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Milestone 5

Test Report - Task 5, Subtask 5.2
Tile to Foam Strength Tests

Cooperative Agreement NCC8-39

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HERCULES

This document is a preliminary report describing the accomplishments to date on the two tests described herein. As a result of these tests heat treated 3.25 pcf foam will not be suitable and hence the remaining testing was interrupted pending evaluation and decision of a more suitable foam such as the 3.25 pcf Rohacell foam without heat treatment or a 4.5 pcf Rohacell foam. An addendum to this report will be provided describing further developments

Laboratory Test Report LTR 6552-4038

SSTO TPS/Cryogenic Foam Insulation System Strength Dogbone Testing
- Interim Report -

November 1994

Abstract

This report summarizes work that has been performed to date on the strength of a cryotank insulation system using Rohacell foam and TUFI-coated AETB-12 ceramic tiles directly bonded to a simulated graphite-epoxy tank wall. Testing utilized a custom specimen design which consists of a long tensile specimen with eccentric loading to induce curvature similar to the curvature expected due to "pillowing " of the tank when pressurized. A finite element model was constructed to predict the specific element strains in the test article, and to assist with design of the test specimen to meet the specific goals of curvature and laminate strain.

The results indicate that the heat treated 3.25-pcf density Rohacell foam does not provide sufficient strength for the induced stresses due to curvature and stress concentration at the RTV bondline to the TUFI tile. The test was repeated using higher density non-heat treated Rohacell foam (6.9 pcf) without foam failure. The finite element model was shown to predict specimen behavior, and validation of the model was successful. It is pertinent to mention that the analyses described herein accurately predicted the failure of the heat treated foams and based on this analysis method it is expected that the untreated 3.25 pcf Rohacell foam will be successful.

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1.0 Background

The task 5 TPS integration portion of TA-1 investigates potential problem areas related to installation and use of the planned insulation system for the SSTO vehicle. This insulation system for the current baseline SSTO configuration includes bonded blocks of Rohacell foam attached to a stiffened graphite-epoxy cryogenic tank wall, and the system also includes various TPS materials (ceramic tiles and/or blankets) bonded to the foam. Although it has been extensively analyzed, the hardware has not been fully tested under the expected service conditions. Two test projects were performed as part of this task, originally listed as items (a) and (b) of task 5 in the Master Program Plan for Reusable Hydrogen Composite Tank System (RHCTS).

2.0 Purpose

The use of Rohacell foam for cryogenic insulation bonded to a graphite-epoxy stiffened panel poses several engineering problems. This program was performed to investigate the effects of tank wall strain and curvature on the composite/foam/TPS system. The data will be used to evaluate the current approach to the baseline SSTO vehicle design.

3.0 Fabrication Procedure for Test Specimens

3.1 Fabrication of Strain Compatibility Specimens (a.k.a. the "giant dogbones")

The test specimen required for the strain compatibility test was an asymmetric composite sandwich panel approximately 59 inches in length by slightly over six inches in width. A sketch of the specimen is shown in Figure DOGBONE-1.

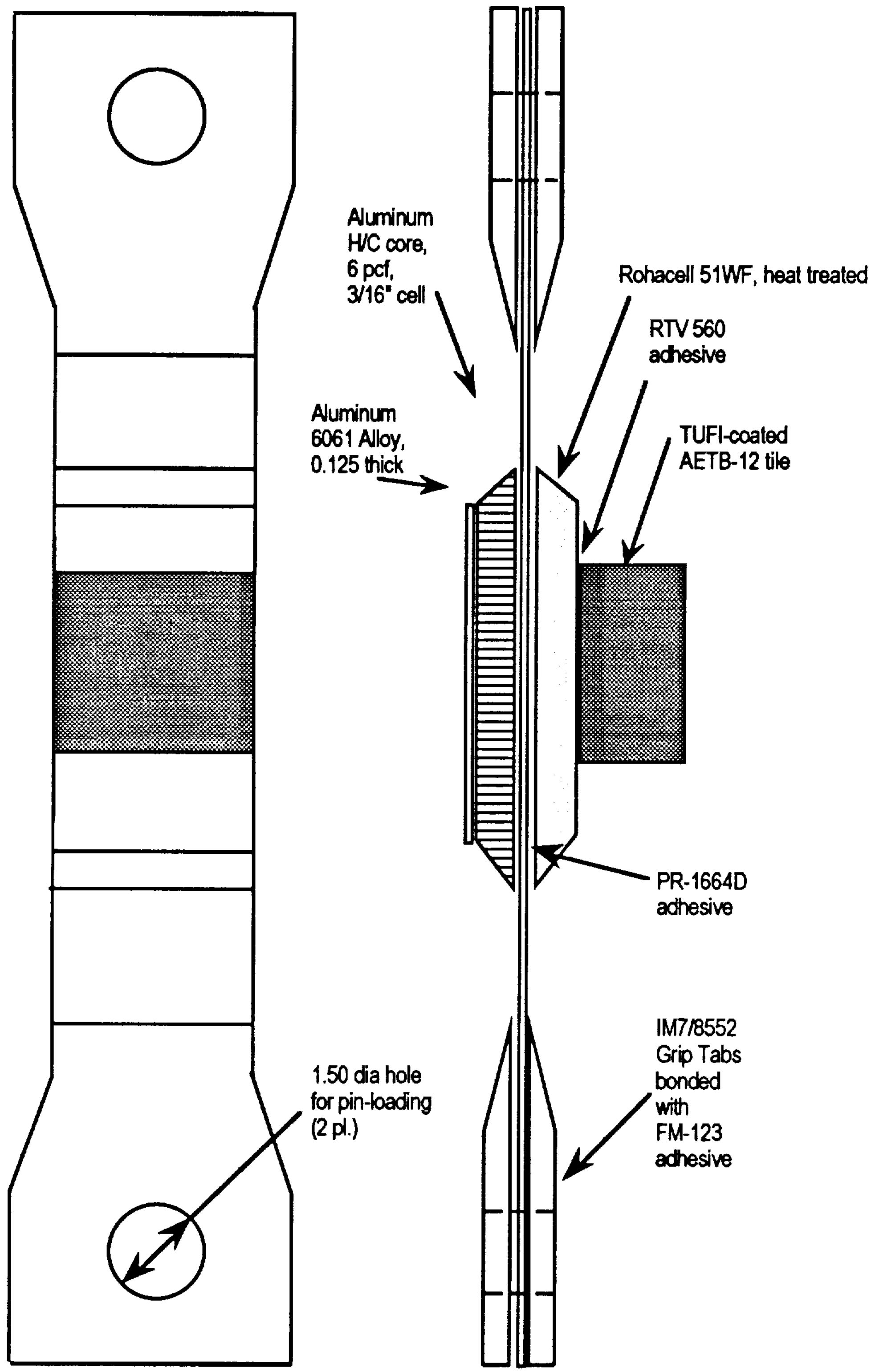


Figure DOGBONE-1: Strain Compatibility Specimen Configuration

Two test specimens were fabricated at Rockwell - Downey using IM7/8552 composite prepreg tape supplied by Hercules. The prepreg material provided by Hercules was 12-inch wide unidirectional IM7-G fiber tape impregnated with 8552 toughened epoxy resin. The composite face sheet panels were flat laminates with bonded grip tabs and the aluminum core had a density of 6 pounds per cubic foot, with 3/16" cell size. The center section of the face sheet to be loaded was fabricated as a rectangle and was then machined into the shape of a traditional "dogbone" tensile coupon, with enlarged areas at each end for pin-loading. The width of this face sheet at the center is 6.0 inches, with an additional 1.5 inches of width in the grip tab area. The laminate simulating the tank wall was fabricated with 20 plies of prepreg tape, $[0_2,[-45,90,+45,0]_2]_S$ for a total cured thickness of 0.109 inches. Grip tabs were fabricated using existing T-300/934 fabric prepreg with a total of 36 plies $[0_2,+45,0_2,-45]_S]_3$. The overall cured thickness of the tab stock was slightly over 0.50 inches, so the stock was machined down to a final thickness of 0.496 inches, with a taper at the end as specified to improve load transition from the tabbed area to the center section. The tabs were bonded to the dogbone using FM123 film adhesive. The grip tab areas at each end have a single pin-hole for a 1.5-inch diameter pin. The pin holes were drilled after bonding of the grip tabs to the facesheet, through the total stacked thickness of approximately 1.1 inches.

The "dogbone" facesheet was bonded to the aluminum core using FM123. The FM123 cure for the grip tabs and honeycomb core was at 250°F for 90 min using 20 psi autoclave pressure (vacuum vented). For these two specimens, since the testing was to be performed at room temperature and because prepreg material was in short supply, the short facesheet on the back of the core was fabricated with 6061-T6 aluminum. The aluminum thickness was chosen to be 0.125 inches in order to match the spring rate (spring rate = EA, or modulus times the cross-sectional area) of the opposite composite panel. [Note: If this test is to be repeated at cryogenic temperatures, it will be required that both facesheets be fabricated from the same material for balanced thermal expansion.] Because of thermal expansion mismatch during the 250F cure cycle, the aluminum facesheet was not bonded with the FM123 adhesive, but was instead bonded with a room temperature adhesive: Hysol EA934 paste adhesive.

The Rohacell foam used for this test was 51WF material (density = 3.25 pounds per cubic foot), heat treated per vendor instructions (48 hours at 400F) and cut into blocks as required. The 18-x-6-x-1-in foam block was tapered using a table saw to create the transition shown at the ends. The foam was bonded to the composite substrate using Courtald's PR1664 two-part polyurethane adhesive. The polyurethane bond required 1-2 psi direct pressure at room temperature. A 6x6x3.0-inch TUFI-coated AETB-12 tile was bonded to the center of the Rohacell foam using RTV 560 silicone adhesive. The tile bond was also performed using direct pressure to reduce adhesive starvation at the edges and corners (reduced in comparison with vacuum bag cure). The tile was instrumented with strain gages prior to bonding. The room temperature bonds (EA934, PR1664, and RTV560) were all performed simultaneously for the first set of specimens using a single set of dams, blocks and dead weights. The ends of the specimen were supported with shims to prevent bowing at the center for proper bonding.

After test, the foam from Panel number 1 was removed, scraped clean and re-assembled using Rohacell 110WF foam. The tile bond surface was machined to remove any remaining foam and the RTV 560. All strain gages were left un-disturbed so that they could be used again. The RTV and polyurethane bonds were repeated using direct pressure.

3.25 Instrumentation of Strain Compatibility Specimens

3.25.1 Location of Strain Gages

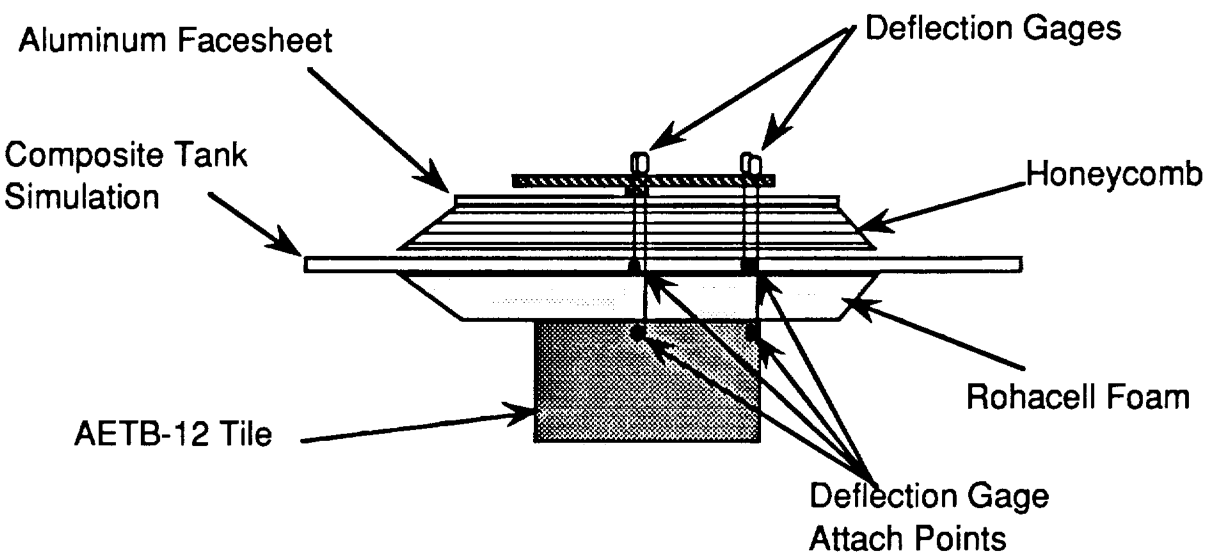
Six strain gages were originally installed on each of the strain compatibility test specimens, including one gage on the composite facesheet in the adhesive bondline between the composite facesheet and the Rohacell foam, four gages on the surface of the TUFI tile, and one gage on the outer surface of the Rohacell foam. A small groove was made in the Rohacell foam to accommodate the lead-wires for the strain gage that was installed on the composite panel at its center underneath the tile.

It was found that the filling of the foam cells required to bond a strain gage on that surface produced questionable strain results, and that the use of an extensometer without filling the foam cell provided a more accurate measure of strain in the foam. The re-bonded specimen with high-density foam utilized only five strain gages, eliminating the gage installed on the foam in exchange for data from an extensometer mounted on the foam surface.

3.25.2 Deflection Gages

Deflection gages were also used to determine the induced curvature in the test specimen by measuring deflections at several locations. The gages used for these tests were simple cantilever beam deflection gages, which utilize a bending beam made of spring steel which has been instrumented with strain gages. The locations were chosen to provide relative deflection between the back facesheet and the foam and tile bondlines at the center and at the edge of the tile.

Figure BEAM-1



4.0 Test Procedure

4.1 Task (a): Strain Compatibility Test Procedure

4.1.1 Test Equipment

The test was performed using an MTS servohydraulic test machine with a 500,000 pound capacity, system A in the Mechanical Properties Laboratory in Building 4 of the Rockwell - Downey facility. The system uses an integral load cell, for which calibration is maintained by the internal Rockwell Metrology Laboratory. The strain gage data were monitored and recorded with a data acquisition system manufactured by Gardner Systems, Inc., using internal signal conditioning and external bridge completion. The gages were originally wired as quarter-bridge elements, and Wheatstone bridge completion into the signal conditioners was accomplished with a 360-ohm resistor for each gage. Excitation voltage was set at 5.0 volts, with full scale strain at 0.020 inch. The strain-versus-load data were recorded originally as binary data files and were converted to ASCII files and then placed into spreadsheet format in Microsoft Excel for analysis. The strain data plots shown in proceeding sections were generated by Gardner Systems data acquisition software routines. The deflection beams used were manufactured in-house and were calibrated using a supermicrometer. The deflection beams are wired as full-bridge devices, and their data were collected with a Hewlett-Packard model 9845B computer system using external signal conditioning. Excitation voltage was set at 2.0 volts, with full scale calibrated to be 0.25 inches.

The specimen was loaded with a single pin, 1.50 inches in diameter, using a pair of clevises with holes of the same diameter. The unsupported width inside the clevis (between clevis and specimen) was approximately 0.1 inches on each side, and this was filled with shims to eliminate side-to-side sliding during the test.

4.1.2 Test Conduct

The first specimen was loaded into the test machine and the strain gages and deflection beams were connected to their respective computer systems. The control system was set to perform a ramp (sawtooth waveform) from zero to max load, which was to be determined by the strain output. After the max load was reached, the return to zero button was pressed on the control console. The max load was predicted to be approximately 42,000 pounds to reach a laminate strain of 0.004 inches per inch, and a radius of curvature of 250 to 300 inches. This prediction was chosen for the initial target, and the strain level was verified to be accurate.

5.0 Results

Panel #1 produced a failure in the heat treated 51WF Rohacell foam at approximately 17,000 lbs of load. The failure occurred 0.25" to 0.75" below the tile bond in the form of a crack the full width of the foam. The crack originated at the surface of the foam then propagated almost instantaneously 0.75" directly toward the simulated tank structure. As the specimen loading continued no other failures were noted but the crack already produced widened as the load increased. No indications of failure occurred in either the tile or the tile/foam bondline.

Panel #2 as in panel #1 failed in the heat treated 51WF Rohacell foam at approximately 19,000 lbs of load. In this specimen failures occurred in the foam both above and below the tile in the full width of the foam. Both failures occurred at approximately the same distance from the tile paralleling the tile face. Again no indications of failure occurred in either the tile or the tile/foam bondline.

Panel #3 was loaded to 42,000 lbs with no indication of failure in the non-heat treated 110WF Rohacell foam. The strain gages placed on the tile did indicate a failure in either the tile or tile/foam interface. This failure occurred at approximately 25,000 lbs. Visually the excess RTV 560 adhesive showed a slight disbond on one corner of the tile. The depth and severity of the failure are unknown at this time.

6.0 STRUCTURAL ANALYSIS

6.1 ABSTRACT

This report summarizes the structural analysis that has been performed to date on the structural integrity of an integrated cryotank insulation system comprised of Rohacell foam and TUFI-coated AETB-12 ceramic tiles. The system is directly bonded to an IM7/8552 Dog Bone Laminate simulating the strength and stiffness characteristics of a cryotank wall. This structural analysis has supported the design, fabrication, and test procedure for the room temperature mechanical strain isolation test.

The primary concerns that directed the test described herein are the structural integrity of the Rohacell foam itself, the AETB tile, and the bonded joint between the tile and Rohacell. The concerns arise from the imposed longitudinal tension in the prototype composite hydrogen tank wall in conjunction with bending induced strains due to classical tank pillowing between frames. The structural integrity concern of the Rohacell foam is due to the imposed longitudinal and transverse tensile strains as well as shear induced strains. This first series of tests are all at room temperature. Only if these tests are successful, will subsequent tests be performed at cryogenic temperature.

To ensure the structural integrity of this design concept, a set of finite element models has been constructed to 'size' the components making up this test assembly. The structural load paths have been 'sized' for positive strength margins of safety for the bounding loading conditions of the test specimen.

6.0 STRUCTURAL ANALYSIS
6.2 TEST ARTICLE
6.2.1 HARDWARE DESCRIPTION:

FIGURE 6.2.1A Strain Isolation Test Hardware Summary

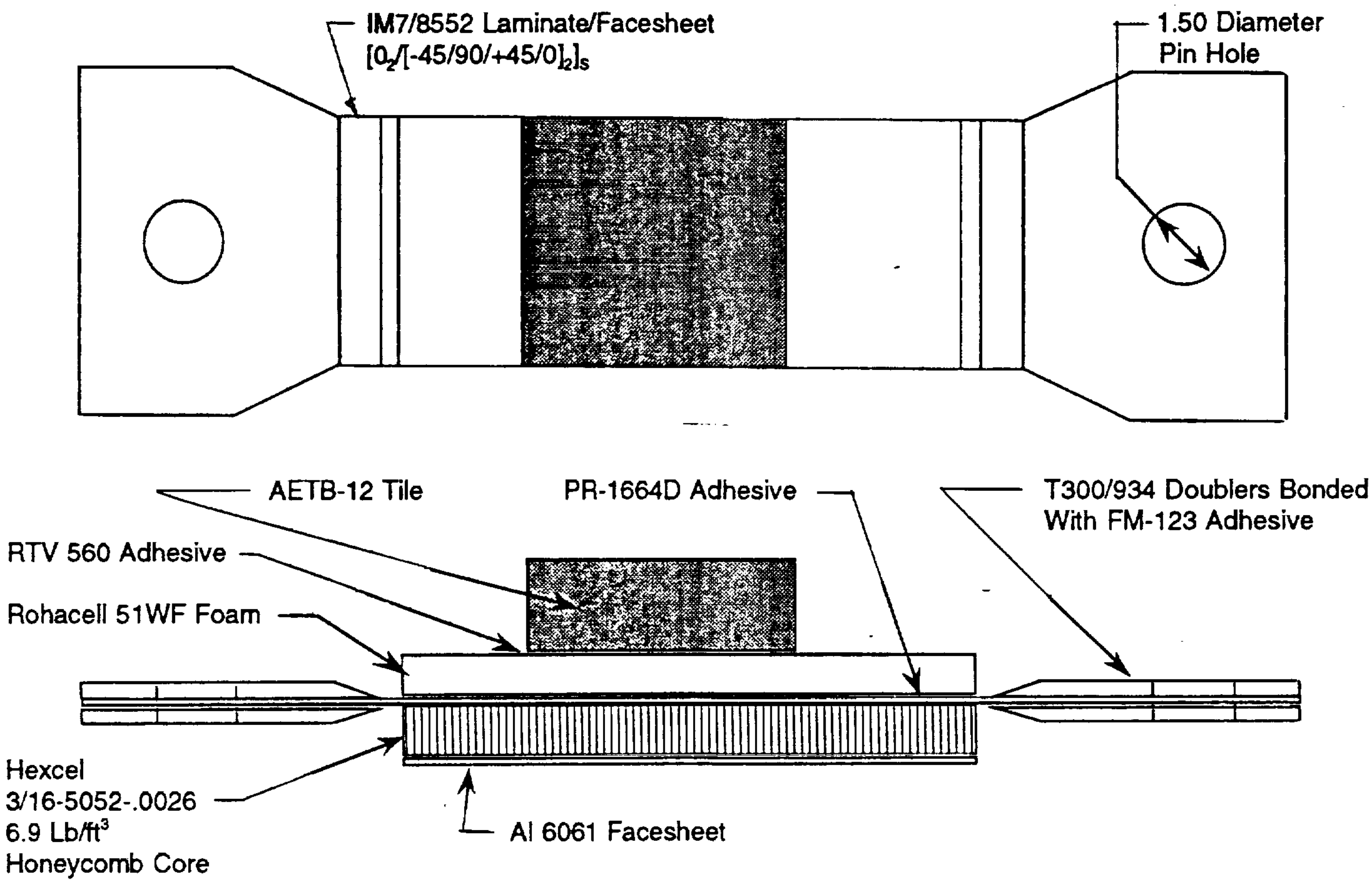
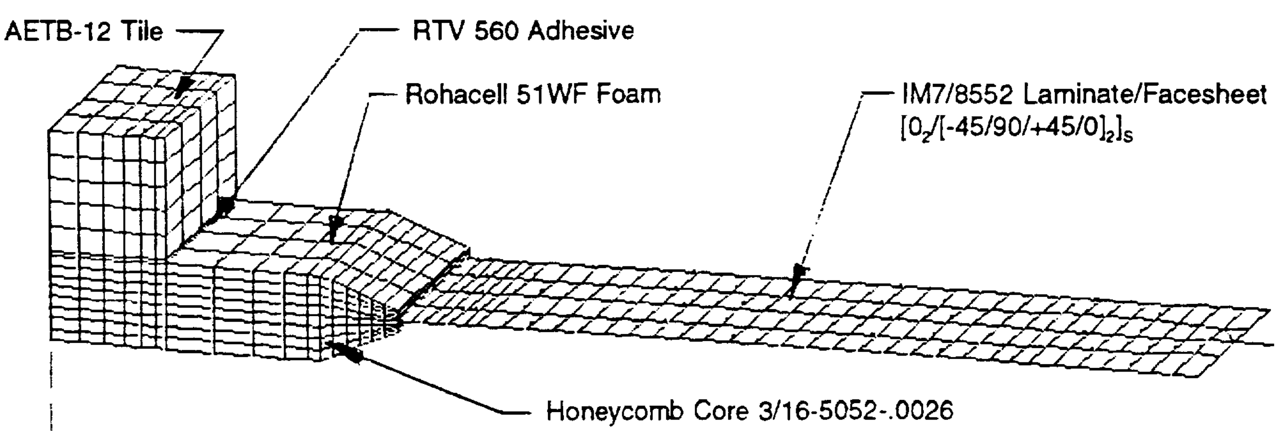


FIGURE 6.2.1B Finite Element Model Representation of Half of Test Hardware



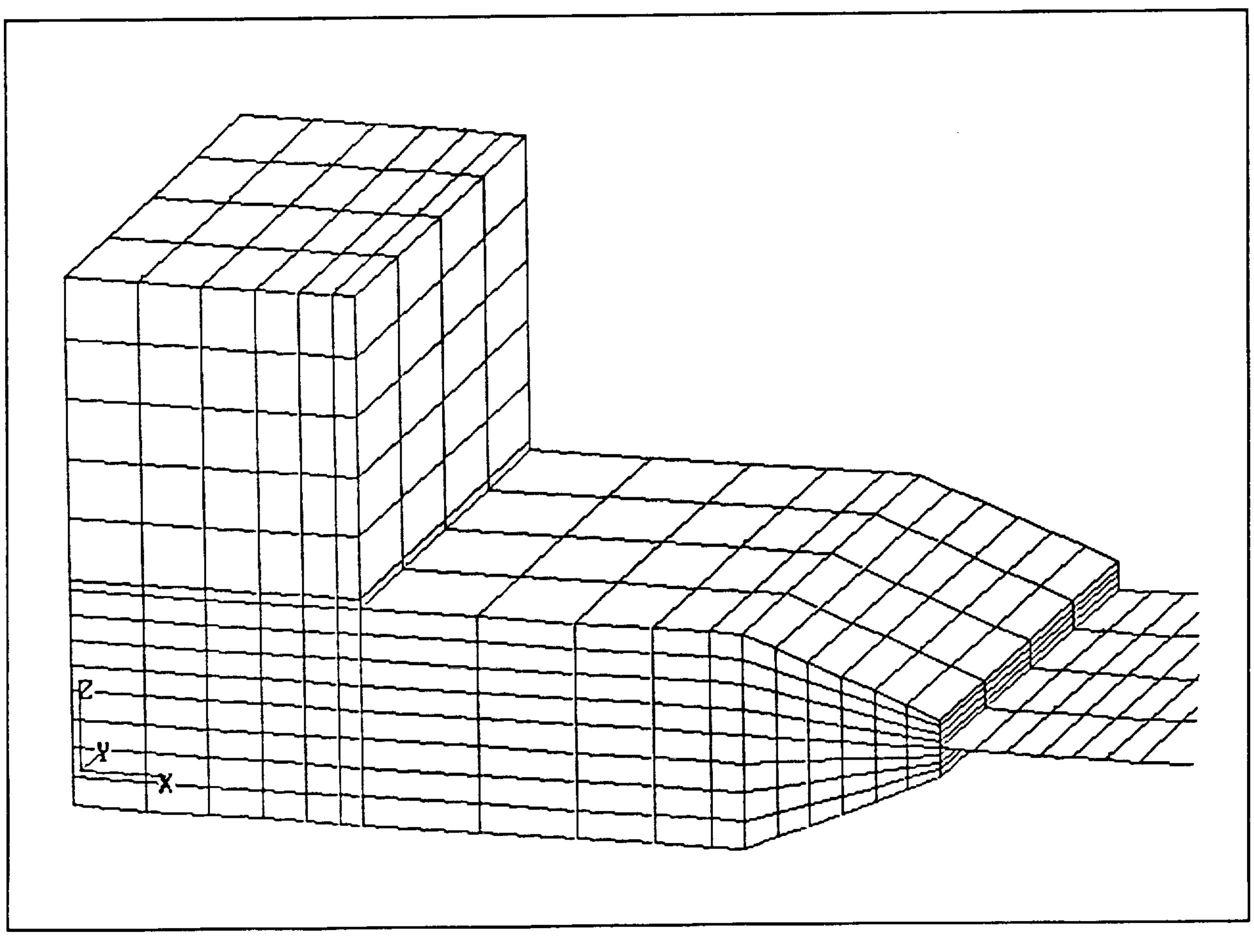
6.0 STRUCTURAL ANALYSIS

6.3 FINITE ELEMENT MODEL DESCRIPTION:

All of the strain isolation test structural analysis produced to date has been performed in a computer charge free environment on a 486-33 MHZ PC with 8 MB RAM. The fiber reinforced composite analysis required to obtain a ply layup satisfactory to the design requirements has been generated with the aid of both SQ5N and the Advanced Composites module in PAL2. The composite bolted joint analysis has been produced with software based on work performed on the NASA ACTS program for NASA Lewis Research Center. The Finite Element Analysis required to perform detail stress analysis required for structural substantiation and to develop the stiffness and geometry required for the correct strain and curvature relationships has been performed with MacNeal-Schwendler's PC version of NASTRAN: PAL2 Version 4.05. MSC MOD has been used as a pre-processor to generate most of the elements used in this analysis.

The FEM Model shown in Figure 6.3A and summarized in Table 6.3B is a mass, and stiffness representative model of the actual test hardware. This model has been used for only static

FIGURE 6.3A Finite Element Model of Symmetry of the Test Hardware Setup.



6.0 STRUCTURAL ANALYSIS
6.3 FINITE ELEMENT MODEL DESCRIPTION

analysis based on the criteria found in Section 6.4.

TABLE 6.3B PAL2 Finite Element Model Summary

Nodes	1196
Degrees Of Freedom	4593
Elements	950
Element Types	3
8 Node Brick Hex Elements	686
4 Node Quad Shell Elements	252
Beam Elements	12

Eight node hex elements are used to represent the AETB-12 Tile in this model. Since there is a large scatter in elastic and strength properties, the 'typical' properties have been employed in this analysis. The Tile is 6.00 by 6.00 by 3 inches thick. It has been modeled with 3 dimensional orthotropic elastic and strength properties to represent the large drop in strength and stiffness for the thickness (z) direction.

Eight node hex elements with isotropic material properties have also been used to represent the .010 inch RTV 560 bondline between the tile and the Rohacell Foam. Analysis shows that the design of this bondline is critical to the tile strain isolation. Since inspection showed that an irregular bondline boundary existed on the test hardware, critical hex elements representing the bond were 'commented' out of the model code, in order to represent this critical load path correctly.

The Rohacell 51WF Foam is another isotropic material represented by eight node hex elements. After the first test, the material properties were changed to reflect recently developed material properties for a 'heat treated' 51WF Foam.

The stiff 6.9 Lb/Ft^3 Hexcel Aluminum Honeycomb Core is another material that required three dimensional orthotropic elastic properties. The standard properties used in this model were obtained from the Hexcel Data Sheets, but the non standard properties required uniquely for this analysis, were computed from equations developed by NASA Lewis' C.C. Chamis and documented in reference 2.

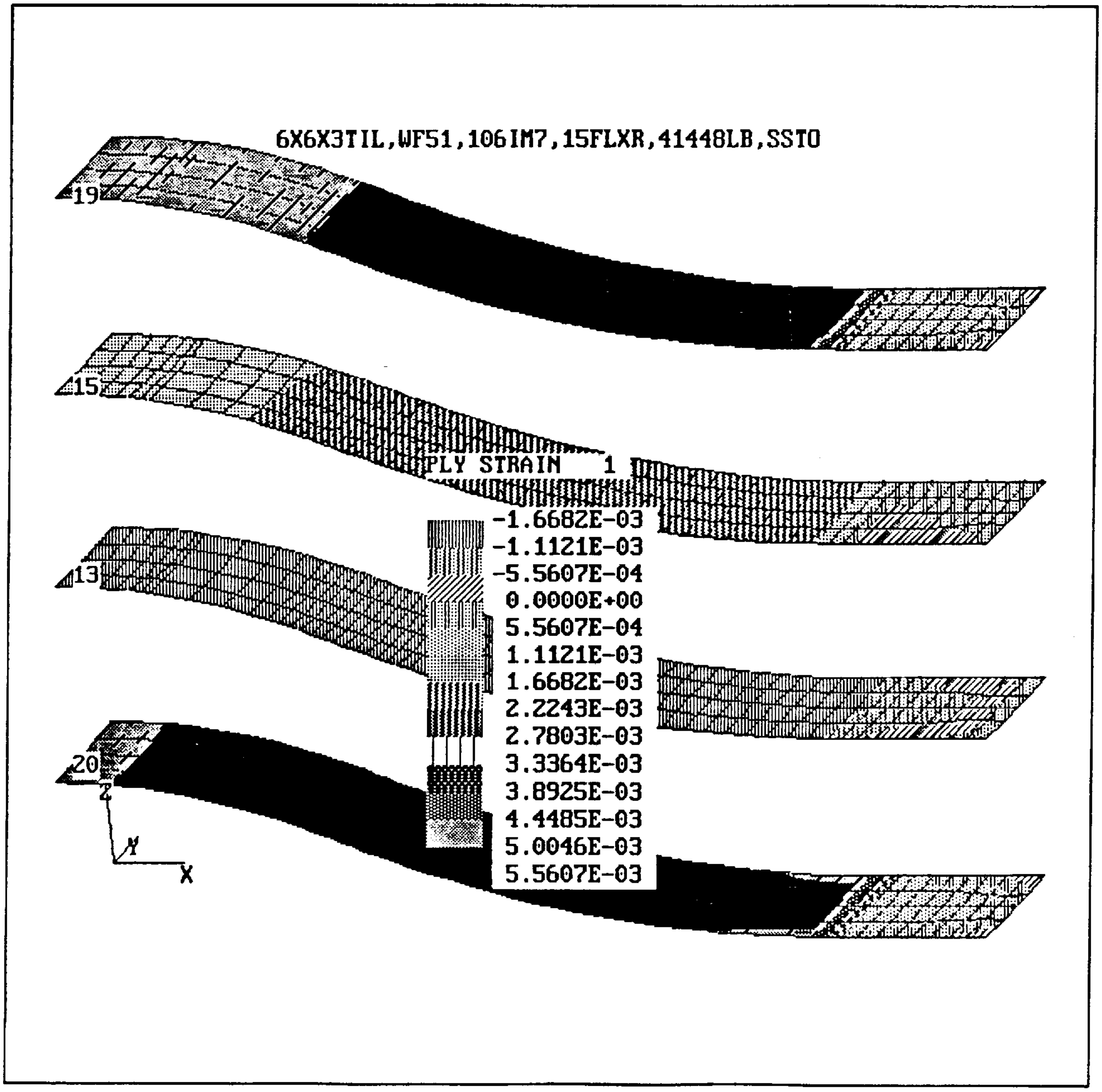
PAL2 has a very good analytical module for representing the orthotropic charcteristics of

6.0 STRUCTURAL ANALYSIS

6.3 FINITE ELEMENT MODEL DESCRIPTION

the IM7/8552 graphite composite primary load path dog bone. Instantaneous graphical post-processing of ply by ply behavior has been performed as a means for zeroing in on the critically loaded regions of the laminate for composite point stress analysis based on detailed internal load recovery. An example is shown in Figure 6.3C below, where IM7/8552 Tape primary direct strain levels have been captured for the two opposing outer zero degree plies and then the first 45 and 90 degree plies at the critical 41,448 Lb axial load required to achieve a 296 inch radius of curvature.

FIGURE 6.3C



6.0 STRUCTURAL ANALYSIS

6.4 STRUCTURAL DESIGN CRITERIA:

The design drivers, making up the structural criteria for this strain isolation test hardware, are broken up here into primary and secondary. The primary design criteria are as follows. Referring to Figure 6.2.1A, the IM7/8552 facesheet defining one side of the honeycomb composite sandwich must experience a membrane component of strain in the neighborhood but greater than .004 in/in over the region shared by the AETB-12 Tile Block. And, at the same time a radius of curvature between 250 in and 300 in must be developed by the composite face sheeted honeycomb sandwich in the same region shared by the Tile Block.

Secondary design drivers address the structural integrity of the components being tested. These design drivers are summarized as follows. Ensure that the peel stresses at the RTV 560 bondline do not result in a disbond. Ensure that the same peel stresses do not promote a flatwise tension failure of the Tile. As the Rohacell Foam approaches the Tile, an abrupt stiffness change occurs which generates a stress riser in the outer fibers of the foam. Design the IM7/8552 facesheet to react .007 to .008 in/in strain levels and at the same time the graphite lugs must be capable of up to a 74,606 Lb axial load. Both the Rohacell Foam and Al honeycomb core have been tapered to "soften" the discontinuity defined by the ending of the "non-loaded" sandwich facesheet which has been defined by a stiffness matched aluminum plate. These issues and more have been addressed in the design and have been summarized in the Test Readiness Analysis and Predictions prepared for the first test.

6.0 STRUCTURAL ANALYSIS

6.5 TEST READINESS ANALYSIS SUMMARY AND PREDICTIONS:

A review of the test hardware was made before the first test. A finite element model was created to reflect the as assembled design. Differences between this and the previous model were: (a) aluminum non-loaded sandwich facesheet (.125), (b) irradic RTV bondline not extending to the tile edge, (c) the addition of soft bar elements representing strain gauges on the hardware for direct correlation of model strains and actual hardware strains. For load verification with graphite laminate strains during the test, it was agreed that a correlation must be achieved at the key milestone load levels defined in Table 6.5A below.

TABLE 6.5A Test Instrumentation Load Level Milestone Description

LOAD (Lb)	STRAIN GAUGE # 6 (in/in)	RADIUS OF CURVATURE (in)	LAMINATE MEMBRANE STRAIN @ #6 (in/in)
0.0	0.00000	Infinity	0.00000
41448.0	.00495	296.0	.00476
49085.0	.00586	250.0	.00564

TABLE 6.5B Predicted Strain Gauge Values at Milestone Load Levels (reference Figure 4C for locations)

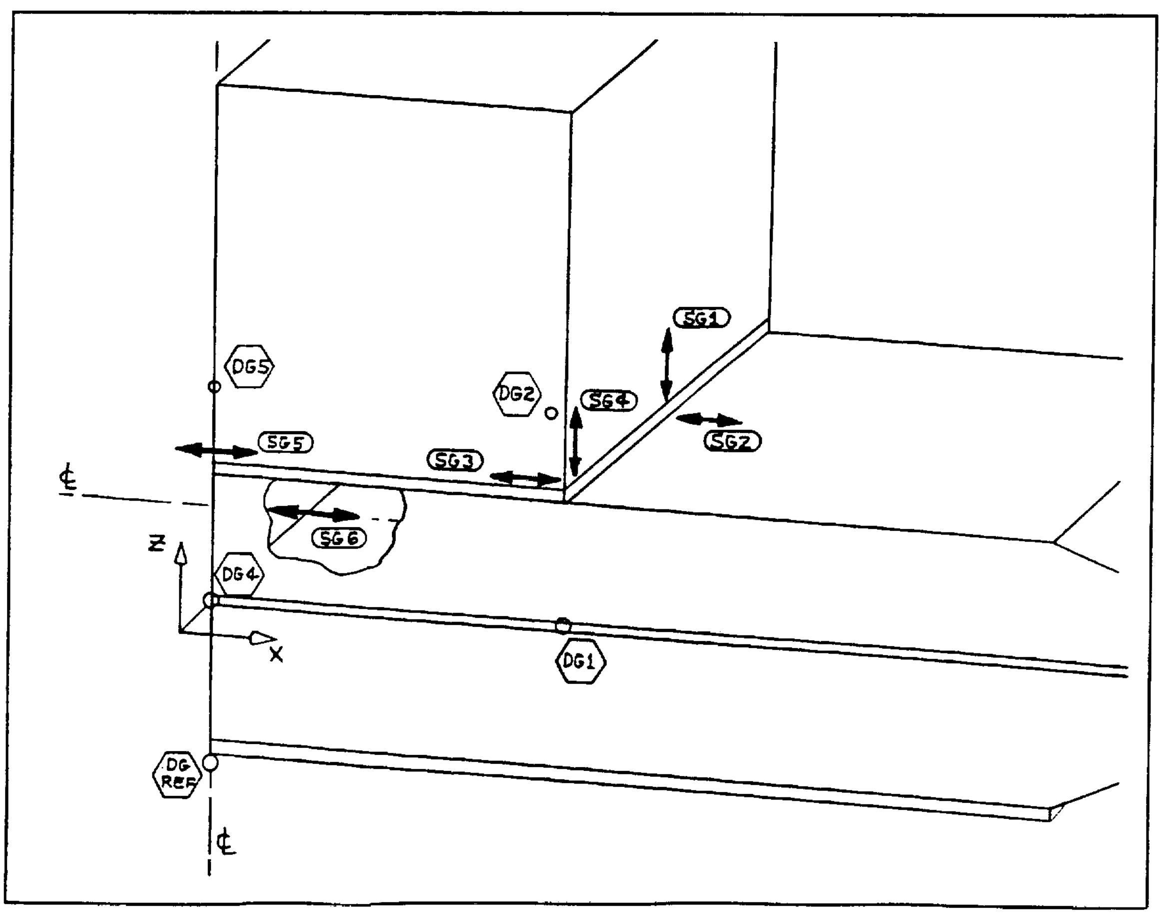
STRAIN GAUGE ID	FEM ELEMENT ID	STRAIN (in/in)		DESCRIPTION OF STRAIN GAUGE LOCATION
		41448 Lb	49085 Lb	
SG1	945	.0027210	.0032230	Tile Peel @ Center of Edge Facing Sandwich Bending Stress Field
SG2	946	.0115000	.0136200	Rohacell Extreme Fiber Membrane & Bending @ Tile Peel Gauge.
SG3	947	.0001337	.0001583	Tile Extension @ Bondline Corner
SG4	948	-.0008917	-.0010560	Tile Peel @ Conrner Edge
SG5	949	.0007145	.0008461	Tile Extension @ Bondline Edge @ Tile Center Line
	950	.004759	.005637	Gauge #6 /FEM Membrane
SG6		.004950	.005862	Gauge #6 /Actual Outer Fiber

6.0 STRUCTURAL ANALYSIS

6.5 TEST READINESS ANALYSIS SUMMARY AND PREDICTIONS:

Instrumentation for the strain isolation testing is summarized in Figure 6.5C below. Strain gauges are identified by ID's SG1 through SG6, and are described in Table 6.5B along with predicted load milestone strains for the first test. Figure 6.5D is a Finite Element plot of the deformed shape predicted at full loading of the specimen. Since the .42 inch maximum lateral displacement is seen to stretch the limits for in house devices requiring this accuracy, a local displacement reference coordinate system was established on the center line of the aluminum facesheet. Refering to Figure 6.5C, at the DG REF location a "thick" knife edge has been bonded to the aluminum facesheet. To this knife edge another aluminum plate has been bonded which acts as a platform for the Displacement Gauge instruments. The Displacement Gauge ID's DG1 through DG5 measure relative Z direction displacements with respect to the platform. These displacements provide the all important means for obtaining Radius of Curvature measurements. Displacement Gauges DG1 and DG4 provide Sandwich primary structure radius of curvature and gauges DG5 and DG2 provide Radius of Curvature of the Tile near the RTV bondline. Predictions are graphically depicted in Figure 6.5E, and tabularized in Table 6.5F. FEM analysis

FIGURE 6.5C Strain Gauge and Displacement Gauge Instrumentation Layout



6.0 STRUCTURAL ANALYSIS
6.5 TEST READINESS ANALYSIS SUMMARY AND PREDICTIONS:

FIGURE 6.5D FEM Model of Symmetry Deformed Shape at Full Specimen Loading.

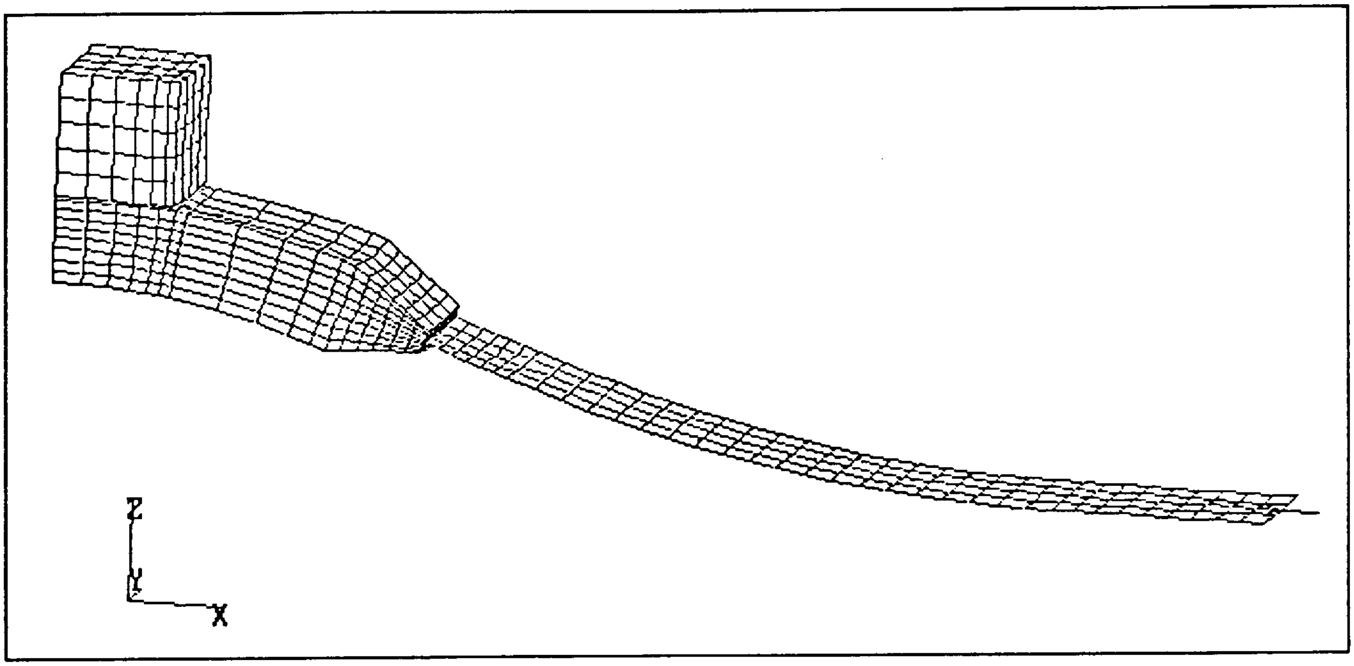
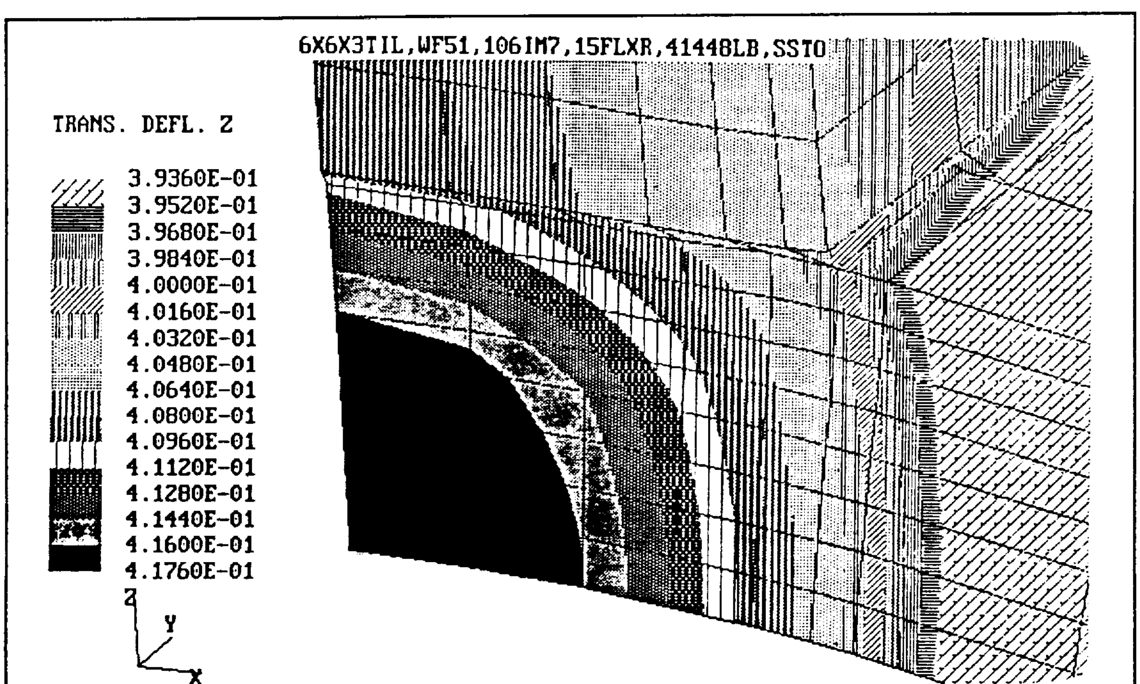


FIGURE 6.5E Local Displacements in Critical Region Under The Tile Profile.



6.0 STRUCTURAL ANALYSIS

6.5 TEST READINESS ANALYSIS SUMMARY AND PREDICTIONS:

TABLE 6.5F Predicted Displacement Gauge Readings @ 41,448 Lb Milestone Load Level

DISPLACEMENT GAUGE ID	FEM NODE ID	PREDICTED GAUGE READINGS @ 41448 LB LOAD	
		TEST #1/Rohacell Foam Modulus = 10875 PSI	TEST #2/Rohacell Foam Modulus = 15082 PSI
DG1	277	-.01787	-.01761
DG4	271	-.00149	-.00154
DG5	71	-.01017	-.00968
DG2	77	-.01503	-.01491
Sandwich Radius of Curvature (in)		274.73	280.03

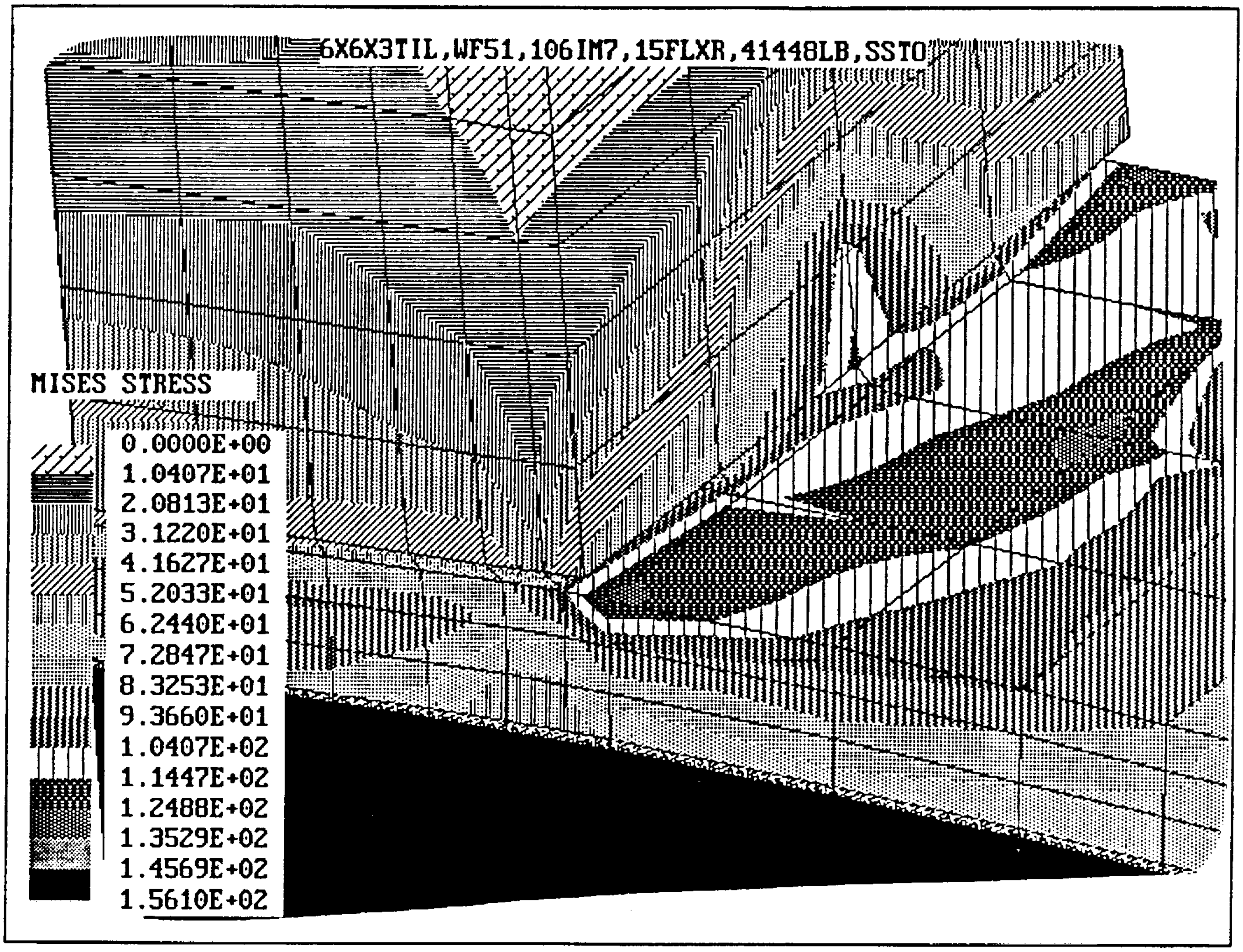
predictions have shown that the relatively flexible Rohacell WF51 Foam acts as a good strain isolator between the stiff graphite primary structure and the relatively brittle AETB-12 thermal tile. Finite Element analyis aided predictions are summarized in Table 6.5E.

Substantiation of the structural integrity of hardware components was produced by detail stress analysis of internal loads generated from the FEM previously described as representing the actual as fabricated test hardware. Finite element plots were produced to aid in locating critical stress states for analysis. Figure 6.5G graphically depicts the Von Mises Stress distributions in the critical region for Tile Peel Stresses and Rohacell Foam Extreme Fiber Tension Stresses in the region of the RTV bondline boundary. The actual stress analysis was based on element by element internal load recovery of elements identified by the plots. Table 6.5H summarizes the Margin of Safety Predictions for Test #1. All margins of safety are positive.

6.0 STRUCTURAL ANALYSIS

6.5 TEST READINESS ANALYSIS SUMMARY AND PREDICTIONS:

FIGURE 6.5G Von Mises Criteria Summary For Critical Tile & Rohacell Foam Interface



6.0 STRUCTURAL ANALYSIS

6.5 TEST READINESS ANALYSIS SUMMARY AND PREDICTIONS:

TABLE 6.5H Test Readiness Hardware Strength Structural Substantiation Summary as a Function of 49,085 Lb Applied Load Required to Achieve 250 in Radius of Curvature

TEST HARDWARE COMPONENT	STRENGTH MARGIN OF SAFETY	DISCUSSION OF CRITERIA
Dog Bone IM7/8552 Fiber Reinforced Composite Primary Structure with T=.106 in by W=6.00 in.	+.730 +.370 +.560 +.294	Max Strain Criteria for 90° ply under Tile. Tsai-Wu Failure Criteria for same ply. Max Strain Criteria for 90° ply near graphite lug taper down from full doubler thickness. For short length these element stress levels are a result of shear lag induced by the orthotropic laminate properties. Tsai-Wu Failure Criteria for same ply.
Graphite Lug Defined by Parent IM7/8552 Laminate Reinforced by T300/934 Doublers.	+.529	Lug Geometry Optimized for Simultaneous Tension Across Net Section and Bearing Failures Based on 'Typical' Basis strength values.
AETB-12 Tile	+1.927 +3.298	Peel Strength @ Strain Gauge SG1 based on 100 PSI average value from recent testing. Elastic properties are average per FRCI published data. Inplane Tension at Tile center line
RTV 560 Adhesive	+.148 <MS< +1.042	With a theoretical .010 in bondline, the critical margin is based on flatwise tension where the available published values vary from 270 psi to 480 psi at room temperature.
Rohacell WF51 Foam	-.458 -.015 +.630 -.528	Extreme fiber tension stress at strain gauge SG2. Stress riser in region of the end of the aluminum honeycomb sandwich. Transverse/Radial Compression under the Tile at the Tile centerline. Extreme fiber tension stress at outer edge of foam under tile corner.
Hexcel 3/16-5052-.0026 Honeycomb Core	+1.227	Shear @ the bondline with the Dog Bone where the aluminum facesheet runs out.

6.0 STRUCTURAL ANALYSIS
6.6 TEST DATA CORRELATION:

A detailed review of the test data will follow in an addendum to this report. The data has been recorded in ASCII files which will be imported to EXCEL for correlation with the finite element analysis. A quick look at the strip charts shows a good correlation between predicted strains in SG6 used to monitor the load levels and the predicted strains for this gauge. We predicted .004759 in/in at the 41,448 Lb. milestone load and consistently achieved .004667 in/in for the three tests performed to date. The strip chart readings for the other 5 strain gauges appear to have a scaling factor error in the plotting of these strains. Therefore it is best to wait for the hard numbers imported to Excel, before we proceed with this correlation.

The foam failed during the first test. The 'heat treated' foam testing performed at Rockwell indicates a 30% to 50% increase in Young's Modulus and roughly a 50% degradation in tensile strength. With these test results, the FEM was modified, a static solution performed, and detail stress analysis performed to predict the behavior of the second test article. We predicted foam failure at 21,866 Lb; from the strip charts it appears that failure occurred at 19,000 Lb.

7.0 Discussion and Recommendations

• Strength of the heat treated 3.25-pcf foam is not sufficient:
Heat treated 3.25-pcf Rohacell foam does not provide the strength required to sustain the loads induced by the strain and curvature of the tank wall. Non-heat treated 3.25-pcf Rohacell foam should be evaluated before the combined effects of thermal and mechanical strains are examined.

• Improvements should be made in the Foam-to-TPS Bond:
The RTV560 bond between the Rohacell foam and the TUFI tile has become a difficult bond to complete successfully using existing Shuttle procedures. One difficulty is the roughness of the Rohacell foam. The surface of the foam pulls away a large volume of the RTV adhesive which is supposed to fill the bondline. One solution is to coat the foam using RTV 560 prior to bonding, similar to bonding AFRSI blankets or Nomex felt used for SIP. This may improve the quality of the RTV bond. Other possible improvements would be densification of the tile IML surface, or densification of the foam OML, or both.

• Improvements Should be Made in the Foam-to-Composite Bond:
The PR1664 adhesive is currently used without an adhesion promoter or primer, and the quality of the bond is highly variable. It has been suggested that there currently exist several potential silicone coupling agents which could be used to pre-treat the surface of the foam and possibly of the composite to improve the bond strength by as much as 100%. This improvement may be necessary to resist the combined thermal and mechanical stresses of the recommended cryo strain compatibility test. Another potential improvement would be to densify the foam at the IML surface to improve load transition from the adhesive into the rest of the system.

• Strain Compatibility Test Was Not Worst Case:
It is recommended that the strain compatibility test be repeated (only after a sucessful room temperature test is achieved) with the back skin of the sandwich panel at cryogenic temperature. Although this test is rather complex and will be expensive to complete using liquid hydrogen, the added severity of thermal expansion mismatch stresses in the foam and bondlines is necessary to form an accurate assessment of system performance under the actual service conditions.

References:

Cooperative Agreement Number NCC8-39, Cooperative Agreement for Research and Development of a Reusable Hydrogen Composite Tank System (RHCTS)

DTP 6552-801, Detailed Test Plan for Task 5 - Subtask 5.2: Tile-to-Foam Strength Tests, dated October 1994.

NASA Technical Memorandum 88787, Fiber Composite Sandwich Thermostructural Behavior: Computational Simulation, May 1986, By C.C. Chamis and R.A. Aiello of Lewis Research Center

Rockwell IL LTR 6552-4038, SSTO TPS/Cryogenic Foam Insulation System Strength Testing -Interim Report-, November 1994

Rockwell Specification MBO-130-119, Type 2 for RTV 560 silicone adhesive
Rockwell Specification MBO 130-136, Type 2, for PR1664 polyurethane adhesive
Rockwell Material Specification(s) for fabrication of AETB tile materials - to be established during this program
Rockwell Material Specification for TUFI coating slurry- to be established during this program
Rockwell Process Specification for TUFI coating process- to be established during this program
Rockwell Process Specification for Direct Bonding of Tiles using RTV 560 Adhesive - to be established during this program

Rockwell Laboratory/ Engineering Notebook E-00156
Rockwell Laboratory/ Engineering Notebook E-00157

SSTO TPS/Cryogenic Thermal Cycling
- Interim Report -

Abstract

This report summarizes work that has been performed to date on the effects of thermal cycling of a cryotank insulation system using Rohacell foam and TUFI-coated AETB-12 ceramic tiles directly bonded to a simulated graphite-epoxy tank wall. Testing examines stresses induced in the Rohacell foam by liquid hydrogen and re-entry heating.

Cryogenic thermal cycling was initiated on the specimens prepared using the heat treated 3.25-pcf foam but was stopped in view of data gained in the foregoing SSTO TPS/Cryogenic Foam Insulation System Strength Testing. The results indicate that the heat treated 3.25-pcf density Rohacell foam does not provide sufficient strength. Testing will be continued upon establishment of the next candidate foam which will be either un-heat treated 3.25-pcf or 4.5-pcf Rohacell foam.

1.0 Task (b): Fabrication of Cryogenic Thermal Cycling Specimens

The specimen tested for cryogenic thermal cycling with reentry heating was a simple flat composite laminate (monocoque construction), with 1.0-inch thick Rohacell foam and a 2.0-inch thick TUFI tile attached to the foam. The panels for this test were fabricated by Hercules from the same 12-inch-wide IM7G/8552 tape prepreg that was used for fabrication of the large strain compatibility specimens discussed above. The panels were approximately 0.092 inch thick (16 plies), and the panels were clamped against a solid aluminum plate with a light coating of conductive grease to provide good thermal coupling as well as to allow some lateral movement due to relative thermal contraction between the composite and aluminum plates. The method of attachment involves bolting of the composite test panel to an aluminum mounting plate with bolts that are only "finger tight" (not more than 10 inch pounds torque). The mounting plate has been bolted onto a mating flange on the cryostat, and it holds liquid hydrogen on the back side when the cryostat is filled. The sealing process was originally planned to be much more complex, but it was simplified when difficulties arose with any conceivable sealing system to clamp the composite plate onto an open aluminum flange. Any relative thermal contraction would have resulted in the composite panel being loaded in compression. The configuration used is shown in Figure CRYO-1.

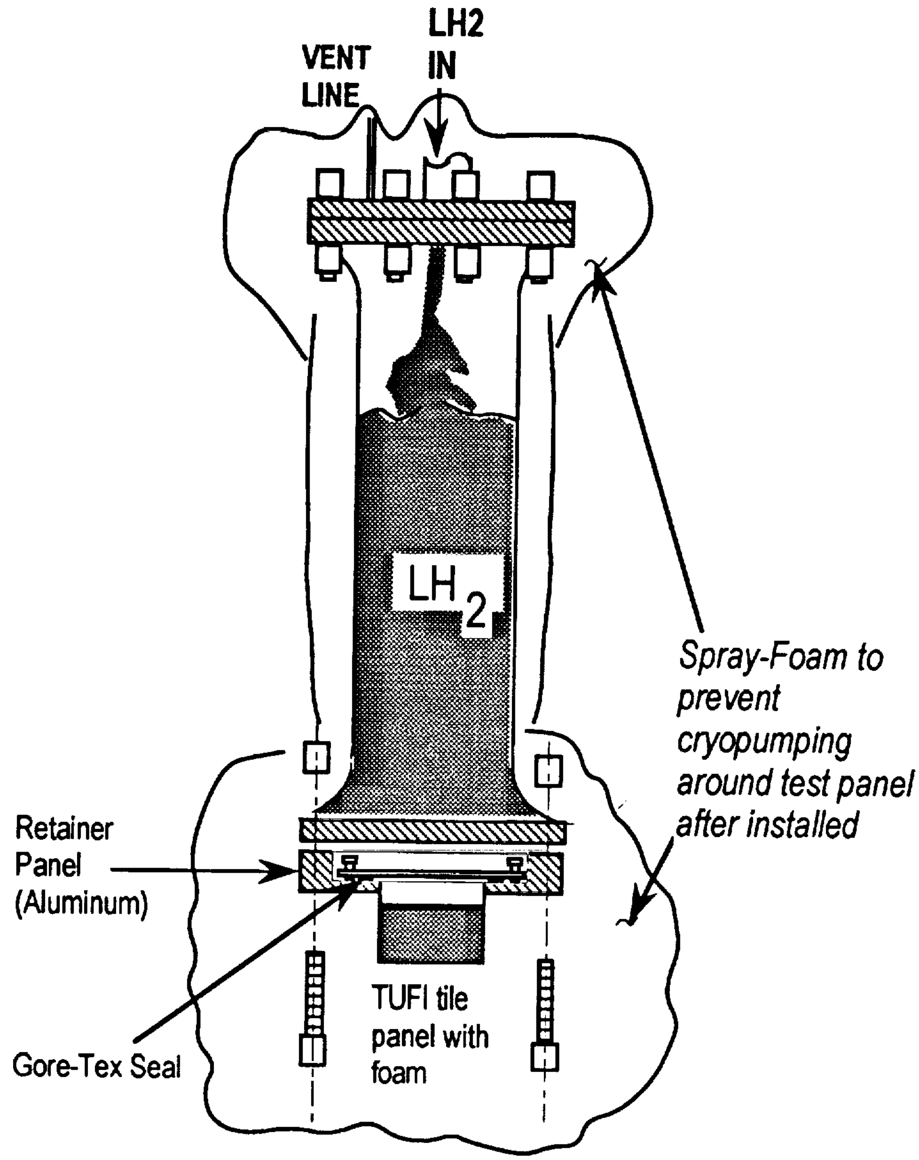


Figure CRYO-1 : Liquid Hydrogen Cryostat System for Thermal Cycling Test

2.0 Foam Bonding

The Rohacell foam used for the thermal cycling specimens was 51WF, with a density of 3.25-pcf, and it was bonded to the composite panel with PR-1664 per MBO 130-136, Type 2, a polyurethane adhesive selected for flexibility and strength at extreme cryogenic temperatures. The Rohacell foam was initially received in block form, in large sheets of 6 feet by 4 feet by various thicknesses. Prior to final machining, the Rohacell foam was heat treated at 180F for a period of 48 hours to provide a thermally and dimensionally stable material. The foam was then shaved down to the correct thickness (1.0 inch) and cut into 6x6 inch blocks. The surfaces bonded with PR1664 urethane adhesive did not require primer coating.

3.0 Tile Bonding

The tiles used for all specimens were TUFI-coated AETB-12 tiles, measuring six inches square, with a thickness of 2.0 inches. The tiles were coated with TUFI completely down to the bondline (without the terminator region commonly used on FRCI-12 and LI-900 Shuttle Orbiter tiles). The tiles were bonded to the Rohacell foam using RTV 560 silicone adhesive. The silicone adhesive has a glass transition temperature of approximately -160°F, so the foam thickness was chosen to provide enough insulation ability to keep the RTV bondline at or above -160°F. Prior to bonding, the surfaces were blown free of debris, using compressed nitrogen, and were wiped clean with MEK solvent. A silicone pre-bond primer (SS-4155) was used for the surfaces in contact with RTV adhesive. The primer was applied to the Rohacell foam with a brush and allowed to air-dry for approximately 1 hour. RTV 560 was applied to both the underside of the tile and to the top of the Rohacell foam, and the two parts were joined and weighted down with about 1 psi (using a 36-pound dead weight) for a room temperature cure. The cure was allowed to proceed a full 72 hours before testing was initiated.

4.0 Cryogenic Thermal Cycling

Cryogenic thermal cycling was initiated on the specimens prepared using the heat treated 3.25-pcf foam but was stopped in view of data gained in the SSTO TPS/Cryogenic Foam Insulation System Strength Testing. The results indicate that the heat treated 3.25-pcf density Rohacell foam does not provide sufficient strength for the induced stresses due to curvature and stress concentration at the RTV bondline to the TUFI tile. Testing will be continued upon establishment of the next candidate foam which will be either un-heat treated 3.25-pcf or 4.5-pcf Rohacell foam.

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