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Response of Graphite/Epoxy Sandwich Panels to Moisture and Temperature Transients

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The Shuttle Orbiter payload bay door is of graphite/epoxy honeycomb sandwich construction. Interaction of this structure with ground environments prior to first launch leads to an outer facesheet absorbed moisture content of about 1% by weight. During re-entry, the temperature climbs to about 177°C and the accompanying drying cuts this amount to about 0.7%. The high temperature combined with the absorbed moisture causes a substantial decrease in strength. In addition, desorption of water from the nylon/phenolic core causes the internal pressure to reach about 350 kPa. This paper discusses the determination of expected moisture levels, the reduction of graphite/epoxy strength due to moisture and heat, and the internal pressure capability of the sandwich panel. It is shown that the hot moist payload bay door has positive design margins in all areas.

Nomenclature

b	= exponent in the moisture equilibrium equation
c	= concentration
D	= diffusion coefficient
H	= relative humidity
H_I	= relative humidity in the honeycomb void volume
I	= signifies the ith material in a multilayered slab
M	= percent moisture by weight
M_u	= equilibrium percent moisture by weight at 100% relative humidity
MW	= molecular weight of water
p	= pressure
p_s	= saturated vapor pressure at temperature T
R	= gas constant
T	= absolute temperature
t	= time
V	= volume
WMA	= weight of absorbed moisture in solid components of the adhesive/core/adhesive substructure
WMT	= total weight of moisture in the adhesive/core/adhesive substructure
WMV	= weight of water vapor in the core void volume
x	= thickness
Δ	= change in
ϕ	= moisture flux
ρ	= density

Introduction

THE unfavorable response of epoxies to a humid environment is a problem of long standing.[1-5] Nevertheless, employment of a graphite/epoxy honeycomb sandwich in the Shuttle Orbiter payload bay door (PBD) saved 450 kg of structural mass. Its use is possible because the Shuttle environment is carefully controlled.

Structurally, the door halves consist of a series of curved frames equally spaced and covered with sandwich-type skin panels. The sandwich panels are composed of thin graphite/epoxy facesheets bonded to a nylon/phenolic core with an epoxy adhesive. The exterior side of the panels is thermally insulated so that the temperature in the outside facesheets rises to a maximum of 177°C during the re-entry phase of the Orbiter, when the panels are also highly stressed by maneuver loads. Figure 1 depicts a typical section of a sandwich panel between adjacent frames under re-entry conditions. The calculation of the moisture distribution in the panels and the experimental determination of their residual strengths will be addressed in the following sections.

Moisture Diffusion Analysis

The ebb and flow of moisture in the sandwich panels was modeled with a numerical solution of Fick's second law[6]

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left[D\frac{\partial c}{\partial x}\right] \tag{1}$$

using an implicit technique.[7] While the diffusion coefficient value changes with temperature and to some extent with moisture concentration, it was assumed constant between time steps allowing Eq. (1) to become

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 M}{\partial x^2} \tag{2}$$

We found it convenient to work in terms of mass percentage of moisture rather than in terms of concentration. This led to Eq. (3) as the form of Fick's second law used in our work.

$$\frac{\partial M}{\partial t} = D\frac{\partial^2 M}{\partial x^2} \tag{3}$$

Equation (3) is applicable to a slab of material of constant composition. We assumed that the graphite/epoxy laminate facesheets were of constant composition. But in the Shuttle Orbiter PBD, moisture must diffuse through several layers of other materials before reaching the panel. The panel itself

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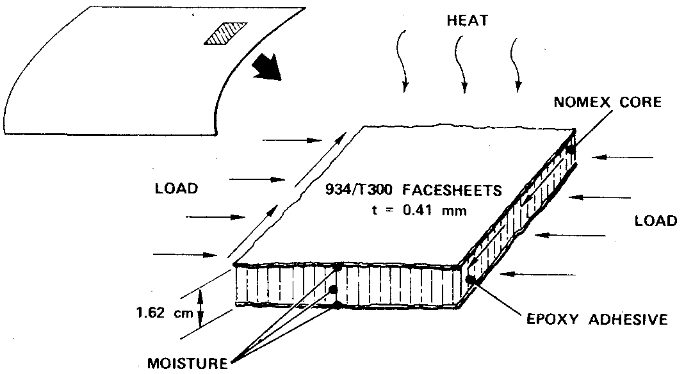


Fig. 1 Problem statement.

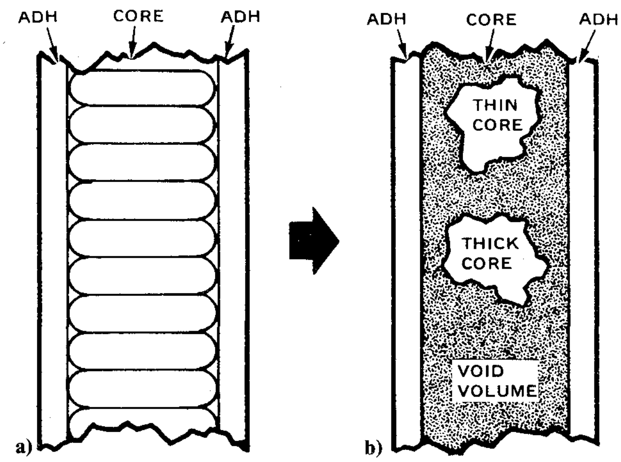


Fig. 2 Core representation: a) physical model, b) mathematical model.

consisted of several layers of different materials. It was, therefore, necessary to consider interfaces between different materials. The result is that two conditions must be satisfied at each interface.

The first of these conditions merely demands that the flux of moisture leaving material I be equal to the flux entering material $I+1$.

Moisture flux is given by Fick's first law[6] suitably transformed to deal with moisture percentage on a mass basis rather than concentration.

$$\phi = -\frac{D\rho}{100}\frac{\mathrm{d}M}{\mathrm{d}x} \tag{4}$$

then,

$$(D\rho)_{I+I}\left(\frac{\mathrm{d}M}{\mathrm{d}x}\right)_{I+I} = (D\rho)_I\left(\frac{\mathrm{d}M}{\mathrm{d}x}\right)_I \tag{5}$$

The second condition requires compatibility of the moisture levels in the two materials at the interface. The instantaneous moisture level M in any material is characterized by the equation[6]

$$M = M_u H^b \tag{6}$$

At the interface, the term H^b in the equations for materials I and $I+1$ can be eliminated if the value of the exponent is the same for both materials so that the interface condition becomes

$$M_i M_{u,I+I} = M_{I+I} M_{u,I} \tag{7}$$

Analysis of Sandwich Panels

In a gross sense, sandwich panels can be analyzed as multilayered slabs if the core material can be regarded as a homogeneous layer with uniformly distributed densities and diffusion characteristics. In the case of honeycomb cores, this idealization is inadequate because the predominant portion of the moisture transfer occurs normal to the surfaces of the core ribbons through the entrapped air in the cells. A more realistic treatment of the problem is the coupling of the adhesive layers to both sides of the core by means of an internal moisture balance which more accurately reflects the core properties. A welcome byproduct of this approach is the calculability of the amount of moisture in the entrapped air space, and corresponding vapor pressure.

Figure 2 (detail A) shows a cross section through a honeycomb-type core with layers of adhesive on both sides. The core ribbons are connected so that the cell walls alternately have single and double thicknesses. The mathematical model in Fig. 2 (detail B) contains the void volume and two moisture absorbers simulating the two cell wall thicknesses. The void volume is defined as the product of core depth and unit area of the panel less the volume of the core cell material. The control volume includes the adhesive layers.

The moisture balance within the control volume is

$$\overline{\mathrm{WMT}}_2 = \overline{\mathrm{WMT}}_1 + (\phi_I - \phi_2)\Delta t \tag{8}$$

where the fluxes ϕ_I and ϕ_2 are governed by Fick's first law. The moisture in the control volume exists as moisture absorbed by the core or as vapor in the void volume. The amount absorbed by the core and adhesive is

$$\overline{\mathrm{WMA}_2} = M_i W_i \tag{9}$$

The difference between $\overline{\mathrm{WMT}_2}$ and $\overline{\mathrm{WMA}_2}$ is the weight of the vapor at the end of the time step

$$\overline{\mathrm{WMV}}_2 = \overline{\mathrm{WMT}}_2 - \overline{\mathrm{WMA}}_2 \tag{10}$$

At the low pressures encountered, the pressure generated by this amount of vapor can be adequately computed from the ideal gas law

$$P = \overline{\mathrm{WMV}}_2 / \overline{\mathrm{MW}} \cdot RT/V \tag{11}$$

where $\overline{\mathrm{MW}}$ is the molecular weight of water. The relative humidity in the cavity is then

$$H_I = p/p_s \tag{12}$$

where p_s is the vapor pressure of water under saturated conditions. H_I is turn sets the boundary conditions at the interface between the internal vapor and the surface of core ribbon or adhesive.

Application to Payload Bay Doors

For the moisture analysis of the PBD components, computer programs were developed for laminates composed of one, two, and nine layers. In all cases, a backward difference formulation was used for the time steps and a backward difference formulation, substituted into a forward difference formulation, was used for the distance steps. The need for a nine-layer slab arose from the construction of the PBD sandwich panels which are shown, typically, in Fig. 3.

Directly attached to the outside facesheet (FS) is a calendered aluminum wire mesh embedded in a layer of epoxy adhesive as lightning protection (LPS). The thermal protection system consists of a reusable ceramic surface in-

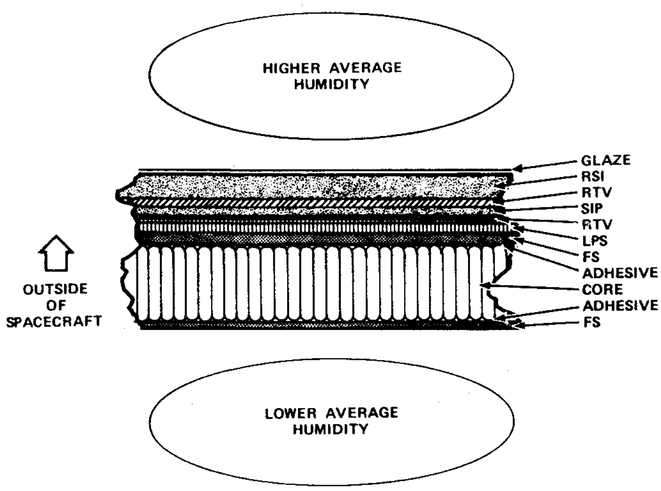


Fig. 3 Payload bay door sandwich panel.

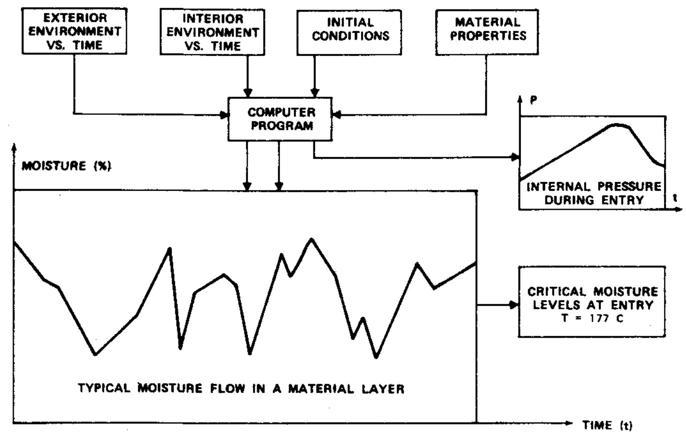


Fig. 4 Analysis process.

sulation (RSI) glazed on one side and separated from the surface of the panel by a pad of felt acting as a strain isolator (SIP). An RTV silicone rubber compound is used for the attachment of the RSI to the SIP, and the SIP to the LPS, respectively. The nine-layered program was used for the material combination GLAZE/RSI/RTV/SIP/RTV/LPS/FS/ADH on the exterior side of the core. The redundant layer in the nine-layered program was lumped into the LPS layer. The two layers, ADH/FS, on the interior side of the core were analyzed with the two-layer program. The coupling of the two programs and the incorporation of the core properties occurred in accordance with the previous section.

The goal of the analysis was the prediction of the moistrue content in each of the layers of the sandwich panel together with the internal pressure during the re-entry mode of the Space Shuttle Orbiter. The ingredients for such an analysis are depicted in Fig. 4. Obviously, the accuracy of the computed values depends directly on the proper description of the initial conditions, the environmental conditions inside and outside the PBD as functions of time, and on the reliable definition of the material properties affecting diffusion.

Initial and Environmental Conditions

The mission environmental time-lines in terms of temperature and relative humidity for Orbiter 101 were readily available and served as input for the PBD analysis. Subsequent to the scheduled delivery, the doors remain at Palmdale, California for 15 months. Regarding the initial conditions, it may be assumed that after 15 months the moisture level in all components of the sandwich panel will be in equilibrium with the rather constant relative humidity (RH) of 30% at that location. The already established mission time-lines prescribed in sufficient detail the environmental conditions after departure from Palmdale for the first 10 missions with respect to temperature and relative humidity. The response of the sandwich panel to the changing environment must be determined in time-step intervals varying, typically, between 1 min and 12 h in duration.

Material Properties

For each material, the properties affecting diffusion are comprised of 1) the diffusion coefficient D as a function of temperature, 2) the maximum absorptivity M_u at 100% relative humidity, 3) the value of the exponent "b" in Eq. (6) defining moisture equilibrium at relative humidities less than 100%, and 4) the density.

Table 1 contains a tabulation of the material properties established for the components of the PBD sandwich panels.

Summary of Computed Results

With the initial conditions, the environmental conditions, and the material properties as input data, the computer program allows the tracking of the moisture distribution and the internal pressure in the sandwich panels during all phases of the Orbiter missions. Figure 5 depicts the calculated moisture content over a period comprising the first five missions. At departure from Palmdale, the moisture content of 0.6% of the facesheet dry weight represents equilibrium with the environment at Palmdale. During the ferry flight to Kennedy Space Flight Center, storage at the Center, and prior to launch, the moisture content rises to about 1.0%. Despite the vacuum on orbit, only insignificant drying occurs because of the very low temperatures. The heavy bars (see Fig. 5) indicate the moisture change due to drying between departure

Table 1 Material properties affecting diffusion

Material	Diffusion constants, $cm^2/s \times 10^{-10}$ 24°C	60°C	21°C	177°C	M max, 100% RH	Density, kg/m^3
Graphite/epoxy (32% resin by wt.) (52% fiber by vol.)	3.1	17	320	6500	2.0	1520
Narmco 329-7 film adhesive ($0.3 kg/m^2$)	1.36	183	518	4800	3.5	1920
Screen plus 329-7 adhesive	3.1	17	320	6500	2.0	2080
Nomex core	3.1	17	320	6500	9.5 hex	88
RTV560	4400	...	...	276,000	0.83	1410

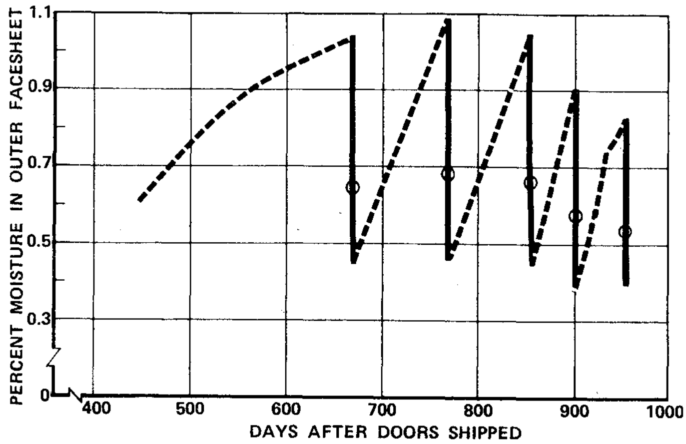


Fig. 5 Facesheet moisture contents during re-entry.

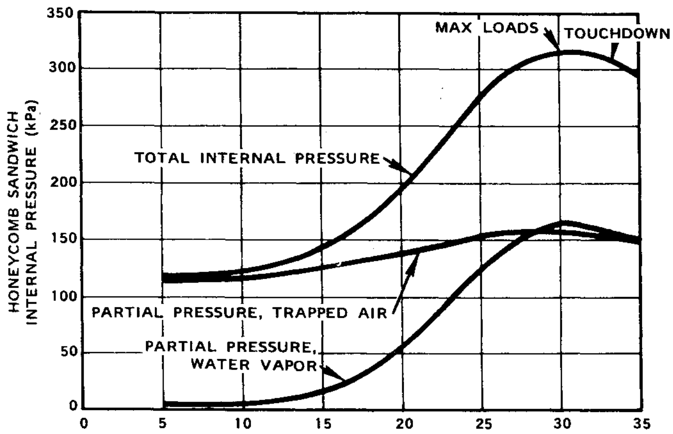


Fig. 6 Panel internal pressure during re-entry.

from orbit and the end of cooldown shortly after landing. The circles indicate the moisture content in the outside facesheets at the critical instant of maneuver load application and at a temperature then of 164°C. A maximum moisture content of 0.7% is expected under such conditions.

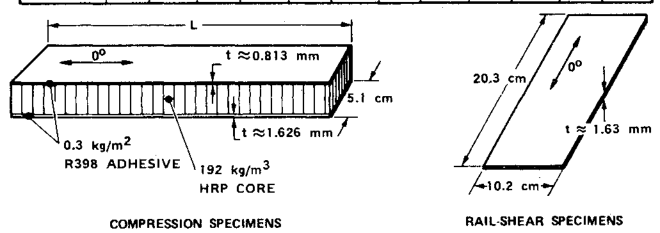
Figure 6 shows the concurrent rise of the internal pressure and temperature in the panel during re-entry. The maximum pressure of approximately 310 kPa is the aggregate of the partial pressure of the water vapor and of the trapped air. It is partially offset by atmospheric pressure at the time of maximum load.

The analysis of the moisture distribution in the sandwich panels is a necessary prerequisite for the proof of structural sufficiency. It remains to be shown with what margins of safety the outside FS's in their moist and hot state, can sustain the maneuver loads and whether the magnitude of the internal pressure threatens the strength of the bond lines.

Degradation of Laminate Strength and Stiffness Properties

During the early design phases of the PBD for the Space Shuttle Orbiter, a reduction of the matrix-dependent laminate strength properties of 934/T-300 graphite/epoxy under moist and hot conditions was anticipated and assumed not to exceed 30% of the dry and hot strengths. A corresponding deterioration of the stiffness properties was not expected. For the final design of the doors, a refinement of these assumptions and their substantiation was an obvious requirement. Since the complexity of the problem precludes an analytical derivation of the moisture effect on the properties of graphite/epoxy, a determination by test was the only alternative. The scope of the test program was limited to the

	SPECIMENS NOT THERMALLY SPIKED						SPECIMENS THERMALLY SPIKED					
	COMPRESSION				SHEAR		COMPRESSION				SHEAR	
	0-DEGREE DIRECTION		90-DEGREE DIRECTION		0-DEGREE DIRECTION		0-DEGREE DIRECTION		90-DEGREE DIRECTION		0-DEGREE DIRECTION	
MOISTURE CONTENT	24 C	177 C	24 C	177 C	24 C	177 C	24 C	177 C	24 C	177 C	24 C	177 C
0.0%	3	3	2	2	3	3	—	—	—	—	—	—
0.6%	3	3	2	2	3	3	3	3	2	2	3	3
0.8%	—	—	—	—	—	—	3	3	2	2	—	—
1.0%	3	3	2	2	3	3	3	3	2	2	3	3



SPECIMEN TYPE	L	TOP FACESHEET	BOTTOM FACESHEET
0° DIRECTION	.483 mm	$[0, \pm 45, 0]_S$	$[0, \pm 45, 0]_{2S}$
90° DIRECTION	.33 mm	$[90, \pm 45, 90]_S$	$[90, \pm 45, 90]_{2S}$

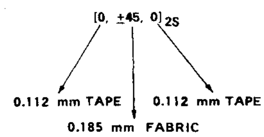


Fig. 7 Test matrix and test specimen configuration.

response of the sandwich panel facesheets considering that all other components of the PBD are less critical either because of lower temperatures, or lower moisture content, or both. In order to keep the test effort within manageable bounds, it was decided to develop reduction factors for the existing 177°C A-basis design allowables for dry laminates rather than to determine bona fide design allowables for moist laminates.[3] Specifically, the test objectives were: 1) the definition of reduction factors for the compression and shear properties in facesheet-type laminates containing various amounts of moisture at room temperature and at 177°C, and 2) the resolution of the question of whether the compression and shear properties of moist laminates are affected further by repeated exposures of moist laminates to 177°C, thus simulating the re-entry condition of the Space Shuttle Orbiter.

Test Program and Test Specimen Description

Testing was limited to the facesheet properties most susceptible to moisture degradation, i.e., compression in the two principal directions of the (0, ±45, 0)-laminates, and in-plane shear. Specimens containing approximately 0.0, 0.6, 0.8, and 1.0% moisture were tested under static loads at room temperature and at 177°C. Additional specimens were moisturized to 0.6, 0.8, and 1.0% and subjected to short-duration exposures to 177°C. After each thermal cycle, the original moisture content was restored and the residual strength of the moist specimens determined after up to 100 thermal cycles. A summary of the test program is contained in Fig. 7. For reasons of compatibility, the test specimens were configured identically to those of the previous design allowables tests, except that the thicknesses and the ply arrangements shown in Fig. 7 were chosen as multiples of the facesheet thickness to obtain pure compression and shear failure modes. All of the laminates had a nominal resin content of 32% and were cured for two hours at 177°C under 586 kPa autoclave pressure, followed by a postcure of four hours at 204°C. Subsequent to the bonding of the sandwich-type compression specimens, the exposed core edges were sealed with aluminum foil. In addition to the test specimens, shorter control specimens of otherwise identical configuration were prepared for the monitoring of the moisture content in the facesheets. The rail shear specimens were partially coated with adhesive to enhance the friction in the attachment areas. The instrumentation consisted of strain gages and thermocouples at the locations of expected failure.

Moisture Control

All specimens were initially placed in a 121°C oven and considered dry when periodic weighings showed no further weight changes. Specimens to be moisturized were then transferred to a humidity chamber maintained at 60°C and 95% relative humidity with the intent of producing a moisture content of approximately 0.6, 0.8, and 1.0% in the facesheets at the time of testing. A precise realization of those percentages was not necessary since, for the purpose of generating plots of specimen strength and stiffness vs moisture content, it sufficed to obtain moisture percentages in the desired range.

Thermal Spiking

Thermally spiked specimens were included in the test program to ascertain the effect of repeated exposures of moist specimens at 177°C on the strength and stiffness of graphite/epoxy laminates. Initially, dry compression and shear specimens were subjected to a constant humidity environment long enough to absorb approximately 0.6, 0.8, and 1.0% moisture in the facesheet. The determination of the laminate moisture levels was guided by analysis and by the absorption rates previously collected and presented in Table 1. After recording their total weight, the moist specimens were placed into a preheated 177°C oven and, upon attaining a temperature of 175°C, allowed to dwell for 5 min. Following the dwell, the test specimens were cooled under ambient conditions, and then returned to the humidity chamber to restore the loss of moisture during the thermal spike. This process was repeated 106 times and 97 times for specimens with 0.6 and 1.0% moisture, respectively, and 36 times for specimens with 0.8% moisture. Subsequently, the specimens were tested in their moist condition, at room temperature, and at 177°C, similar to the nonspiked specimens. The thermal spiking process is defined in Fig. 8.

Test Procedure and Test Results

The compression tests were performed under four-point loading with constant crosshead speeds of 5 mm/min for the 0°-direction specimens and 2.55 mm/min for the 90°-direction specimens. The high-temperature test sspecimens were inserted into a preheated 177°C oven. Upon attaining 174°C in approximately 10 min, the application of loads led to specimen failure at 177°C after an additional thermal exposure of 2-4 min.

The test procedure for the rail shear specimens was similar except that tensile loads were applied with a crosshead speed of 12 mm/min. The heating to 174°C required up to 20 min because of the heat sink effect of the test fixture. Specimen failure occured at 177°C after an additional thermal exposure of 2-5 min.

The test results for the strength and stiffness response of the compression specimens are summarized in Figs. 9-12. The solid lines link test data for unspiked specimens at room temperature and at 177°C. The test data for thermally spiked specimens are represented by solid circles. In each case the lowest, highest, and average test values are depicted. The scatter of the 0°-direction specimens is pronounced but, compared to the similar scatter of dry specimens in the previous design allowables test, apparently more a characteristic of the test method than the moisture content. Figures 13 and 14 contain similarly treated test results for the rail-shear specimens.

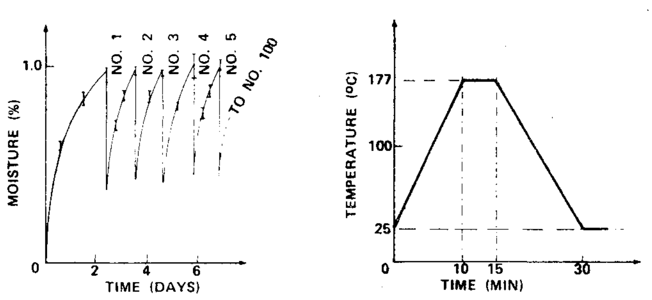


Fig. 8 Thermal spiking of test specimens.

Summary of Test Results for Laminates

The test results show that: 1) at ambient temperature the compression and in-plane shear strengths are not adversely affected by moisture; 2) the compressive and in-plane shear strengths at 177°C are reduced substantially and in proportion to the moisture content; 3) the exposure to thermal spikes of the desired severity and at constant moisture levels has no significant deterioration effect; and 4) the stiffness properties of the 934/T300 laminates at room temperature and at 177°C are not degraded by presence of moisture.

Degradation of the Bond Strength of Sandwich Panels

The sandwich panels consist of thin graphite/epoxy facesheets bonded to a non-vented phenolic core with an epoxy-based adhesive. At elevated temperature and in partial vacuum, the vaporization of the moisture absorbed by all components of the panel and the presence of the entrapped air in the core cells produce an internal pressure which tends to separate the facesheet from the core. In accordance with Fig. 6, the maximum pressure 30 min after departure from orbit, at 177°C, is approximately 310 kPa comprised of a partial vapor pressure of 159 kPa and a partial air pressure of 152 kPa. Considering the moisture/heat weakened condition of the epoxy adhesive, the ability of the panels to sustain such pressure loads could not be taken for granted. Fortunately, only a few square feet of door panel area will be exposed to the 177°C maximum temperature.

Internal Pressure Capability of Sandwich Panels

A quantitative evaluation of the internal pressure capability of the PBD skin panel is difficult in several respects. Since the thin facesheets tend to bulge between supporting cell walls,

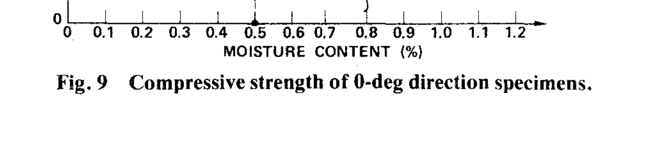


Fig. 9 Compressive strength of 0-deg direction specimens.

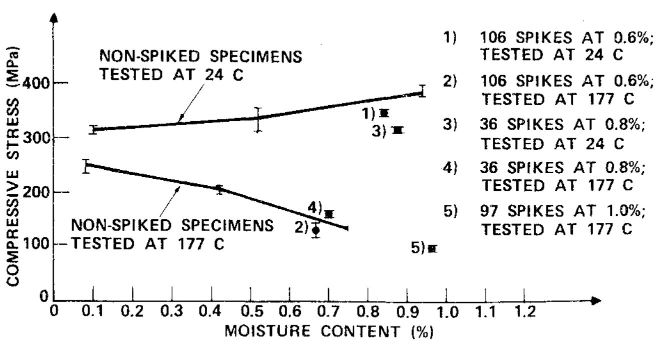


Fig. 10 Compressive strength of 90-deg direction specimens.

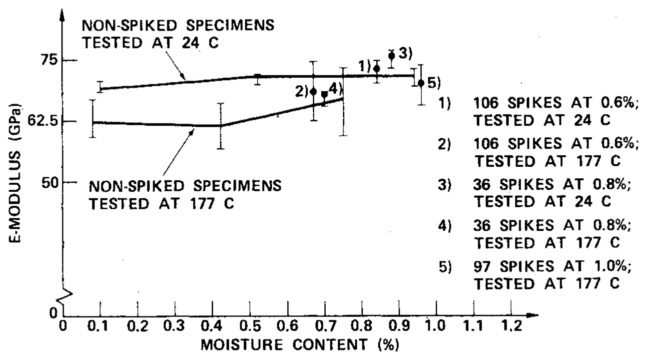


Fig. 11 Stiffness of 0-deg direction specimens.

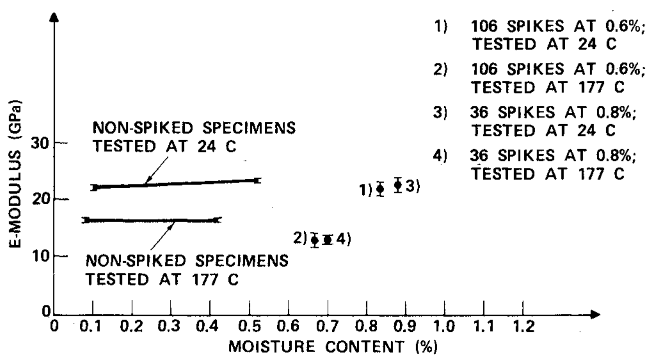


Fig. 12 Stiffness of 90-deg direction specimens.

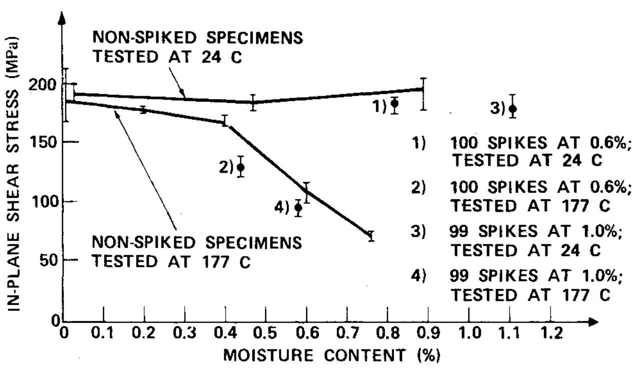


Fig. 13 Strength of rail-shear specimens.

stress concentrations occur in the fillets of the adhesive which promote a failure in the adhesive layer rather than a tensile failure of the core. The expected failure mode precludes a strength investigation by flatwise tension tests since the standard test apparatus constrains the critical deformations of the facesheets. A direct measurement of the pressure rise in a single cell of the nonperforated core must also be ruled out because any one cell may not be descriptive of the panel behavior, not to mention the difficulty of accurate pressure measurements in very small volumes.

Test Specimens and Test Procedure

These considerations led to the choice of 0.30- ×0.36-m sandwich panels as test specimens. The center portion of the panels were of flight configuration except that each cell of the core was vented, either by perforating or by slitting of the cell walls, to allow uniform pressurization of the entire panel interior. The relatively fragile phenolic core was surrounded by a narrow strip of dense and perforated aluminum core for the stabilization of the panel periphery. Several of the panels contained a deliberately induced adhesive void of either a 13- or 19-mm diameter between one of the facesheets and the core

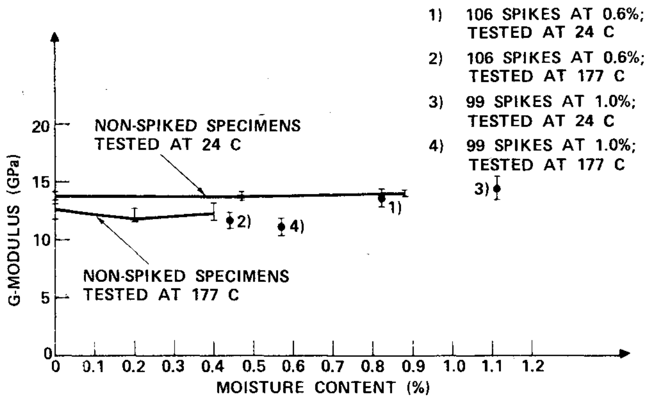


Fig. 14 Stiffness of rail-shear specimens.

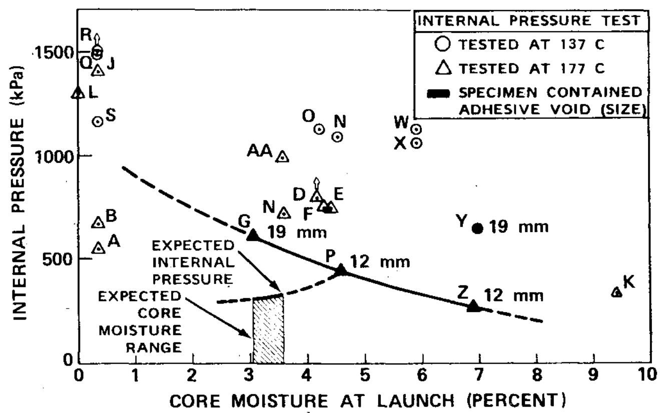


Fig. 15 Internal pressure test results.

in order to assess the significance of such disbonds. Disbonds as small as 6 mm in diameter can be detected by nondestructive testing methods.

The test objective was the determination of the maximum internal pressure the panels were capable of sustaining in dry and moist states at temperatures in the 138-177°C range. The latter temperature was included to provide information beyond the scope of the PBD problems. Panels to be tested in the dry state were allowed to contain up to a total of 1.5 g moisture. The panels to be tested moist were exposed to a humidity chamber maintained at 95% relative humidity and 60°C after sealing the panel edges with aluminized tape to preclude the entrance of moisture through the vented core walls. The panels were weighed periodically until an analytically prescribed moisture gain was achieved which, at elevated temperature, produced the vapor pressure expected during the re-entry phase of the Shuttle Orbiter.

The test specimens were mounted in a picture-frame type aluminum fixture capable of sealing the panel edges by means of silicone rubber inlays. An external N_2 supply was tapped into the fixture for augmentation of the vapor pressure. The resulting panel pressures were measured by two pressure transducers located at opposite panel edges; a third transducer was attached to the N_2 line. Thermocouples were used to monitor the test specimen facesheet and frame fixture temperatures.

The mounted test specimens were placed in an oven. The oven temperature was then raised from ambient to the desired test level of 177 or 138°C. The resulting pressure due to the entrapped air in core cells and the vaporizing moisture was then increased through the N_2 source until panel failure occurred. The heatup time of the panel to 177°C was approximately 40 min. Analysis showed that almost no moisture would be lost from the interior portion of the panel (adhesive layers and core) during the 40-min heatup time. The N_2 pressurization phase required between 5 and 10 min.

Test Results

A total of 24 test panels were prepared. In the early phases of the test program, sealing problems were encountered with panels A and B, rendering their test results useless. Fourteen panels were tested in the moist condition. Of the remaining eight, five panels (J, L, Q, R, and S) were tested dry at 177 and 138°C; two panels (T and U) were used for creep tests prior to failing them in the dry state at 177°C; and one panel was a spare. Panels A and B were used in the development of the pressurization method. The results for panels A and B are shown in Fig. 15, but were discarded.

Of the panels tested in the dry condition at 177 and 138°C, panels J, L, Q, R, T, and U sustained in excess of 1310 kPa before failing or, as indicated by the upward directed arrow in Fig. 15, before leakage of the seals forced the termination of the test. Panel S, at 138°C, failed unexpectedly low at 1186 kPa. The presentation of the test results in Fig. 15 of the moist panels vs moisture in the core at launch is self-explanatory.

Panels T and U were used for a study of potential creep damage in the hot and moist adhesive. Panels T and U were placed in a humidity chamber operated at 50% relative humidity and 82°C with the intent of complete saturation at that humidity level. The moisture gain, after approximately 90 days exposure, was measured as 6.2 and 5.6 g, respectively, i.e., in the range of the other moist panels, but apparently with a somewhat different moisture distribution. The creep tests commenced with the application of a test temperature of 177°C in the facesheets at which combined vapor and trapped air pressures of 269 kPa in panel T, and of 228 kPa in panel U, were measured. Subsequently, the internal pressure was increased to 345 kPa and maintained at that level for 25 h at 177°C. The loss of internal pressure due to the drying of the panel was continually balanced by the addition of N_2 gas. During the test, no abnormal effects were observed. After 25 h, the panels were found completely dry and were then pressurized after reaching 1351 kPa and 1517 kPa in panels T and U, respectively. In both cases, however, the tests were discontinued because of seal leakage.

Summary of Test Results for Sandwich Panels

Figure 15 showed that, at the level of moisture expected to be in the adhesive/core substructure at entry, the capability of the panel is more than twice the expected panel internal pressure. It must be emphasized that most of the panel area will be exposed to temperatures considerably lower than 177° C. It is, therefore, apparent that from an internal pressure standpoint the design of the graphite/epoxy PBD is adequate.

Summary

Computational methods have been developed for predicting the level of absorbed environmental moisture in the Space Shuttle Orbiter graphite/epoxy panels. Based on analytical results, the requirements for a test program were defined to obtain "knock-down" factors for A-basis allowables previously determined for dry graphite/epoxy laminates at 24 and 177°C. Drying data and sandwich panel internal pressure data gather from the test program have been used in turn to validate the analytical methodology.

Application of the "knock-down" factors to the sandwich panels of the Space Shuttle Orbiter showed positive design margins in all areas. Results of the internal pressure portion of the test program proved that the small area of the PBD subjected to 177°C can withstand the maximum internal pressure expected.

The combined analytical/test program has demonstrated the integrity of the Space Shuttle Orbiter graphite/epoxy PBD design.

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