Primary Adhesively Bonded Structure Technology (PABST)

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The objective of the U.S. Air Force Flight Development Laboratory's Primary Adhesively Bonded Structure Technology (PABST) program awarded to the Douglas Aircraft Company in February 1975, is to improve the structural integrity and durability of future Air Force aircraft while providing significant cost-of-ownership savings (20% goal). Presented is the structural design arrangement selection process which examines static strength, fatigue, and damage tolerance criteria. The surface treatment optimization program, which examines phosphoric acid and chromic acid anodize (using optimized sulfuric-acid/sodium-dichromate [FPL] etch as a standard), is reviewed with current test results. The maximized corrosion resistance afforded by these surface treatments is the key to increased durability. The adhesive selection process is presented with test data. The proposed structural development test plans are discussed. The paper concludes with the projected design, manufacture, and test plans for the full-scale Advanced Development Program (ADP) component. This 52-ft section is the entire cargo compartment of the YC-15 aircraft.

Introduction

BONDING of aircraft structures has been used for a long time. Capabilities of Redux were first demonstrated in 1942. In 1944, de Havilland bonded a wooden spar web to a metal cap on the DH-103 Hornet. Fokker VFW produced the first F-27 in 1955 with all fuselage longerons (in constant section) bonded (Redux) to the skins, and the wing spar caps and stringers were built up by bonding thin metal pieces together to form the required area. This aircraft is still in full production with no bonding service problems to data. Today, virtually all aircraft have bonded metal parts, but they are restricted almost entirely to secondary structures and almost all have experienced delamination before the primary structures have reached full service life.

Why consider bonding primary structures at this time? New developments in surface treatment show greatly improved environmental resistance. A new generation of adhesives (250°F cure modified epoxy) having increased durability have been produced. And finally, skyrocketing aircraft costs, both of acquisition and ownership, demand savings wherever possible. For these reasons, the U.S. Air Force has launched the Primary Adhesively Bonded Structure Technology (PABST) program. This paper presents a summary of major work performed during the first 18 months of the 4½-yr program.

Background

On Aug. 28, 1972, the Manufacturing Technology Division of the Air Force Materials Laboratory sponsored a joint Air Force/industry manufacturing cost reduction study.[1] Seventy participants met at the Sagamore Conference Center, N. Y. to identify costs of major airframe structural components, determine the best approaches to significant end item acquisition cost reduction, and define specific activities to demonstrate cost savings. Conference participants reached this conclusion: "Proliferation of detail parts and the requirements to assemble these with fasteners is the heart of the cost problem" (p. 97, Ref. 1).

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A program is required with adequate depth to fabricate and test candidate fuselage structures. Cost reduction potential of 30% in fabrication seems likely. For intermediate-size transport aircraft, the wing costs 38% of the total and the fuselage 48%. Skin panel fabrication and assembly are the big cost items in the fuselage. Figure B-3 of Ref. 1 shows the relationship.

A follow-on low-cost manufacturing/design seminar was held at French Lick, Ind. in May 1973.[2] Again, it was pointed out that considerable savings could be made by the application of adhesive bonding to primary fuselage structures. However, an overriding constraint is the required long-term durability of the bonding systems. A seminar committee recommended a program of design, analysis, and tests. These studies should be in the depth required to produce good manufacturing/design interface. A realistic program should be initiated to collect and correlate past service data along with controlled tracking of presently produced bonded structure. The program also must include controlled laboratory-type specimen testing for both simulated and service exposure. Design/analysis data, including information on static strength, fatigue, fracture, durability, and interface with Quality Assurance on allowable defects, must be generated.

The PABST Program

An effective adhesive bonding system that will permit the elimination of many of the primary rivets traditionally used in assembling an aircraft is showing promise in the Primary Adhesively Bonded Structure Technology (PABST) research program. The PABST program is sponsored by the Air Force Flight Dynamics Laboratory, Advanced Metallic Structure Section, at Wright-Patterson Air Force Base.

The specific objective of this procurement action is to achieve significant improvements in cost, weight, integrity, and durability of primary fuselage structure applicable to the AMST and other wide-body transports through 1) the development and ultimate validation by full-scale test of adhesively bonded structures technology, and 2) the prompt and thorough transfer to the aerospace community of the resulting body of knowledge and data. The baseline AMST aircraft used to make the structural shape and loading realistic is the Douglas YC-15. Work started in February 1975 and is planned to be completed during the first quarter of 1979. This paper will present the significant work accomplished to date.

Surface Treatment

Douglas was required to evaluate three current surface treatments using sulfuric-acid/sodium-dichromate (FPL) etch as a reference standard. Evaluation of the surface treatments would be based on results of the wedge-crack test suggested by Bethune[3] for use in studying the environmental resistance of aluminum metal bond surface treatments. The Bethune method is a low-cost test that can be run fairly rapidly. The procedure is to surface treat two 6×6-in. plates and bond them together, leaving one edge unbonded so the wedge can be driven in. The cured panel then is cut into five 1-in. wedge-crack specimens, and each specimen is wedged open (Fig. 1) and allowed to stabilize for 1 hr at room temperature and environment. Crack ends then are marked and the specimens exposed for 1 hr in 95 to 100% relative humidity at 140° F environment. Crack growth is noted at 1 and 3 hr, and the parts are split apart to examine the mode of failure – adhesive or cohesive. It was a program goal to select the surface treatment that exhibited only cohesive failures.

Each of the three surface treatments selected was optimized within the specification of the originating organization. Optimization was performed by conducting a testing matrix of the anodizing extremes allowed by each specification. For the chromic acid anodizes, the sealing processes were optimized in the same manner: 1) phosphoric acid anodize, specification BAC 5555, Boeing Co., 2) chromic acid anodize, specification BPS FW4352, revision G, Bell Helicopter Co., 3) chromic acid anodize, specification PS 13201, McDonnell Douglas Corp., and 4) FPL etch, specification BAC-5514, Boeing Co. The adhesive system selected for the surface treatment wedge-crack tests was FM73 adhesive with a mat carrier and a corrosion-inhibiting primer, BR127. Both 2024-T3 bare and 7075-T6 bare were used to test surface treatments.

For purposes of control and elimination of variables, all process operations after anodizing were the same. The adhesive primer was applied to the plates within 2 hr after anodize drying. Primer thickness was maintained at the vendor's recommended 0.0002 in. Primed specimens were air-dried for a minimum of 30 min, then forced-dried in an air-circulating oven for 60 ±5 min at a temperature of 255 ±5° F. One layer of adhesive film was placed in each bond line and the specimens were cured in an autoclave at 245 ±5° F for 90 min at 40 psi. Heat-up rate, a critical feature of FM73 adhesive, was maintained at 3 to 6°F/min. Pressure was maintained during cool down to 150° F.

The alkaline cleaner used for all processing sequences was Turco 4215S. This nonsilicated alkaline cleaner was an acceptable material on all process specifications under investigation for the program. Of the two recommended deoxidizers specified by Boeing BAC-5555, Amchem 6-16 deoxidizer was chosen. The sulfuric acid-sodium dichromate solution, at 140 to 160° F, was used to deoxidize all specimens processed with the Bell Helicopter chromic acid anodize per BPS FW4352, Revision G.

The phosphoric acid anodize matrix used (Table 1) is typical for all systems. The numbers in the matrix represent crack growth in wedge-crack segments after 1 hr of exposure at 140° F and 95 to 100% RH.

A head-to-head comparison was made of the two chromic acid anodize systems. The Bell Helicopter system showed some adhesive failures and excessive crack growth on bare 2024-T3. The McDonnell Douglas system had no adhesive failure with either alloy. The sealing solution for the McDonnell Douglas chromic acid anodize which gave the best results was obtained when potassium dichromate concentration was maintained at 6%, PH was 4, sealing temperature was between 185 and 205°F, and the sealing time was between 8 and 17 min.

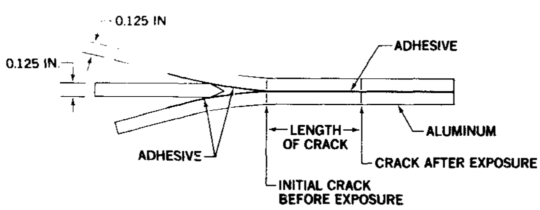

Fig. 1 Wedge-crack specimen.

Table 1 Phosphoric acid anodize matrix, 7075-T6 bare wedge crack

		CONC 11 OZ/GAL		CONC 16 OZ/GAL	
TEMP	TIME (MIN)	VOLTAGE 8	VOLTAGE 12	VOLTAGE 8	VOLTAGE 12
65°F	20	0.045	0.033	0.055	0.060
		0.050	0.015	0.050	0.095
		0.065	0.020	0.050	0.092
		0.030	0.043	0.045	0.066
		0.065	0.065	0.057	0.008
	25	0.053	0.088	0.017	0.040
		0.026	0.076	0.020	0.010
		0.032	0.063	0.040	0.005
		0.015	0.155	0.020	0.045
		0.015	0.047	0.008	0.046
90°F	20	0.092	0.100	0.042	0.045
		0.112	0.075	0.045	0.030
		0.087	0.132	0.041	0.000
		0.023	0.017	0.021	0.000
		0.051	0.061	0.010	0.030
	25	0.078	0.063	0.045	0.0100
		0.010	0.039	0.100	0.090
		0.005	0.030	0.090	0.075
		0.016	0.027	0.047	0.035
		0.010	0.012	0.065	0.080

NOTE: ALL FAILURES WERE COHESIVE

The phosphoric acid anodize finally was selected because it gave cohesive failures over the full range of the test matrix (Table 1) whereas the chromic acid anodize only would produce cohesive failures all of the time if held within very close limits, such as anodizing times of 35 to 40 min in tank with temperature ranges from 95 to 100°F. To date, some 3000 phosphoric acid anodize specimens have been tested and all had cohesive failures. Most of these were made in a simulated production situation while making the test parts. It was found that phosphoric acid anodized surfaces could be contaminated by handling – whether with clean white cotton gloves, kraft paper, or bare hands – prior to application of primer. As a result, the PABST program has decreed that parts will not be touched after anodizing, and will be primed while on anodizing racks.

Adhesive Selection

Four film adhesive and corrosion-resistant primer systems of the latest environment-resistant 250°F cure type were selected for evaluation. Initial selection was based on data generated by the adhesive manufacturers and what test data were available from industry. These four systems were evaluated extensively to allow selection of a single system to be used on the full-scale test article. Tests performed included initial mechanical properties, evaluation of environmental resistance, and verification of processing tolerance allowables, as well as other tests to determine performance when exposed to other variables that are expected when fabricating the final article.

Selected for testing in the program were the following adhesives along with their primer and manufacturer, respectively: 1) M1133 – primer 6740, Narmco Materials, Inc.; 2) AF55 – primer XA3950, 3M Company; 3) FM73 – primer BR127, American Cyanamid; and 4) EA9628 – primer 9202, Hysol Division, The Dexter Corp. FM73 was provided with a mat carrier whereas the other three adhesives were provided with a woven carrier.

The manufacturers' recommended procedures were used for the priming and curing of the adhesive systems. The phosphoric acid anodize surface treatment system was used in all adhesive tests. The alloys used for the adhesive tests were mainly 2024-T3 bare and 7075-T6 bare. All metal-to-metal tests were conducted using 0.045-psf adhesive film weight. Tests included in this evaluation were lap shear, double lap

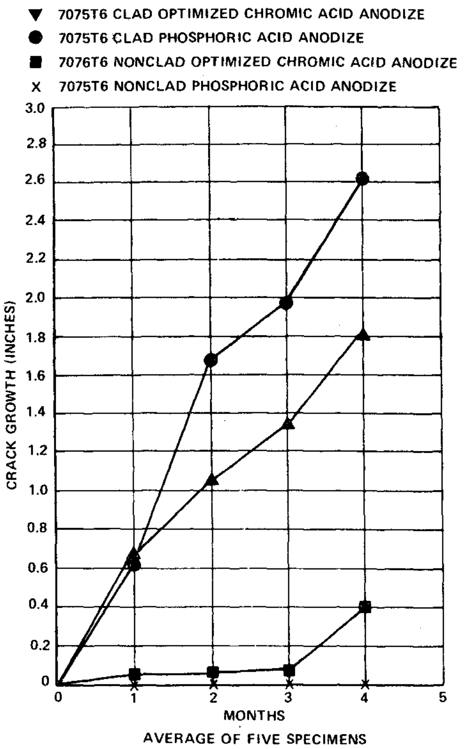

Fig. 2 Beach exposure test.

shear, T-peel, creep, climbing drum, flatwise tension, beam shear, thick adherend (fatigue and shear modulus), napkin ring (shear and tension modulus), torsion pendulum (shear modulus), and double cantilever beam. Most of these tests were performed at three temperatures: −70°F, room temperature, and +180°F. Creep and flatwise tension tests were performed at room temperature and 180°F. Beam shear, napkin ring, and double cantilever tests were performed at room temperature.

For the primer systems, two levels of primer thickness were investigated as well as two temperatures of primer cure. The tolerances for the primer thickness tests were based on the manufacturers' thickest and thinnest recommendations. No problems with the primers within these variables were found. A problem does exist in training painters to apply the primer properly and in methods of measuring the primer thickness applied. Tested electronic thickness measuring methods do not appear to be as accurate as desired. The use of color chips can be misleading, since the color of the primers normally depends on the corrosion inhibitor they contain, which has a very high settle rate. Primer not properly agitated during application will appear thinner than it actually is.

The adhesive variable tests included heat-up rates and adhesive out-time. A simple matrix similar to that used for the surface treatment tests was employed. Three levels of out-time in the controlled bond room were cured at two cure heat-up rates. One adhesive system could not be exposed to room temperature for the total 2-month time. Another of the adhesives was sensitive to a rapid temperature heat-up rate. This adhesive had a tendency to bubble if the heat rise exceeded to 7°F/min. Since production tooling will be large to accommodate the expected large size of the panels to be bonded, a heat-up rate of 3 to 4°F/min is expected.

Several auxiliary tests are included in the program. Included in these tests are the mechanical and environmental resistance of clad adherends vs nonclad adherends. Beach environment exposure tests will be made at El Segundo for a minimum period of 12 months. These include stressed lap shear and wedge-crack specimens. Figure 2 shows the results of the first 4 months of wedge-crack tests; these results illustrate the effects of clad vs nonclad on 7075-T6 material.

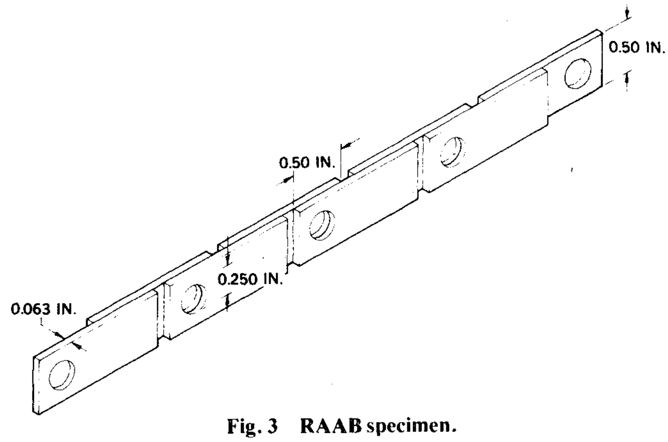

Fig. 3 RAAB specimen.

Scanning electron microscope examinations of one clad wedge crack shows delamination occurring in the sacrificial clad layer between the anodized surface and the alloy.

Environmental tests were conducted to verify the resistance and durability of the surface treatment and adhesive systems to the conditions that are expected to exist in a production aircraft. These environments include fuel, hydraulic fluid, temperature variations, humidity, salt, cleaning compounds, fire extinguisher compounds, and de-icer compounds. Besides the laboratory tests, beach environment exposure tests are in progress. Aircraft environments for primary structures include stressed and cycle-stressed loads on the adhesive bond. The types of test specimens used for the environmental phase of the program include double cantilever, lap shear, peel, wedge crack, neat, and thick adherend, and specialized specimens typical of final article joint design. The tests to date on the double cantilever specimen include all four adhesive systems with their associated primers tested at ambient temperature and at 140°F and 100% RH for 120 days.

The test results indicate a wide difference in the results of the different adhesive systems. Part of the problem may be the difference in the carriers used for the different adhesives. The adhesives with woven carriers showed large crack growth with associated corrosion in the adhesive-adherend interface in tested and nontested areas. This growth was apparent after the 120-day, 140°F, and 100% RH exposure. Subsequently, the specimens that were used as controls were placed at the beach exposure site.

The RAAB specimen, Fig. 3, was developed by American Cyanamid. It consists of a blister-detection-type lap shear of 0.5-in. overlap and 0.5-in. width. A 0.25-in.-diam. hole is drilled into the center of the overlap. This provides a specimen with approximately 0.2 $in.^2$ of bond area and 2.75 linear inches of exposed glue line. It has no engineering design value but is very good for comparing the resistance of similar adhesives in stressed and cycle-stressed environments. Present tests are in progress at various load level cycle rates and environments. The cycles now are 1 hr loaded and 15 min unloaded. Other cycle rates are in test. It should be noted that the cycle-stressed specimens fail in fewer hours than specimens with a constant stress on them, even at a lower stress level. In these tests, again, the adhesive with the mat carrier performs better in the stressed and cycle-stressed tests. Alternate carrier systems for each adhesive are being tested to determine if the carrier or the adhesive resin system is the primary consideration. The cycle-stressed test was started after review of the works of Boeing and Bell Helicopter. Their tests first indicated to Douglas the problems of cycle-stressed testing in an environment and the adhesive characteristics that had to be considered before a bonded primary structure aircraft could be built.

Figure 4 shows the average number of hours of sustained load each adhesive tested withstood when exposed to 140°F and 95 to 100% RH. Figure 5 shows the comparison of the

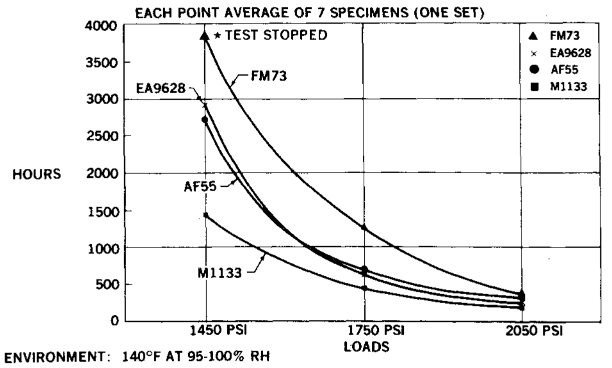

Fig. 4 RAAB sustained load.

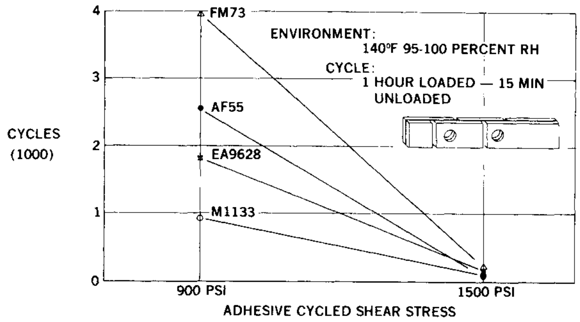

Fig. 5 Cycled load/environment test.

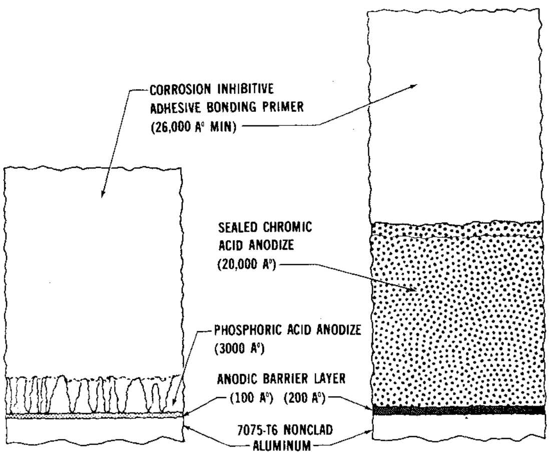

Fig. 6 Surface treatment, corrosion inhibition adhesive bonding primer.

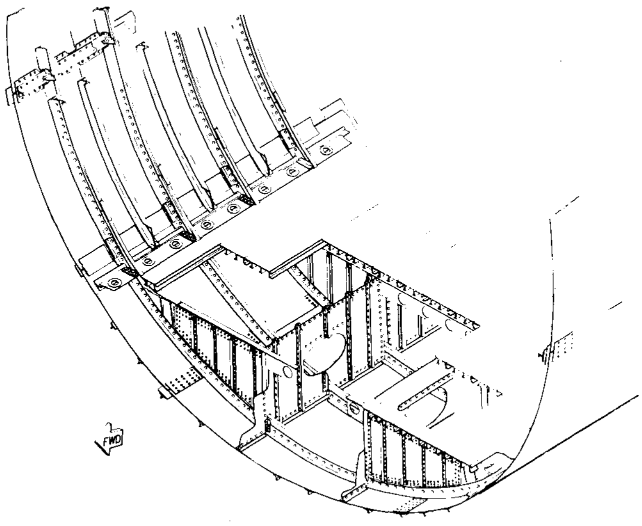

Fig. 7 Selected structural concept.

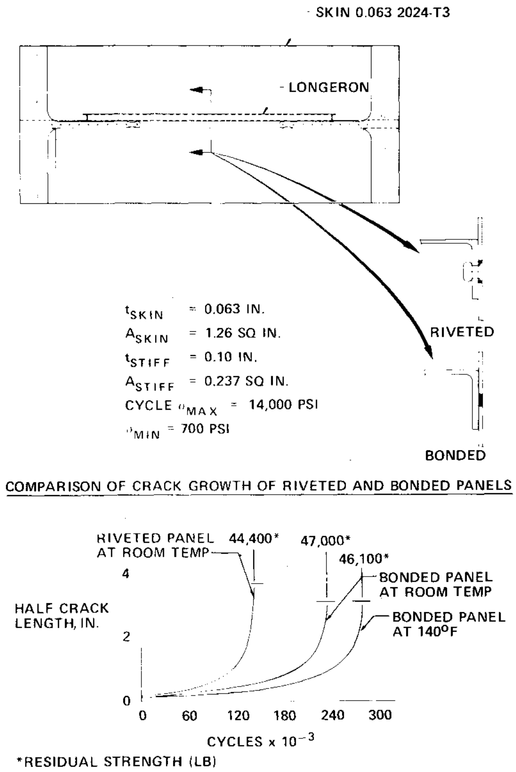

Fig. 8 Damage tolerance test specimen.

four adhesives tested under cycled loads and exposed to 140° F and 95 to 100% RH. After reviewing all of the static and environmental tests, the PABST program has selected the American Cyanamid adhesive system, FM73 (Mat) adhesive with BR127 primer, for use during the remainder of the program.

Coatings

Since it has been determined outside the PABST program that a clad surface in the bond faying surface is undesirable, an extensive corrosion control program was conducted. By itself, phosphoric acid anodize has poorer corrosion resistance than the chromic acid anodize. However, when the adhesive primer RB127 is applied to both anodizes, they perform equally well.

Several exterior coating systems used by the Air Force were tested environmentally and the following conclusions reached. The optimum exterior coating system over the BR127 is MIL-P-23377 primer plus MIL-C-83286 topcoat. This system inhibited exfoliation better than the Corogard system. The optimum interior coating systems over the BR127 are divided into those above the floor area and those below. Above floor, the use of MIL-P-23377 primer is recommended; below the floor, MIL-C-83286 topcoat is applied over MIL-P-23377 primer. Figure 6 shows a comparison of the two anodize systems.

Structural Evaluation

The design phase began with a wide-open design evaluation of all possible structural arrangements. Design detail was sufficient to determine comparative manufacturing costs and weights so that the three most promising designs could be selected. The baseline aircraft is the YC-15 AMST. The external loads and geometry were used. The fuselage diameter is 216 in. and the cabin is pressurized to a maximum of 7.15 psi.

In September 1975, Douglas selected three configurations and received Air Force concurrence. One configuration was

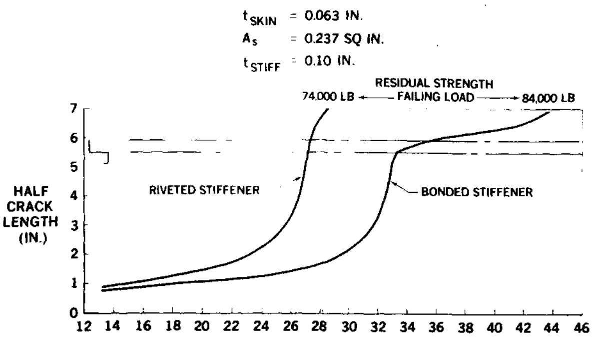

Fig. 9 Crack growth comparison test (initial gross stress $-\tau_{max} = 14,000$ psi, $R = 0.05$).

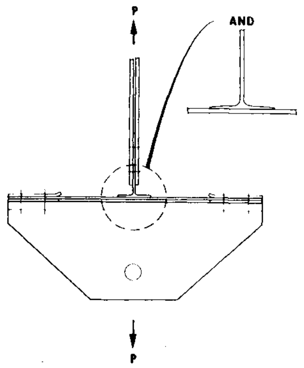

Fig. 10 Tension tee test specimen, for testing tension in the bond joint between the skin and the frame/shear tee.

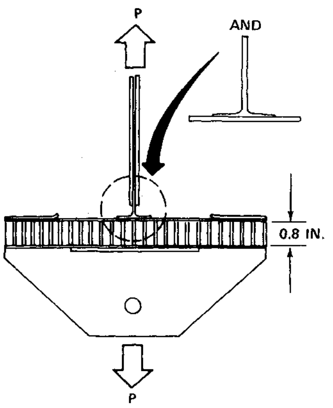

Fig. 11 Tension tee test specimen, for testing tension in the bond joint between honeycomb skin and the frame/shear tee.

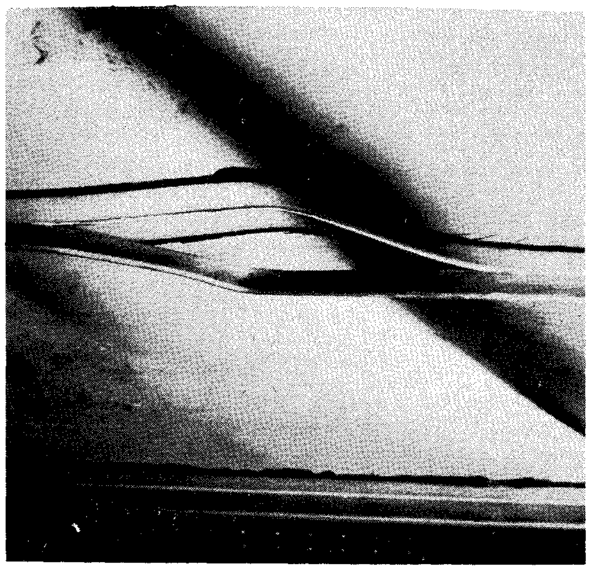

Fig. 12 Shear panel failure.

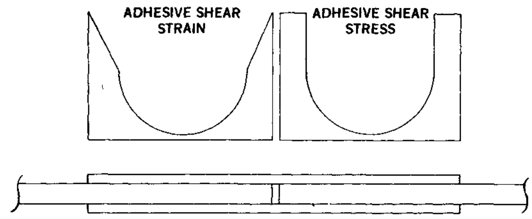

Fig. 13 Double lap joints.

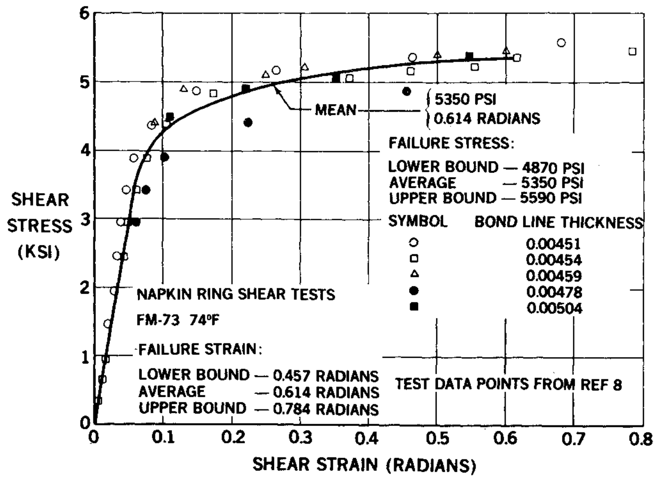

Fig. 14 FM-73 adhesive stress-strain diagram.

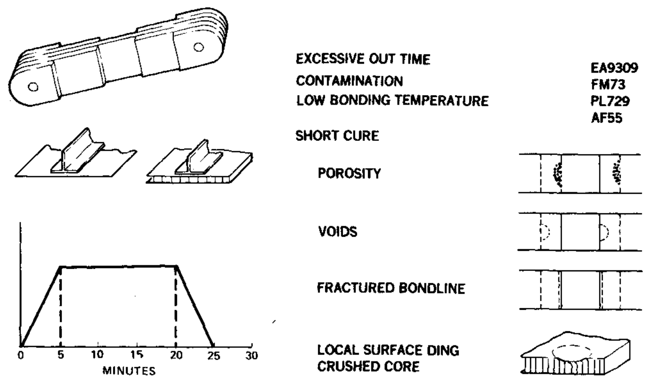

Fig. 15 Effects of defects.

essentially the conventional design arrangement used for riveted structures and identified as an internally stiffened structure. The second configuration is identical to the first, except that the longitudinal stiffeners are placed on the outside of the skin which is ideal structurally. This arrangement eliminates frame cutouts for the longerons. The major drawback outside of appearance is the added drag. The third configuration is a honeycomb sandwich design. With this type of skin stiffening, many frames are removed and no longerons are required. In order to maintain the same weight as the preceding designs, very light face sheets are required. This is not practical since the thin 0.025-in. skins are easily subject to foreign object damage and associated costly repairs. The design proceeded using arbitrarily heavy face sheet to reduce susceptibility to damage. Also, current Air Force and commercial aircraft service experience with honeycomb panel failures has all but ruled out their use.

At the August 16-20 PABST program review by the Air Force team, Douglas recommended the structural arrangement shown in Fig. 7. The area above the floor is of conventional structure using bonded internal longerons. It can be seen that longerons were virtually eliminated on the sides because of the low load levels. The external longerons

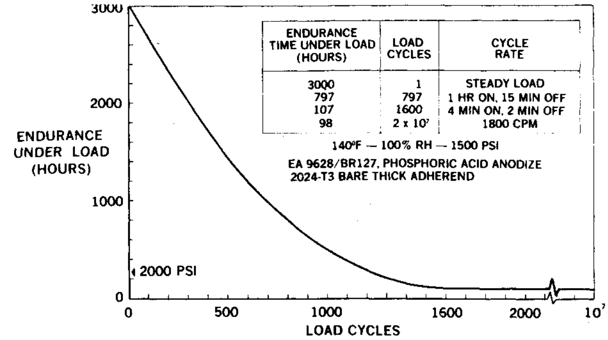

Fig. 16 Effect of cycle rate on endurance.

Table 2 Ultimate failing loads, frame/shear tee-to-skin joint

SKIN	ADHESIVE	PRIMER	FAILURE LOAD TEST TEMP			DESIGN LOAD
			-50 ± 5^oF	R.T.	140 ± 5^oF	-50^oF
0.090 7075-T6	FM 73	BR 127	1740 LB			249 LB
0.040 7075-T6	FM 73	BR 127	1595 LB			389 LB
0.090 7075-T6	AF 55	XA 3950			4000 LB	249 LB
0.090 7075-T6	M 1133	BR 127	2170 LB			249 LB
0.090 7075-T6	AF 55	XA 3950	5910 LB	5050 LB	5075 LB	249 LB
0.090 7075-T6	M 1133	BR 127	2640 LB	4650 LB		249 LB
0.040 7075-T6	AF 55	XA 3950	1670 LB	3700 LB	4220 LB	389 LB
0.040 7075-T6	M 1133	BR 127	2105 LB	3275 LB	3358 LB	389 LB

are used below the floor and will challenge the bond shop because members are bonded to both sides of the fuselage skin. Attempts to date have shown it is difficult to get good (proper) pressure at intersections.

During the initial design study phase, it became apparent that several quick tests should be run to see if any "show stoppers" existed in bonded designs. Failure to get allowable equivalent to riveted structure could defeat the program. The first two tests examined the effectiveness of a bonded longeron in arresting a crack. These tests showed that the

Table 3 Ultimate failing loads, frame/shear tee-to-honeycomb joint. (adhesive 1133, primer BR 127)

FACESHEET THICKNESS	CORE DENSITY (PSF)	TEE THICKNESS (IN.)	TEST TEMPERATURE (°F)	FAILING LOAD (LB)	TYPE OF FAILURE*	DESIGN LOAD (LB)
0.020 7075T6	3.4	0.050	−50 AMBIENT +140	2580 2530 2460	(1) (1) (1)	462
0.020 7075T6	5.2	0.050	−50 +140	3720 3830	(1)	462
0.020 7075T6	7.9	0.050	−50 +140	5210 3340	(2) (2)	462
0.020 7075T6	5.2	TAPERED	−50	3580	(1)	462
0.040 7075T6	5.2	0.094	−50	4100	(1)	392
0.040 7075T6	7.9	0.094	−50	6975	(1)	392

*(1) CORE SHEAR (2) FACESHEET TO CORE BOND DELAMINATION (TENSION)

adhesive joint retarded the skin crack growth more as it passed under the stringer than when compared to a riveted stringer design. The results are shown in Figs. 8 and 9. It was decided to make small specimens to show load effects produced from cabin pressurization. The skins resist the pressure and therefore expand, tending to pull away from the frame which then puts a bonded joint in tension. Figures 10 and 11, together with Tables 2 and 3, show the results. The bond joint can resist the tension/peeling action that exists.

A large number of shear panels were tested using extremes in skin gages, stiffener spacings, and hot-to-cold environment. Again the bonded joint was as capable as rivets in resisting the attack of the deepening shear wrinkle. Table 4 summarizes the pure shear test results and shows the level of shear required by structure. Figure 12 shows how well the adhesive works by causing the stiffener to fracture instead of the bond line. A series of interaction tests, shear plus tension and shear plus compression, have been run, and again the allowables exceed the theoretical values.

Intact adhesive-bonded joints have been analyzed for three situations: 1) the double-strap joints used in longitudinal splices, 2) the flush single-strap joints used on circumferential splices, and 3) the peeling apart of the skin and stiffening

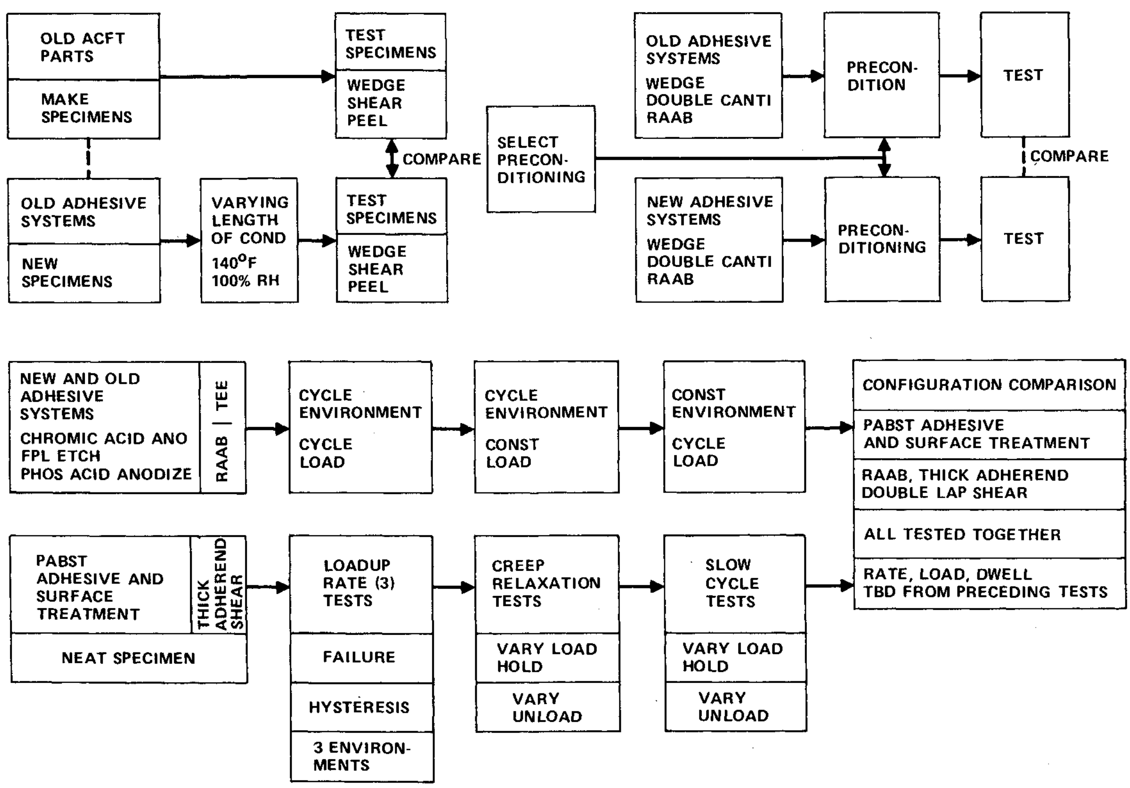

Fig. 17 Environmental program.

Table 4 Shear static test panel, primer BR 127

SKIN 7075T6 (IN.)	LONGERON	ADHESIVE	TEST TEMP	TEST SHEAR (KSI)	DESIGN SHEAR (KSI)	ANALYSIS FAILURE PREDICTION (KSI)
0.04		FM73	−50°F	19.8	13.0	18.3
0.09		RIVETED	R.T.	24.6	20.0	21.8
0.09		FM73	R.T.	26.5	20.0	21.8
0.04		M1133	−50°F	27.5	13.0	18.3
0.04		M1133	140°F	25.3	13.0	18.3
0.09	NONE	FM73	140°F	19.6	20.0	10.6
0.09*	NONE	FM73	140°F	23.8	20.0	12.6
(2024T3) t_o = 0.02, t_i = 0.020**	NONE	FM73	R.T.	42.6	13.0	23.5
t_o = 0.04, t_i = 0.04**	NONE	FM73	140°F	48.0	39.0	23.5
0.0434		FM73	140°F	30.7	13.0	23.3

*12 IN. FRAME SPACING
**48 IN. FRAME SPACING

Table 5 Major resource element content, percent breakdown

RESOURCE ELEMENT	BASELINE	INTERNAL LONGERON	EXTERNAL LONGERON	HONEYCOMB
MFG LABOR				
FABRICATION	13.4	17.4	19.1	13.1
ASSEMBLY	56.8	36.9	32.1	19.9
METAL BOND	–	10.1	11.0	18.4
SUBTOTAL	70.2	64.4	62.2	51.4
INSPECTION	8.7	10.1	9.8	15.9
TOOLING	7.7	10.0	11.5	13.0
PLANNING	5.1	5.1	5.1	4.7
RAW MATERIALS	8.0	10.4	11.4	15.0
TOTAL	100.0	100.0	100.0	100.0

elements under internal cabin pressure. Tests have been performed for each of these categories. The test results have confirmed the predictions, where a comparison could be made, and established the adequacy of the bonded joints for the ultimate mode in those applications required for PABST, i.e., thin and only moderately thick components. The conclusions for the bonded joints in intact structure may be summarized as follows. The metal elements are more critical than the adhesive for loads less than sufficient to yield the metal. Once yielding occurs, the adhesive fails progressively, as long as the associated loads are maintained, until complete failure occurs. Figure 13 shows the strain and stress distributions obtained by analysis during the program.[4] Figure 14 shows the adhesive data used in the analysis.

Two other important areas are being investigated, but have not been finished. One is the determination of the effects of defects. The other is the effect of cycle rate. When NDI inspection reveals some porosity, absence of adhesive, fractured bond line, or anything that might reduce the bond strength, it is imperative to know what can be left unrepaired. Therefore, a series of slow cycle environment tests will be run with specimens containing various kinds of flaws. Figure 15 shows typical specimens. The next curious phenomenon of adhesives is the effect of cycle rate. Figure 16 shows data on hand. These were run with thick adherends and show great variation in cycle life. For the PABST full-scale test article where longitudinal splices must carry cabin pressure each flight, two lifetimes are 38,000 cycles (based on current YC-15 information). A greatly expanded environmental program was started in October 1976. Figure 17 shows the broad attack made on environmental tests to know where we stand. No one will build an aircraft structure using adhesives in place of rivets until the environmental picture is understood clearly.

Table 6 Cost summary by major resource element, constant 1975 dollars

RESOURCE ELEMENT	BASELINE	INTERNAL LONGERON	EXTERNAL LONGERON	HONEYCOMB
MFG LABOR				
FABRICATION	82,151	82,256	89,576	50,779
ASSEMBLY	347,701	174,279	150,514	77,499
METAL BOND	–	47,882	51,381	71,648
SUBTOTAL	429,852	304,417	291,471	199,926
INSPECTION	53,591	47,853	45,706	61,700
TOOLING	47,122	47,122	53,799	50,604
PLANNING	31,423	23,930	24,038	18,449
RAW MATERIALS	49,347	49,505	53,153	58,567
TOTAL	611,335	472,827	468,167	389,246
COST RATIO	1.00	0.773	0.766	0.637
CHANGE FROM BASELINE	0.0	−22.7%	−23.4%	−36.6%

Cost Study

Sufficient detail was put into the three structural arrangements so that a good side-by-side cost comparison could be made. Table 5 presents a distribution of the costs to major elements. It can be seen that the baseline numbers (distribution) are similar to those found in Ref. 1. Detailed "grass roots" cost estimates were made. This meant counting parts and looking at tool requirements, numbers of fasteners, etc. The final estimated costs were summarized in Table 6. Even though the honeycomb design is cheapest, it was discarded because of foreign object damage sensitivity.

Conclusions

The proposed PABST adhesive system offers tremendous advantages from a durability standpoint to any previously in use. System features are listed below.

1) Use only bare aluminum alloy surface in bond line faying surface.

2) Phosphoric acid anodize using wedge-crack tests for verification.

3) Do not handle anodized surface prior to priming.

4) Apply corrosion-inhibiting primer, BR127, to all anodized surfaces and cure.

5) Use new generation, 250°F cure, modified epoxy adhesive film FM73 with mat carrier (cure at 40 psi for 90 min.).

6) Exterior and below floor coating: MIL-P-233 epoxy-polyamide primer and MIL-C-83286 polyurethane topcoat.

7) Interior coating above the floor: MIL-P-23377 epoxy-polyamide primer. Static, fatigue, and damage tolerance testing shows that the above adhesive will give equal or greater structural reliability than a riveted structure.

More environmental tests need to be conducted and the results compared with existing systems to gain complete confidence that the adhesive system can be used for primary structure. The upcoming full-scale test will provide a final check of the ability of the metal in a bonded fuselage to resist normal aircraft loads.

References

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[3] Bethune, A. W., "Durability of Bonded Aluminum Structure," *SAMPE Journal*, Vol. 11, July-Sept. 1975, pp. 4-10.

[4] Hart-Smith, L. J., "Analysis and Design of Advanced Composite Bonded Joints," Douglas Aircraft Company, NASA CR-2218, Jan. 1973.