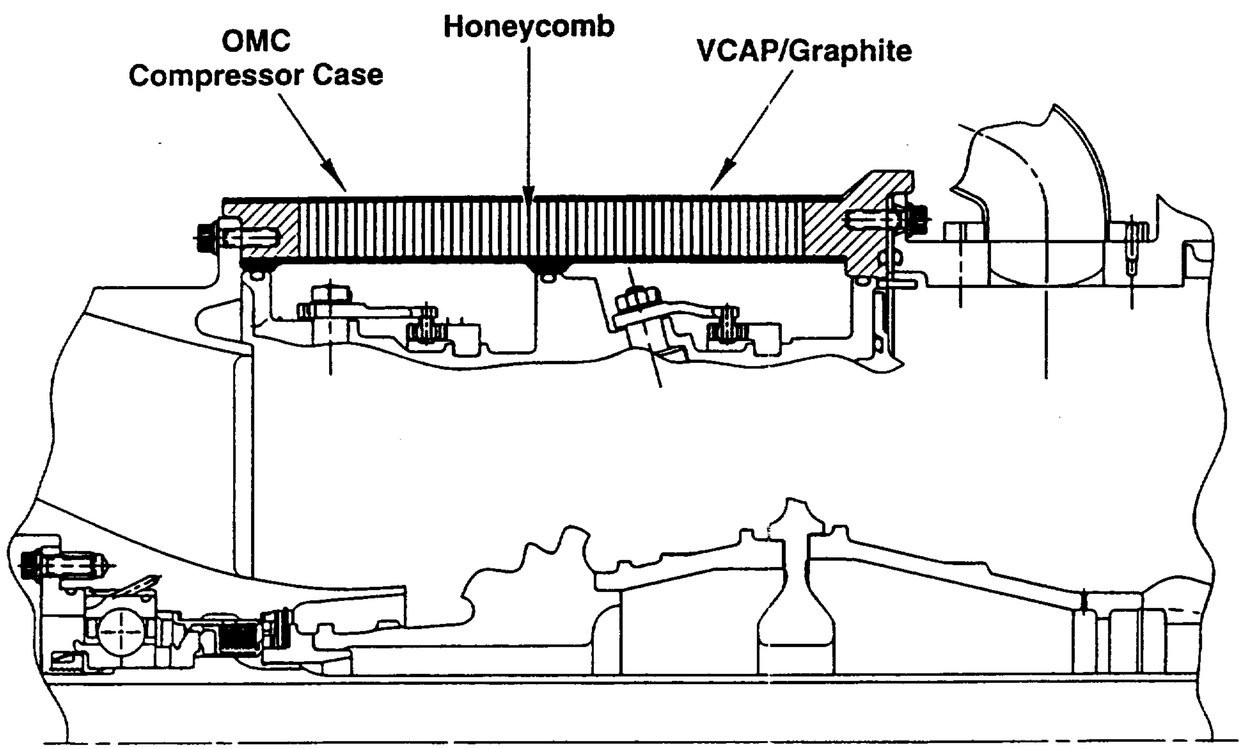

Figure 3-2. JTAGG I Compressor with OMC Compressor Case

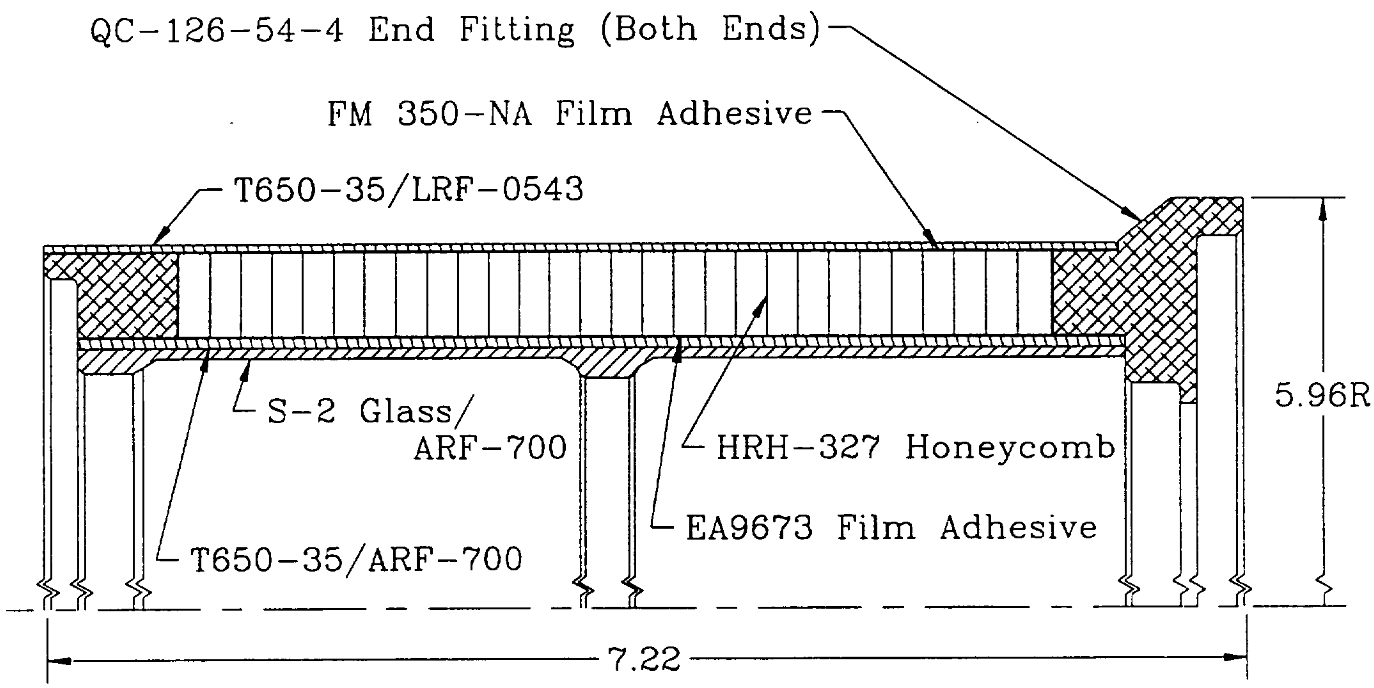

Figure 3-3. OMC Compressor Case Construction

Table 3-1. Construction

- High Temperature Inner Shell
  - High Temperature Resin – V-CAP or AFR-700B
  - Glass Cloth/S-2 Glass Helicals [±80°]
  - T650-35 Graphite [±20°, ±80°, ±20°]

- Core
  - Film Adhesive – Hysol EA 9673
  - Honeycomb Core – HFR-327
  - Film Adhesive – FM-350

- Molded End Closures
  - QC-126-54-4 – proprietary resin system filled with microballoons and chopped glass.

- Epoxy Outer Shell
  - LRF-0543
  - T650-35 Graphite [±20° and 90°]

4.0 MANUFACTURING

This section describes the final process used to fabricate the two OMC Compressor Cases. Details of the previous manufacturing development operations are described in Appendix A. A manufacturing flow diagram is shown in Figure 4-1 which outlines the specific operations used. The compressor case was filament wound on a segmented steel mandrel, which provided close tolerance sealing surfaces on the I.D. of the part. The wind mandrel was segmented to allow removal of the inner skin (see Figures 4-2 and 4-3). To assist in winding the low angle (±20°) helicals, temporary wooden domes were used that were subsequently removed from the curing operations. The mandrel also featured a built in vacuum system for bagging operations.

The mandrel was covered with a thick layer of the high temperature resin to serve as a gel coat. Next, a wet-impregnated layer of 120 glass cloth was laid-up to add substance and thickness to the gel coat. The wind operation started with 90° (hoop) winding of glass roving into recesses in the mandrel, which define the sealing surfaces. All winding was performed using a wet resin bath with the resin's solid content mixed at 70 to 75 percent monomer solids. The glass inner skin was wet wound using ±80° helical fibers with the high temperature resin to a 0.078 inch thickness. In earlier units, these glass layers were used as machining stock to provide the sealing surfaces. These features are now molded in-place using a segmented mandrel (see Appendix B).

Next, the glass laminate was imidized and autoclave cured (details of the curing operations are covered in Section 4.1). The inner skin assembly was completed by winding three layers of graphite (T650-35) at ±20°, ±80°, and ±20° for a thickness of 0.063 inches (see Figure 4-4). The graphite sequence was imidized and autoclave cured directly on the glass laminate.

Following cool down, the segmented mandrel was disassembled and the part removed. Machining operations included trimming to length and grinding a slight taper (see Figure 4-5) at each end to assist with bonding the end closures. The end closures (see Figure 4-6) consisted of a vinyl-ester type resin and chopped glass with microballoon filler which were seated in place using a high temperature film adhesive (EA 9673). Table 4-1 tabulates the molding compound's properties. Hexcel HRF-327 honeycomb was installed between the end closures and the film adhesive. Special care was required to index the molded reinforcement in proper orientation for future through-the-wall port machining (see Figure 4-7). The assembly was overwrapped with shrink tape and the film adhesive cured.

With the closures bonded in place, it was no longer possible to return the assembly back on the segmented mandrel. Therefore, a water solute sand mandrel was cast into the parts I.D. to support it during subsequent winding/curing operations. A second set of larger diameter wooden domes were installed and the bonding surfaces of the honeycomb and molded end closures covered with a lower temperature film adhesive (FM-350).

Fabrication was completed by overwrapping the assembly with graphite roving (T650-35) and LRF-0543, a high temperature epoxy resin. The final wind patterns consisted of a ±20° helical followed by two hoop plies. The part was then oven cured and the water soluble sand mandrel removed by introducing a stream of hot water into its interior.

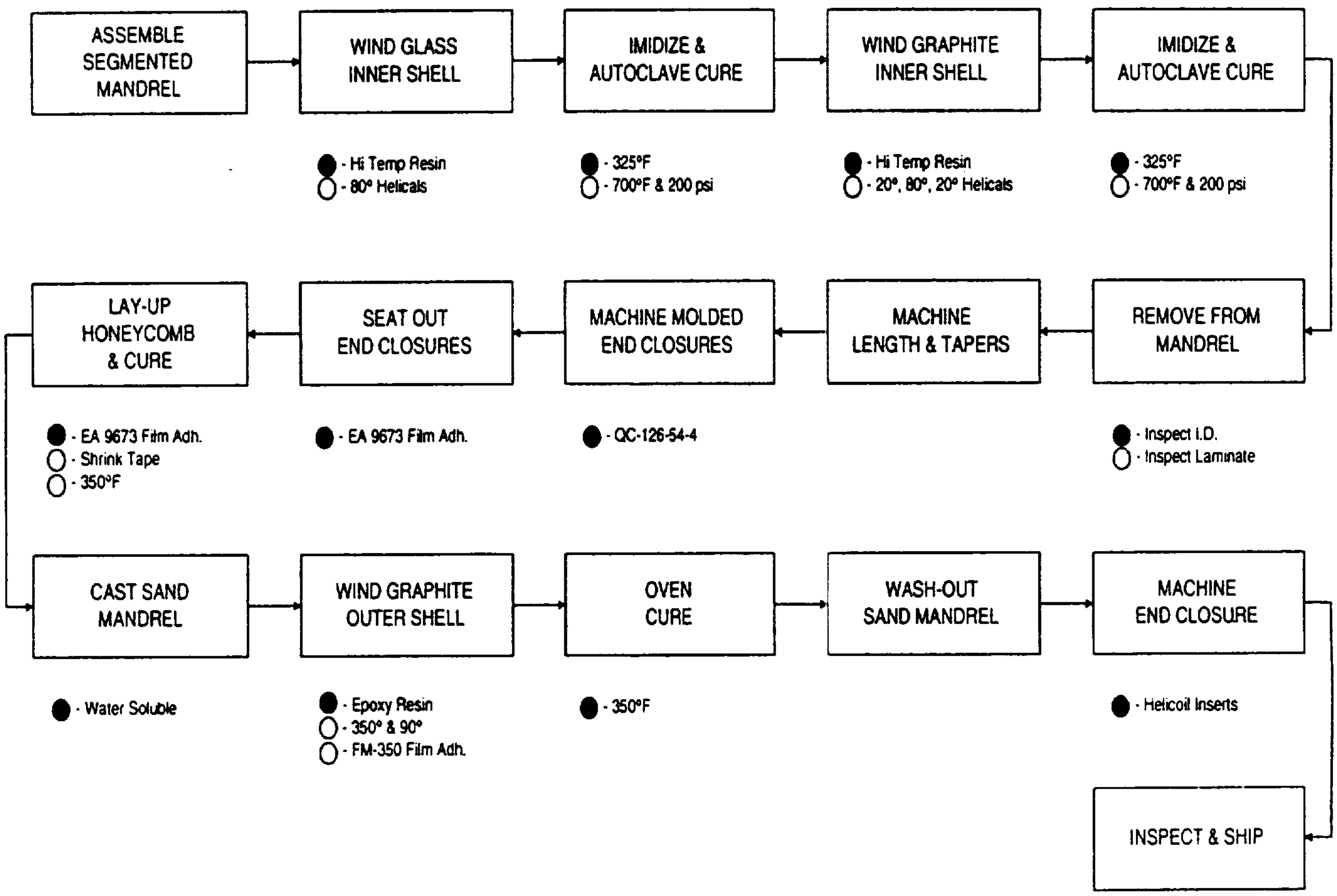

Figure 4-1. Manufacturing Flow Diagram

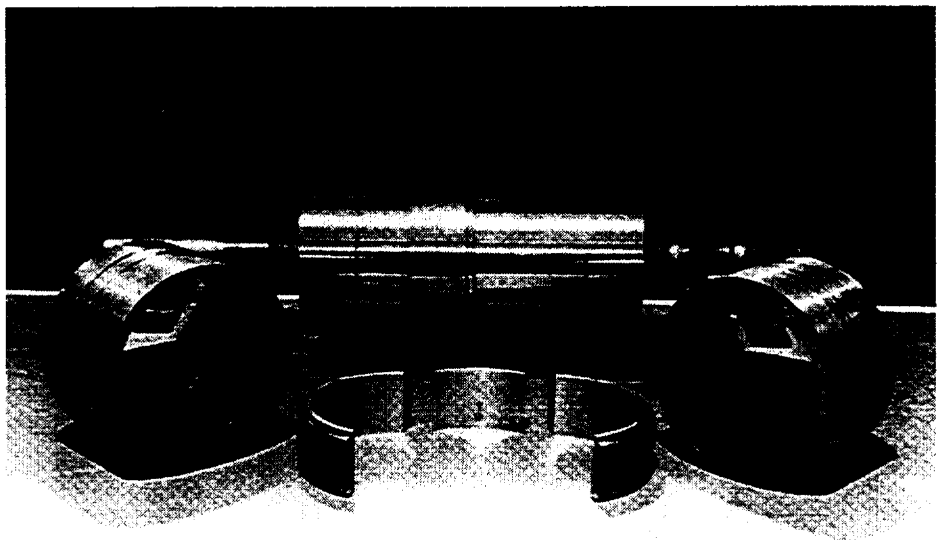

Figure 4-2. Segmented Steel Mandrel

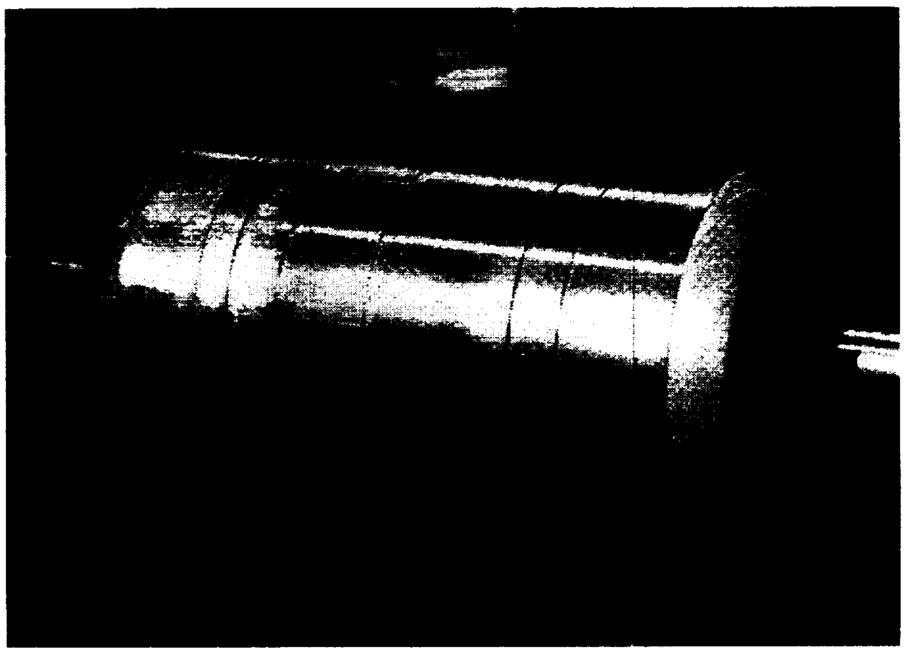

Figure 4-3. Assembled Mandrel

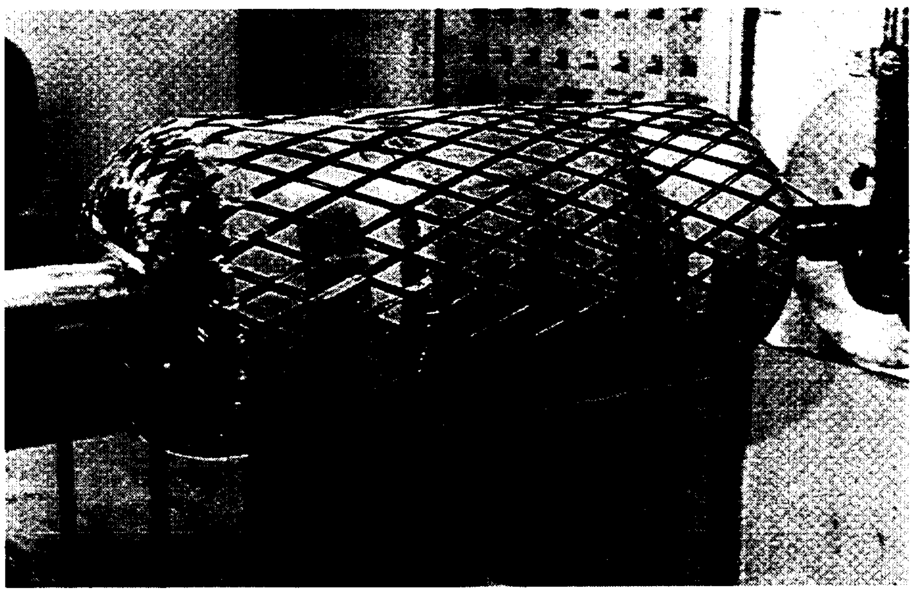

Figure 4-4. Graphite Overwrap of Glass Sequence

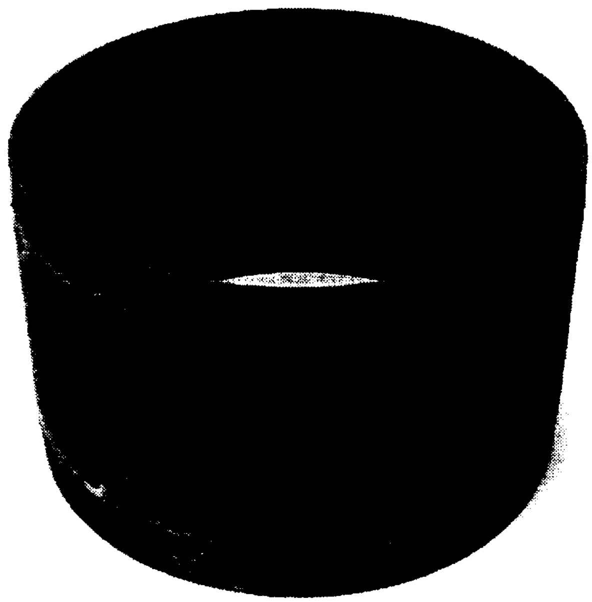

Figure 4-5. Inner Skin – Cured, Trimmed, and Tapered

Table 4-1. QC-126-54-4 Molding Compound

Material	QC-126-54-4
Lot Number	060551
Glass Fiber (%)	49.5
Specific Gravity	1.31
Shrinkage (in./in.)	0.0000
Flexural Strength (psi)	39.300
Flexural Modulus (x 10^6 psi)	1.56
Tensile Strength (psi)	22,500
Tensile Modulus (x 10^6 psi	1.99
Izod Impact, noted (ft*lb/in)	32
Thermal Expansion, CTE (in./°F)	10 - 11 x 10^{-6}

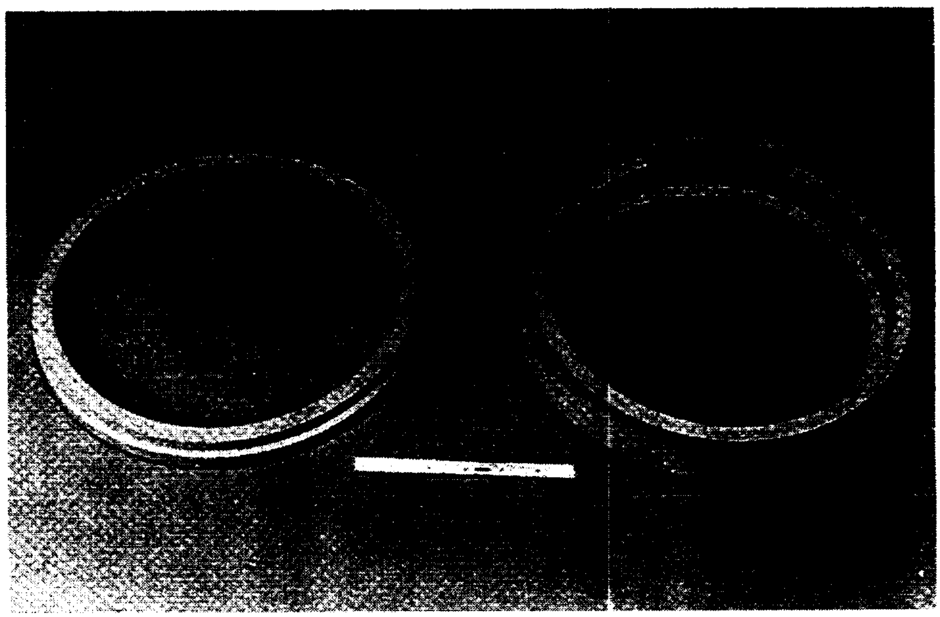

Figure 4-6. Molded End Closures

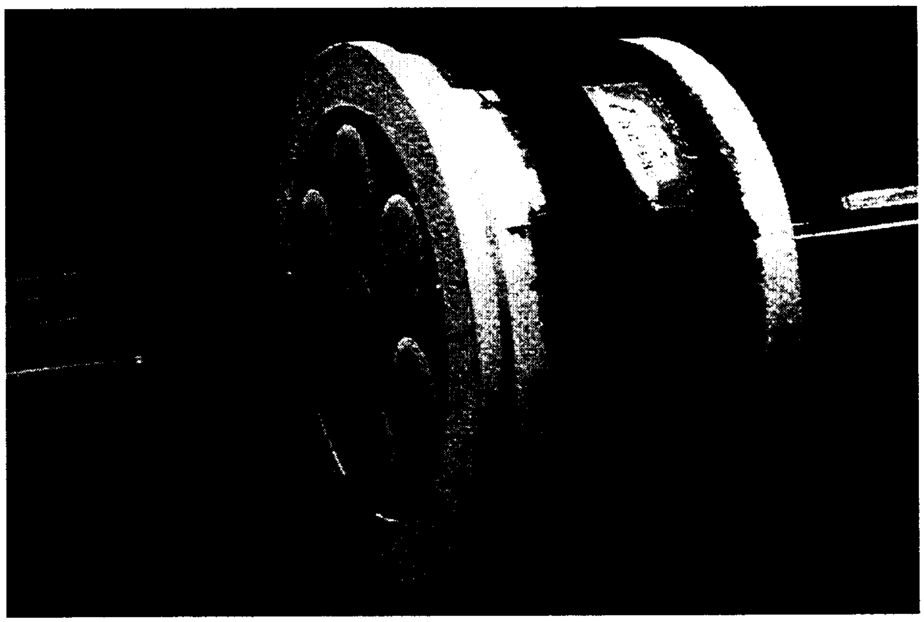

Figure 4-7. Inner Skin Sub-Assembly on Sand Mandrel

The last manufacturing operation consisted of machining the outboard edges of the end closures to meet the requirements of drawing TE-39917. Holes were drilled in the molded closures and helicoils installed to complete the assembly (see Figure 4-8).

4.1 Cure Details

Immidization cycles for all sequences and both resin types were identical at 325°F for 1 hour. The autoclave cure cycle for the glass laminates were the same for both resins.

- Glass Sequence Hold — 1 hour 45 minutes at 700°F
- Graphite Sequence Hold — 12 hours at 700°F

Table 4.1-1 outlines the standard autoclave cure cycles used for both resin systems. The resin chemistry is similar for the two resins and the proposed cure cycles were identical. For the glass sequences, the 200 psig autoclave pressure was applied for only 15 minutes after reaching 700°F. However, for the graphite sequence, the temperature level at which the 200 psig autoclave pressure was applied was changed. The original V-CAP cure specified pressure application after reaching 700°F – it was determined that maintaining vacuum pressure at this high of temperature was marginal. This was changed after performing a flat panel study, which indicated acceptable laminates could be made by applying pressure at a lower temperature. The implemented changes were:

- V-CAP – Full vacuum pressure (200 psig) applied after reaching 700°F, 7 hours after starting 400°F hold.

- AFR-700B – Full vacuum pressure (200 psig) applied after 550°F hold; 3 hours, 15 minutes after starting 400°F hold. Ramp rate to 700°F was unchanged.

The performance of the bag was closely monitored after applying pressure at 550°F on the AFR-700B part. Vacuum bag leakage was noted after 15 minutes into the 700°F hold. It is not known just when this leakage may have occurred on the V-CAP part, but its void content was 15 percent while the AFR-700 unit was 7 percent. It is apparent that by applying the autoclave pressure earlier in the cure cycle that a much lower void content was produced. Based on this data, it is probable that the vacuum bag was already leaking when 200 psig was applied to the V-CAP part.

Table 4.1-2 shows the resin burn out data for V-CAP and AFR-70B. Based on this data, it is probable that the vacuum bag was already leaking when 200 psig was applied to the V-CAP part.

The resin and void contents were measured from the trimmed edges of the cured parts. It is assumed that these are not representative of the mid-section of the unit, which would be less influenced by edge effects. However, the resin burnout data does provide a comparative basis between the two cure cycles without destroying the units.

Figure 4-8. Completed Compressor Case

Table 4.1-1. Standard Autoclave Schedule

- Apply Full Vacuum
- Ramp to 400°F and Hold 1 Hour
- Ramp to 500°F and Hold 1 Hour
- Ramp to 550°F and Hold 1 Hour
- Ramp to 650°F and Hold 1 Hour
- Ramp to 700°F and Hold 15 Hours
- Apply Full Autoclave Pressure (200 psig)
  - At 700°F for the V-CAP
  - At 550°F for the AFR-700B
- Hold at 700°F
  - 1 Hour, 45 Minutes (Glass Sequence)
  - 12 Hours (Graphite Sequence)
- Turn Off Autoclave (Slow Cool Down)
- Remove Autoclave Pressure at 325°F
- Keep Door Closed Until 200°F

Table 4.1-2. Resin Burnout Results (%)

	V-CAP	AFR-700B
E-Glass Laminate		
Resin (by weight)	19.3	20.4
Fiber Volume	59.6	63.5
Void Volume	14.9	7.6
Graphite Laminate		
Resin (by weight)	24.8	24.9
Fiber Volume	56.2	65.3
Void Volume	15.7	6.8

5.0 TEST REQUIREMENTS

This section describes the loads and the test fixture used to statically test both the V-CAP and the AFR-700B compressor cases. The tests were performed by Allied Signal at their Phoenix, Arizona location. Appendix C contains Allied Signal's test plan.

5.1 Design Requirements

Structurally, the compressor case is subjected to an 8000 pound compressive axial load in conjunction with an 8400 inch-pound torsional load and an internal pressure of 45 psi. The compressor case operates in an environment which results in an internal gas temperature of up to 450°F and an external gas temperature of approximately 150°F. Energy is assumed to be transferred from the surrounding gas to the structure primarily through convection.

5.2 Test Description

The compressor casing was installed in a test rig which allowed for the simultaneous application of compression and torsion loads at the extremes of the operating environment. This test rig is shown in Figures 5.2-1 and 5.2-2. The compressor casing was sandwiched between two large steel plates which were mounted to a steel box-section frame. The entire frame was then bolted to a stable test bed enclosed in an environmental chamber which maintained the 150°F external air temperature. The internal hot air (450°F) was supplied through a supply port and bled off through a bleed valve in a manner which maintained the internal pressure. Both of these ports, as well as ports for instrumentation were in the aft plate. The compression load was applied through a centrally located stretch bolt which also acted as a shaft for application of the torsional loads. The torsion load was applied by a system of pulleys attached to the frame which connected to lever arms welded to the aft plate.

Instrumentation consisted of fourteen (14) strain gauges, ten (10) in the hoop direction and four (4) in the axial direction. Four (4) digital deflection gauges were applied to the case, two (2) in the axial and two (2) in the tangent direction. Thermocouples measured internal and external temperatures and pressure gauges controlled the internal pressure.

6.0 TEST RESULTS

Both rig and engine tests were planned for the OMC Compressor Case. Unfortunately, the engine tests were not accomplished. This was primarily due to the late delivery of the units and further complicated by the transfer of responsibility from Textron Lycoming to Allied Signal. The window for performing the low cost engine tests had passed when the two units were complete. However, the rig tests were performed on both units; the V-CAP units was tested first followed by the AFR-700B compressor case.

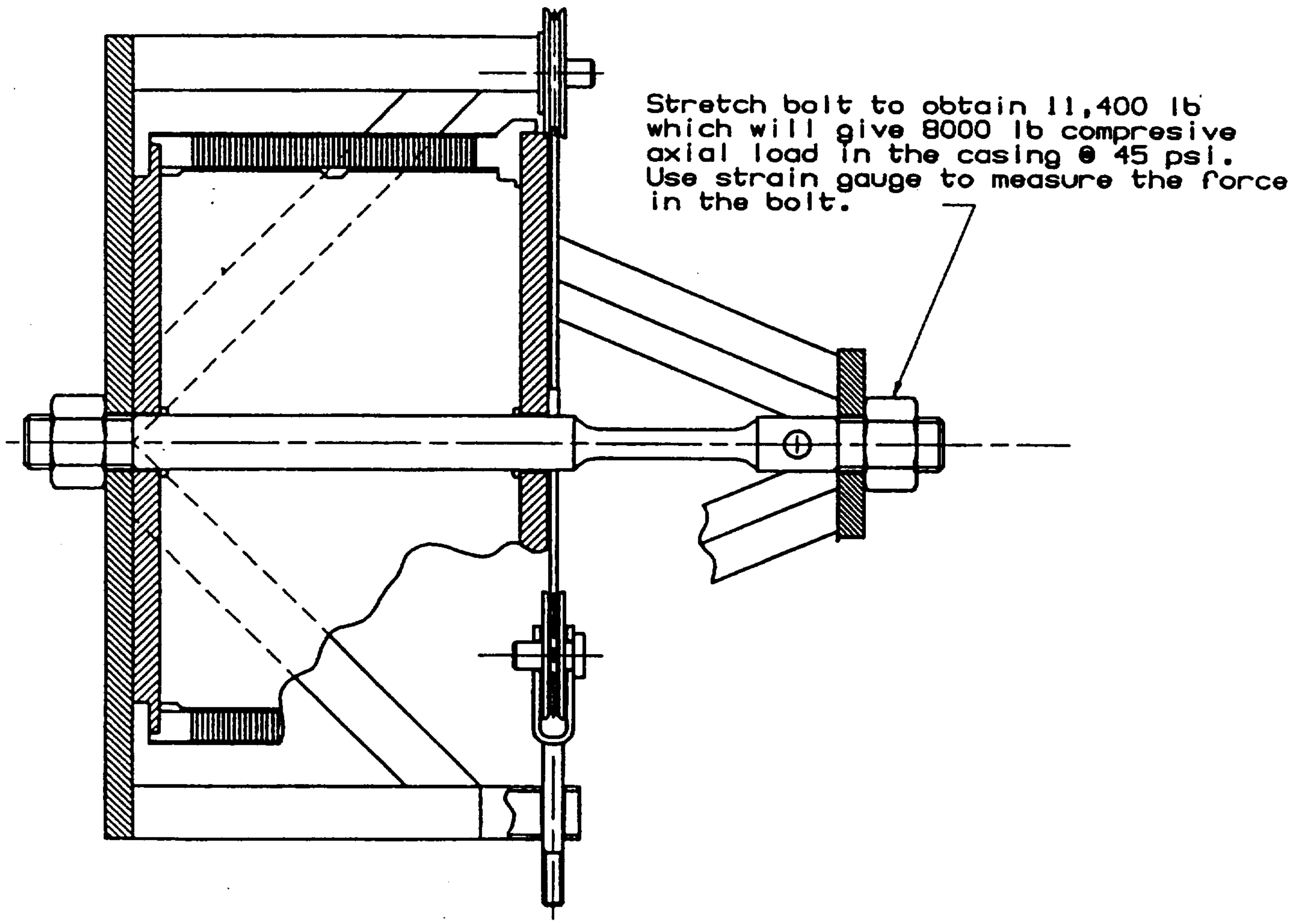

Figure 5.2-1. Test Rig – Side View

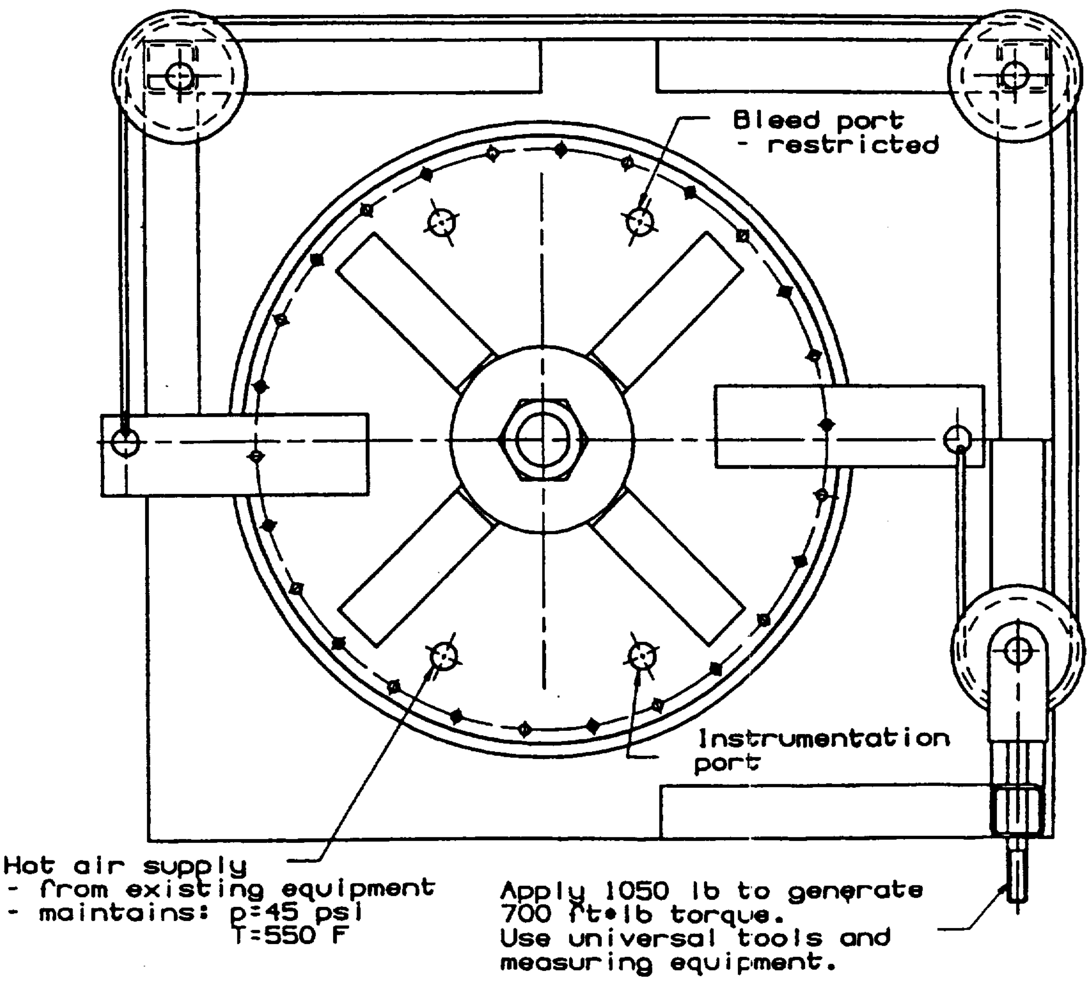

Figure 5.2-2. Test Rig – Top View

6.1 V-CAP Unit

The unit withstood one and half (1.5) times the limit load at 450°F without any obvious defects of permanent damage. The test plan had called to take the part to failure, but it was not possible due to limited axial loading capabilities.

Post test visual examination and by x-ray showed the bond line between the forward end closure and the inner skin had failed, probably from the torsion loads. During cure, a large thermal expansion mismatch existed between the molded end closures and the graphite inner skin. This was somewhat overcome by the use of tapers and by overfilling with film adhesive. However, a process improvement to increase the reliability of the bond should be considered. Use of a liquid shim (i.e. paste adhesive in conjunction with the bismaleimide film adhesive) will be investigated for future units.

6.2 AFR-700B Unit

The AFR-700B compressor case was tested to failure at eight (8) times the limit load. The compressor casing was conditioned in the test apparatus until thermal equilibrium was achieved. Next, the case was subjected to a stabilization load cycle to 50 percent limit. The unit was then loaded as follows: (all percentages refer to load factors applied to the aforementioned limit loads)

50% → 100% → 150% → 200% → 300% → 400% → 500% → 600% → 700% → 800% (failure)

The case failed just under eight (8) times the limit load. The internal pressure was not scaled above limit loads. It was maintained at 45 psi throughout all loading conditions at and above limit. The AFR-700B units was weighed following test and was determined to weigh 4.95 pounds. This indicates a 25 percent weight savings over a titanium unit.

Post test inspection indicated that the failure initiated as a compressive bearing failure of the inner skin at the edge interface between the aft end fitting and the inner skin (see Figure 6.2-1). Secondary to this initial failure of the inner skin, the wall became unstable and the outer skin also fractured near the aft fitting (see Figure 6.2-2).

7.0 FINITE ELEMENT MODEL

A detailed finite element analysis of the structure was performed to determine the thermal profile and corresponding stresses and margins of safety. The axisymmetric model, shown in Figure 7-1, was constructed and evaluated using the ANSYS finite element analysis program (Version 5.3). The model consists of 1522 elements, 1575 nodes, and almost 5000 degrees of freedom. The thermal solution is obtained using an ANSYS thermal element type (PLANE75) and the structural response is subsequently determined using the corresponding structural element type (PLANE25). Both of these elements allow for an axisymmetric structure to be subjected to nonaxisymmetric and/or "out-of-plane" loads (i.e. torsion) through a harmonic function. The end plates from the test fixture and bolted joints are included in the model. The end plates are modeled with axisymmetric elements

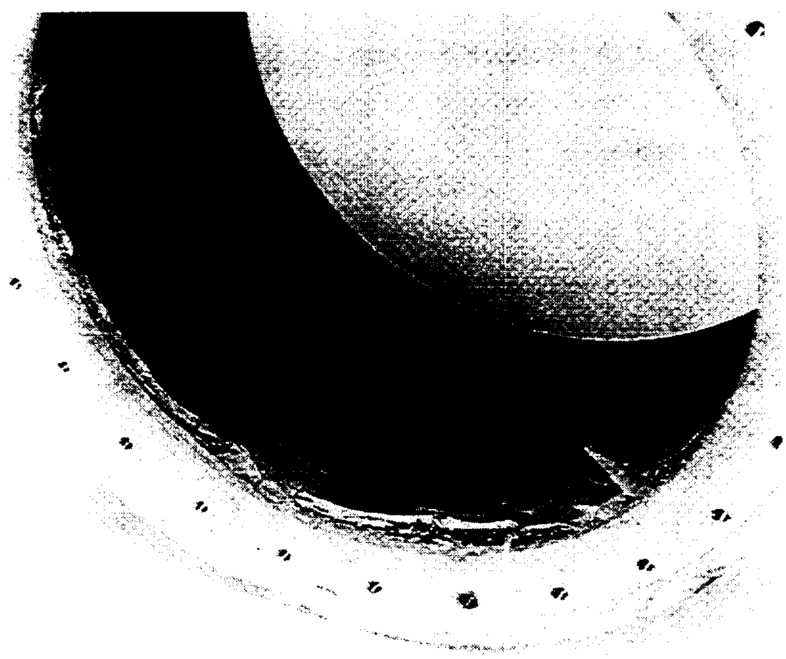

Figure 6.2-1. AFR-700B Unit, Inner Skin Bearing Failure at Eight Times Limit Load

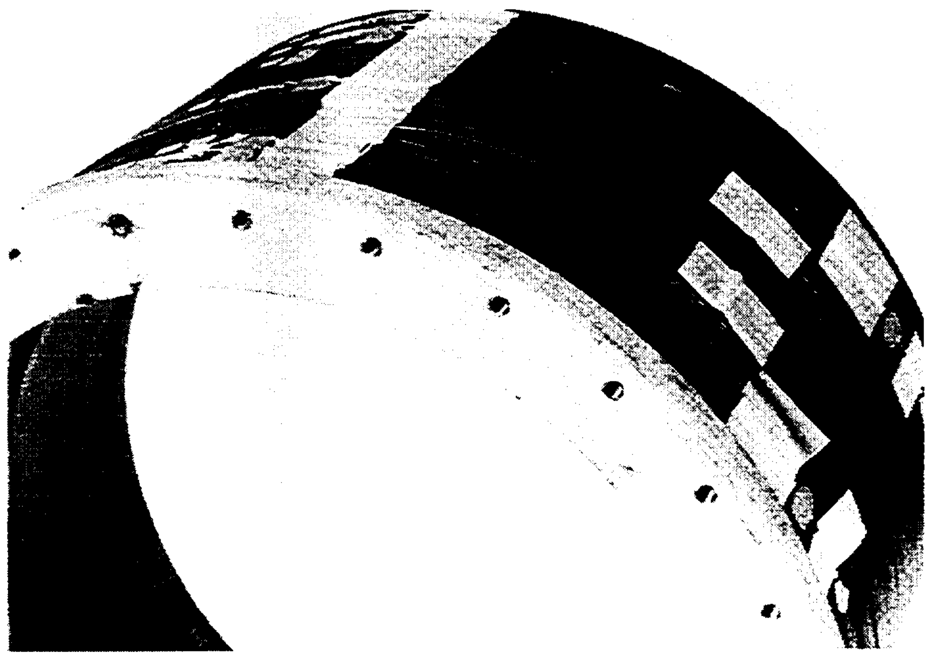

Figure 6.2-2. AFR-700B Unit, Outer Skin Secondary Failure at Eight times Limit Load

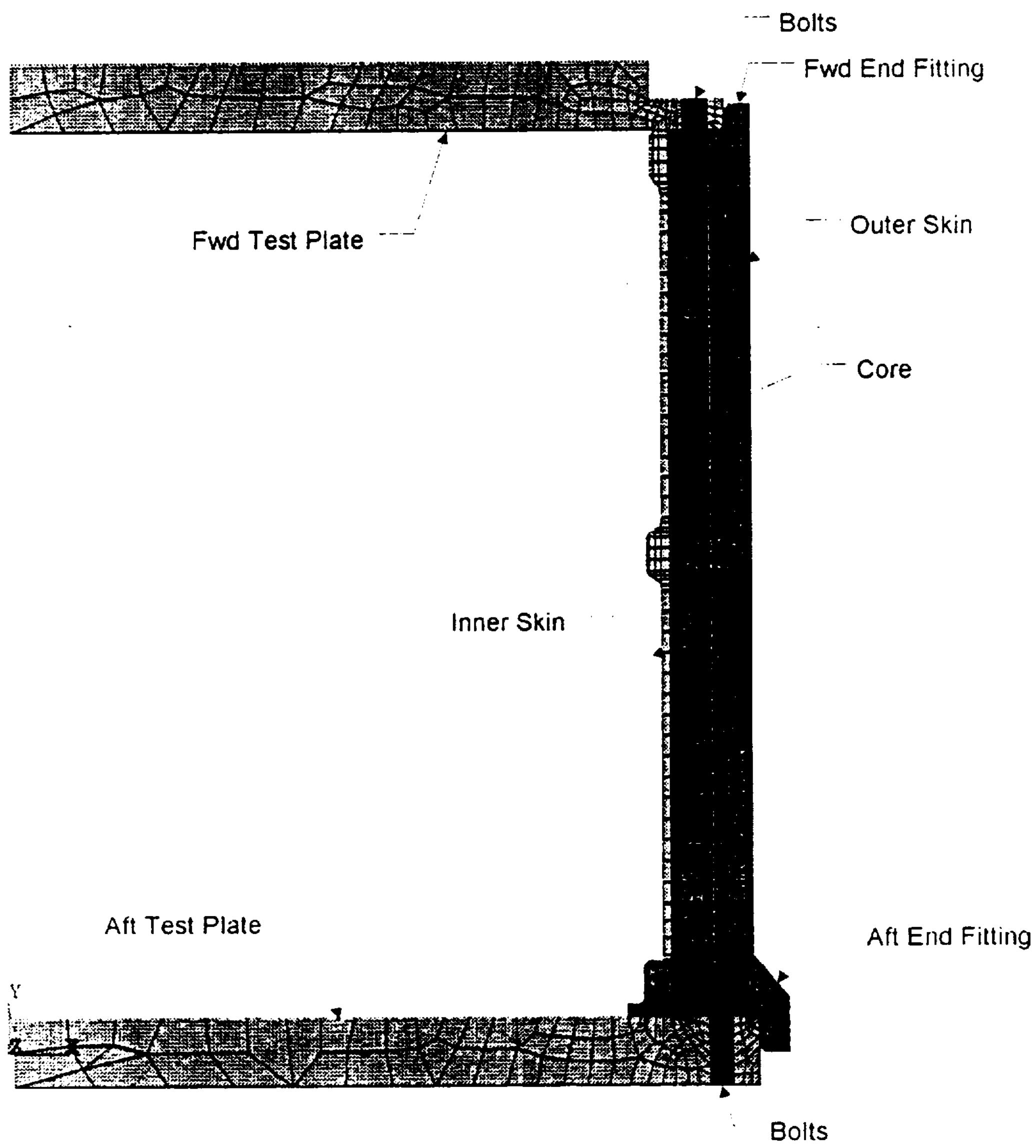

Figure 7-1. Finite Element Model

(PLANE25), and the bolts utilize plane stress elements (PLANE42) with a depth representative of the stiffness of the bolt ring. Careful consideration of all geometric features, such as fillets and chamfers, assures that any significant stress concentrations will be identified.

Material behavior is represented using typical room temperature properties. All properties are considered to be linear with the exception of the nonlinear stress-strain behavior of the film adhesive modulus. Since the stiffness of the materials used in construction of the compressor casing tend to soften when subjected to elevated temperatures, predicted stress concentrations will be conservative. The analysis is steady state (no thermal shock) and requires no transient parameters such as heat capacity. The key properties used for this analysis include stiffness, Poisson's ratio, coefficients of thermal expansion and thermal conductivity, and allowable strengths. The orthotropic nature of the respective material properties is accounted for where appropriate.

Boundary conditions include convective heat transfer on the inner and outer surfaces, and structural loads and constraints in the attach regions on the forward and aft test plates. These loads and constraints are applied uniformly around the circumference of the structure. All components are considered to be the "stress-free" condition at room temperature (70°F). The assumptions and boundary conditions used to model the finite element analysis are tabulated in Table 7-1.

8.0 ANALYTICAL RESULTS

Graphical and tabular summaries of the analytical results are presented in Table 8-1 and Figures 8-1 through 8-4. It is readily apparent from these figures and table that the thermal loading is more significant to the structure than the applied structural loads (at limit). The maximum deformation and stresses are due to the relatively large thermal expansion of the molded end fittings compared to the carbon composite skins. The fittings tend to want to "roll" away from the main body of the casing as they expand. The test plates restrain this rolling action, forcing the rings to remain approximately flat as they expand. This results in local stresses in the face skins and film adhesive in the end fitting regions.

The minimum margins of safety (MS = Factor of Safety -1) and maximum deformations are summarized in Tables 8-1 and 8-2. The margins are greater than 3.2 under combined loading, indicating a very safe structure. The high stress regions include the material immediately adjacent to the end fittings and attachment area. The maximum deformations tabulated in Table 8-2 and the deformed shapes depicted in Figures 8-1 and 8-2 clarify the dominance of the thermal loading on the anticipated structural response. Net stresses on the section are shown in Figure 8-3. This gives a graphical representation of which components of the structure carry the various loads. The axial loads are carried primarily by the ±20° carbon helicals, while circumferential loads are carried by the circumferential (±80° and 90°) carbon layers.

The analysis reveals potentially high stresses in the adhesive at the edges of the molded end fittings. These correspond to areas of high stress in the face skins and end fittings. A more detailed analysis including consideration of the thermal dependency of the film adhesive, as well as improved nonlinear properties, will tend to

Table 7-1. Finite Element Modeling

- ANSYS 5.3 Finite Element Analysis
  - Detailed Representation of Geometry
    - Discontinuities and Test Fixture Modeled
  - Bolt Circles Represented as Plane Stress
    - Equivalent Stiffness/Conduction
    - "Perfect" Joints - No Interface Modeling
  - Axisymmetric
    - Harmonic Load Capability for Torsion
- Materials
  - All "Typical" Linear Properties Except Film Adhesive
    - Testing Needed to Develop More Accurate Properties
  - Properties Assumed to be Temperature Independent
    - Conservative Prediction of Stress
- Boundary Conditions
  - Loads/Restraints Applied at Forward and Aft Test Plates
  - Surface Loads (Pressure/Temperature) are Applied Over Entire Surface
    - Stress-Free Temperature Assumed to be 70°F
    - Convective Transfer at Inner and Outer Surfaces
    - No Thermal Contact Resistance at Boundaries

Table 8-1. FEA Minimum Martins of Safety, Limit

Component	Thermal	Structural	Combined
IS S-2 Glass	5.5	63	7.2
IS T650-35	**3.1**	**4.5**	**3.2**
OS T650-35	4.2	16	4.0

Table 8-2. FEA Maximum Deflections, [in.]

Direction	Thermal	Structural	Combined
Axial	-0.013	-0.004	-0.013
Circumferential	0.000	0.001	0.001
Radial	0.014	0.003	0.015
Total	0.019	0.004	0.019

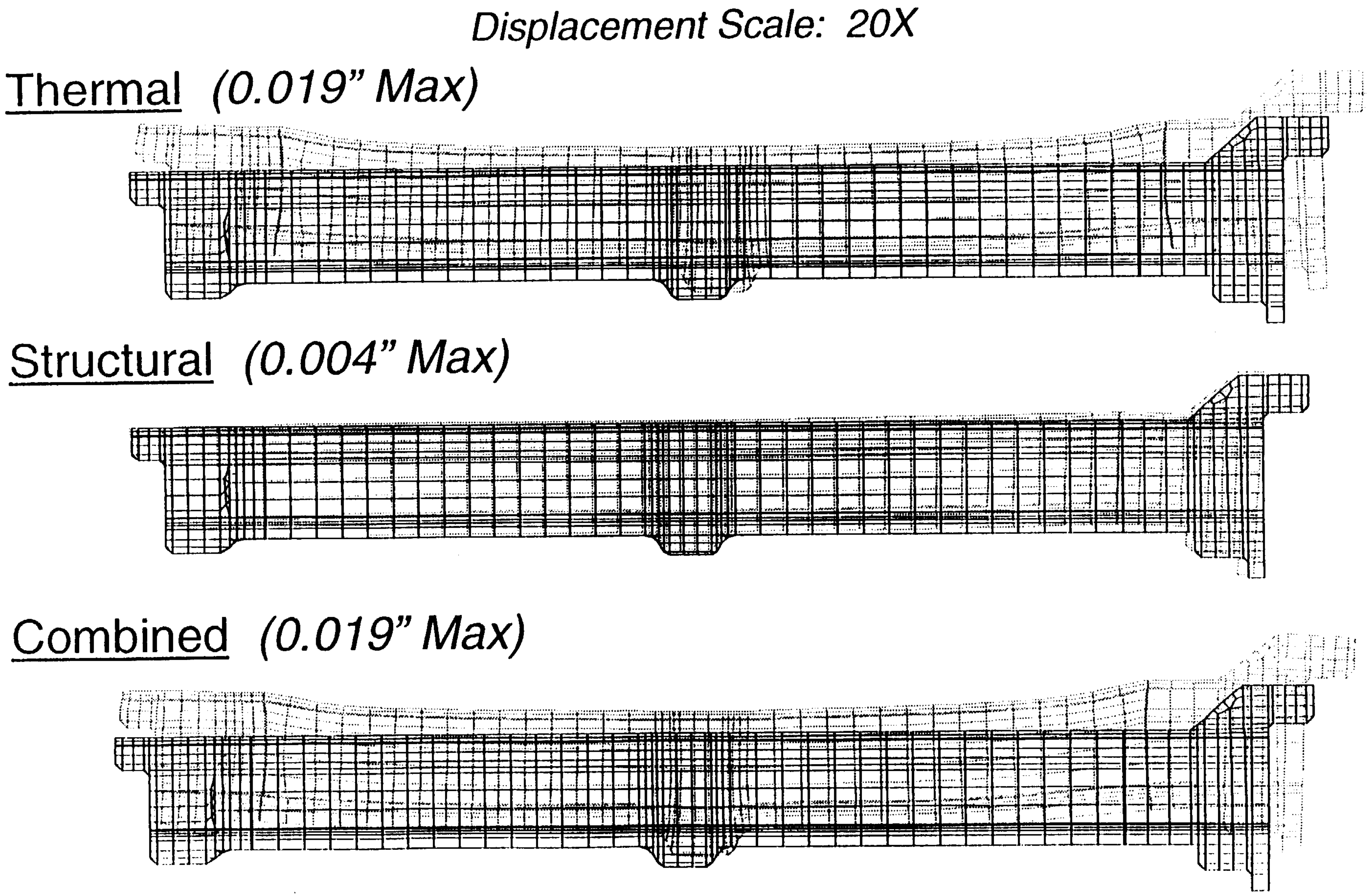

Figure 8-1. Exaggerated Deformations, Limit

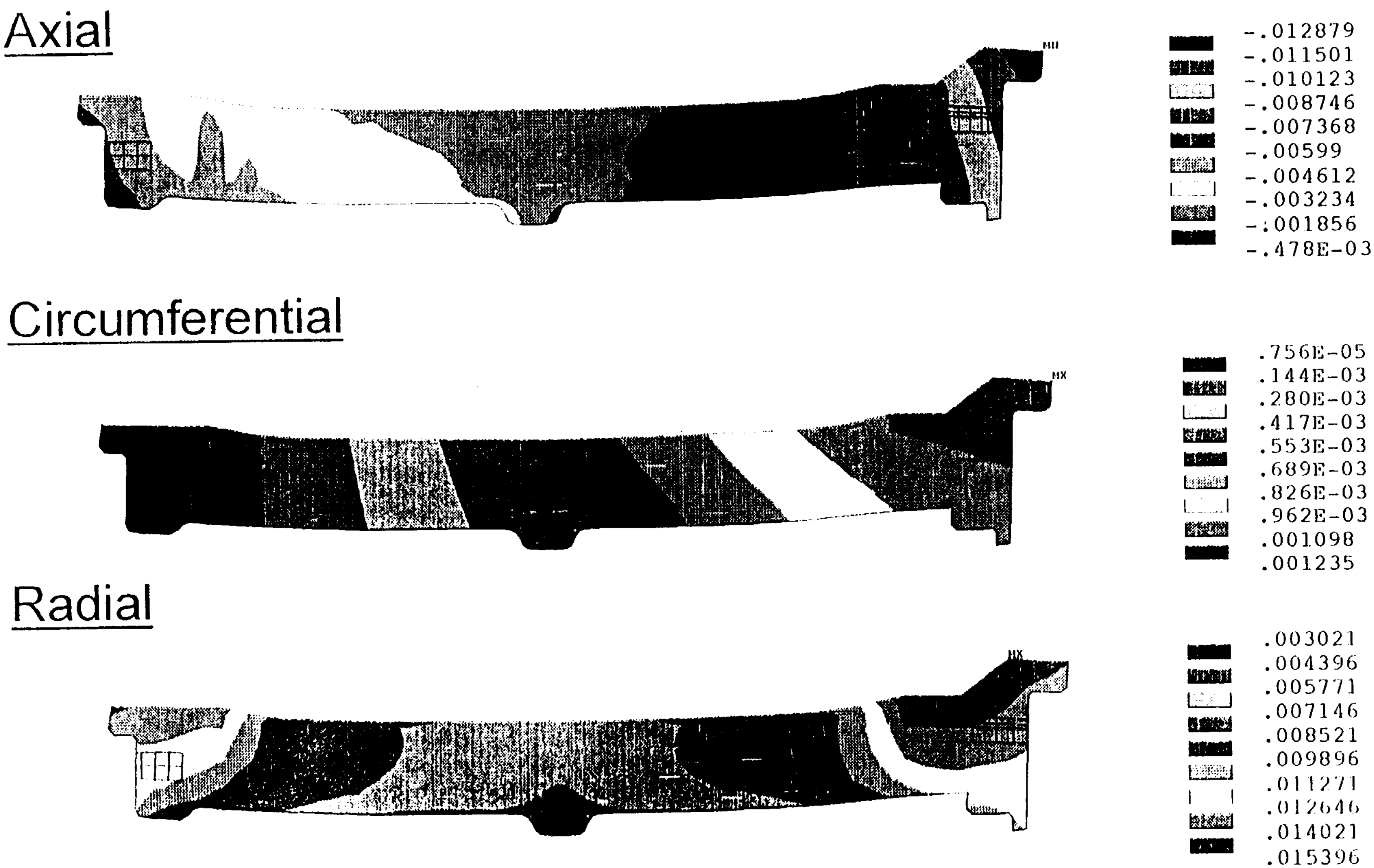

Figure 8-2. Combined Limit Loads, Deformations [in.]

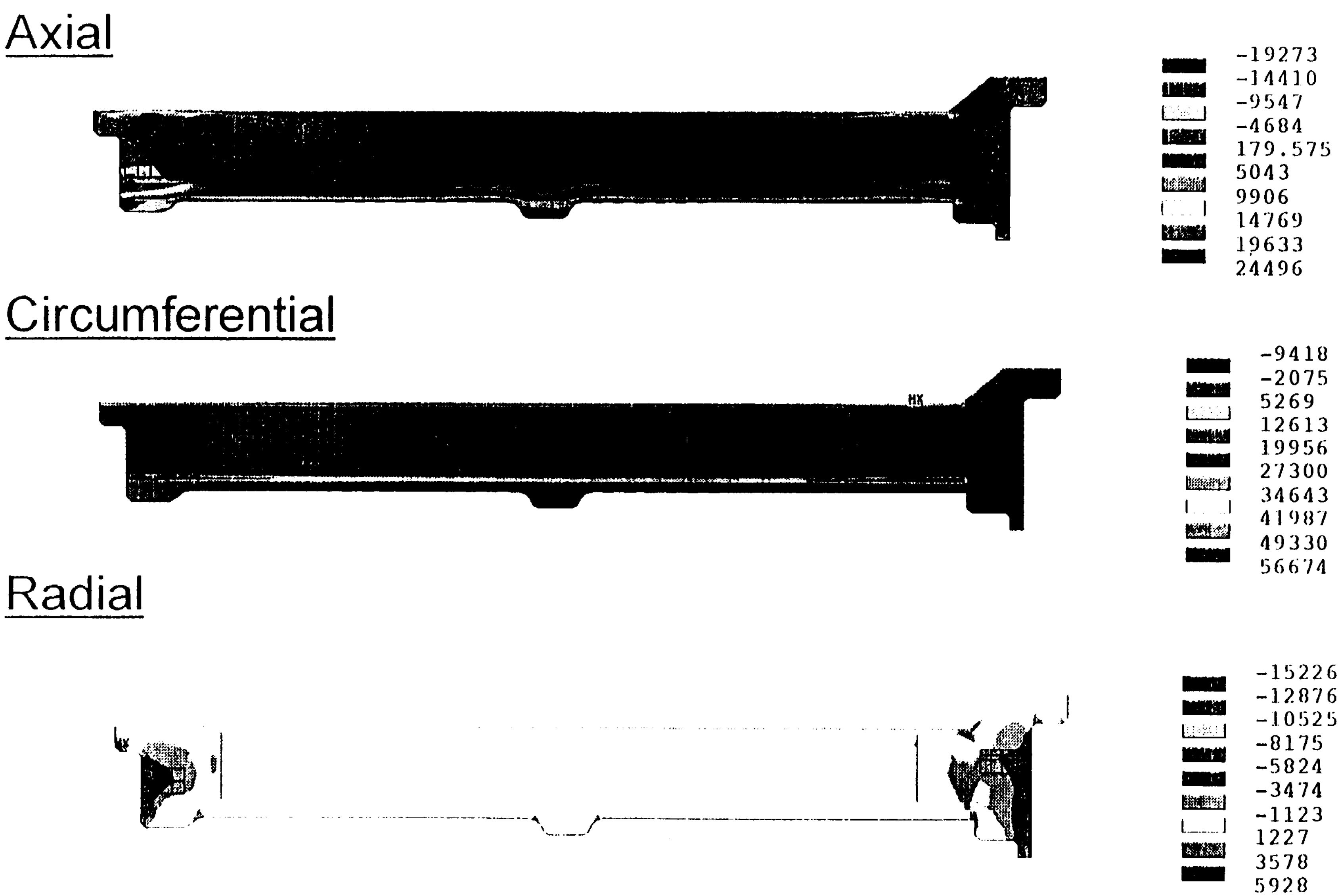

Figure 8-3. Combined Limit Loads, Stress [psi]

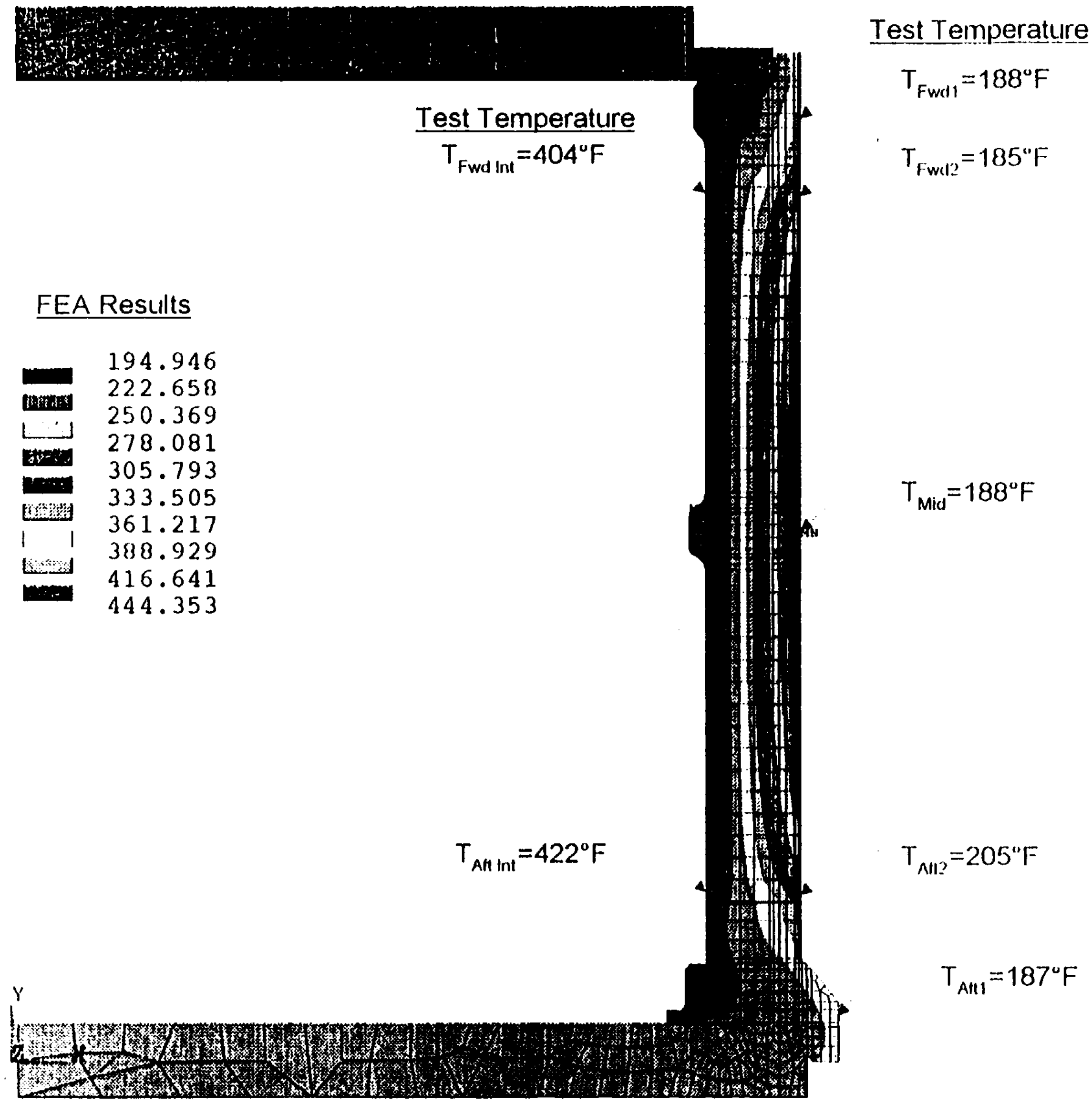

Figure 8-4. Temperature Distribution, [°F]

reduce these stresses. Additionally, further optimization of the end fittings will help further reduce these stresses by creating a more efficient shear ply. A slight taper is included in the existing prototype as a manufacturing aid.

Figure 8-4 depicts the thermal profile of the structure. The environment results in a structure temperature ranging from 195°F to 445°F. Analytically, the end-plates are introducing heat into the composite structure through the end fittings. This skews the thermal profile up at both the forward and aft ends.

9.0 DISCUSSION OF FEA RESULTS

It is important to note that the primary focus of this development was to demonstrate the suitability of organic matrix composites to the environmental extremes introduced by a jet engine environment. With this in mind, the compressor case was designed conservatively to avoid the added expense of developing statistically significant material properties for each material system considered. A common practice in the design of continuous fiber composite structures is to design a desired fiber stress level. Since the fibers are significantly stiffer than the matrix at all temperatures, the strength contribution from the matrix can be neglected. As long as the matrix remains stable in the operating environment, this assumption will remain conservative. The advantage to this approach is that the extent of material development for each fiber/matrix combination is greatly reduced. The disadvantage is that the predicted deformation of the laminate (i.e. strain) may be less accurate.

The objectives of this analytical effort, on the other hand, are directed toward accurate evaluation of the overall behavior of a complex composite structure subjected to both thermal and structural loads. There are a number of simplifying assumptions which are necessary to limit the scope of the analytical effort (see Section 7.0). The purpose of this correlation is to identify what effect those assumptions have on the accuracy of the predicted response of the structure. There are two significant simplifications in this analysis that result in obvious deviations between the anticipated response and that which is measured. These include the use of "typical" linear room temperature properties for elevated temperature analysis and the level of refinement in the finite element representation of the bolted joint.

The use of "typical" material properties implies that the properties are for a different material system than the component is constructed of. The analytical lamina properties are developed through micromechanics using the known fiber properties and "typical" epoxy resin properties. For predicting the response of a composite structure to external physical loading, the errors introduced by this approximation are not significant. Thermal transport and expansion properties, however, may vary significantly from these "typical" values. This is evident in Table 9-1 and Figure 9-1 which indicate that the predicted thermally induced strains differ from the measured (corrected) values, on the average, by a factor of 5. This large deviation indicates that the estimated expansion coefficients for some of the constituent materials are inaccurate. Additionally, without complete definition of the thermal conductivity properties of all materials, the temperature distribution in the structure is only a first order approximation. The actual part temperature during test was somewhat affected by the combined loading effects of internal pressure, air flow, and axial loading compensation. Figure 9-2 shows the scatter that resulted during the test sequence.

Table 9-1. Test Loading (to failure) Sequence

Test Condition					Test Data							FEA Data						
					Axial Strain		Circumferential Strain					Axial Strain		Circumferential Strain				
Record	Point	Axial Load [lb]	Torque Load [in-lb]	Pressure [psi]	Upr	Lwr	Aft1	Aft2	Mid	Fwd1	Fwd2	Upr	Lwr	Aft1	Aft2	Mid	Fwd1	Fwd2
5	0	-27	118	1	-503	-418	446	483	121	539	416	-2243	-2549	2314	2190	982	1469	2245
8	1	5647	4166	23	-33	14	161	151	144	159	158	-53	-12	166	218	88	64	42
10	2	11375	8466	44	-141	-94	182	187	251	253	233	-112	-28	337	442	173	127	84
12	3	15380	12637	45	-334	-213	213	204	285	376	286	-179	-62	472	615	199	153	110
15	4	27380	25021	46	-682	-378	532	428	448	656	609	-384	-165	877	1134	274	228	188
17	5	43376	41673	45	-1011	-555	888	653	590	924	947	-662	-307	1419	1830	368	325	290
19	6	59363	59408	45	-1503	-940	1305	870	519	1096	1177	-939	-447	1960	2523	465	424	393
20	7	65848	66902	46	-1798	-1244	1891	1291	477	1179	1292	-1049	-502	2178	2804	506	465	435

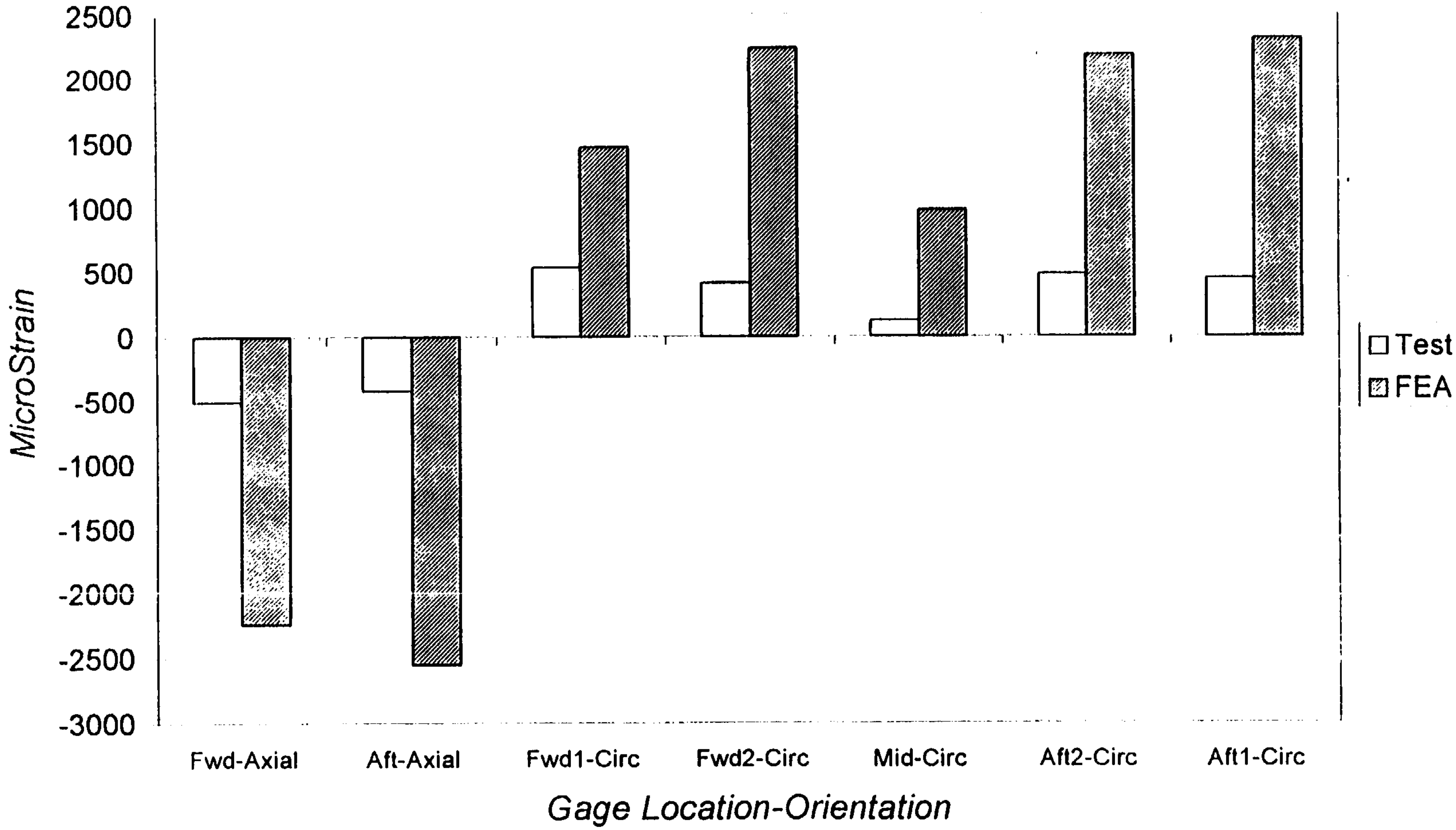

Figure 9-1. Thermally Induced Strain Comparison

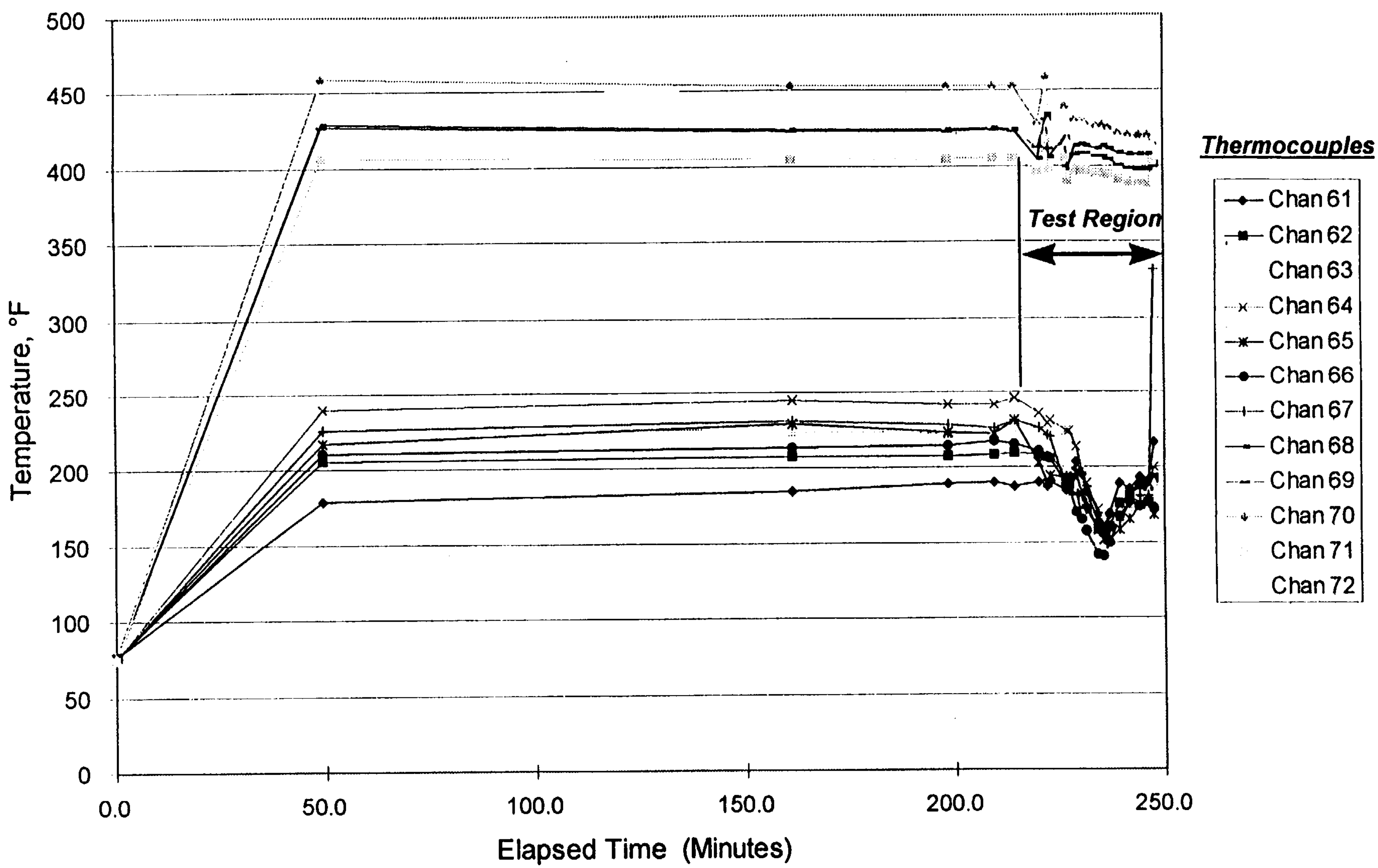

Figure 9-2. Environmental Temperature Control

Figure 9-3 depicts the axial strains induced solely by structural loads (neglecting the thermal loading). This plot indicates that the predicted structurally induced axial strains differ from the measured (corrected) values, on the average, by a factor of 2. Due to the high proportion of circumferentially oriented fiber in this structure, this axial deformation is more dependent on the behavior of the matrix than the circumferential deformation. Therefore, since the matrix properties are not as well defined, it is expected (and verified in Figures 9-3 through 9-5) that there will be more deviation between the predicted and measured axial strain than between the circumferential strains. Figure 9-3 also exemplifies the primary problem associated with using room temperature laminate properties to predict elevated temperature performance. As anticipated, the measured strains are higher than predicted. This is an expected result of the softening of the matrix at elevated temperatures. Additionally, if the "typical" epoxy resin modeled tends to be stiffer than AFR-700B, this will also explain some of the axial strain deviation.

The linearity of the material systems is also a simplifying assumption that affects the analytical results. In particular, the rate of shear load transfer between various parts of the structure are highly dependent on the stress-strain behavior of the adhesive. Without modeling accurately this nonlinear behavior of the film adhesive at the equilibrium temperature, it is difficult to predict stresses at the "free edges" of the structural components. In particular, it appears that load is transferred from the end fittings to the skin over a very short distance. This results in high localized stresses at either side of each end fitting in the fittings, skins, and film adhesive. These stresses may or may not be a real concern depending on the nonlinear behavior of the adhesive joints. Past experience indicates that these local stresses tend to be significantly lower than the predicted (linear) levels. The fiber reinforced materials tend to behave more linearly through failure. Therefore, the small degree of non-linearity in the behavior of these materials is negligible.

Finally, there is also some discrepancies apparent in the correlation that indicates that the finite element representation of the bolted joints could be improved. In particular, as evident in Figure 9-3, the finite element analysis indicates that the bending induced in the wall occurs primarily at the aft end of the fitting. The test data, however, indicates that the bending is present to approximately the same extent at each end. In fact, by averaging the FEA circumferential strains and comparing these to the average measured circumferential strains (see Figure 9-4) it is apparent that the overall structurally induced circumferential deformation prediction is very accurate. This is also evident in the mid-cylinder gauges depicted in Figure 9-3 (Symbol "X"). The result of this concentration of bending at the aft end is exaggerated lamina stresses at the inboard edge of the aft end fitting. It is in this region that the relatively low margins of safety (3-4) in the inner and outer carbon plies are predicted. If this bending deformation is averaged between both end fittings, the limiting stress becomes the 7.2 margin of safety in the inner skin glass plies. Since the peak stress in the inner glass layer occurs at another discontinuity introduced by the simplified modeling approach, it is also conservative.

The primary problem with the modeling of the bolted joints is that they are assumed to be a continuous structure. As shown in Figure 8-3, the axial stress in the inner skin is greatly exaggerated by the bending of the forward plate being entirely reacted by the inner skin. This is the most extreme effect of this modeling

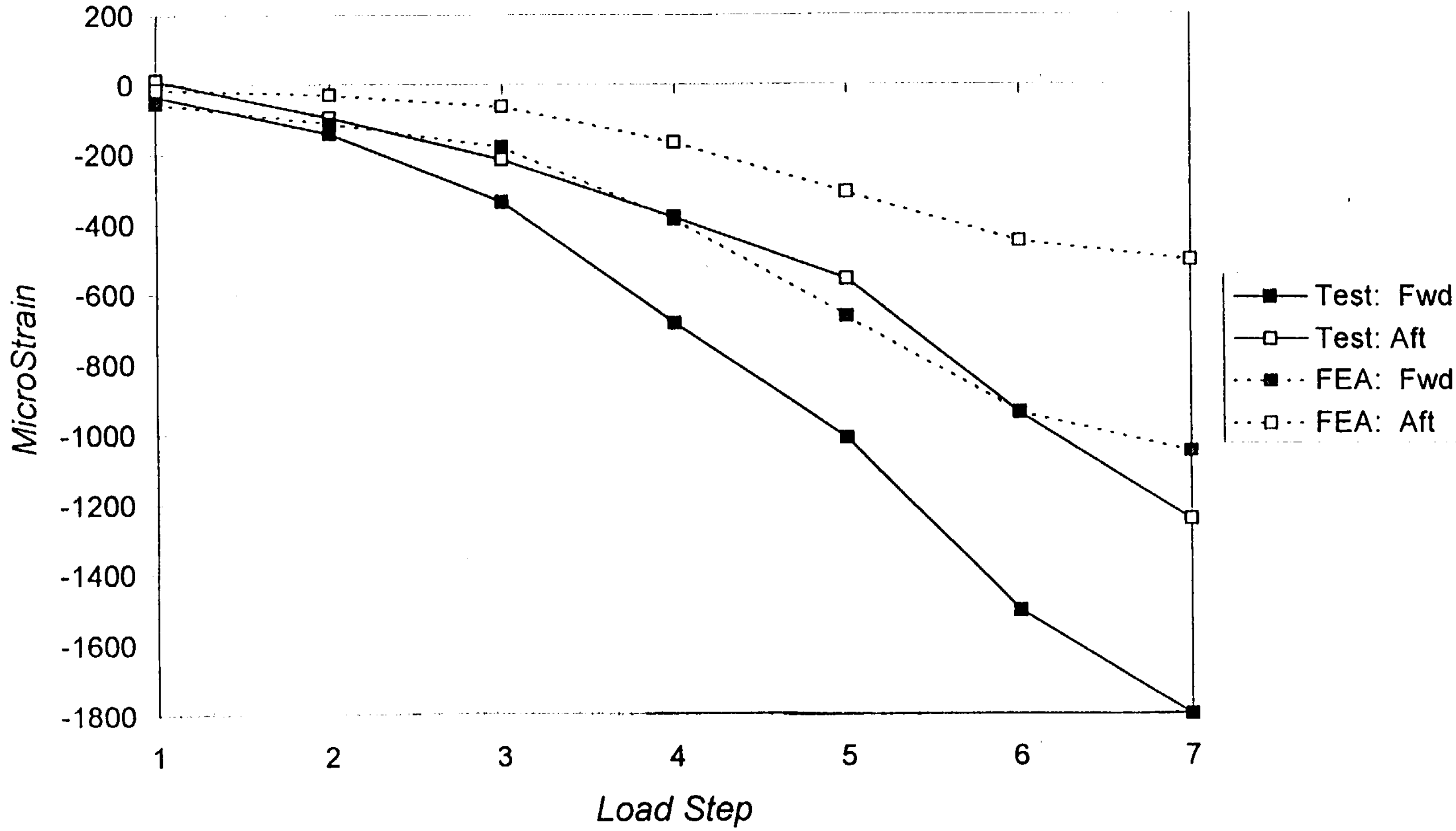

Figure 9-3. Axial Strain Comparison

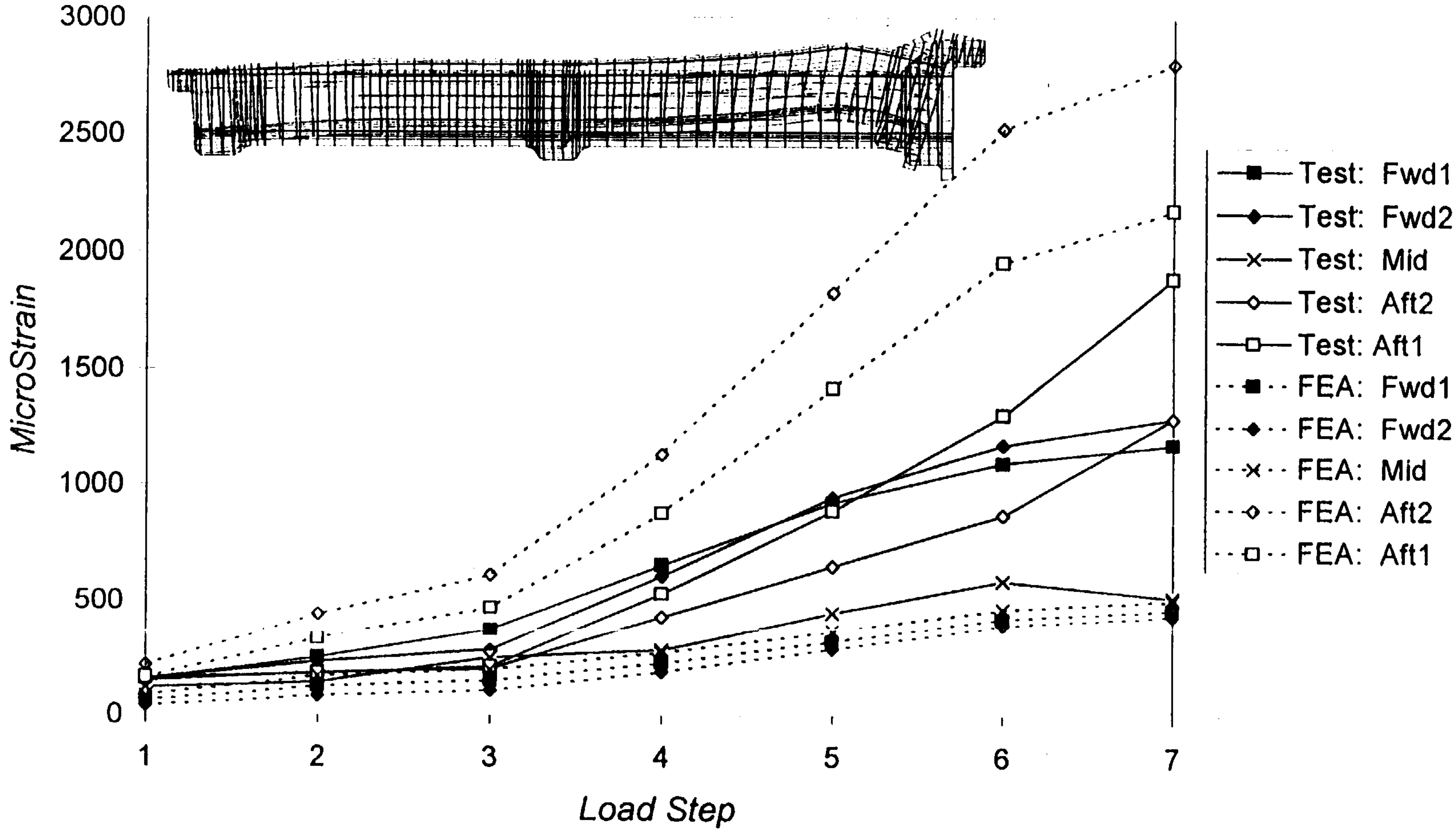

Figure 9-4. Circumferential Strain Comparison

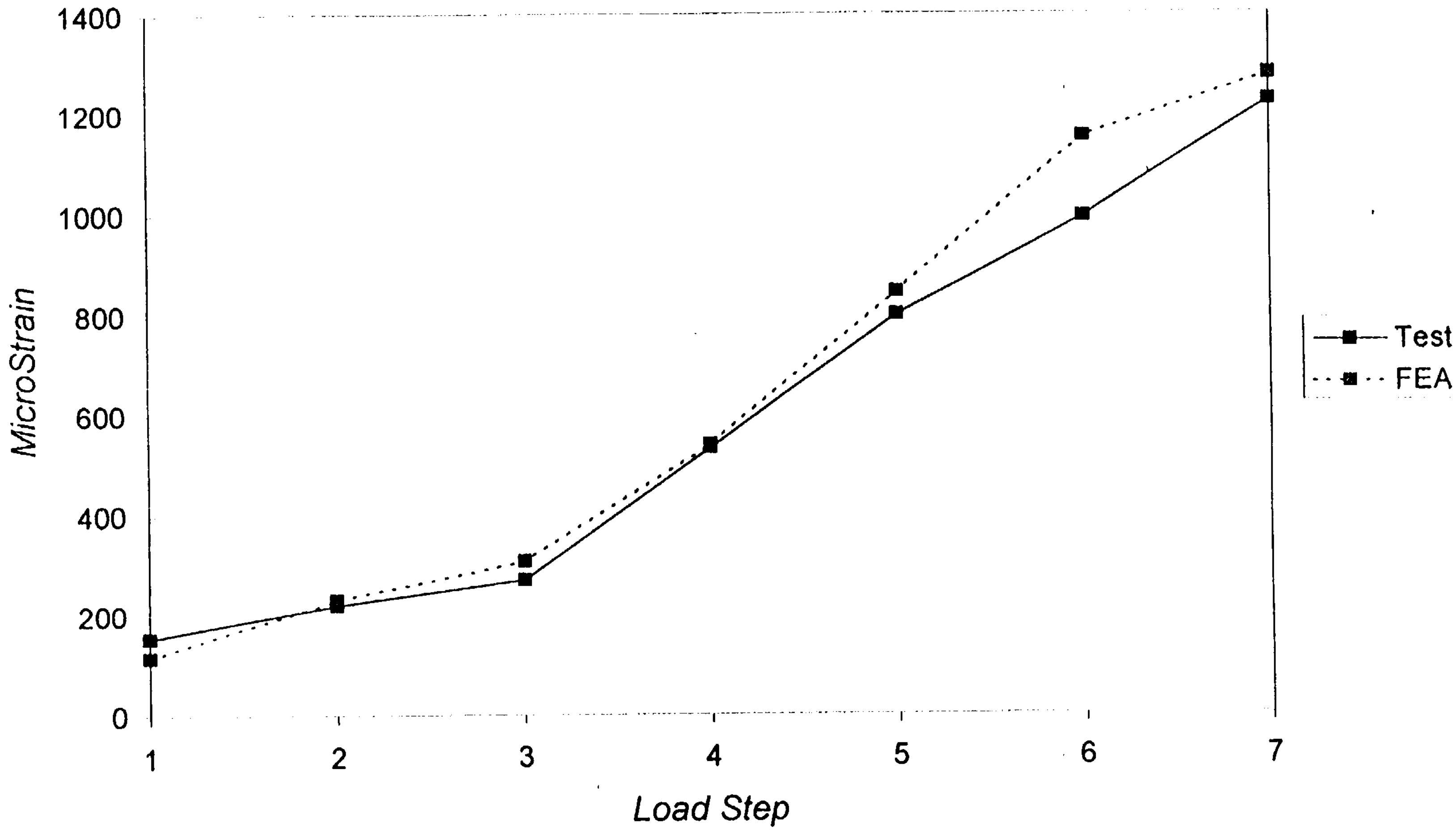

Figure 9-5. Average Circumferential Strain Comparison

simplification and most likely the cause of the previously discussed skewed bending. Both the tension and compression portion of this load couple occur on the inner skin. In real life, the tension portion of this couple must be transferred through the center of the bolt. This will increase (3-5X) the moment arm for reacting this bending and, therefore, will reduce both the peak compressive and peak tensile loads in that region. The continuous structure model also allows perfect heat conduction across the joint. It is recognized, and evident in the temperature deviations identified in Figure 8-4, that this results in an overstatement of the thermal distribution in the regions of the end fittings. Iterations on the contact resistance across this joint will lead to a more accurate thermal profile prediction.

10.0 CONCLUSIONS AND RECOMMENDATION

The program was successfully completed and all of the major goals were met with the exception of the engine tests.

10.1 Specific Conclusions

- Organic matrix composites are suitable for high temperature environments typical of jet engine applications.
- Static testing at elevated temperatures validated that high margins of safety are inherent with the two-skinned honeycomb structure. Particular attention needs to be paid to the joints between dissimilar materials and to characterization of thermal properties.
- Both resin systems (V-CAP and AFR-700B) performed adequately, but further testing of specimens cut from the tested carcasses would be required to rank their structural performance.
- The finite element method has proven to be a valuable tool for evaluating the response of structures to thermal and structural loads.
- The composite OMC Compressor Case presents a lower weight (25 percent) option to the existing titanium unit.

10.2 Specific Recommendations

- A molding compound for the end closures with a lower thermal coefficient of expansion should be sought.
- Improved bonding methods between the inner skin and the molded fittings should be developed. Use of a "liquid shim" in conjunction with the film adhesive is recommended.
- Improved accuracy of FEA analysis should be developed. Specifically needed:
    - Better thermal expansion and high transfer coefficiencies are needed.
    - Non-linear material properties at elevated temperatures are also required.

11.0 REFERENCES

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2. Humphrey, W.D., J. Ayorinde, T. Westerman, J.K. Sutter, and R. Allred, "OMC Compressor Case (An Update," HITEMP Conference, October 1995.

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4. Humphrey, W.D., J. Eaton, J. Ayorinde, "Filament Winding with V-CAP Resin for Composite Compressor Case," High Temple Workshop XV.

APPENDIX A

SEQUENTIAL OVERVIEW OF PROGRAM'S PROGRESS

SEQUENTIAL OVERVIEW OF PROGRAM'S PROGRESS

This appendix section summarizes the significant occurrences of the OMC Compressor Case program. Summary statements are taken from the bi-monthly reports.

WORK PERFORMED (February 1995 through December 1995)

The first item scheduled was procurement of the raw materials which included V-CAP prepreg roving on both T650-35-12K graphite with HTS finish and S-2 glass, 750 yield with 933 finish. Adherent Technology, Albuquerque, New Mexico was awarded a contract on February 14, 1995 to produce 13 pounds and 15 pounds of graphite and glass prepreg, respectively. Trial quantities (2 pounds of each reinforcement) were impregnated during the week of February 13 with representatives of NASA and Lincoln Composites assisting.

The material was delivered to the Lincoln facility where subscale parts were wound and cured to assess the prepreg's suitability for winding. The material was determined to be easy to process and approval was given to Adherent Technology to proceed with the balance of the order.

The two pound quantities of prepreg were used to wind high angle (±80°) helical patterns on a 5.75 inch cylindrical mandrel. Four cylinders were wound, all at ±80° high helical angles at thicknesses varying from 0.062 to 0.150 inches. Two specimens were wound using T650-35 fiber (one prepregged, the other wet wound) and two specimens were wound using S-2 glass (one prepregged and one wet wound).

None of the specimens had wrinkles in the laminate that normally would have been present from the loss of resin components during cure typical of hoop wound polyimide structures. This verified that the high angle helical is an acceptable processing method and that the cut-hoop technique formally used can be abandoned.

Table I summarizes data obtained from these specimens. The data shows that a high void content is present in all specimens, approximately 20 percent for prepreg and 11 percent for wet-wound laminates. The resin contents of the prepregged materials remain basically as prepregged, while the wet wound laminate retained a lower resin content than desired.

Future in-house studies were scheduled to determine techniques to reduce the void volume while maintaining the resin content. NASA-Lewis provided a suggested cure/pressure cycle that has been successfully used in high-pressure, press cured laminates. Lincoln Composites attempted to modify this cure cycle for filament wound laminates and 200 psig pressure cycles.

The new molding compound (QC-126-54-4) was evaluated by molding a trial end closure. The flow properties of the compound were not completely satisfactory. Based on insufficient flow properties being obtained, Lincoln Composites subcontracted with Quantum Composites to perform the molding operation at their facility. This work included molding and testing specimens to provide the material properties required for the finite element analysis.

Table I. Wound Tube Data, 80° Helical/V-CAP Resin Process Improvement Studies

Sample S/N	Description	B.W./ No. Spools	No. of Layers	Thick (inch)	%Resin (by wt.)	% Fiber (by vol.)	%Voids (by wt.)
001	Graphite Prepreg	0.240-2	4	0.105	38.1	46.0	18.7
002	S-2 Glass Prepreg	0.200-2	4	0.091	33.5	41.9	21.9
003	S-2 Glass Wet Wound	0.200-2	4	0.062	13.6	70.3	10.8
004	Graphite Wet Wound	0.167-1	6	0.093	29.4	58.0	11.9

Area Glass = 4.15 x 10^{-4} (solve for K)

Where:

$$t\ comp = \frac{No.\ Plies\ x\ No.\ Spools\ x\ Area\ /\ Spool\ x\ Bulk\ Factor\ (K)}{Bandwidth}$$

% Voids

$$SN\ 002 = 0.091 = \frac{2\ x\ 2\ x\ 4\ x\ 4.15\ x\ 10^{-4}\ x\ K}{0.200} \qquad K = \frac{0.091\ x\ 0.200}{66.4\ x\ 10^{-4}} = 2.7\ (prepreg)$$ 21.9

$$SN\ 003 = 0.062 = \frac{2\ x\ 2\ x\ 4\ x\ 4.15\ x\ 10^{-4}\ x\ K}{0.200} \qquad K = \frac{0.062}{0.091}(2.7) = 1.84\ (wet)$$ 10.8

Area Graphite = 6.93 x 10^{-4} (solve for K)

$$SN\ 001 = 0.105 = \frac{2\ x\ 2\ x\ 4\ x\ 6.93\ x\ 10^{-4}\ x\ K}{0.240} \qquad K = \frac{0.105\ x\ 0.240}{110.9} = 2.27\ (prepreg)$$ 18.7

$$SN\ 004 = 0.093 = \frac{2\ x\ 1\ x\ 6\ x\ 6.93\ x\ 10^{-4}\ x\ K}{0.167} \qquad K = \frac{0.093\ x\ 0.167}{83.16} = 1.87\ (wet)$$ 11.9

At Allied Signal, the follow-on work was underway. An improved design was completed by Allied Signal to simplify the through-the-wall penetrations. The larger ports were eliminated, thereby reducing the total number of penetrations from four to two. This helped simplify the machining operation as well as reduce the weight of the molded interface members.

Preliminary drawings were prepared by Allied Signal showing the critical dimensions of the part interfacing with existing mating components in the PT-210 engine. These drawings and expected loads were used by Lincoln Composites in completing the design of composite skins.

Responsibility for finite element analysis (FEA) was assumed by Lincoln Composites since existing modeling tools and material subroutines were readily available.

Critical Design Review -- (July 25 and 26, 1995)

An extensive, detailed review of the program's status was presented by Lincoln Composites and Allied Signal's personnel. This included a FEA analysis of the compressor case. The design was accepted as presented and the following action items were assigned and outstanding questions resolved.

1. Prepreg Status: It was noted in the meeting that the second lot of prepreg received from Adherent Technologies appeared drier than the previous lot which was used for the process improvement work. Also, the resin content and the range in resin content were greater than the initial lot. This data is summarized in Table II for all roving using the revised step cure developed by NASA. Lincoln Composites was directed to document those differences to Adherent Technology.

2. Finite Element: A paper was assigned to Mike Case of Lincoln Composites at the HITEMP review describing the analysis as presented at the CDR.

3. Testing: Allied Signal presented test plans and showed schematics of rig test fixtures. It was noted that the rig test would be performed in August/September, but the engine tests could not be performed until mid-1996. This was predicated on successful passing of the rig test.

Immediately following the CDR, the inner skin assembly (glass and graphite) was cured and tapers machined for bonding of the molded end fittings.

Tests were performed on the trimmed sections and it was determined that the void content and shear strengths were not acceptable. Work on the units was put on hold while the prepreg was studied. Wound and press-cured laminates using the second lot of prepreg were fabricated and tested and found to have void contents of 16 to 22 percent and shear strengths near 2600 psi. Both values are fractions of the properties measured for the initial roving lot (see Table II).

The prepreg supplier was contacted and it was agreed that replacement materials would be provided. Rewinding of the inner skin commenced immediately after receipt of the new material. In the meantime, further tests were performed at Lincoln Composites to determine if there was any way to salvage the prepreg.

Table II. Summary of Roving, Lot I vs. Lot II

Roving Samples	% Voids NASA Cure 200 psi	% Voids NASA Cure 500 psi	Short Beam Shear NASA Cure 200 psi	Short Beam Shear NASA Cure 500 psi
Lot I (April delivery):				
1. 80° Winding – Flatten for Press Cure (glass)	0.17 - 6.81	0.14 - 0.27	10,700	11,503
Lot II (July delivery):				
1. 80° Trim for Inner Skin Flattened for Press Cure (glass)	16.3	---	2,600	---
2. 90° Mat Flattened for Press Cure (glass and graphite)	22.3 (glass)	---	6,450 (glass)	---
	16.0 (graphite)	---	6,500 (graphite)	---

S/N 001 (Rejected by Lincoln Composites)

The replacement prepreg was received and the first unit was fabricated during September 1995. During machining of the I.D. surfaces to meet Allied Signal's Drawing No. TE 39917, it was found that the mid-thickness of the laminate was poorly bonded and that the prepreg roving was intermittently too dry and porous. The laminate, in all probability, would not hold the 45 psi internal air pressure expected during static test (i.e. leakage could be expected through the laminate).

Two changes had occurred between this unit and the previous contract; 1) pre-impregnated roving was used, where earlier units were wet-wound, and 2) the inner skin glass thickness was increased from 0.150 to 0.250 inch.

Wet winding, although somewhat messy and less efficient with respect to resin usage (high wastage in resin bath), does succeed in putting excess resin where its needed in the part. Therefore, wet winding will produce a resin rich part which is highly desirable when machining is required. The prepreg roving used in this program was difficult to uniformly impregnate and the solvent (methanol) was difficult to keep at a constant level suitable for filament winding to allow easy removal from the spool.

The second problem was due to the increased thickness. Trial winds at 0.150 inch thickness on a 5.5 inch mandrel with the first batch of prepreg produced high quality parts free of the above problems. The need for increased thickness resulted from a design change required by Allied Signal to increase the diameter of the bolt circle to fit the interfaces required for engine testing. Quality thick laminates have always been a problem when using condensation curing polyimide matrices. Its much easier to produce low void laminates using flat panels (with all fibers cut) than with wound parts with continuous fiber paths. However, both require very high pressures for consolidation.

Corrective Actions

Lincoln Composites proposed the following corrective actions to rectify the above mentioned problems.

1. Tooling changes to eliminate machined surfaces.
2. Returning to wet-winding.
3. Slightly larger diameter mandrel.

Specifically, these actions called for the following changes. A segmented (three piece mandrel) to provide the finished inside contours without any machining would be designed and procured. This tooling concept would prevent potential leakage as well as decrease the glass laminate thickness to a minimum. Also, a thick gel coat backed up with glass cloth would provide the inner glass "barrier". Wet winding and wet impregnation of the cloth would be used to maximize the resin content of the inner laminate to preclude gas leakage. This entire subassembly would be autoclave cured prior to proceeding to graphite layers. The above corrective actions were adopted and a revised budget prepared.

WORK PERFORMED (January 1996 through October 1996)

Receipt and Inspection of Tooling

The new segmented mandrel (SK 92303) was fabricated, received, and inspected. The tool met drawing requirements and was accepted for inner skin fabrication studies to be performed under Lincoln Composites' internal research funds.

First Trial Epoxy Part

Trial winding and gel coat development work was funded by Lincoln Composites' IR&D program. Details are included in Appendix B. The first trial unit consisted of a gel coat, glass cloth lay-up, and filament winding with S-glass (wet winding). Its purpose was to evaluate the tool, its ability to be removed internally, and to assess the quality of the inside "molded" surface produced by the new tool.

Initial attempts to remove the tool were unsuccessful and the glass overwrap had to be mechanically machined off the tool. It was determined that the epoxy resin (LRF-0092) had run into the tools' various segments and bonded them together, thus preventing removal.

A corrective action was suggested, which called for coating all segmented joints with an RTV rubber (GE #102) prior to assembly. This RTV layer would serve as a barrier to prevent the low viscosity resin from running into the joints.

Second Trial Epoxy Part

The second epoxy part incorporated the RTV rubber concept which proved to be very successful. The unit consisted of gel coat, glass cloth, and wet-wound glass roving. In addition, the T650-35 graphite inner skin sequence was over wound and co-cured with the glass. For simplicity, all layers were wound using a ±80° helical pattern [except the o-ring groove which required hoop (90°) windings].

The part was easily removed from the tool and the inside surface was found to be of high quality, fully suitable for its intended end usage.

Mixing of V-CAP Resin at Lincoln Facility

Jim Sutter of NASA visited the Lincoln facility during the first week of March 1996 to supervise the formulation of methanol solutions of V-CAP-75. Two different monomer solid contents were prepared at 77.6 and 75 percent for a total of 10 pounds of mixed resin.

First Trial V-CAP Inner Skin Assembly

The first V-CAP inner skin was fabricated during May/June 1996 to evaluate a 700°F temperature on the segmented tooling. The earlier epoxy evaluations were limited to 300°F cure temperature. Again these investigations were funded under Lincoln Composites' IR&D program (see Appendix B for details).

Several problems occurred with the V-CAP inner skin assembly that may have been caused by a malfunction of the autoclave. It was determined in a post test evaluation that the left bank of heating elements had shorted out and the mandrel assembly was not heated evenly. A second occurrence was the usage of improper thermocouples, which malfunctioned at the high temperature. As a result of the incorrect thermocouple readings, the 200 psi autoclave pressure may have been applied too late to fully consolidate the part.

As a result of the above cure problems:

1. The I.D. of the part was considerably out of round (T.I.R. - 0.149).
2. The interface between glass and graphite delaminated making the part unusable.
3. The cured part was very difficult to remove from the segmented mandrel due to the T.I.R. problem.

Corrective actions were:

1. Replace defective autoclave heating elements.
2. Specify proper high temperature thermocouples in detailed cure instructions.
3. Modify cure processing to fully cure the glass inner skin prior to the graphite overwrap. It was believed this change would minimize the chance of delaminations by minimizing the CTE mismatch between uncured glass/graphite.

Fabrication and Delivery of OMC Compressor Case

The corrective actions noted above were implemented and resulted in the successful fabrication of the OMC Compressor Case. Significant events follow:

1. The hybrid inner skin with V-CAP resin and glass/graphite layers was manufactured free of any defects. It was sound without any delaminations, was dimensionally very good with only minor dimensional variations (T.I.R. of less than 0.014 inch), and inside diameters at the seal locations within 0.006 inch of the program's goal.

2. Resin burnouts were performed on the hybrid inner skin fabricated using V-CAP resin. Results are as follows:

E-Glass Portion	
Resin (by weight)	19.32%
Fiber Volume	59.64%
Void Volume	14.97%
Graphite Portion	
Resin (by weight)	24.84%
Fiber Volume	59.18%
Void Volume	15.68%

The resin content by weight and the fiber content by volume were about as expected; however, the void volumes were disappointingly high. The void content was determined to be primarily occurring in macro voids between cross-overs of plies in the helical patterns (±80° glass and ±20° graphite). Generally with the epoxies, the low viscosity resin fills these macro voids; however, the higher flow viscosity of the polyimides inhibits the outward migration of resin into the unfilled spaces between bridged fibers.

Additionally, the samples were taken from the trim edges of the part where the degree of macro voids are more extreme due to pattern reversals and bridging. A sample taken in the middle of the unit would be expected to show less voids. Following mechanical testing, it may be worthwhile to evaluate void content in the middle of the part.

3. All other construction features (i.e. imide ester mold end rings, high temperature film adhesive honeycomb core, and the epoxy/graphite outer skin) were implemented into the unit with no problems.

4. Strain gauges were installed and the part sent to Allied Signal on August 27, 1996 for testing.

Static Test Results (Quick Look)

The V-CAP Compressor Case successfully passed ultimate loads (50 percent higher than design) without damage. Originally it was intended to load the compressor case to failure; however, due to limited capability of axial loading, this was not possible due to limitations of the test fixture.

1. Test Plan (Allied Signal)

   The test plan used to evaluate the compressor case is included as Appendix C to this report.

2. Test Results

   A data disk with strain gauges and thermocouple records was received from Allied Signal. This data would be reduced and included in the updated FEA analysis.

   The test log is shown in Figure 1 which shows the loading sequence. Prior to testing, two digital deflection gauges were applied (one longitudinal and the other tangential). Unfortunately, these gauges did not function at 150°F and the data was lost.

   The case was successfully tested to limit loads while pressurized to 45 psi without incident. Next, it was tested to ultimate load (50 percent higher) without any pressurization. It was necessary to omit internal pressurization in order to meet the axial loading requirements. Testing was terminated due to equipment limitations (axial loading capacity).

   Post test examination showed the unit had survived without damage with only minor discoloration of the molded end closure at the aft 0.250 inch slot. The unit was returned to Lincoln Composites for examination. Precise dimensional inspections verified that the part's length and diameters were unchanged.

Time	Remark	Record No.
12:05	Establish Thermal Equilibrium	08, 09
12:10	Zero Out Gauges	10
12:15	Apply Preload – "Fit Check:" 100 lbs. axial load (8000 limit) 25 in-lbs torque $\delta_1 = 0.0715$, $\delta_2 = 0.200$	11
12:25	Apply 0.5 Limit Load* 5710 lbs. axial load 22.5 psi 560 in-lbs torque	12, 13
12:30	Unload	14
12:42	Apply Full Limit Load 11420 lbs. axial load 45 psi 1120 in-lbs torque	15, 16
12:45	Unload	17
12:47	Pre-Loading	18, 19
1:00	Apply 0.5 Limit Load	20
1:01	Apply Limit Load	21
1:03	Apply Ultimate Load** 12000 lbs. axial load 12600 in-lbs torque	22, 23
1:04	Unload	24

*Compressive load is increased to offset the pressure inside the case in order to meet appropriate net axial loading requirement (5710 pounds applied = 4000 pounds net).

**Pressure omitted in order to meet axial loading requirement due to fixturing limitations.

Figure 1. V-CAP Compressor Case Static Load Testing Test Log

APPENDIX B

IR&D TASK

DDM 543

DESIGN AND DEVELOPMENT MEMO

Develop High Temperature Gel Coat Barrier/Structure

January 22, 1997

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Prepared by:

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Abstract:

Developed technology for fabricating a V-CAP/fiber reinforced gel coat fiber reinforced barrier structure. Used new segmented mandrel for lay-up over complex contour. Establish preferred method with epoxy, then verified with the V-CAP resin system.

Descriptors:

Gel Coat, LRF-0092, RTV Rubber, Segmented Mandrel, Spring Back, T.I.R, V-CAP Resin

THIS WORK WAS COMPLETED UNDER 46002

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1.0 INTRODUCTION

Earlier activities using V-CAP resin in cylindrical structures employed prepreg roving in order to minimize winding time and to guarantee the desired resin content. Unfortunately, the pre-impregnated process of V-CAP resin proved to be unsatisfactory. The roving differed from batch-to-batch particularly in tackiness and in the amount of solvent remaining in the prepreg material.

It was obvious by examining the inside surface of the test article, which had been machined after cure, that the resin did not flow adequately. Dry unbond areas and loose fibers were common on the newly machined surface. The quality of the part was not satisfactory, so Lincoln Composites elected to stop work at that time and redirect these activities.

Continued development work with the V-CAP resin would be performed using a wet winding method and employing a new molded inside surfaces rather than machined. This IR&D effort attempted to implement this technology using newly designed segmented tooling (wind mandrel) to produce a high quality V-CAP cylinder.

2.0 APPROACH

Obtain a new segmented mandrel and prepare wind disks. Lay-up glass reinforced gel coat using epoxy resin. Experiment with various lay-ups/materials, then over wind with epoxy/E-glass and B-stage/cure.

Evaluate cured part and select preferred method for use with the V-CAP resin system. Lay-up/wind inner gel coat barrier assembly with wet wound V-CAP resin. Imidize, cure, and inspect part for suitability as barrier structure.

3.0 RESULTS

3.1 First Trial Epoxy Part

The first trial unit consisted of a gel coat, glass cloth lay-up, and filament winding with S-glass (wet winding). Its purpose was to evaluate the tool, its ability to be removed internally, and to assess the quality of the inside "molded" surface produced by the new tool.

Attempts to internally remove the tool were unsuccessful and the glass overwrap had to be mechanically machined off the tool. It was determined that the epoxy resin (LRF-0092) had ran into the tool's various segments and bonded them together thus preventing removal.

A corrective action was suggested, which called for coating all segmented joints with an RTV rubber (GE - #102) prior to assembling. This RTV layer would serve as a barrier to prevent the low viscosity resin from running into the joints. In addition, the RTV will not bond to other substrates or materials.

3.2 Second Trial Epoxy Part

The second epoxy part incorporated the RTV rubber concept, which proved to be very successful. The unit consisted of the same glass cloth, gel coat, and wet-wound glass cloth sequences. In addition, the T650-35 graphite inner skin sequence was wound and co-cured with the glass. For simplicity of manufacture, all layers were wound using a ±80 degree helical pattern [except the O-ring grooves, which required hoop (90 degree) winds].

Table 3.2-1 summarizes the dimensions of the second epoxy part. Figure 3.2-1 shows locations of these measurements. The total run-out (T.I.R) was only 0.002 to 0.003 inches.

3.3 First Trial V-CAP Part

The first V-CAP inner skin was fabricated during May/June 1996 to evaluate a 700°F cure on the segmented tooling. The earlier epoxy evaluations were limited to a 300°F cure temperature. All of these investigations were funded under Lincoln Composites' IR&D program.

Several problems occurred with the V-CAP inner skin assembly that may have been cause by a malfunction of the autoclave. It was determined in a post test evaluation that the left bank of heating elements had shorted out and the mandrel assembly was not heated evenly. A second problem was the usage of improper thermocouples, which malfunctioned at the high temperature. As a result of the incorrect thermocouple readings, the 200 psi autoclave pressure may have been applied too late to consolidate the part properly.

As a result of the above cure problems:

1. The I.D. of the part was way out of round (T.I.R. - 0.149).
2. The interface between glass and graphite was delaminated to the point the part was unusable.
3. The cured part was very difficult to remove from the segmented mandrel, due to the T.I.R. problem.

Corrective actions were:

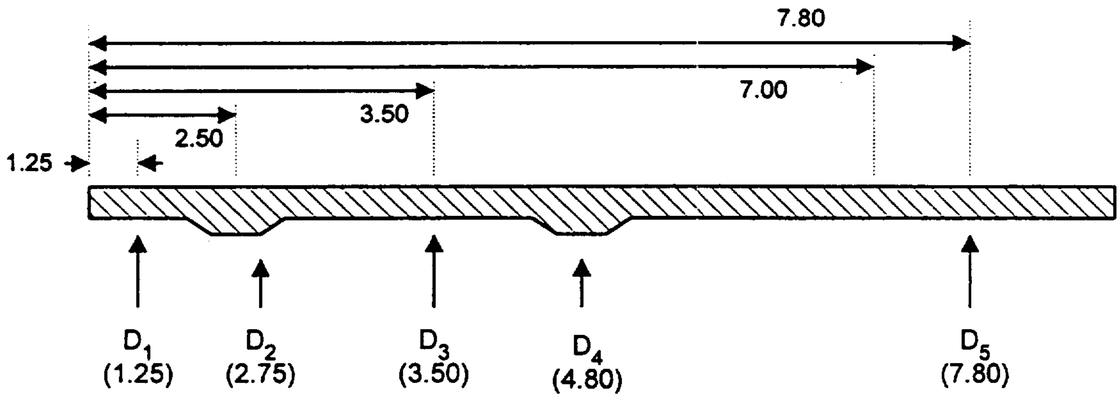
1. Replace defective autoclave heating elements.
2. Specify proper high temperature thermocouples in detailed cure instructions.
3. Modify cure processing to cure the glass inner skin prior to winding and curing the graphite overwrap. It is believed this change will minimize the chance of delamination by eliminating the CTE mismatch between uncured glass/graphite.

3.4 OMC Compressor Case (reference only)

The above corrective action items were implemented into the next inner skin assembly, which was funded by NASA, and was manufactured free of any defects. It had no delaminations, was dimensionally very good with only minor dimensional variations, T.I.R. of less than 0.015 inch and inside diameters at the seal locations within 0.006 inch of program goals. This data is summarized in Table 3.4-1. The calculated spring back (+0.024 inch) agreed very well with the actual part (+0.027 to 0.030 inch). This subassembly was used to manufacture the OMC Compressor Case which has subsequently passed ultimate load and temperature testing at Allied Signal.

Table 3.2-1. Spring Back – Inner Skin Assembly, Epoxy Part

Location	Tool	Part Average	Spring Back Diameter	Spring Back Radius	Drawing Requirements	Δ Diameter	T.I.R.
D_1	9.986	9.994	+0.008	+0.0040	10.01	+0.007	0.003
D_2	9.817	9.824	+0.007	+0.0035	9.84	+0.017	0.003
D_3	9.986	9.994	+0.008	+0.0040	10.01	+0.007	0.002
D_4	9.747	9.754	+0.010	+0.0050	9.77	+0.017	0.002
D_5	9.986	9.991	+0.005	+0.0025	10.01	+0.010	0.003



*Measured four places at each location. Select maximum and minimum positions.

Figure 3.2-1. Measurement Locations* I.D. of Inner Skin, Typical V-CAP and Epoxy

Table 3.4-1. Spring Back – Inner Skin Assembly, V-CAP Part

Location*	Tool	Part Average	Spring Back Diameter**	Spring Back Radius	Drawing Requirements	Δ Diameter	T.I.R.
D_1	9.986	10.016	+0.030	+0.0150	10.010	+0.015	0.010
D_2	9.817	9.844	+0.027	+0.0135	9.841	-0.003	0.014
D_3	9.986	10.016	+0.030	+0.0150	10.010	+0.015	0.008
D_4	9.747	9.777	+0.030	+0.0150	9.771	-0.006	0.007
D_5	9.986	10.015	+0.029	+0.0150	10.010	+0.014	0.008

*Locations per Figure 3.2-1.
**Tooling designed for +0.024 diameter growth (spring out) from cure.

4.0 CONCLUSIONS/RECOMMENDATIONS

Manufacturing techniques were developed that led to the successful manufacture of the hybrid (glass/graphite) inner skin using the high temperature V-CAP resin. Some lessons learned:

1. Use RTV rubber as a means of preventing resin migration into the joints of the segmented tooling.
2. Lab autoclave should be scheduled for periodic calibration and maintenance checks.
3. Upgrade processing to include more detail such as type cf thermocouples to be used. Do not make unnecessary assumptions.
4. Take all available steps to minimize CTE mismatches such as completely curing an inner skin sequence prior to overwrapping with a different reinforcement material.
5. Even though there was no visible delaminations within the part, the void content result was uncharacteristically high.

APPENDIX C

ALLIED SIGNAL'S TEST PLAN

ALLIEDSIGNAL TEST PLAN
VCAP COMPRESSOR CASE

Introduction

This documents presents the plan for testing the VCAP compressor case constructed under NASA NRA Contract NAS3-27442. The component was fabricated by Lincoln Composites and will be tested by AlliedSignal Engines (AE). This program was initiated in order to demonstrate the feasibility of organic matrix composites for high temperature (500F) environments typical of jet engine usage.

Purpose

The objective of this test is to prove the limit load and 1.5x ultimate capability of the VCAP compressor case as defined by Lincoln Composites. Based on the results of this testing, a failure load will be established.

The limit loads are 45PSI internal, 8000 lbs compressive and 8400 in-lbs of torque at an internal temperature of 450F and an external temperature of 150F. A test rig has been designed that will apply these loads in a linear fashion to reach the above combined limit loads.

Two deflection indicators must be added, one in line with the compressive load cell and one in line with the torque cable to measure any permanent hysteresis.

Construction Details

The compressor case is an axisymmetric sandwich construction consisting of filament wound composite inner and outer skins separated by a light-weight composite core. The inner skin is constructed of a layer if S-2 Glass/VCAP and 3 layers of graphite/VCAP. The outer skin is comprised of two layers of graphite/epoxy (LRF-0543). The core is a fiberglass reinforced polyimide honeycomb construction. The forward and aft flanges of the case are constructed of vinyl ester sheet molding compound. The skins, core and flanges are bonded together with a modified BMI film adhesive (EA 9673) at the inner skin and a high temperature (350F) epoxy film adhesive at the outer skin.

Design Requirements

Structurally, the compressor case is subjected to an 8000 lb compressive axial load in conjunction with an 8400 in-lb torsional load and an internal pressure of 45 psi. The compressor case operates in an environment which results in an internal gas temperature of 450F and an external gas temperature of 150F. Energy is assumed to be transferred from the surrounding gas to the structure primarily through convection.

Instrumentation

There are 14 strain gages and 11 thermocouples to be monitored throughout the test.

Test Procedure

Limit load verification test procedure:

1. Establish thermal equilibrium throughout the test part and outside fixturing. This may take 3-4 hrs. Record thermocoulple (TC) values every 15 minutes until successive TC measurements are within 10 degree F of the prior value.

2. Zero out strain gages and deflection indicators

3. Apply 1/2 the limit load vector slowly (4000 lbs net axial compression thru case, 22.5 PSI pressure and 4200 in-lbs of torque). Record strains, TC's and deflections.

4. Unload part and record strains, TC's and deflections. Note any hysteresis in deflections. If so, repeat steps 2 thru 4.

5. Load to 1/2 limit load. Record strains, TC's and deflections.

6. Apply full limit load (8000 lbs net axial force, 45 PSI pressure and 8400 in-lbs of torque. Record strains, TC's and deflections.

7. Remain at load for 30 minutes. Record strains, TC's and deflections.

8. Unload part and record strains, TC's and deflections. Note any hysteresis.

9. Load part to 50% limit load. Record strains, TC's and deflections.

10. Increase load to full limit load. Record strains, TC's and deflections.

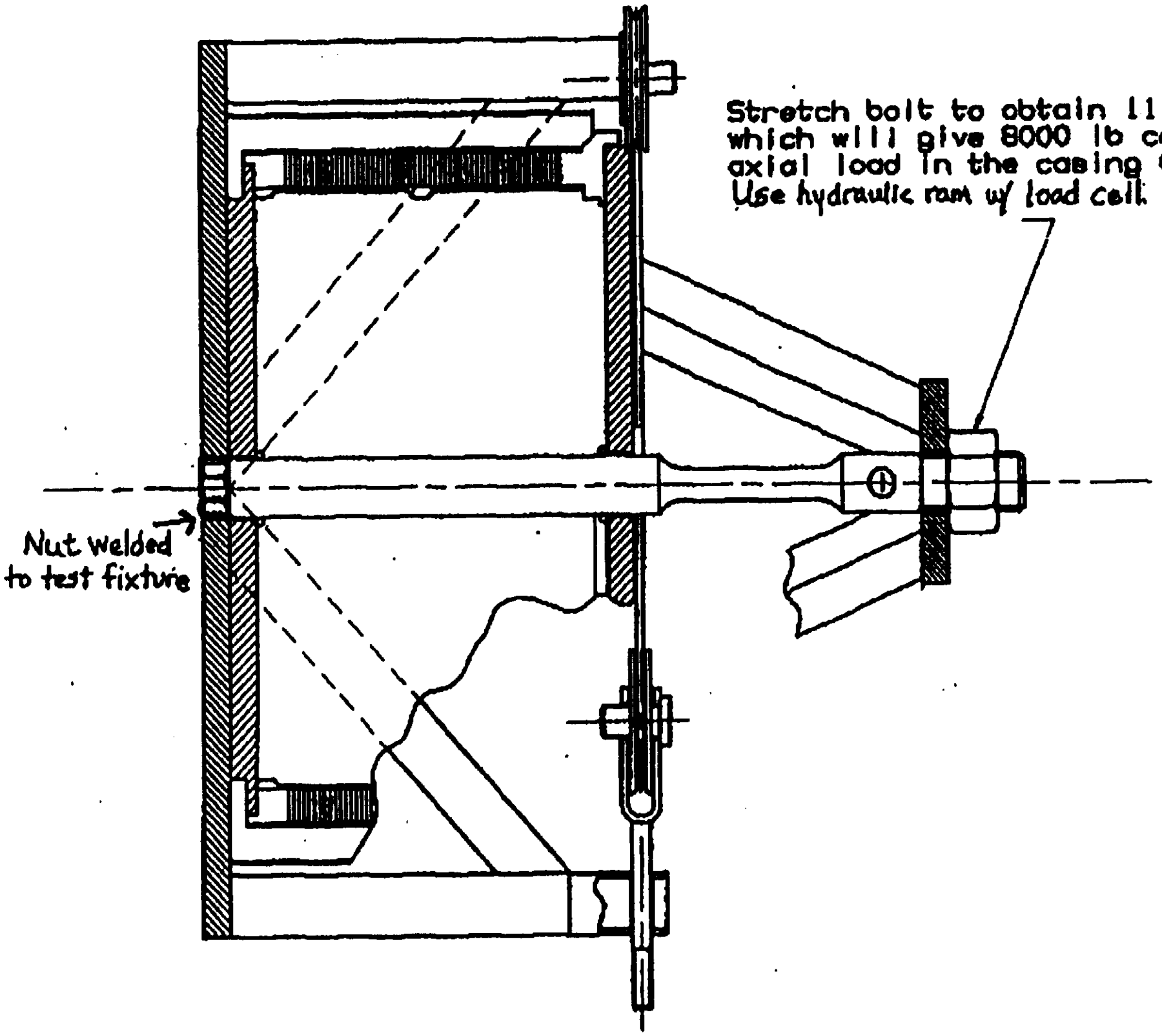
11. Increase load to full ultimate (12000 lbs net axial, 67.5 PSI pressure and 12,600 in-lbs of torque). Record strains, TC's and deflections.

12. Increase load at TBD increments to failure. Record strains, TC's and deflections at each stopping point.

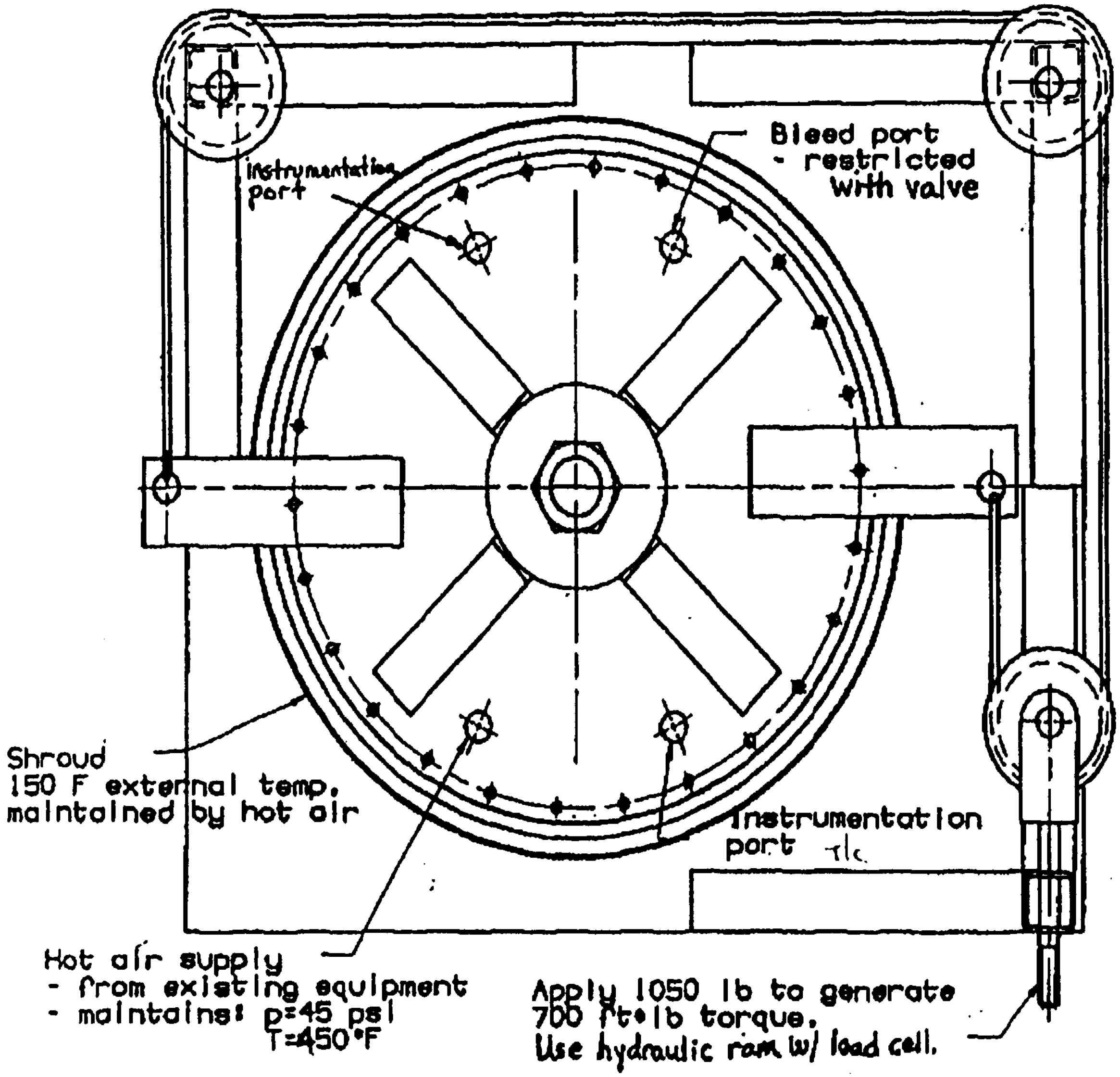
Status

Test fixture (see attached figures) is complete and case has been assembled for testing. AE is ready to test and targeted date for testing is Tuesday October 15.

COMPOSITE COMPRESOR HOUSING
TEST RIG - SIDE VIEW



COMPOSITE COMPRESSOR HOUSING
TEST RIG - TOP VIEW



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

This report summarizes efforts expended in the development of an all-composite compressor case. Two pre-production units have been built, one utilizing V-CAP and one utilizing AFR-700B resin systems. Both units have been rig tested at elevated temperatures well above design limit loads. This report discusses the manufacturing processes, test results, and Finite Element Analysis performed. The V-CAP unit was funded by NASA-Lewis Research Center in 1994 under contract number NAS3-27442 for Development of an All-Composite OMC Compressor Case. This contract was followed by an Air Force study in 1996 to build and identical unit using the AFR-700B resin system in place of the V-CAP system. The second compressor case was funded under U.S. Air Force contract F33615-93-D-5326, Advanced Materials for Aerospace Structures Special Studies (AMAS3), Delivery Order 0021 entitled "Advanced Polymeric Composite Materials and Structures Technology for Advanced High Temperature Gas Turbine Engines." Initial studies using the V-CAP resin system were undertaken in 1993 under a NASA Lewis contract (NAS3-26829). A first prototype unit was developed in a joint program between Textron-Lycoming (now Allied Signal) and Brunswick (now Lincoln Composites). This unit included composite end closures using low density, high temperature molded end closures. The units was similar in size and shape to a titanium case currently used on the PT-210 engine and was funded as part of the integrated High Performance Turbine Engine Technology (IHPTET) initiative of DOD and NASA.

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