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Preface

The work described in this report was performed by the Engineering Mechanics Division of the Jet Propulsion Laboratory.

All of the sample structures discussed in this report were fabricated and most were tested by Rohr Corporation at Riverside, California under JPL Contract 951612.

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Abstract

Extraterrestrial planetary entry probes require new concepts in lightweight entry-vehicle design if the scientific payloads of missions are to be maximized. For a number of missions, communications and sensing requirements imply the need for an RF transparent aeroshell structure. Such an aeroshell would increase the view angle of the transmitters and receivers while providing equivalent protection from the entry environment.

Presented are the results of an extensive study of lightweight resin-fiberglass honeycomb-sandwich structures that was performed to define the fabricability and economics of RF transparent structures and to provide design data for detail analysis. As part of this study, a comparison was made with lightweight adhesive-bonded aluminum honeycomb-sandwich structures so that any penalties for RF transparency could be established. The results showed that there was little difference in strength to weight in lightweight configurations for resin-fiberglass and aluminum honeycomb-sandwich structures. Aluminum showed some advantage in stiffness to weight, but resin fiberglass was easier and less expensive to fabricate and was adaptable to a wider range of aeroshell configurations.

Fabrication Development of Lightweight Honeycomb-Sandwich Structures for Extraterrestrial Planetary Probe Missions

I. Introduction

Entry into the atmosphere of planets other than earth is primarily constrained by our lack of knowledge about the particular atmospheres and by either tenuous atmospheres or high relative velocities at entry. To decelerate at high enough altitudes to allow significant atmospheric data sampling and to prevent excessive heating at high velocities, vehicles with low ballistic coefficients (essentially, weight per unit area) become extremely desirable. Typical ballistic coefficients for atmospheric probing of Venus or Mars are as much as an order of magnitude lower than low ballistic coefficients for earth reentry vehicles (i.e., in the *Apollo* program). Fabrication of lightweight structures for the very low ballistic coefficient probes is often limited by minimum gage material constraints. Preliminary atmospheric entry studies at the Jet Propulsion Laboratory (JPL) indicated that honeycomb-sandwich constructions have wide applicability to a variety of potential missions. A study program was initiated at JPL to define minimum gage in honeycomb-sandwich construction and to compare resin-fiberglass and metallic honeycomb with each other and with monocoque structures or other common alternatives. Resin-fiberglass structures proved to be of special interest because of their potential RF transparency requirements and apparent potential to make significant decreases in cost for the same performance.

To follow the directions indicated by the study program, a contract was granted to Rohr Corporation to investigate lightweight honeycomb-sandwich structures. The data from this investigation are reported in Ref. 1. In the present report, the data are analyzed and compared to expectations. Recommendations are made regarding the use of the data, and specific comparisons are made between adhesive-bonded resin fiberglass and adhesive-bonded metallic honeycomb-sandwich constructions.

II. Matrix of Parameters Studied

A systematic program was followed to investigate the effect of individual honeycomb-sandwich configuration-parameters on the performance of samples fabricated under normal or close to normal shop practices. Details of the program are presented in Ref. 1. Tooling costs were held to a minimum and all curing was done under vacuum bag pressure. The latter constraint was important because successful demonstration of structural efficiency using vacuum bag pressure precluded the requirement for large autoclaves for anticipated large (>20-ft diam) vehicles. The specific material parameters investigated in the program are listed in Table 1. The values of individual design parameters were perturbed about some nominal material combination, and important variables were combined to test coupling effects.

Table 1. Material parameters investigated

Facesheet	Adhesive	Core
Resin fiberglass honeycomb sandwich		
Resin system A-stage vs B-stage impregnation Initial resin content Reinforcement material Fabric style Fabric yarn Fabric finish Number of plies Rotation of warp Facing splice Facing repair	Resin system Thickness or unit weight Support	Resin system Support fabric Cell shape Cell size Number of resin dips Thickness Core splices Core repairs
Adhesive bonded aluminum		
Alloy Heat treat Thickness	Resin system Thickness or unit weight Support	Alloy Heat treat Cell shape Cell size Thickness Core splice

Table 2. Nominal lightweight resin-fiberglass honeycomb-sandwich composite

Control parameter	Nominal value
Facesheet	
Resin	Phenolic (Adlock 851)
Reinforcement	E-glass (cloth)
Glass cloth weave	Style 112
Glass cloth yarn	Two-strand twisted
Glass cloth finish	Volan A 1100
Number of plies	4
Ply rotation	45-deg rotation of warp direction on each succeeding ply
Splices	None
Repairs	None
Adhesive	
Resin	Epoxy (FM96U)
Scrim cloth	None (unsupported)
Unit weight	0.03 lb/ft^2 (4 mils thick)
Core	
Resin	Phenolic (HTP)
Reinforcement	Fiberglass cloth
Cell shape	Hexagonal
Cell size	$\frac{3}{16}$ in.
Core thickness	$\frac{3}{4}$ in.
Extra resin dips	None on 4-lb/ft^3 core
Splices	None
Repairs	None

Initial studies were made on flat panels. Fabrication requirements were first determined and properties measured on these panels with the appropriate ASTM test standard (see Ref. 1 for details). The best material combinations selected from the flat-panel investigation were further utilized in the fabrication of small doubly curved 2-ft-diam sphere-cone models. These models had a two-fold function. First, they proved or disproved fabricability in complex shapes for the various preferred material combinations. Second, they furnished models for a test program to verify reproducibility in complex structure fabrication and to investigate the coupled effects of sterilization, launch, space transit, and entry environments on structural performance. The data from the overall investigation were also utilized to build a 6.5-ft-diam phenolic fiberglass honeycomb-sandwich aeroshell for an early Mars probe mission as part of the Capsule System Advanced Development (CSAD) program at JPL. The fabrication of this aeroshell is reported in Ref. 2.

III. Flat Resin-Fiberglass Configurations

Early in the program a nominal lightweight resin-fiberglass honeycomb-sandwich composite was chosen before significant data were available. The nominal configuration is shown in Table 2. The particular high-temperature phenolic resin was chosen somewhat arbitrarily because of availability. Four plies of a plain weave fiberglass cloth (such as style 112) was initially thought to be a reasonable minimum gage when each succeeding ply was rotated 45 deg, because the non-isotropic weave properties would tend to balance out. The adhesive selected was the only one available at that time combining low unit weight with good fabricability and strength. The core was also standard and the lightest available in small-cell sizes. Each of the 20 control parameters was investigated separately by making samples, when possible, which differed from the nominal in only one parameter. The results of these studies are discussed below.

A. Facesheet

1. Resins. The 27 facesheet resin systems investigated in this program are listed in Table 3. The selection of resins was based on JPL and Rohr experience and

Table 3. Resin systems investigated for facesheet fabrication[a]

Resin systems	Eliminated after initial test	Fully evaluated
Phenolics		
Adlock 851		X
Adlock 453		X
91 LD		X
Conolon 506		X
SC 1008		X
Phenyl silane		
SC 1013		X
Epoxies		
EG-35		X
EG-9300		X
E 740 B		X
E 792		X
Narmco 588		X
Narmco 500	X	
Epon 815/Z	X	
Epon 815/CL	X	
Epon 826	X	
Epon 828/1031	X	
EG-4B	X	
E-787	X	
BP-907	X	
Epoxy novalacs		
DEN 438		X
DEN 431	X	
Polyesters		
PG-HTA		X
Vibrin 135	X	
Vibrin 136	X	
Polyimides		
2501	X	
Trevarno F170		X
Narmco 1832		X

[a]For supplier source see Ref. 1.

manufacturer claims of good fabricability or high-temperature stability. Initial screening was done with 8-ply laminate flexure tests at various temperatures. The flexure results for representative average materials are shown in Fig. 1. One of the epoxies (marked "highest-temperature epoxy" on the figure), all of the phenolics, and the polyimides were almost identical in flexure. The apparent dropoff in the polyimide samples at 350°F may have been caused by the relatively low-temperature cure utilized, which does not allow achievement of the full high-temperature strength of the material. The polyimide flexure data may be compared to the extensive laminate flexure data in Ref. 3 measured at NASA Langley Research Center (LaRC). The data obtained by the Rohr Corp. have about the same curve shape but are 25% lower than the data obtained by LaRC. This shift was expected since each ply was rotated 45 deg at Rohr, whereas the warp direction was aligned in each ply at LaRC. The low-temperature epoxies, which were difficult to handle, were eliminated with the Vibrin polyesters and the Dupont 2501 polyimide, which, in the available B-stage form, did not have the proper tack to allow adequate handling during fabrication. The B-stage preimpregnated cloth was found to be simpler to fabricate and more reproducible in end product than the A-stage wet layup resin systems, and all further work was done with B-stage resins. The fabricable materials with adequate high-temperature strength were fully evaluated (Table 3).

Sandwich-flexure facing strength and edgewise compressive strength are shown in Fig. 2 for each of the generic resin systems studied. The low values shown for facing-flexure strength perpendicular to the core-ribbon direction were probably caused by inadequate test-sample geometry rather than any significant facesheet strength difference in the two directions. The weaker core-shear properties perpendicular to the ribbon direction could have caused premature failure if the sample length-to-width ratio had not been large enough to constrain the failure mode to the facesheet. The phenolic and polyimide data represent the averages of the resins studied, since little real difference was apparent. The epoxy data are for EG 35, which showed considerably better high-temperature properties than the other epoxies. In fact, the measured properties of the EG 35 were so similar to one of the phenolic systems that the infrared spectra had to be examined to verify the large differences in molecular structure. Based on these data and the 8-ply laminate flexure shown in Fig. 1, the phenyl silane, epoxy novalac, and polyesters were dropped from further consideration. The phenolics, the epoxy, and the polyimides

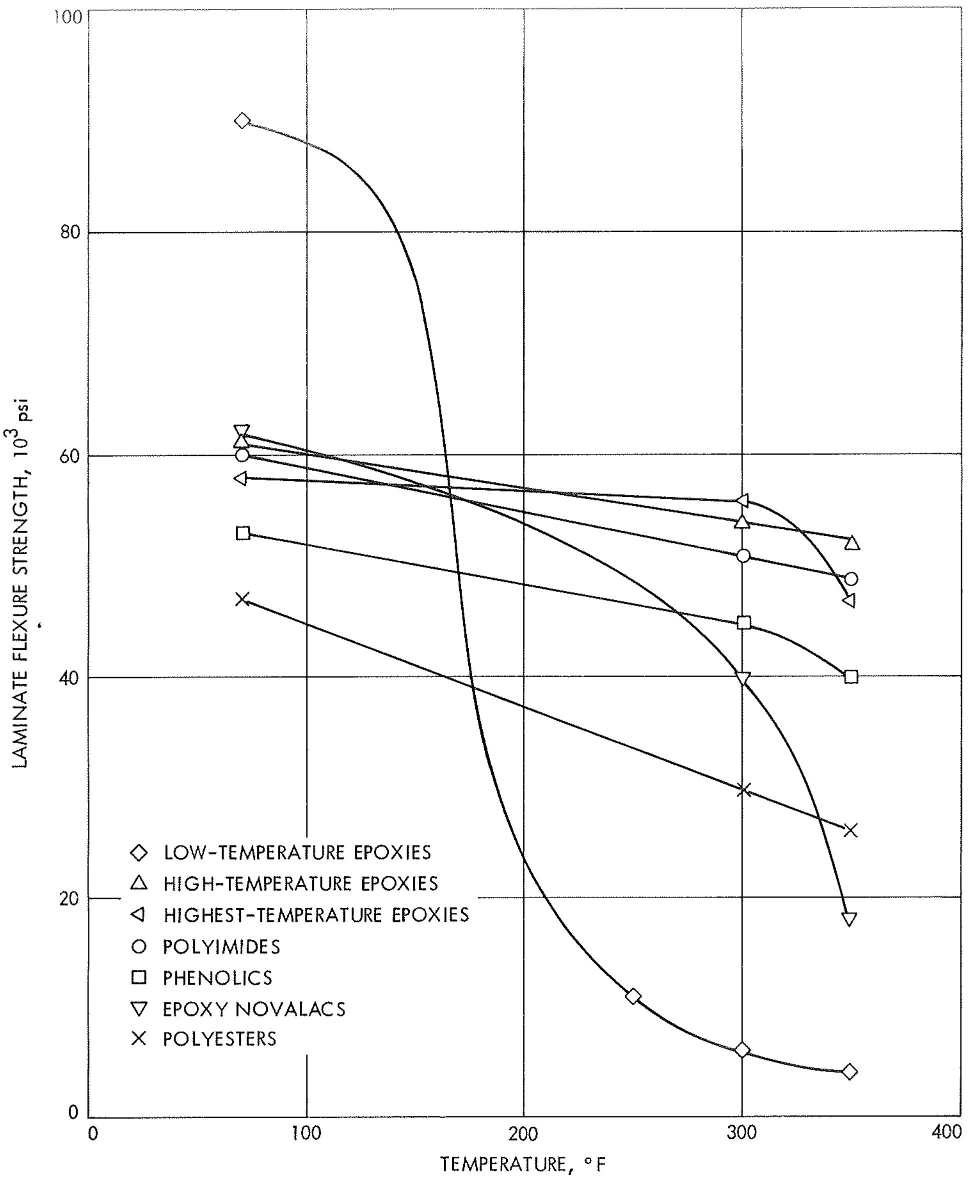


Fig. 1. Flexure strength of 8-ply laminates

have little difference in room-temperature flexure or edgewise compression strength.

In Fig. 3, the same properties are compared for these three resin systems at −150°F and 350°F. The superiority of the polyimide for high-temperature utilization is indicated. The percent of room-temperature strength at 350°F is 80% for the polyimides, 35% for the phenolics, and 15% for the epoxies. Polyimide would apparently be more desirable for any high-temperature use environment and would therefore be a likely candidate for a Venus entry-probe structure. Phenolic is much easier to handle during fabrication and, since it has sufficient short-time strength at temperatures up to 600°F, it is considered a suitable candidate for a Mars entry-probe structure and was used as the nominal material for the rest of the parameter perturbation.

2. *Fabric material.* Only standard E glass and the newer high-strength S glass were examined in this study. The only lightweight S-glass fabric available was in style-120 weave. The comparative flexure strengths and edgewise compressive strengths of the two materials are shown in Fig. 4. The edgewise compression data for the S-glass configuration show the same 25% increase in strength over E glass normally encountered. The

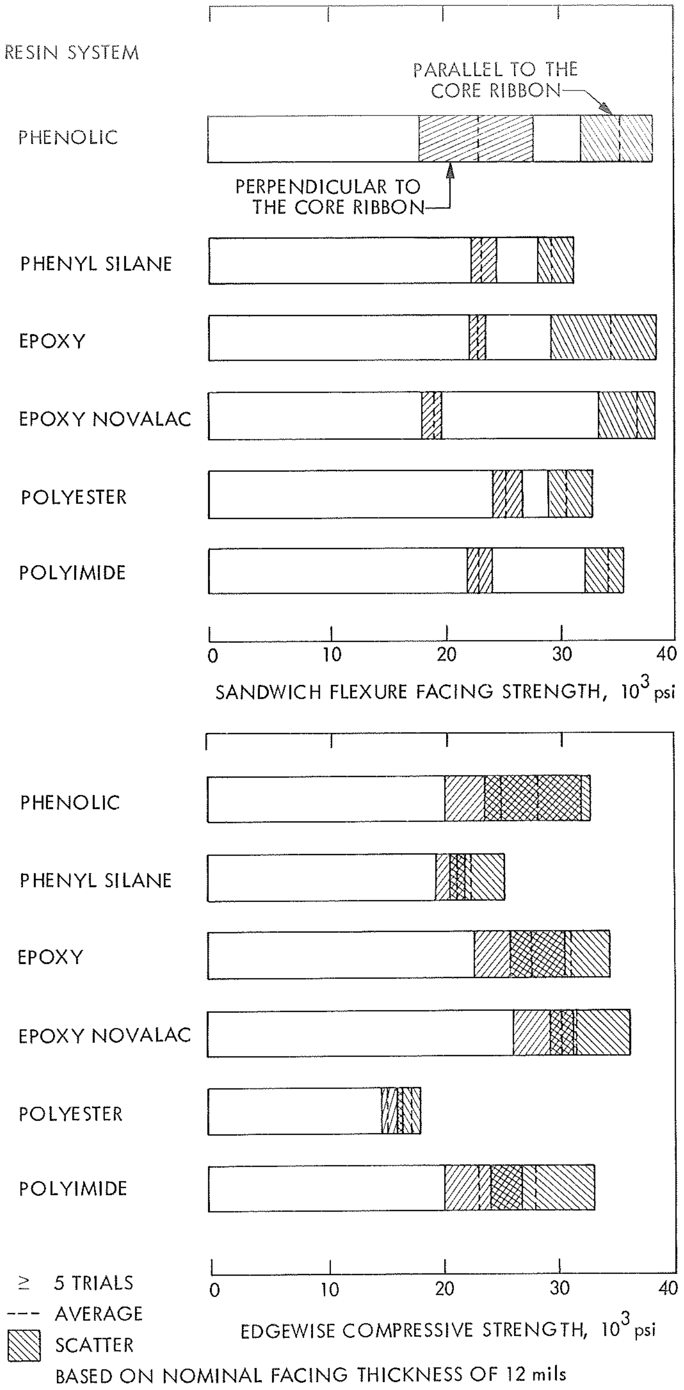


Fig. 2. Comparison of lightweight honeycomb-sandwich facing strengths for best available resin systems

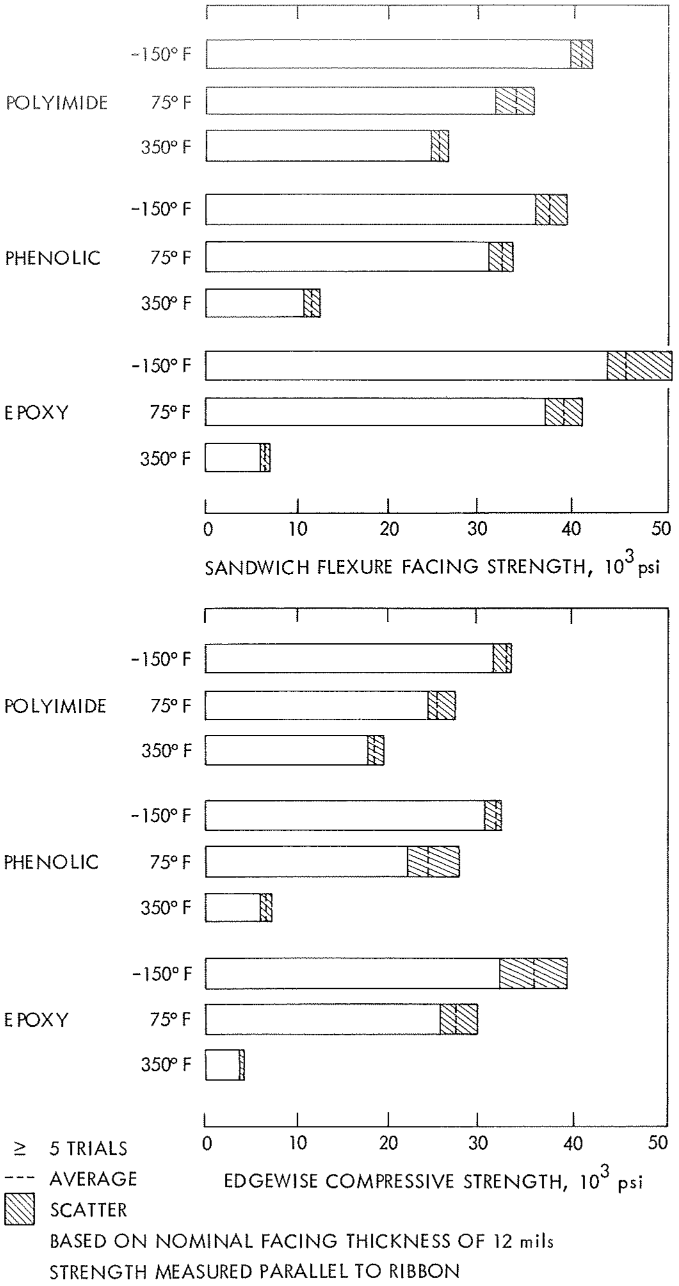
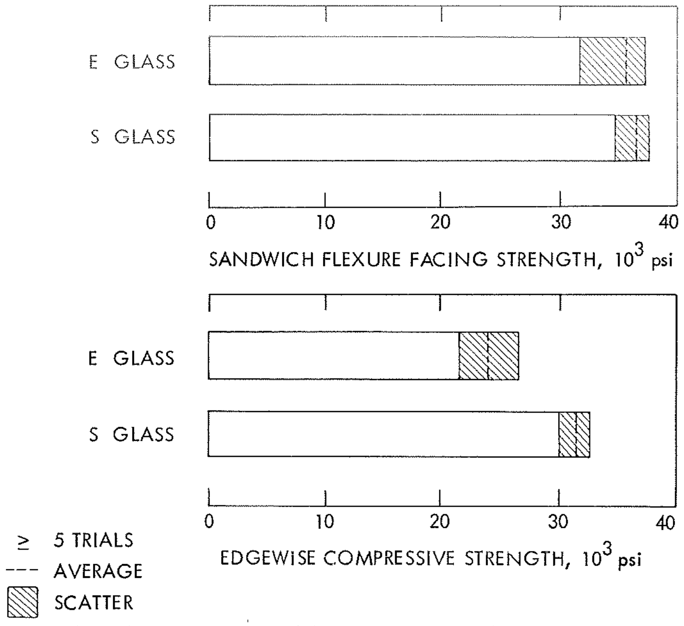


Fig. 3. Effect of temperature on principal honeycomb-sandwich facing properties for major resin systems

sandwich-flexure data, however, show little improvement in strength with the use of S glass. For the particular 10-in. span used in the flexure measurement, the added strength of S glass may not be realizable because of premature core failure. However, this possibility has not been determined because longer spans and other S-glass configurations were not tested as part of this study.

The D glass was considered in the program, but in this honeycomb-sandwich configuration the dielectric improvement over E glass could not be realized. High modulus carbon or graphite cloth was also considered in this program. Preliminary investigation implied a



MATERIAL IS STYLE-120 CLOTH WITH NOMINAL FACING THICKNESS OF 15 mils

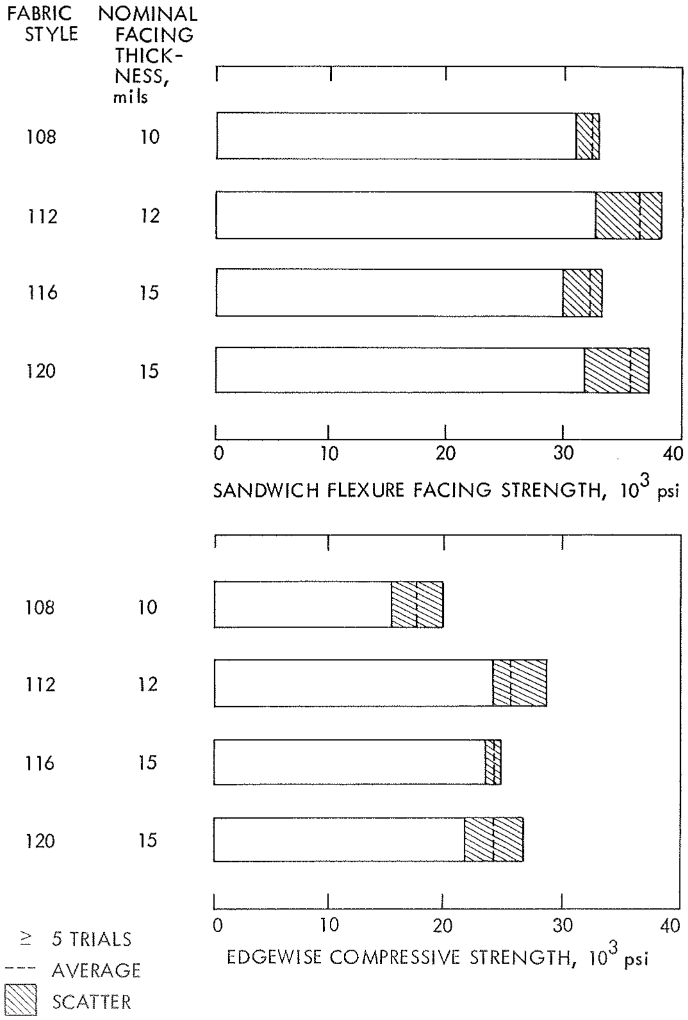
STRENGTH MEASURED PARALLEL TO RIBBON

Fig. 4. Comparison of facing strengths for fabric materials

potentially competitive strength-to-weight ratio with special advantages for specific mission constraints. The lack of available resources prevented full investigation of this fabric material.

3. ***Fabric weaves.*** Fabric weaves were chosen to emphasize isotropic properties whenever possible. The four lightweight varieties studied are compared in Fig. 5. Fabrics of styles 108, 112, and 116 are all plain weaves (one under, one over). The two major directions (warp and fill) are essentially identical in styles 112 and 116, but the fill direction is only 60% of the strength of the warp in style 108. The lighter fabric was not available in a balanced weave. Style-120 cloth is a crowfoot satin weave (three over, one under) that is identical in apparent strength with style 116, but is more easily conformed to complex shapes. There is no apparent difference in flexure strength between the four styles. On the other hand, style 108 appears to be considerably weaker in edgewise compression. There are three possible reasons for this apparent weakness, none of which have been confirmed in this program. First, the fill direction is considerably weaker than the warp direction and this should be indicated by both flexure and edgewise compression data. Second, flatwise tension data were also low, implying potential adhesive failure in the edgewise compression tests. And third, the measured facesheet thicknesses for style 108 are not consistent with the other nominal fabric thicknesses and this inconsistency may contribute to the calculated differences in strengths. In any case, style 108 was dropped from further consideration and style 112 was chosen as the lightest cloth consistent with good strength properties.

4. ***Fabric yarns.*** Standard yarns used in weaving cloth consist of two twisted strands that are used to decrease the effect of local weaknesses caused by imperfections in one of the strands. With modern techniques, local strand imperfections can be reduced, and equivalent strength fabrics can be made from single larger strands in which the detrimental effect of twisting is eliminated. A single strand equivalent of style 112 was made specially for this program by J. P. Stevens & Co. In Fig. 6, flexure



STRENGTH MEASURED PARALLEL TO RIBBON

Fig. 5. Comparison of facing strengths for lightweight fabrics

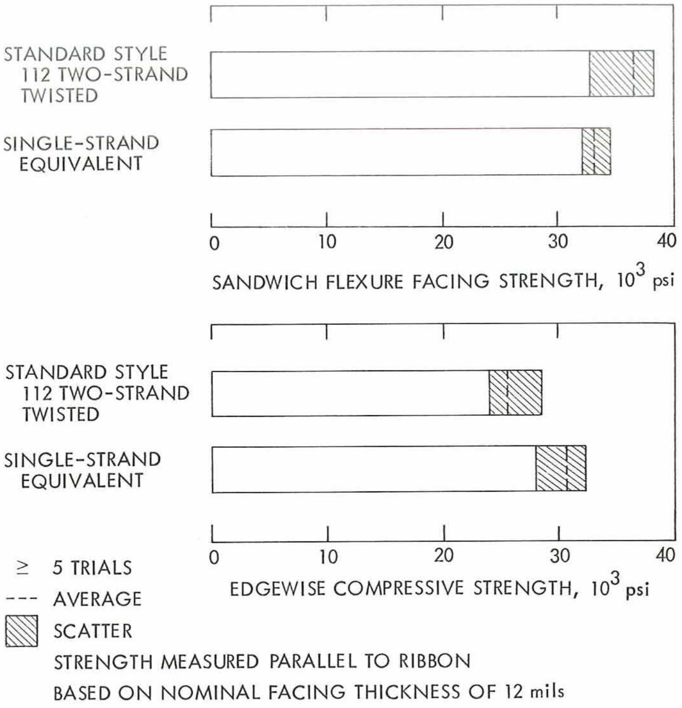


Fig. 6. Comparison of facing strengths for fabric yarns

strength and edgewise compressive strength of honeycomb-sandwich samples that used this special fabric are compared with the nominal configuration. Although edgewise compressive strength appears to be slightly improved, unit panel weights are similar, and the apparent increase is not sufficient to overcome the additional cost of manufacture. Lighter cloth is potentially possible using this technique, but present requirements do not warrant the effort.

5. *Fabric finish.* In this program, S-935 silane finish was compared to Volan A chromate finish on style-112 facing fabric. The comparison is shown in Fig. 7. Silane fabric finishes are supposed to provide greater composite strength than the more standard chromate finishes because they provide a better bond between the glass and the resin. Actually, in these tests, the silane finish composites provided apparent decreases in strength over the Volan A finished composites. Since sufficient data were taken to imply that the drop was real, the apparent disagreement is probably the result of a configuration effect or an inadequate application of the silane finish to these particular style-112 fabrics. It was not believed that a better application of the finish would provide significant improvement in properties for this configuration, so silane finishes were not considered during the rest of the program.

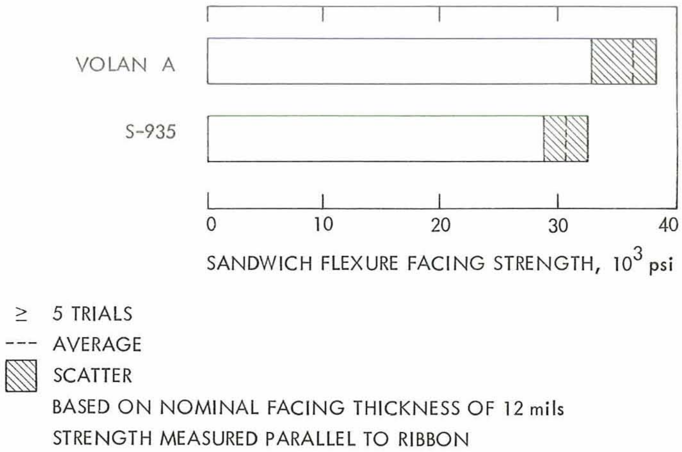


Fig. 7. Effect of fabric finish on honeycomb-sandwich facing strength

6. *Number of plies.* To show layup effects on strength, 2-, 4-, 6-, and 12-facesheet plies were investigated. The comparative strengths shown in Fig. 8 imply no significant change in strength for a nominal facing thickness of 3 mils per ply. The slight drop in edgewise compressive strength for the 2-ply sandwich could be caused by local buckling of the thin facesheet but the magnitude of the drop is not necessarily significant. The other directions gave similar results, so even the 2-ply sandwich can be considered reasonably isentropic.

Since 2-ply sandwiches are reasonably isentropic, comparison of similar thicknesses, but different numbers of plies, seemed apropos. Figure 9 shows the flexure strength of two sandwich composites, one with the 18-mil facing made from six plies of style-112 cloth, and the second from two plies of style-181 cloth. Although the two plies appear somewhat stronger, that fact is not significant when Fig. 9 is compared to Fig. 8. It would appear, though, that thickness may be achieved by almost any combination of cloths as long as the warp and fill directions provide somewhat similar strengths.

7. *Rotation of plies.* When the plies are rotated 45 deg, a 45-deg gap is created between the directions of the individual yarns. Once six plies are achieved, 60-deg rotation is possible with one warp reinforcing one fill and only 30 deg between yarn directions. Such a facing should be more isentropic but may be slightly weaker in the major directions since a smaller number of yarns are parallel to the test direction. Figure 10 tends to support this conclusion. No greater differences are apparent in other properties or in other test directions.

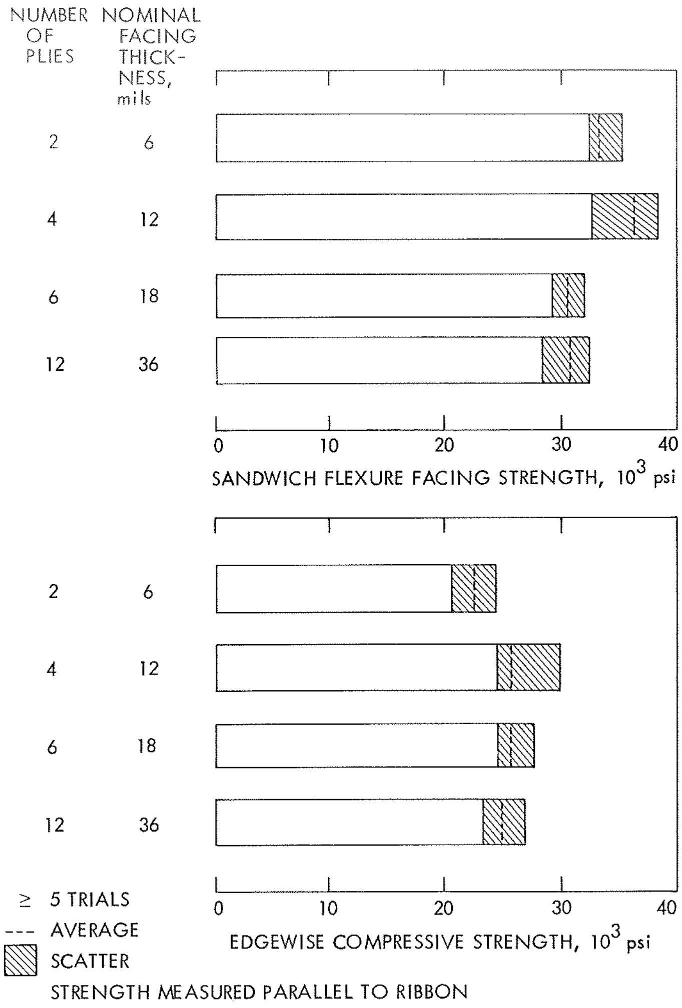


Fig. 8. Honeycomb-sandwich facing strength as a function of the number of facing plies

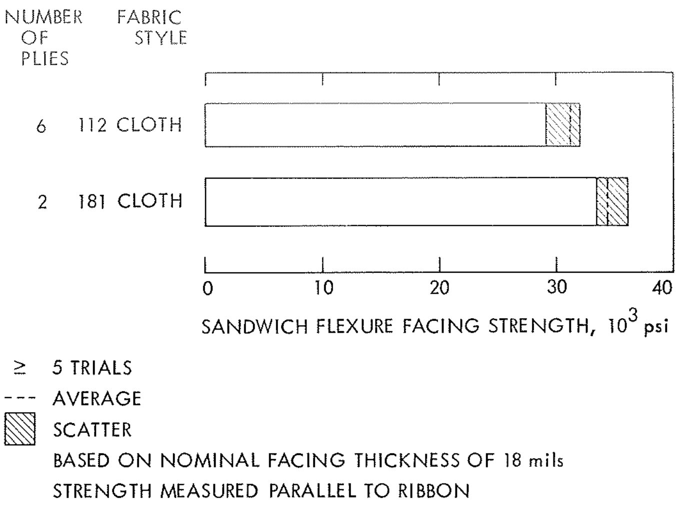


Fig. 9. Comparison of flexure facing strength for different fabrics of different plies

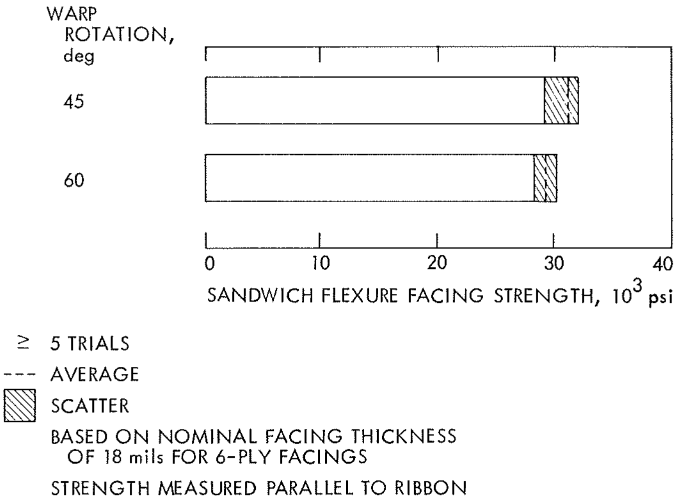


Fig. 10. Effect of ply rotation on flexure facing strength

By the same reasoning that indicated the 2-ply facesheet to be reasonably isentropic, the 3-ply with a 60-deg rotation between plies should be considered even better. This reasoning also allows greater thickness control for the thinner facesheet requirements.

8. *Splices.* Large constructions require facesheet splices, so some estimate of the decrease in strength caused by splices was necessary. The potential effect of splices being accidentally or purposely aligned from ply to ply also had to be investigated. Figure 11 presents a comparison of the effects on flexure strength of aligned, staggered, and no splices. The presence of splices contributed no apparent degradation in composite strength, although some increase in panel-unit weight must be allowed for in any structural design. The staggered splice is recommended over the aligned splice, even though no apparent difference in strength was noted.

9. *Repairs.* In resin-fiberglass sandwich construction, imperfections or damage to the facesheets can be repaired if the plies are carefully stripped back one at a time, which leaves a stepped effect as shown in Fig. 12. New adhesive and new plies can then be fitted back in place and vacuum-bag cured without degradation to the original structure. Flexure- and flatwise-tension tests across the stepped repair splice show the same lack of degradation as the facesheet splice data in Fig. 11. This sandwich construction has a particular advantage over metallic honeycomb in that it allows local repairs without significant change in panel weight.

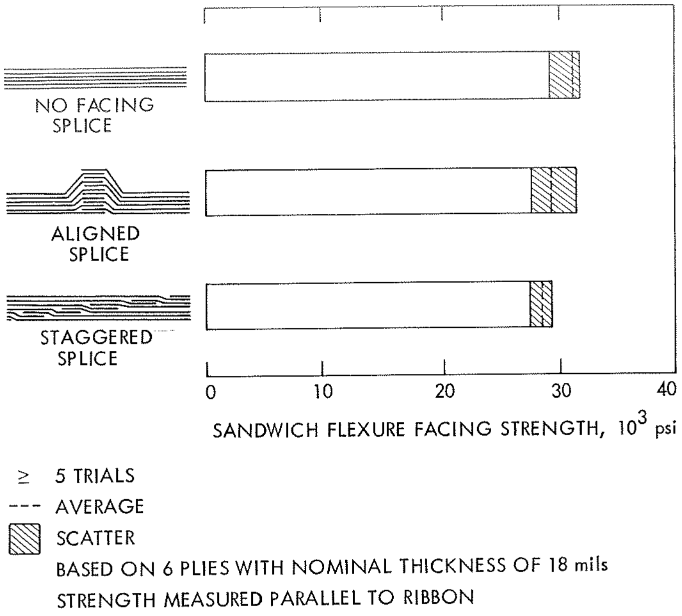


Fig. 11. Effect of facesheet splicing on flexure facing strength

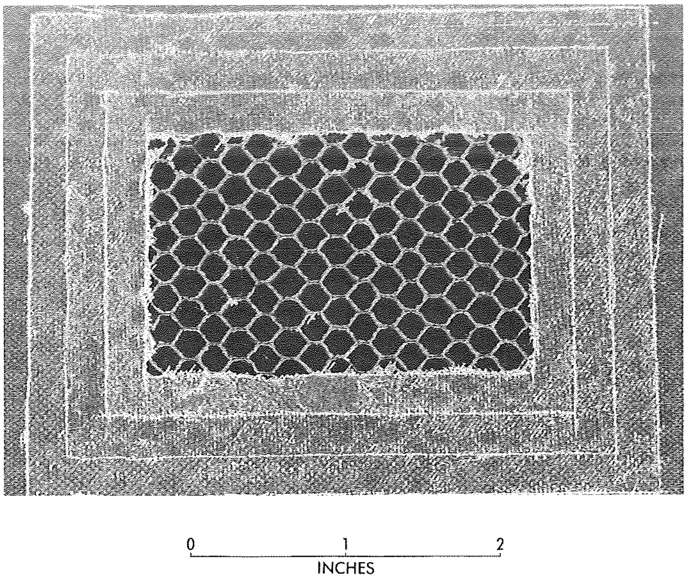


Fig. 12. Facesheet repair technique

B. Adhesive

1. Resins. Lightweight epoxy, epoxy-phenolic, and polyimide adhesives were investigated at different stages in the program. A summary of the flatwise tensile strength data for all of the configurations investigated is shown in Table 4. The epoxy and epoxy-phenolic data were obtained for phenolic facesheets and core, the polyimide data were obtained for polyimide facings and core. For equivalent reinforcement (see 1070 glass-cloth-supported samples) the epoxy and polyimide adhesives provide the same strength, and the epoxy-phenolic is about 20% lower. The polyimide/1070, on the other hand, showed twice the peel strength of the epoxy/1070 adhesive (5.0 vs 2.5 psi).

Important differences are shown in the temperature effects depicted in Fig. 13. The polyimide retains about 75% of its room-temperature strength at 350°F but the epoxy retains less than 20%. A drop in flatwise tensile strength at −150°F is also shown in Fig. 13, and this drop contrasts with the flexure-strength increase shown in Fig. 3. The decrease in low-temperature strength implies transition to some brittle mode of adhesive failure. As long as the adhesive is epoxy, little difference is seen with epoxy or phenolic facings or with four or six plies. The epoxy-phenolic adhesive, though not shown in Fig. 13, has considerably better properties than the epoxy adhesive at higher temperature and, in spite of its slightly lower room-temperature strength, is preferable for most entry-probe designs in which high allowable structure temperatures after entry are desirable. During the course of this study, the epoxy adhesive was found to be incompatible with nomex core, A-staged phenolics when cured together, Vibrin polyesters, and all of the polyimides.

Table 4. Adhesive comparison

Adhesive resin	Designation[a]	Unit weight, lb/ft^2	Flatwise tensile strength, psi		
			Average	High	Low
Epoxy	FM96/nylon[b]	0.025	420	520	350
	FM96U[c]	0.03	610	720	510
	FM96/1070[d]	0.05	700	780	640
	FM96U	0.06	650	740	550
Phenolic-epoxy	HT435U	0.03	470	500	540
	HT435/1070	0.05	460	510	420
	HT435U	0.06	490	570	430
	HT435/112[e]	0.135	310	340	300
Polyimide	FM34/1070	0.06	600	620	600
	FM34/112	0.135	510	520	500

[a] See Ref. 1 for supplier source.

[b] Nylon—Nylon scrim cloth.

[c] U—Unsupported.

[d] 1070—Style of glass scrim cloth.

[e] 112—Style of glass scrim cloth.

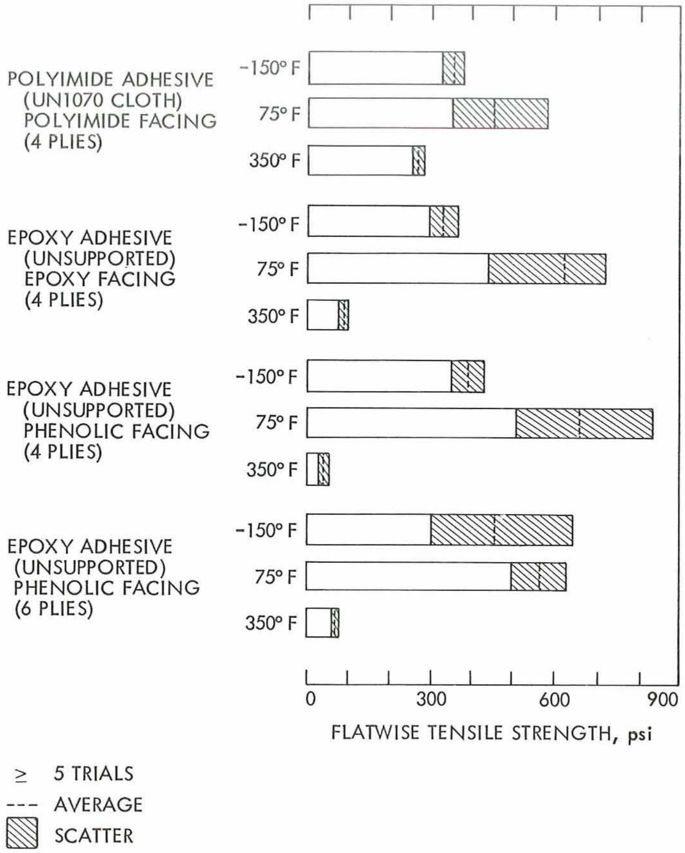
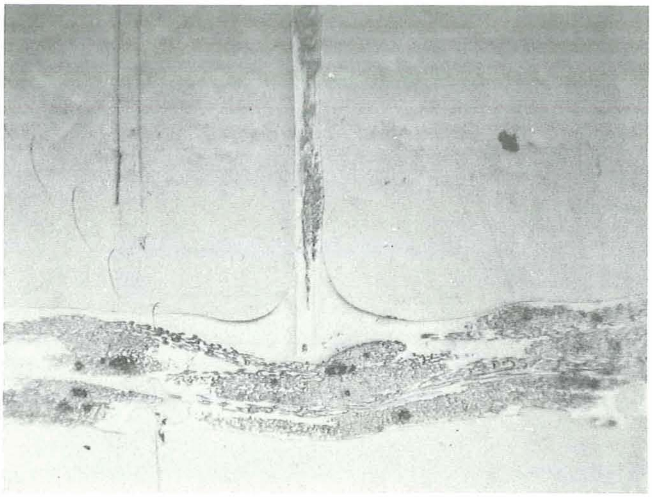


Fig. 13. Effect of temperature on adhesive strength

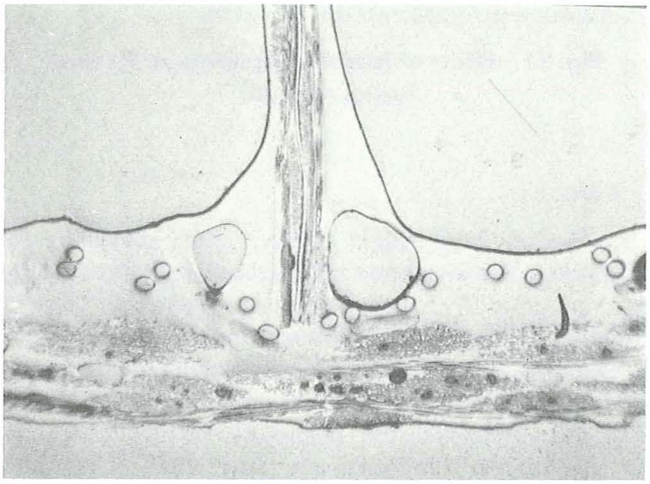
2. *Support.* Unsupported film adhesive provided facesheet-to-core adhesive strength that was as good as, or better than, that of the supported varieties (Table 4) for lightweight honeycomb-sandwich construction. For resin-fiberglass construction, adhesive support cloths are just extra noncontributing weight. Scrim cloths tend to compete through capillary action for the adhesive resin, and the result is poorer filleting than that obtained from the unsupported films. Unsupported films, on the other hand, tend to fillet the core uniformly and draw most of the normally useless film from the center of the core cell. A comparison of paste and adhesive filleting is shown in Fig. 14. The paste adhesive fillet is seen to be typically poor. Use of the nylon scrim cloth provides a lighter but weaker adhesive film with the additional problem of the brittleness of nylon in a vacuum.

3. *Unit weights.* The lightest available unsupported film adhesive gave as good a bond as the heavier varieties, which indicates that the availability of additional resin does not add to filleting efficiency (Table 4). Added adhesive thickness, therefore, merely adds to the panel weight. For epoxy- and phenolic-sandwich

(a) UNSUPPORTED 4-mil EPOXY FILM ADHESIVE



(b) NYLON-CLOTH-SUPPORTED 8-mil EPOXY FILM ADHESIVE



(c) ALUMINUM-FILLED EPOXY PASTE ADHESIVE

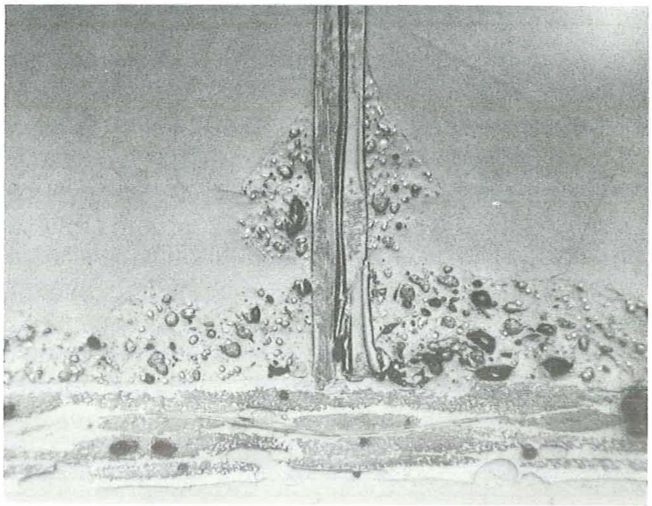


Fig. 14. Comparison of adhesive filleting

constructions, the 0.03-lb/ft^2 epoxy-phenolic adhesive is recommended for all applications requiring performance at higher than room temperature. Style 1070 glass-cloth-supported polyimide is the lightest and best polyimide presently available, but production of an unsupported polyimide adhesive film is a desirable goal for the future.

C. Core

1. ***Resins.*** Only phenolic and polyimide resins were investigated as core impregnants. No significant difference was observed between the two resin systems (Table 5); this result supports the earlier similarity found in facing strengths.

2. ***Support fabric.*** Only nomex-paper support was compared to the standard glass-cloth support. Although the nomex support provided considerably lighter core density, it had low values of strength and some incompatibility with the available adhesives; therefore, it was unacceptable for this program. Carbon- or graphite-cloth support was also considered for this program, but the lack of sufficient funds prevented a complete investigation.

3. ***Cell size.*** An increase in the cell size decreases the compressive and shear strength of the core in more than a direct proportion to the decrease in cell density (Table 5). Small cell size is desirable so that failure caused by local buckling can be minimized. However, small cell size must be balanced against density and flatwise compressive strength for any particular use.

4. ***Cell shape.*** The three cell shapes investigated are shown in Fig. 15. Both the flexcore and dovetail core were developed to provide more flexibility in two directions. Although some data were generated (Table 5), it is difficult to make more than qualitative comparisons. The flexcore material is somewhat closer in size to the ¼-in. rather than the ³⁄₁₆-in. hexagonal core and, as such, provides compressive strengths similar to the larger hexagonal core. In all other properties, the flexcore samples provide less strength than the hexagonal-core counterparts, and the dovetail-core sandwiches are almost identical to the hexagonal. Lighter-weight dovetail and smaller-cell lighter-weight flexcore are needed before a significant comparison can be made. Until such advancements are made, the antielastic behavior of doubly curved hexagonal core can be partially relieved by either forming the hexagonal core in the partially cured state or by taking the weight or strength penalties associated with utilization of the available flexcore or dovetail core.

Table 5. Comparison of lightweight cores

Lightweight cores	Flatwise compressvie strength, psi		
	Average	High	Low
Standard phenolic core			
Hexagonal cell size: ³⁄₁₆ in. Thickness: ¾ in. Density: 40 lb/ft^3	550	590	470
Other resins			
Polyimide equivalent	560	570	550
Other cloth reinforcements			
Phenolic/nomex paper supported	350	360	340
Increasing cell size to lower density			
Hexagonal cell size: ¼ in. Density: 3.5 lb/ft^3	390	410	340
Other cell shapes			
Flexcore: 4.2 lb/ft^3	390	460	350
Dovetail core: 5.5 to 6.0 lb/ft^3	745	790	718
Extra resin dips			
1 dip Density: 4.5 lb/ft^3	930	940	910

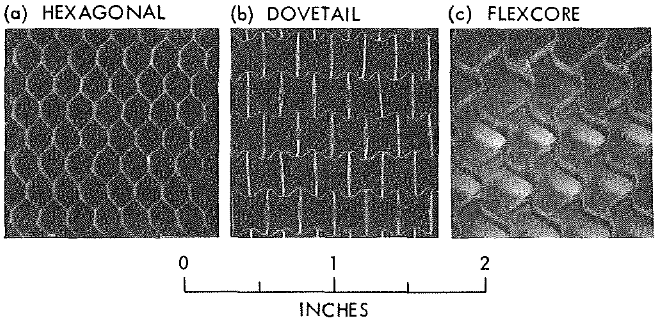


Fig. 15. Comparison of core cell shape

5. ***Extra resin dips.*** Dipping the finished core in the original impregnating resin adds approximately 0.5 lb/ft^3 in density to the core per dip without significant change to other factors. This 12% increase in core weight provides a 50% increase in core flatwise compressive strength (Table 5) and about a 15% increase in core-shear strength without significant variation in the other properties. If increases are needed in these particular strength properties, then dipping is an inexpensive way of manipulating them without major changes in ribbon fabric, cell size, etc.

6. *Splicing.* The three alternative core splicing techniques considered in this program are shown in Fig. 16. No significant degradation in any of the composite strength properties was found from either the one-cell-minimum, two-cell-maximum crush-overlap splice, or the foaming film-adhesive splice except equivalent increases in weight. Although the crush-overlap splice would appear to have a weakness in the reverse crush direction, this did not appear to affect composite properties. The crush overlap appears slightly lighter and is generally more desirable when anticipated high-temperature utilization would degrade the strength of the foam adhesive.

7. *Repair.* Core repair must be accomplished patiently with a razorlike tool. Sections of core can be replaced by the use of the crush-overlap or foam-adhesive technique without degradation in the core functional strengths. However, a small local increase in weight is experienced.

IV. Flat Aluminum Configurations

At the beginning of this investigation, the aluminum-honeycomb sandwich was conceived as an all 2024-T4 or 2219 sandwich so that full utilization of the properties of the highest strength alumnium alloys available could be achieved. Because of material compatibility problems, the actual composites studied (Table 6) did not utilize only these highest strength aluminum alloys. Alloy 2219 was eliminated completely for incompatibility with adhesive bonding. Alclad alloy 2024-T4 facesheets were found to be readily available in the 10- and 16-mil thicknesses, but the 5-mil facesheets had to be chem-milled from the 10-mil stock with the result that the cladding layers were removed and the composition of the contact surface was changed. The 2024-T4 core, which was difficult to obtain in sufficient quantity for the full-test matrix, came in extremely limited size and density ranges and appeared to have a slight incompatibility problem with the epoxy adhesive. As a substitute, 5052 and 5056 core, available in several low densities, was used.

A. Facesheet

1. *Materials.* Aluminum alloys 2219 and 2024 were investigated as representative high-strength alloys available in sheet and foil form. Alloy 2219 was eliminated because of adhesive bonding problems that may have been due to the copper used as an alloying element. Only Alclad alloy 2024 was actually used in the flat-panel study in the T3 rather than T4 condition. The only other implied effect of facesheet material is an apparent drop in flatwise tensile strength for the 5-mil sheet. This drop could be the result of a difference in bonding between the clad 10- and 16-mil sheet and the chem-milled (unclad) 5-mil sheet. (Cladding provides a high aluminum surface layer.) The drop in tensile strength could also be the result of accentuated waviness or local effects caused by the sheet thinness. However, the exact cause of the drop in tensile strength has not been determined.

2. *Thickness.* The effect of facesheet thickness is shown in Fig. 17. Edgewise compressive strength, as expected, was directly affected by facesheet thickness in the thin-gage samples. As the facesheet gets thinner, waviness effects are accentuated and local intercell buckling weakens the effective strength of the honeycomb-sandwich composite. When sufficient span length was used in the flexure tests, typical facesheet strengths near 60,000 psi were realized, similar to those for the thick-skin edgewise compression samples.

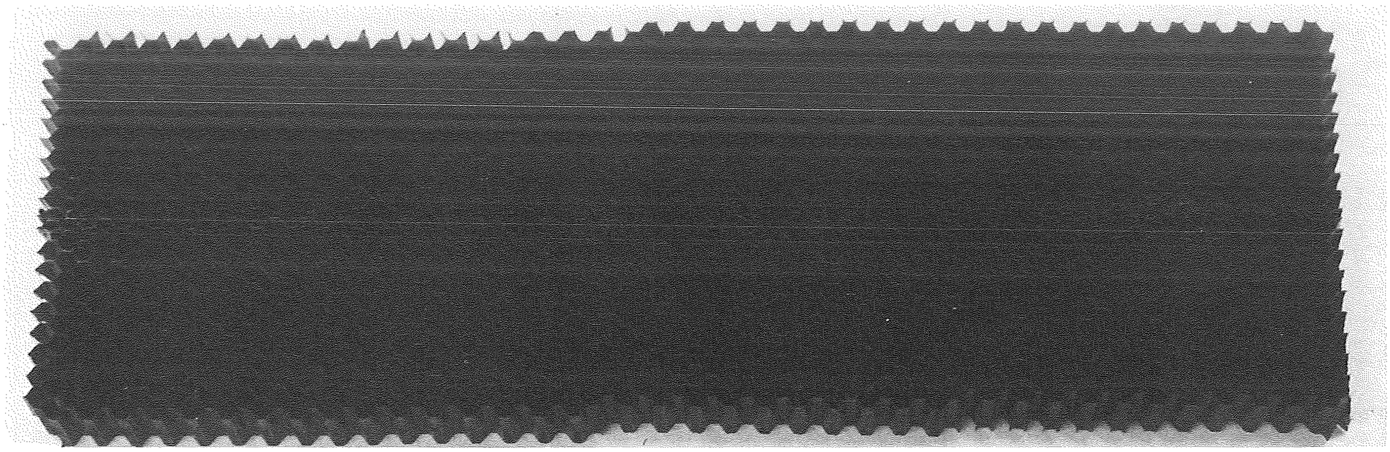
B. Adhesive

1. *Materials.* Only epoxy adhesives were used on aluminum sandwich in this program. Anticipated planetary entry aeroshells would have higher temperature requirements, and epoxy-phenolic or polyimide adhesives similar to those tested in the resin-fiberglass program would have to be used. It is expected that the epoxy-phenolic adhesive will be compatible with the aluminum and will have only a slight decrease in adhesive strength. The effect of facesheet thickness on apparent adhesive strength is shown in Fig. 18. Heavier facesheets apparently stabilize intercore buckling of the facesheets and allow greater realization of bonding strength.

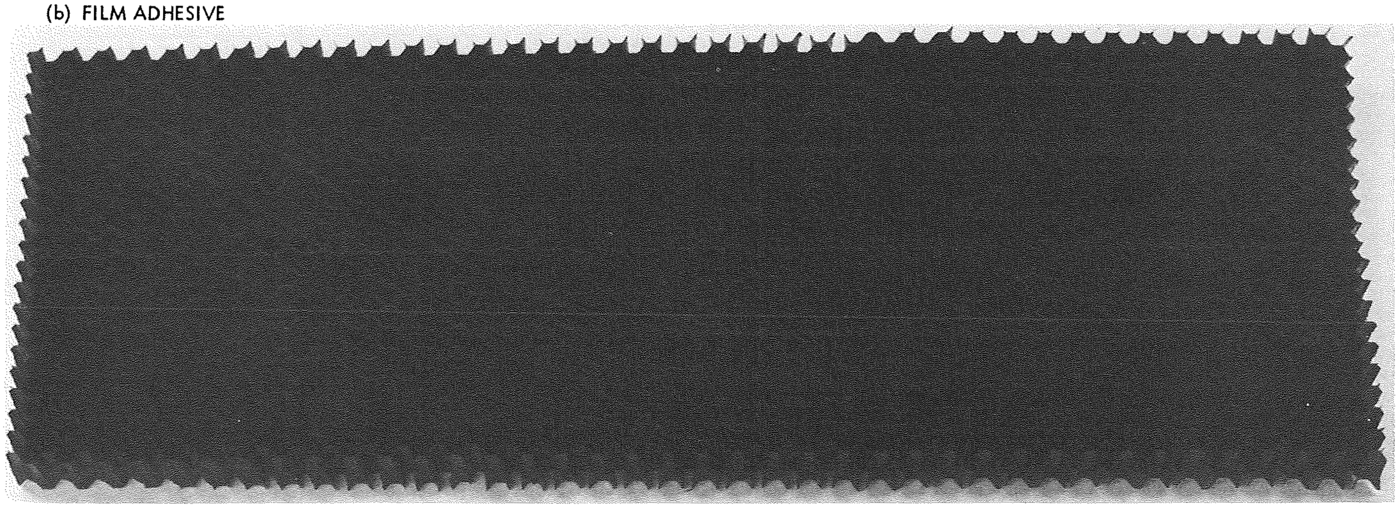
2. *Support.* Preliminary tests of scrim-cloth reinforced adhesive showed no apparent benefit in having a scrim cloth for these configurations. The unsupported film adhesive gave an excellent fillet, utilizing all of the adhesive film trapped in each cell and requiring no primer to enhance adhesion.

3. *Thickness.* The thinnest, lightest adhesive that provides an adequate bond is the most desirable in lightweight structures. The lightest adhesive available, 0.03 lb/ft^2, did not give sufficient adhesive strength reproducibly. Any inherent facesheet or core waviness is not accommodated by the vacuum bag pressure, and sufficient adhesive must be provided both to fill the gap and to produce an adequate fillet. It was found that 0.06 lb/ft^2 of unsupported adhesive provided the desired bond strength.

(a) CRUSH OVERLAP



(b) FILM ADHESIVE



(c) FOAMING FILM ADHESIVE

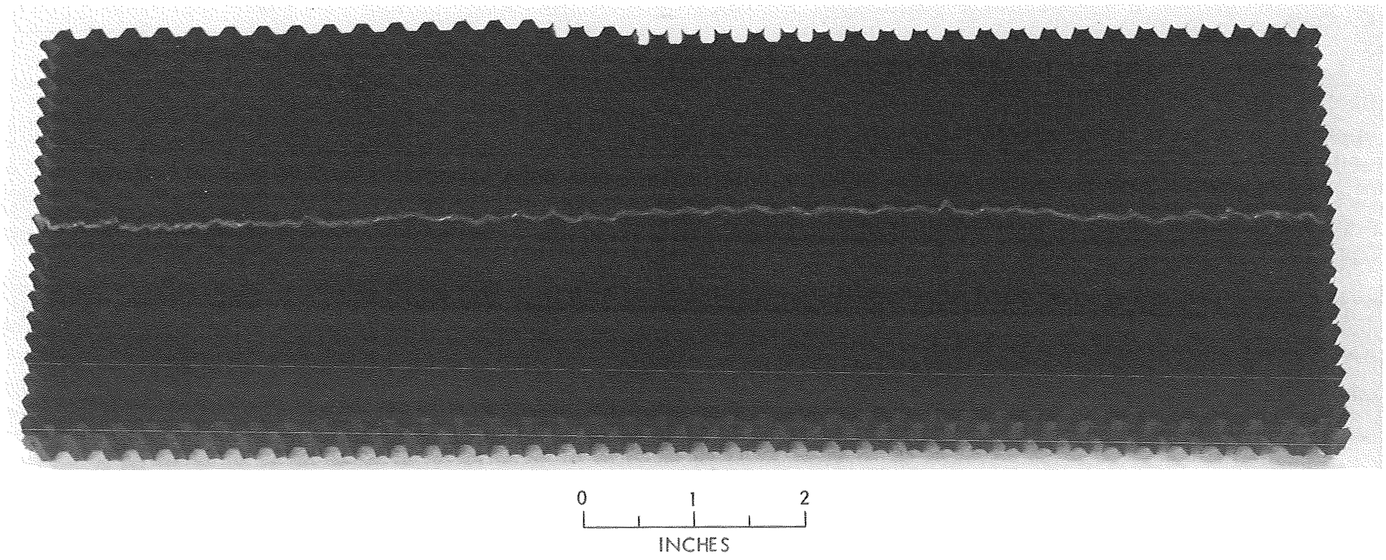


Fig. 16. Alternative core splicing techniques

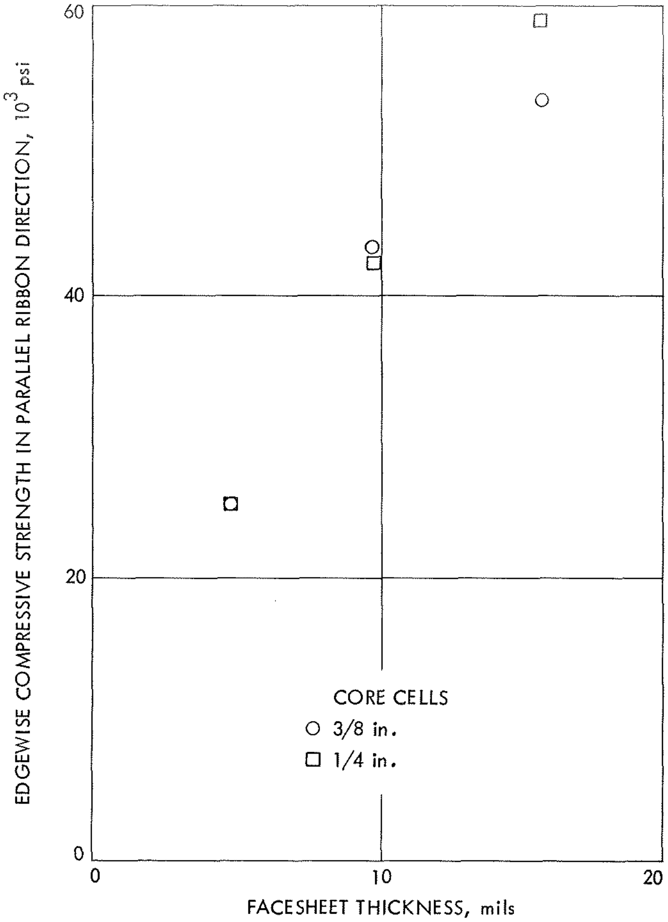


Fig. 17. Effect of facing thickness on edgewise compressive strength of resin-bonded aluminum honeycomb sandwich

C. Core

1. *Materials.* Initial studies of 2024-T4 core, which is unclad, showed an apparent incompatibility with the epoxy adhesive. Since the adhesive was not incompatible with 10- and 16-mil 2024-T4 facesheets, it appeared that their compatibility was linked to clad facesheets versus unclad core foil or exposure to the copper alloying agent. The 5052 and 5056 alloys used magnesium as their main alloying element and showed no incompatibility with the adhesive. Strengths of these cores were not significantly different from the 2024-T4 core and, therefore, these cores were used in this study.

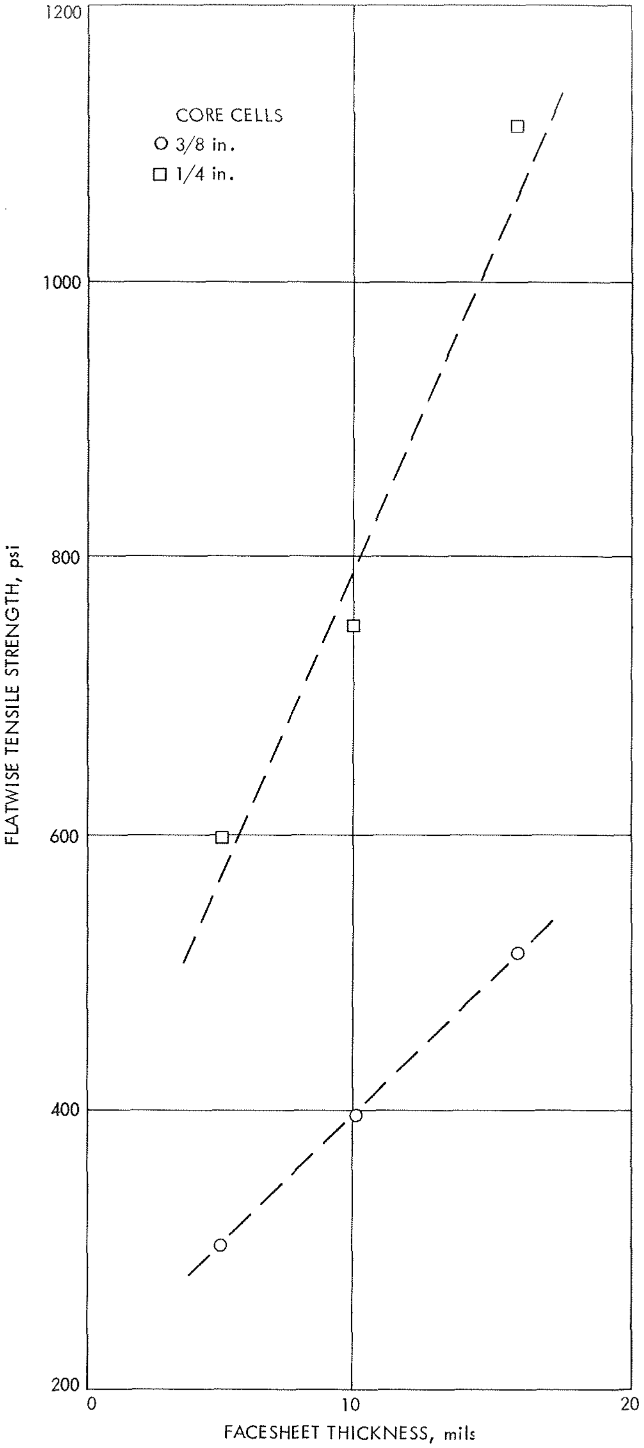


Fig. 18. Effect of facesheet thickness on flatwise tensile strength for aluminum panels

2. *Cell size.* Core cell size is related to density and affects not only the direct core properties but also those facesheet and adhesive properties that are controlled by local buckling across the cell. Therefore, ¼-in. cells and ⅜-in. cells with the same 0.002-in. foil differ by a factor of 2 in flatwise compressive strength. On the other hand, $\frac{3}{16}$-in. cells with 0.0015-in. foil are about the same density and give the same flatwise compressive strength as ¼-in. cells with 0.002-in. foil.

Table 6. Material parameters of lightweight resin-bonded aluminum honeycomb-sandwich composites

Parameter	Value for indicated composite number					
	1	2	3	4	5	6
Facing material	2024-T3	2024-T3	2024-T3	2024-T3	2024-T3	2024-T3
Facing thickness, mil	5	5	10	10	16	16
Adhesive material	FM96U	FM96U	FM96U	FM96U	FM96U	FM96U
Adhesive unit weight, lb/ft^2	0.06	0.06	0.06	0.06	0.06	0.06
Core material	5056	5052	5056	5052	5056	5052
Core shape	[a]	[a]	[a]	[a]	[a]	[a]
Core size, in.	¼	⅜	¼	⅜	¼	⅜
Core density, lb/ft^3	4.3	3.0	4.3	3.0	4.3	3.0
Core thickness (unsupported)	0.5	0.5	0.5	0.5	0.5	0.5

[a] Hexagonal.

These identical compressive strength cores do not give the same flatwise tensile strength and edgewise compressive strength. Under conditions when local cross-cell buckling becomes important, the smaller cell size appears effectively stronger. This effective strength is also proportional to facesheet thickness as discussed in Section IV-B.

V. Fabrication and Test of Small Model Aeroshells

In reality, aeroshell structures are seldom flat. However, to prove the adequateness of a structural concept, the problems of fabricating singly and doubly curved models had to be investigated. Double curvatures accentuated the problem, so in this program they were investigated first. The models constructed were essentially similar to the schematic shown in Fig. 19. The model is the nose of a 12-ft-diam blunt-cone vehicle with a 0.1-in.-diam nose radius. This was a popular size when the contract was initiated several years ago. The reinforcement ring is required for tests that are discussed in the following subsection of this report.

A. Resin-Fiberglass Aeroshells

A photograph of a completed resin-fiberglass honeycomb-sandwich aeroshell model is shown in Fig. 20. The model was easily constructed from a simple extension of the lightweight flat-sample technology. The B-stage resin-impregnated cloth (0.004-in./ply) was adequately contoured to the doubly curved shape without wrinkles and with only limited distortion. Green (partially cured) hexagonal core was molded to contour before cure. Cell distortion was reasonably distributed with an effective slight increase in density and strength. Flexcore or dovetail core is more readily formed to contour, but was not available in competitive cell sizes as a state-of-the-art material. The lightest adhesive (0.03 lb/ft^2) was again found compatible when exposed to vacuum bag pressure before final cure because of the conforming ability of the resin-fiberglass system.

A typical fabrication sequence (see Ref. 1 for details) is to lay up the first multi-ply facesheet in a female mold, vacuum bag cure, and inspect it as a free-standing sheet to ensure maximum strength in the outer or heat-shield attaching face. The adhesive and contoured core are then laid in place in the female mold on the accepted facesheet, and they are vacuum bag cured. The individual fillets are then inspected visually to ensure proper bonding. The potting compounds are then added, the inner adhesive film and facesheet are laid up, and the entire aeroshell vacuum bag is cured again. With practice, the whole operation can be done in one cure with identical results, but no in-process visual inspection can be done. No inherent problems were evidenced during the fabrication of this difficult shape. A 6.5-ft-diam sphere cone was then constructed (as reported in Ref. 2) with the resin-fiberglass technology developed in this program. The technology was extended to include integration with fiberglass attachment and reinforcement rings and with titanium stiffeners having nearly identical coefficients of thermal expansion. No problems are anticipated in extending this experience to vehicles of sizes up to 20 ft in diameter.

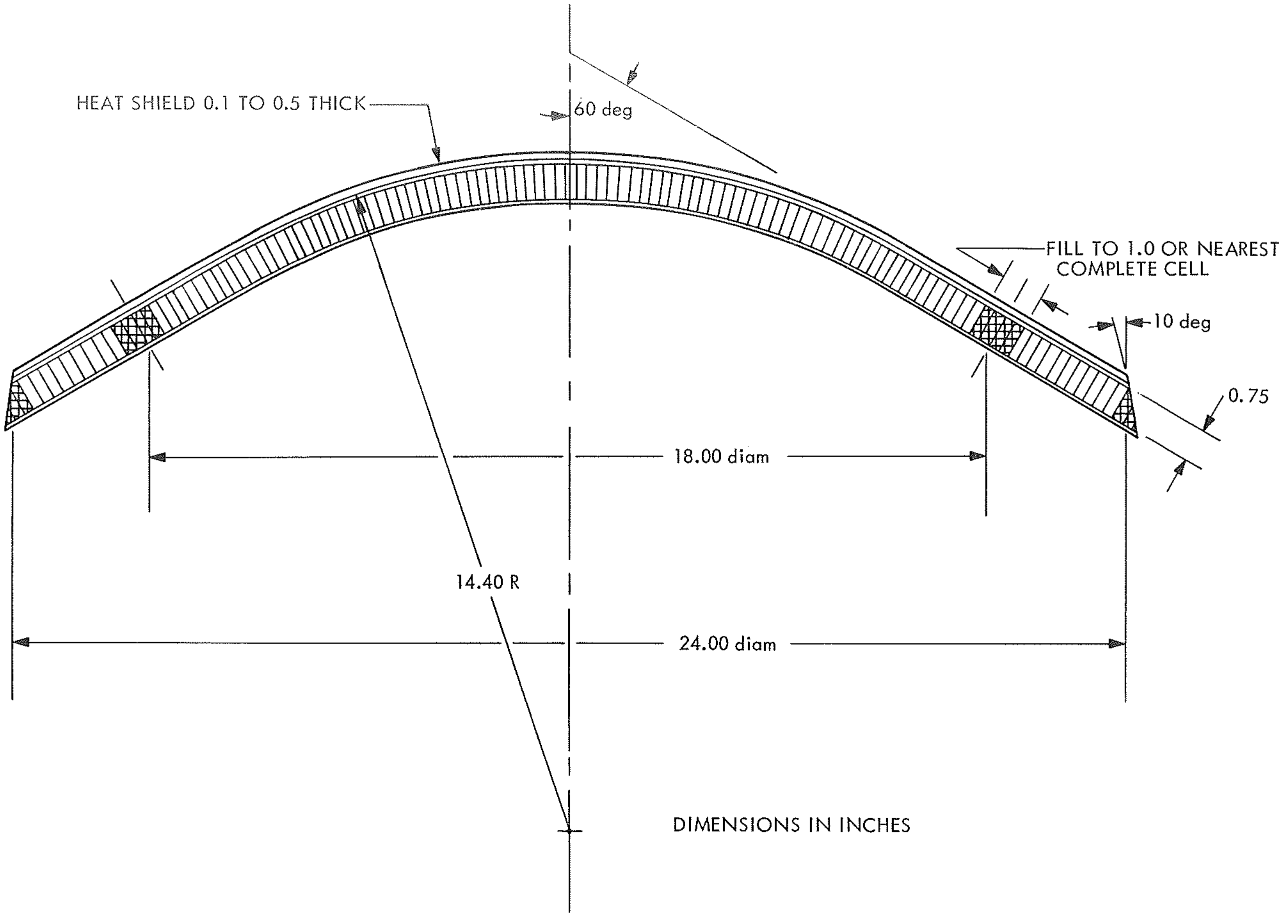


Fig. 19. Schematic of small, doubly curved developmental aeroshells

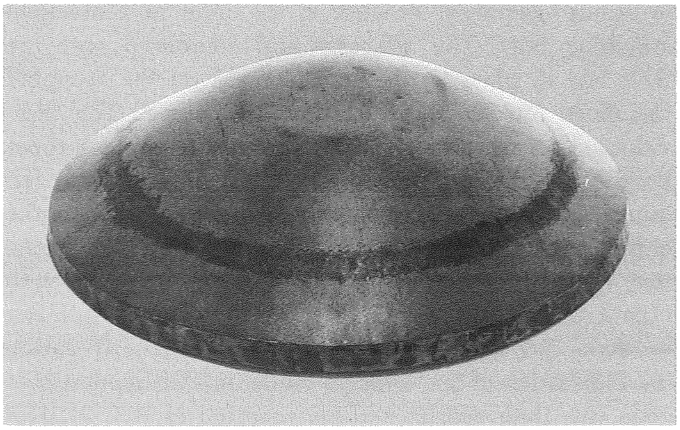


Fig. 20. Completed resin-fiberglass aeroshell model

In an attempt to establish fabrication reproducibility and to verify analysis techniques, a simple pressure test was devised for the 2-ft resin-fiberglass model aeroshells. In this test, a strain gage instrumented model (Fig. 21) was supported at the 18-in. reinforcement ring and was placed in an aluminum cylinder. An inflatable rubber bag was also placed in the cylinder on top of the aeroshell (see Fig. 22). A large flat plate was placed on top of the cylinder, and the entire assembly was retained between the platens of a testing machine. When the bag was inflated, an even pressure was applied across the entire aeroshell. This pressure provided compressive hoop loads and tensile and compressive loads along a radial meridian. As the pressure was increased, the strain gages closely followed the calculated values. Unfortunately, because of the strength and number of plies used in the construction, the aeroshell failed in shear by punching out the center (see Fig. 23) at about half the pressure necessary to achieve the calculated failure in the facesheets. Four aeroshells were tested with the calculated shear at failure ranging between 125 and 160 psi. These values are close to the shear strength measured on flat samples. There was not enough time to make additional aeroshells with thinner facesheets (fewer plies) and/or

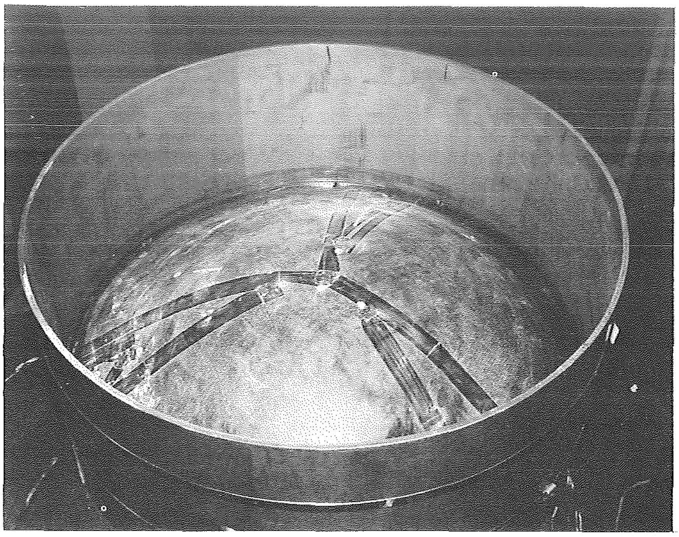


Fig. 21. Instrumented aeroshell in compression fixture

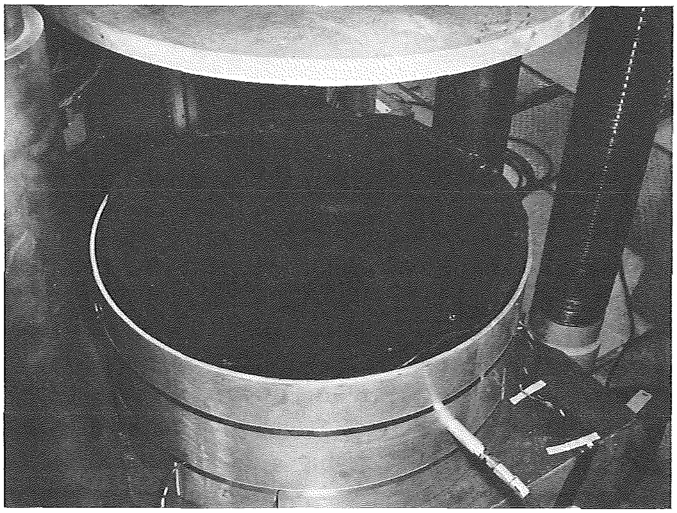


Fig. 22. Placement of pressure bag in compression fixture

stronger core (by extra resin dips) to verify the facesheet strengths as well as the core strengths. It is not anticipated that the variation in facesheet strengths will be any greater than the variation in core strengths actually measured by this test.

B. Adhesive-Bonded Aluminum Aeroshells

A photograph of a completed adhesive-bonded aluminum-honeycomb sandwich aeroshell model is shown in Fig. 24. Considerable difficulty was encountered in fabricating this model and several compromises were finally necessary. High-strength aluminum alloys did not have the elongation necessary to stretch to this shape in one piece. Attempts to stretch from annealed 2024 facing material produced rupture or at best an orange peel effect that caused the facing material to rupture during adhesive bonding. To produce the aeroshell as pictured, a low-strength, high-elongation 1100 alloy had to be used, eliminating the competitive position of aluminum with resin fiberglass. Forming gore segments and welding retrieves the strength-to-weight competitive position, but the cost of tooling to form, weld, and resize to tolerance increases by nearly an order of magnitude.

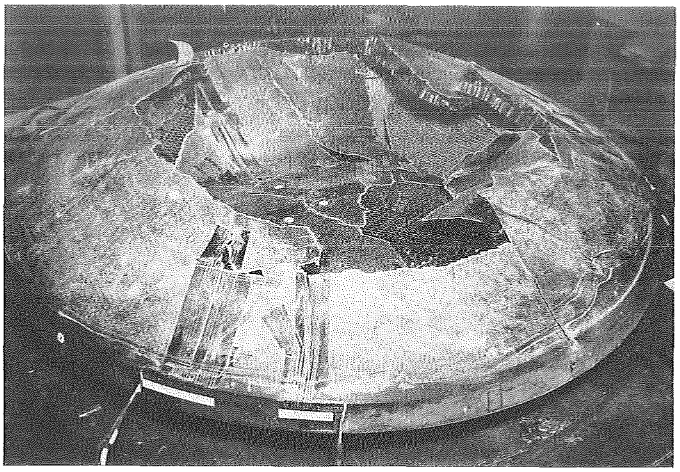


Fig. 23. Collapsed aeroshell after compression test

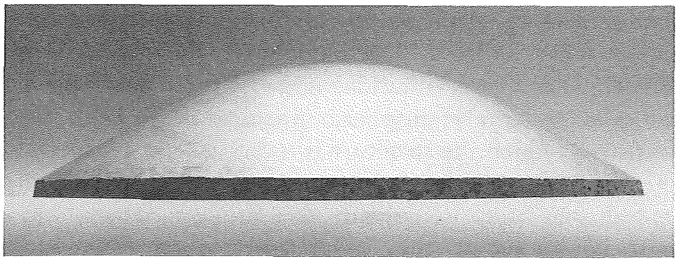


Fig. 24. Completed resin-bonded aluminum aeroshell model

On first glance, single curvature cones would appear to eliminate the forming and tooling cost problem since sheet can be rolled to contour and cut to size by relatively inexpensive and simple techniques. In actuality, this is essentially true, except that as the size of the cone increases, the practical tolerance mismatch between inner and outer rolled and welded sheets and their sandwiched honeycomb core is accentuated, and adhesive thickness and, therefore, weight is increased with the result that the effective strength-to-weight ratio is reduced. Typical

¾-in. panel-unit weights for either resin fiberglass or aluminum are in the order of 0.50 lb/ft^2, so the minimum weight adhesive of 0.03 lb/ft^2 per bond represents 6% of the resin-fiberglass composite weight. Flat aluminum required twice as much adhesive or 12%. For complex curvatures, even greater thicknesses of adhesive may be required to keep equivalent bond strength. Complete welding or brazing eliminates this problem, but cost can again become prohibitive.

VI. Compatibility With Special Environments

A planetary entry aeroshell has to survive many environments other than the structural loading during entry. While still on the ground, it must survive weathering, handling, spillage of control-rocket fuels and oxidizers during the assembly before launch, and dry-heat sterilization and ethylene oxide (ETO) surface decontamination when utilized. During launch, the aeroshell is subjected to severe vibrations and the rapid pumpdown places a sudden atmospheric pressure load from the inside out, which the structure is not necessarily designed for. Even though the structure survives this load, nonvented structures will retain this preload, which then must be added to the design load when estimating failures. The aeroshell is then exposed to vacuum for many months and is vibrated while cold (and brittle) during midcourse guidance corrections and planetary injection. Upon entry there is a time lag in the pressure actually experienced by the structure, so that while the structure is being flexed by the intense forebody pressures on the heat shield, the structure itself may still be in a vacuum. To keep the insulation requirements of the heat shield to a minimum, the temperature of the back surface of the heat shield must be allowed to rise as high as the load-carrying requirements of the contacting structure will allow. Fortunately, the time of peak back-surface temperature is long after the time of peak pressure load so the structure must retain only 30% or less of its design strength at that time. Because of the severity of some of these environments, it was considered apropos to examine some of the effects during the advanced development program to make sure that the concepts were not later proved infeasible.

A. Dry-Heat Sterilization and ETO Surface Decontamination

Sample panels of the nominal (except for 6-ply facesheets) resin-fiberglass construction were exposed to ETO gas for surface decontamination (168 h at 122°F, etc.) and dry-heat sterilization (552 h at 275°F, etc.) as specified in Ref. 4. The results for the following material combinations are provided in Table 7.

(1) Facesheet—6-ply Adlock 851; style-112 glass cloth; Volan A finish.

(2) Adhesive—0.03 lb/ft^2 FM96U.

(3) Core—Phenolic honeycomb, ¾ in. thick; 3/16 in. hexagonal cell; 4.0 lb/ft^3 density.

The only change observed during visual inspection was a deepening of the natural red color, which indicated additional and normally beneficial cure. No significant difference is seen between the surface-decontaminated and sterilized samples and the untreated control samples (Table 7). For high-quality, high-temperature resin systems, sterilization and surface decontamination at these levels do not appear to be a problem.

Table 7. Effect of sterilization on structural properties of sample lightweight honeycomb-sandwich composites

Structural properties	Control samples			Sterilized samples[a]		
	Average	High	Low	Average	High	Low
Flatwise tensile strength, psi	570	630	500	670	730	530
Flatwise compressive strength, psi	570	590	550	550	560	540
Sandwich flexure facing strength[b] (parallel to ribbon direction), 10^3 psi	31.2	32.0	29.2	32.6	35.6	27.2
Edgewise compressive strength[b] (parallel to ribbon direction), 10^3 psi	25.8	27.4	24.4	24.2	26.2	23.6

[a] ETO decontamination—168 h at 122°F; Dry-heat sterilization—552 h at 275°F.

[b] Based on nominal facing thickness of 0.018 in.

B. Launch Pumpdown

Several 8 × 12-in. sample panels of resin-fiberglass honeycomb sandwich were sealed at the edges, and a pressure transducer was attached to monitor internal pressure. The instrumented samples were then pumped down in a bell jar simulating launch pumpdown (a decrease in pressure of approximately 1 decade/min for 8 min). No failures in the samples were witnessed. The internal pressure of the 2-, 4-, and 6-ply samples gradually lowered to that of the vacuum, which indicated some degree of venting through porous facesheets. The 12-ply facesheets did not provide this same equalization, which implied that there was sufficient thickness to promote sealing of the facesheet.

C. Transit Vacuum Exposures and Vacuum Structural Properties

All of the resins investigated in depth in this program have been tested for vacuum stability in other programs and are well within the established standards of weight loss performance (Ref. 5). Since the structure, during entry, was to be flexed while at reduced pressure, tests were designed to duplicate two of the major properties under vacuum conditions. A vacuum system was modified at Rohr Corp. (see Ref. 1) so that vacuum-laminate flexure and sandwich-flatwise tension tests could be performed. The results of these tests are listed in Table 8. Vacuum did not affect either 8-ply laminate flexure strength, which would indicate facesheet resin changes, or flatwise tensile strength, which would indicate adhesive changes.

Table 8. Vacuum performance of lightweight resin-fiberglass composites[a]

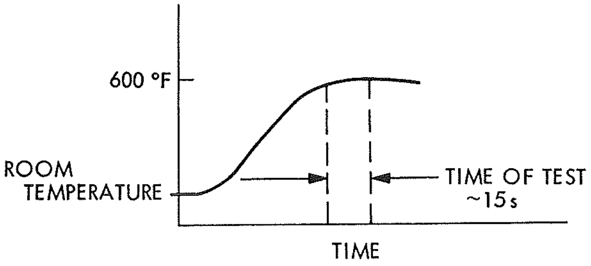
Parameter	Control samples	Samples tested in air[b]	Samples tested in vacuum[b]
Flatwise tensile strength, psi			
Average	620	610	630
High	710	740	690
Low	530	520	610
8-ply laminate flexure strength, 10^3 psi			
Average	46.3	—	—
High	47.0	—	50.5
Low	45.6	—	47.6

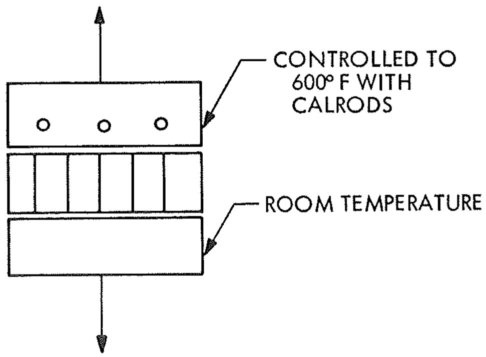
[a] 6-ply Adlock 851; style-112 glass cloth; Volan A finish; 0.03 lb/ft^2 FM96U adhesive; 3/16-in. hexagonal cell; ¾-in. thick; phenolic honeycomb core; 4.0 lb/ft^3 density.

[b] After 12 h at < 10^{-6} torr.

D. Maximum Heat-Shield Back-Surface Temperature on Entry

Thermal analysis indicates that when the back surface of the heat shield (which is the same as the front surface of the aeroshell structure) reaches 600°F, the temperature of the back surface of the structure has not risen significantly. Short-time performance of high-temperature phenolic and polyimide laminates at 600°F are normally expected to be better than 50% of their room-temperature performance. It was considered critical that the adhesive be examined to verify this performance. The test fixture on a flatwise tension rig was modified to control the temperature of one loading block with Calrod heaters while the other loading block was maintained near room temperature. Tests were then run to define the temperature ramp and to time the load initiation to ensure failure at approximately 600°F. The setup and results of this test are shown below.





Structural material	Flatwise tensile strength, psi		% of room temperature
	At room temperature	At 600°F	
FM96U (0.03 lb/ft^2)	500	80	16
HT435/1070 (0.05 lb/ft^2)	500	180	36

Under the optimum test conditions for this apparatus, the epoxy adhesive retained 16% of its room-temperature strength while the higher temperature epoxy-phenolic adhesive retained 36%. This strength retention is a time-at-temperature function. The test provides an order of magnitude greater time at temperature under optimum conditions; therefore, the strength indicated is probably a lower bound value. Although the epoxy adhesive cannot be used, the epoxy-phenolic adhesive is acceptable for missions with anticipated back-surface temperatures of the order of 600°F and accompanying loads of 25% of design or less.

VII. Recommended Design Data

When the basic development work has been completed, material property values can be selected to design an entry-vehicle aeroshell structure. The scatter in data and the problems experienced in fabrication of complex curved structures indicate the need to determine the balance between weight and reliability that should be selected for various planetary entry missions. The following paragraphs concern recommended material property values that are based on work accomplished in this program.

A. Resin Fiberglass

The recommended construction for resin-fiberglass honeycomb-sandwich structures is listed in Table 9. Because of ease of fabrication, phenolic fiberglass was selected for mild entry environments like Mars, but polyimides are required for the more severe ambient conditions of Venus. These structures are easy to fabricate, inexpensive, highly efficient in a light weight, and adaptable to a wide range of attachments and feedthroughs. Resin-fiberglass structures are also RF transparent so that signals may pass through them for radar altimeter measurements, for receipt of commands, or for transmission of instrument-data signals that might normally be occluded by the aeroshell.

Table 10 lists the recommended structural properties to be used in design. These values are based on an engineering judgment of the actual data and reflect what is considered to be a proper degree of conservatism. The numbers in parentheses (Table 10) are extrapolations from general literature rather than data actually measured in this program. Considerable data were obtained, and considerable time was spent verifying the validity of each datum point. The general strengths of the three resin systems were identical. Where averages appeared to recommend one or the other resin system, the scatter in the data eliminated any apparent advantage. The major difference between systems is that the epoxy-phenolic adhesive is slightly weaker than the epoxy or polyimide counterpart. The polyimide is also somewhat more difficult to fabricate primarily because of relatively poorer quality control in the individual components at this stage in its development. Normal improvement in the next several years should alleviate this problem.

The degree of conservatism that might be inherent when one face of the composites is coated with a compatible heat-shield material was also examined. Flexure tests on flat lightweight honeycomb-sandwich composites, typical of those considered for some Mars missions, showed no change in strength when the composites were coated with various thicknesses of a silicone elastomer heat-shield material. Silicone elastomer heat shields, at least, should not be considered as a strength contributor in any aeroshell design.

Table 9. Recommended construction for lightweight resin-fiberglass honeycomb-sandwich aeroshells

Components	Material construction
Facesheet	
Resin	High-temperature, high-reproducibility phenolics, epoxies, or polyimides
Support	Standard style-112 E-glass cloth with Volan A finish
Plies	Two plies or more in pairs with each ply warp rotated 45 deg from preceding ply, staggered 0.25-in. minimum overlaps
Adhesive	
Resin	0.03 lb/ft^2, unsupported epoxy phenolic or epoxy; 0.05 lb/ft^2, 1070 cloth-supported polyimide
Core	
Resin	High-temperature, high-reproducibility phenolics, epoxies, or polyimides
Configuration	$3/16$-in. hexagonal cell; 4 lb/ft^3 density-crush overlap splices and thickness determined by stiffness criteria

Table 10. Design structural properties for lightweight resin-fiberglass honeycomb-sandwich aeroshells

Design structural properties	Materials		
	Phenolic	Epoxy	Polyimide
Flexure strength (facesheet), psi			
Parallel to ribbon	28,000	28,000	28,000
Perpendicular to ribbon	21,000	21,000	21,000
Edgewise compressive strength, psi			
Parallel to ribbon	20,000	20,000	20,000
Perpendicular to ribbon	20,000	20,000	20,000
Flatwise shear strength, psi			
Parallel to ribbon	220	(200)	180
Perpendicular to ribbon	120	(120)	100
Flatwise compressive strength, psi	450	(500)	500
Flatwise tensile strength, psi			
Unsupported; 0.03 lb/ft^2	400	500	—
1070 support; 0.05 lb/ft^2	400	550	550
Peel strength, in.-lb/in.	(2.0)	2.0	3.5
Temperature effects		(See Fig. 25)	

Figure 25 shows the variation from room-temperature strength at other temperatures, which accounts for the same balance between weight and conservative reliability. Figure 25a delineates the adhesive-related properties. Strength decreases for these properties both below and above room temperature. The facesheet and core-related properties in Fig. 25b are stronger below room temperature but decrease above room temperature.

B. Adhesive-Bonded Aluminum

The recommended construction for adhesive-bonded aluminum honeycomb-sandwich structure is listed in Table 11. Based on the problems of fabricating doubly curved structures that are discussed in Section V-B, there is some difficulty in justifying the use of the 2024-T4 facesheet. At this time, a 5- to 9-mil facesheet is not available unless it is chem-milled, but facesheets of 10 mil, 16 mil, and greater thicknesses are generally available. The recommended construction is similar to that of general experience within the industry except that tolerance and adhesive minimization requirements tend to be more stringent.

Table 11. Recommended construction for lightweight resin-bonded aluminum honeycomb-sandwich structures

Components	Material construction
Facesheet	5 mils or more of 2024-T4 aluminum alloy
Adhesive	0.06 lb/ft^2 of unsupported epoxy-phenolic or epoxy
Core	1.5-mil foil of 5056 aluminum alloy in $\frac{3}{16}$-in. hexagonal cell; density (4.4 lb/ft^3) and thickness determined by stiffness criteria

Table 12 lists the recommended structural properties to be used in design. Again the data are susceptible to adjustment for other degrees of optimism. The major difference between the 5- to 9-mil facings and those of 10 mil or more is that the former are unclad and the latter are clad. Unclad 2024-T4 exposes the copper alloy to the adhesive; the fact that the copper alloy is incompatible with the adhesive appears to slightly lower bonding strengths. There is also an accentuation of local buckling for the thinner facesheets that decreases edgewise compressive strengths. Facesheets of 16 mil or more

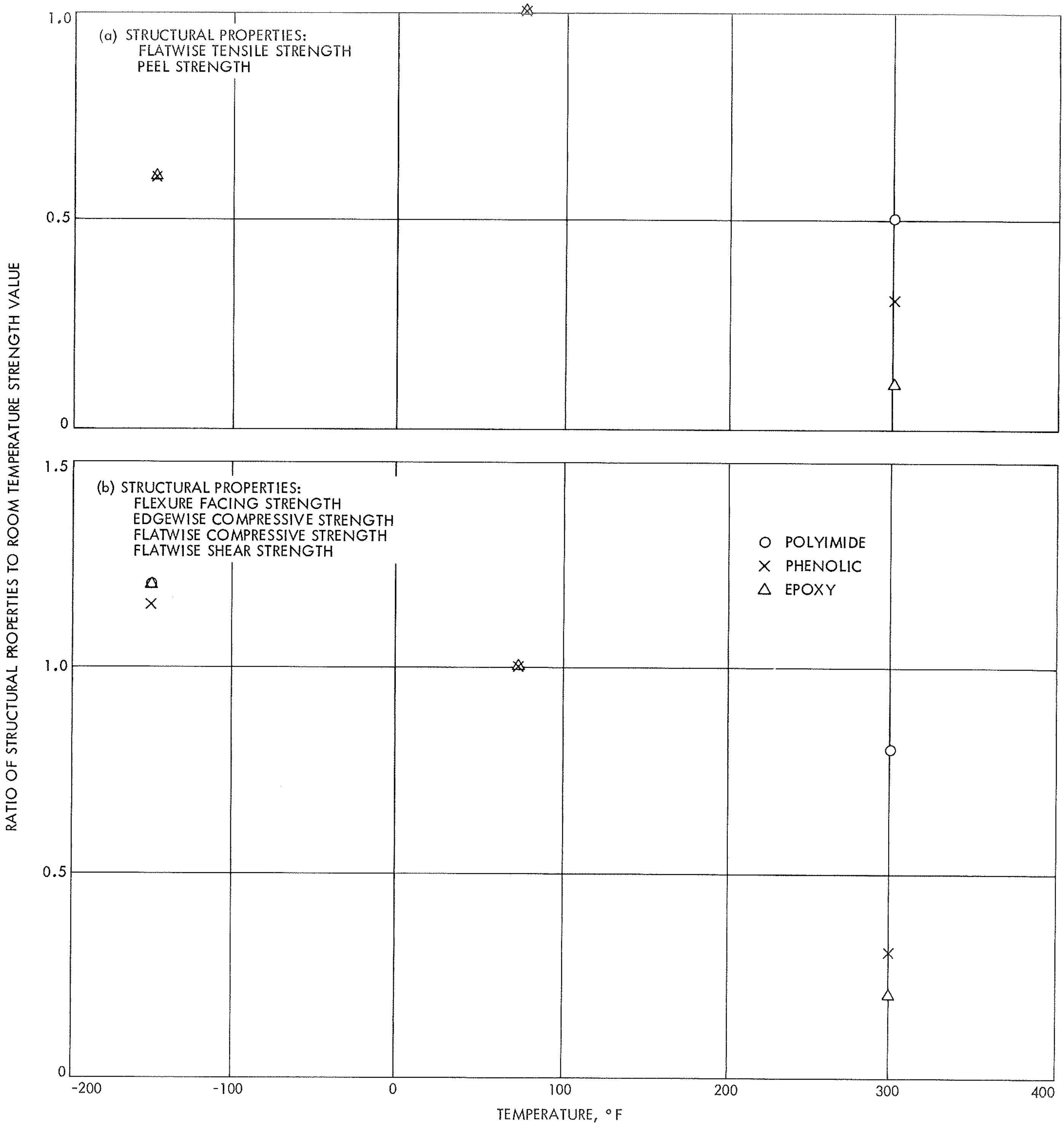


Fig. 25. Change in honeycomb-sandwich structural properties with temperature

Table 12. Design structural properties for lightweight resin-bonded aluminum honeycomb-sandwich structures

Design structural properties	Facings	
	5 to 9 mils	10 mils or more
Flexure facing strength, psi		
Parallel to ribbon	55,000	55,000
Perpendicular to ribbon	55,000	55,000
Edgewise compressive strength, psi		
Parallel to ribbon	30,000	40,000
Perpendicular to ribbon	30,000	40,000
Flatwise shear strength, psi		
Parallel to ribbon	350	350
Perpendicular to ribbon	200	200
Flatwise compressive strength, psi	550	550
Flatwise tensile strength, psi	600	700
Peel strength, in.-lb/in.	2.0	2.0

will provide even greater edgewise compressive strength (55,000 psi) and flatwise tensile strength (1000 psi), again because of the elimination of local buckling, but the increases are not significant to the present requirements.

The effect of temperature on the adhesive-related properties is approximately the same as shown in Fig. 25a. A representative curve of the change in 2024-T4 aluminum properties in relation to temperature is shown in Fig. 26. Strength decreases rapidly above 300°F, so additional heat shield is needed to maintain the temperature of the structure below this value.

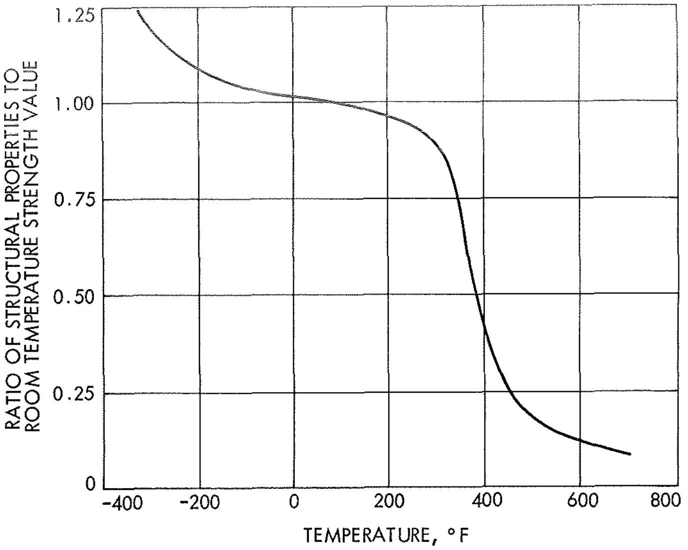


Fig. 26. Representative change in 2024-T4 aluminum structural properties with temperature

VIII. Comparison of Resin-Bonded Aluminum and Resin-Fiberglass Honeycomb-Sandwich Structures

In this section, the relative strengths of equivalent panel weights of resin-bonded aluminum and resin-fiberglass honeycomb-sandwich structure will be discussed. To reduce the large stiffness advantage of aluminum over fiberglass, the thicknesses of the aluminum honeycomb and fiberglass were assumed to be 0.50 and 0.75 in., respectively (Table 13). Core densities were assumed to be the same, so the thinner core provides balancing weight for the additional adhesive required by the aluminum. When flexure strength and edgewise compressive strength are multiplied by the pertinent facesheet thickness to give a measure of the relative load-carrying ability of the two structures, the two constructions are not very different on a comparative basis. The resin fiberglass shows slightly stronger skin-related properties; the aluminum shows slightly stronger core-related properties. Minimal adjustments in the selection of core and facesheets could equalize this. The major difference lies in elevated temperature properties as shown by Figs. 25b and 26. Phenolic becomes superior to aluminum in high-temperature performance by allowing a higher heat-shield back-surface temperature during entry.

The difference between 600°F and 300°F in allowable back-surface temperature is worth a considerable weight of insulation that cannot be made up by any relative superiority of resin-bonded aluminum structures over resin-fiberglass structures. Also, it is not necessarily obvious that the nominal aluminum structures can be fabricated in the specific strengths quoted. New developments in beryllium, magnesium, or titanium honeycomb technology may provide stronger and lighter honeycomb-sandwich structures, but they are not proven today. Lightweight resin-fiberglass structures, on the other hand, are competitive in strength, considerably easier and cheaper to fabricate, and much more adaptable to a wider range of mission-oriented constraints.

IX. Summary

Entry into the atmospheres of the solar system planets can be costly. To maximize the delivered experimental

Table 13. Comparison of equivalent resin-bonded aluminum and resin-fiberglass honeycomb-sandwich structures[a]

Structural properties	Resin-bonded aluminum	Resin fiber-glass	Resin-bonded aluminum	Resin fiber-glass
Panel weight, lb/ft^2	0.49	0.49	0.68	0.69
Facesheet thickness, mils	6	12	10	24
Flexure facing strength, psi,				
Parallel to ribbon	330	336	550	672
Perpendicular to ribbon	330	252	550	504
Flatwise shear strength, psi,				
Parallel to ribbon	350	220	350	220
Perpendicular to ribbon	200	120	200	120
Edgewise compressive strength, psi,				
Parallel to ribbon	180	240	400	480
Perpendicular to ribbon	180	240	400	480
Flatwise tensile strength, psi	600	400	700	400
Flatwise compressive strength, psi	550	400	550	400
Peel strength, in.-lb/in.	2.0	2.0	2.0	2.0

[a]Aluminum core was 0.5 in. thick, 3/16 in. hexagonal core of 4.4 lb/ft^2 density. Fiberglass core was 0.75 in. thick, 3/16 in. hexagonal core of 4.3 lb/ft^2 density.

payload, it is necessary to increase the operational efficiencies of as many of the vehicle subsystems as possible; this in turn reduces their total contribution to boostable weight. One of the major subsystem weights is that of the atmospheric entry-survival container or aeroshell. Although metallic structures have been emphasized in the past, recent developments in the plastics industry indicate that fiberglass equivalents may be competitive in strength, relatively less expensive to fabricate, and transparent to RF signals to lessen communication view-angle constraints.

The investigation of design properties and fabricability of lightweight resin-fiberglass honeycomb-sandwich composites was the main purpose of this program. A secondary purpose was the comparison of these plastic composites to adhesive-bonded aluminum honeycomb-sandwich structures. The aluminum structures have been used in internal studies at Jet Propulsion Laboratory and elsewhere as a performance standard for lightweight entry-vehicle design. Throughout the structural materials investigation, low cost, ease of manufacture, and adaptability to a wide variety of designs have been emphasized.

As part of this program, numerous parameters were investigated: the facesheets, which were varied in relation to the resin system; the fabric material, weave, yarn, and finish; the number and rotational relationship of plies; and methods of splicing or repair. The resin, support, and unit weights of adhesives were also varied. The core was investigated for different resins, support fabrics, cell sizes and shapes, extra resin dips, and core splicing and repair techniques. It was found that both phenolic and polyimide resins were easy and inexpensive to fabricate reproducibly in adequate strengths with a reasonably simple layup technique, simple tooling, and vacuum-bag cure. Strength of the individual resin-fiberglass composites proved to be primarily a function of the resin and support material and their specific fabricability. Since the same nominal thickness had the same strength, the cloth style, yarn, and finish or the number or rotation of plies appeared to have only a secondary effect. Reasonably isotropic properties were found in all facesheet samples with nominal rotation of plies down to an apparent minimum of two plies of style-112 cloth rotated 45 deg to each other and with a total nominal facesheet thickness of 6 mils. For resin-fiberglass composites with compatible polymeric systems, the thinnest available unsupported adhesive (0.03 lb/ft^2) provided the best facesheet-to-core bond when both strength and weight were considered. Selection of core was constrained to the smallest cell size consistent with weight and strength requirements and to a thickness consistent with required rigidity.

Tests were also made that confirmed the compatibility of resin-fiberglass structures with ETO surface decontamination, dry-heat sterilization, rapid-launch evacuation, and transit-vacuum exposure. No changes in properties of phenolic systems were noted when these systems were tested in a vacuum or after sterilization. Short-time performance at 600°F was also investigated. A set of recommended structural design properties for resin-fiberglass honeycomb-sandwich entry-probe configurations is given, based on a selection of the available test data from this program.

Doubly curved aeroshell models were also fabricated and proved to be a simple extension of the flat-specimen technology. The various lightweight cloths conformed to a wide range of facesheet curvatures without significant degradation of mechanical properties. Phenolic core in the partially cured condition could be molded to shape with simple tools and without unacceptable distortion. Verification tests showed core failure at the same levels measured in the flat specimen program.

Comparative data were also obtained on the relative strength and fabricability of adhesive-bonded aluminum honeycomb sandwich. The aluminum composites were varied as to facesheet and core alloy, the facesheet thickness, the core-ribbon thickness and cell size, and the adhesive material, support, and unit weights. Aluminum honeycomb-sandwich composites were less capable of conforming under vacuum-bag pressure and hence required twice as much adhesive to provide the same reliability in bonding as that experienced with resin fiberglass. Not all aluminum alloys were compatible with the available high-temperature lightweight adhesives. Given all variations, though, the flat aluminum samples of the same unit weight proved to be essentially equal to the resin fiberglass in strength; however, aluminum had some advantage in rigidity.

Doubly curved adhesive-bonded aluminum aeroshells required expensive tooling to provide tolerances consistent with low-adhesive weight and high-performance reliability. As adhesive weight goes up, the performance of aluminum relative to resin fiberglass degrades and other constraints become more important. Unless improvements in technology could show a clear performance advantage of metallic honeycomb sandwich, resin-fiberglass composites appear to provide an advantage in cost, ease of fabrication, and adaptability to a wide variety of entry-vehicle configurations.

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16. Abstract

Extraterrestrial planetary entry probes require new concepts in lightweight entry-vehicle design if the scientific payloads of missions are to be maximized. For a number of missions, communications and sensing requirements imply the need for an RF transparent aeroshell structure. Such an aeroshell would increase the view angle of the transmitters and receivers while providing equivalent protection from the entry environment.

Presented are the results of an extensive study of lightweight resin-fiberglass honeycomb-sandwich structures that was performed to define the fabricability and economics of RF transparent structures and to provide design data for detail analysis. As part of this study, a comparison was made with lightweight adhesive-bonded aluminum honeycomb-sandwich structures so that any penalties for RF transparency could be established. The results showed that there was little difference in strength to weight in lightweight configurations for resin-fiberglass and aluminum honeycomb-sandwich structures. Aluminum showed some advantage in stiffness to weight, but resin fiberglass was easier and less expensive to fabricate and was adaptable to a wider range of aeroshell configurations.

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