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System Integration and Demonstration of Adhesive Bonded High Temperature Aluminum Alloys for Aerospace Structure - Phase II

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FOREWORD

Systems Integration and Demonstration of Adhesive Bonded High Temperature Aluminum Alloys for Aerospace Structures (Contract No. NAS1-18560, Task Assignment 7, Phase II) was performed by the Boeing Defense & Space Group, Research and Engineering Division, Seattle Washington, for the NASA Langley Research Center (LaRC), NASA, Hampton Virginia. This phase follows the initial program on Systems Integration and Demonstration of Advanced Reusable Structure for ALS (SIDARS), Contractor Report 187509, June 1991. Mr. Dick Royster, of the NASA LaRC Applied Materials Branch, was the Contract Technical Monitor.

Mr. Curt C. Chenoweth was the program manager and Mr. John H. Laakso was the task manager. Anthony Falcone and Martin Gibbins were the principal investigators. Steve Hahn performed analysis of the compression and toughness test specimens. Erich Freitas bonded the test specimens and Oscar Davis performed much of the mechanical testing. Noel Gerken assisted in establishing the original adhesive test matrices.

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CONTENTS

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FIGURES

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SUMMARY

Adhesive bonding materials and processes were evaluated for assembly of future high-temperature aluminum alloy structural components such as may be used in high-speed civil transport aircraft and space launch vehicles. A number of candidate high-temperature adhesives were selected and screening tests were conducted using single lap shear specimens. The selected adhesives were then used to bond sandwich (titanium core) test specimens, adhesive toughness test specimens, and isothermally aged lap shear specimens. Moderate-to-high lap shear strengths were obtained from bonded high-temperature aluminum and silicon carbide particulate-reinforced (SiC_p) aluminum specimens. Shear strengths typically exceeded 3500 to 4000 lb/in^2 and flatwise tensile strengths exceeded 750 lb/in^2 even at elevated temperatures (300°F) using a bismaleimide adhesive. All faceskin-to-core bonds displayed excellent tear strength. The existing production phosphoric acid anodize surface preparation process developed at Boeing was used, and gave good performance with all of the aluminum and silicon carbide particulate-reinforced aluminum alloys investigated. The results of this program support using bonded assemblies of high-temperature aluminum components in applications where bonding is often used (e.g., secondary structures and tear stoppers).

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1.0 INTRODUCTION

Many future aerospace vehicle designs such as the High-Speed Civil Transport (HSCT) airplane and space launch vehicles proposed for the National Launch System (NLS) will require adhesive bonded structure that will perform effectively at elevated temperature. High-temperature aluminum alloys appear advantageous for application in many of these designs because of their high performance and thermal stability. Structural adhesives that are presently in common use are not suitable for these elevated service temperatures because they will degrade. Appropriate surface preparations and primers are also needed for high-temperature aluminum alloys.

Future aircraft and aerospace designs will also require lighter weight aluminum alloys and alloys with higher stiffness than those used in present designs. Higher stiffness aluminum alloys have been produced through the addition of particulate reinforcement such as silicon carbide. Other aluminum alloys achieve lower density through the addition of lighter alloying elements such as lithium. Adhesives and surface preparations for bonded structure from these aluminum alloys will be required.

Thermal analysis of NLS propulsion/avionics (P/A) module designs, HSCT aircraft, and other aerospace vehicle designs demonstrate the needs for high-temperature materials. P/A modules may experience temperatures between 200° and 900°F during reentry (ref. 1). HSCT and military tactical aircraft designs subject areas of the wing and fuselage to temperatures between 200° and 350°F for long periods during flight.

In addition to high-temperature aluminum alloys and metal-matrix composites, titanium is also being considered for high-temperature structure. However, the industry does not have a widely accepted method for surface preparation of titanium without using compounds containing heavy metals, such as chromium, for structural bonding in production. Titanium surface preparation methods requiring hazardous compounds with heavy metals are being phased out by industry. Also, titanium surface preparations often exhibit inadequate long-term performance at elevated temperature. Therefore, high-temperature aluminum alloys, such as 8009 aluminum, may be an attractive alternative to titanium for aerospace vehicle structures subjected to elevated temperatures during flight; however, the low alloy toughness must be accounted for in designs.

The U.S. Advanced Launch System (ALS) was intended to improve launch cost effectiveness over current systems. One approach was to incorporate the highest cost/mass elements, the main engines and avionics hardware, in a reusable propulsion/avionics (P/A) module. Designs were developed in Phase I of this effort for recoverable launch vehicle P/A modules which relied on adhesive bonded aluminum alloy structure in system integration and demonstration of advanced reusable structure (SIDARS, ref. 1).

Adhesive bonding materials and processes were evaluated for assembly of future high-temperature aluminum alloy structural components such as may be used in HSCT aircraft and space launch vehicles. A number of candidate high-temperature adhesives were selected and screening tests were conducted using single lap shear specimens. The selected adhesives were then used to bond sandwich (titanium core) test specimens, adhesive toughness test specimens, and isothermally aged lap shear specimens.

The aluminum alloys selected for this study are listed in figure 1.0-1. The alloys included 8009, a high-temperature aluminum alloy produced by Allied-Signal, Weldalite RX818-T8, a weldable, high-strength aluminum-lithium alloy supplied by Reynolds, and silicon carbide particulate-reinforced versions of 8009 and another aluminum-lithium alloy (8090) from BP Metals. These alloys were selected because they offer higher operating temperature capability, lower weight, high strength, or higher stiffness compared with conventional aluminum alloys.

Since a range of mach numbers are under consideration for various aerospace vehicle designs and each vehicle type has different thermal profiles, several high-temperature adhesives (fig. 1.0-2) were selected for screening tests to cover a range of service temperatures consistent with the capabilities of the aluminum alloy facesheets. Polyimide and bismaleimide adhesives are higher temperature classes of resin which are leading candidates for high-temperature bonded structure.

Aluminum Alloy and Manufacturer	Alloy Composition	Percent silicon carbide particulate	Sheet Thickness (in)	Description
8009, Allied Signal	Al - 8 Fe - 1.3V - 1.7 Si	N/A	0.095	High-temperature. Powder metallurgy process
SiCp/8009, Allied Signal	Al - 8 Fe - 1.3V - 1.7 Si	11%	0.080	High-stiffness and temperature, particulate-reinforced metal matrix composite
Weldalite RX818-T8, Reynolds	Al - 3.5 Li - 6.5 Cu - 6.0 Mg - 1.0 Si - 1.0 Zn	N/A	0.088	High-strength, weldable Al-Li alloy. Ingot metallurgy.
SiCp/8090, BP Metals	Al - 2.5 Li - 1.1 Cu - 0.9 Mg - 0.13 Zr - 0.15 Fe - 0.05 Si	20%	0.080	High-stiffness, particulate-reinforced metal matrix composite.

Figure 1.0-1. High-Temperature and High-Performance Aluminum Alloys Investigated

Adhesive and Manufacturer	Type of Resin	Approximate Maximum Operating Temperature Range	Description
XEA 9674, Dexter Hysol	Bismaleimide	275° to 350°F	Modified bismaleimide for improved toughness
X2550, BASF	Bismaleimide	275° to 350°F	Modified bismaleimide
FM 680, American Cyanamid	Polyimide	400° to 450°F	Condensation thermoset polyimide
PT resin, Allied Signal	Phenolic triazine	300° to 350°F	Developmental adhesive resin. Phenolic triazine network
LARC-TPI, Mitsui-Toatsu	Polyimide	400° to 430°F	Thermoplastic polyimide, from polyamic acid.
AF 191, 3M	Epoxy	160° to 230°F	350°F cure epoxy

Figure 1.0-2. Adhesive Systems Investigated

The family of polyimide resins, which includes bismaleimide (BMI) resins, have been extensively investigated, and formulations have been developed for a wide range of high-temperature, high-performance applications, ranging from graphite reinforced composites to molded parts (ref. 2). Polyimides are often synthesized by reacting an aromatic diamine with an aromatic dianhydride in a polar aprotic solvent to form a poly(amic acid), which is then thermally or chemically dehydrated to form the polyimide. The class of BMI polyimides are thermosetting polyimide polymers terminated with two maleic anhydride molecules, hence the term bismaleimides.

Two polyimide adhesives for 325° to 400°F continuous service were selected, and two BMI adhesives for 250° to 300°F continuous service were selected. The Dexter Hysol XEA 9674 is a modified bismaleimide supported film adhesive with long-term structural capability at 300°F, and shorter time exposures to 550°F. The X2550 is a bismaleimide produced by BASF for composite and adhesive applications. The polyimide adhesive, FM 680, produced by American Cyanamid, is a commercial polymide adhesive and is well established. The Langley Thermoplastic Polyimide (LARC-TPI) resin is a resin developed at the NASA Langley Research Center, and licensed to several companies, for high-temperature adhesive and composite applications. Phenolic triazine (PT) resin is an experimental resin under development at Allied Signal and may be suitable for 325° to 375°F service.

Phenolic triazine resins are synthesized by the cyclotrimerization of cyanate ester groups to form a phenolic triazine network (ref. 3). The triazine network results in improved thermal stability compared with conventional phenolics which have networks of weaker methylene bridges. Since PT resin cures by an addition reaction, no volatile byproducts are produced — avoiding porosity in the bondline and lower strengths.

The 3M AF 191 epoxy adhesive was selected based on prior Boeing experience to bond the SiC_p/8090 and Weldalite single lap shear specimens, and lap shear tests were conducted to verify the quality of the AF 191 adhesive bond, primer, and surface preparation with these aluminum alloys. The commercial AF 191 epoxy adhesive was selected for bonding to avoid overaging the alloys at temperatures above 350°F.

Appropriate primers were selected for each adhesive. Often the primer is a dilute solution of the specific adhesive being used for bonding. The primer has a low viscosity and wets out the metal bonding surface more completely than the adhesive would, improving the bond strength between the adhesive and the adherends. The primer also preserves the bonding surface preparation until the adhesive can be applied, because in production, bonding cannot always be performed within a short time after the surface is prepared. The surface preparation cleans and, in the case of metals, oxidizes the surface and also chemically activates the surface. Without a primer or prompt application of the adhesive, the chemically active groups would disappear and the adherend surfaces could become contaminated.

Phosphoric acid anodize (PAA) was selected because it is the standard surface preparation used by Boeing and others in industry to prepare aluminum components for bonding. PAA prepared bonds have demonstrated very good durability and strengths.

The Phase I portion of this program defined the adhesive bond test specimens that were fabricated and tested in Phase II. These specimens were selected to demonstrate the performance of competing high-temperature adhesive systems in four critical areas: (1) lap shear strength, (2) sandwich-to-core bond strength, (3) joint fracture toughness, and (4) effects of thermal cycling and thermal aging. The specimens and tests were also selected using the requirements of High Speed Civil Transport (HSCT) aircraft designs because higher temperature bonded structure is a critical part of all HSCT designs under consideration.

Single lap shear testing was used to assess the relative performance of each adhesive system (which includes primer and surface preparation). The lap shear test is a standard test performed with adhesives to measure shear strength, which is a critical parameter in adhesive bond strength. The single lap shear specimen also experiences peel stresses under load as do many bonded joint designs. The lap shear testing with AF 191 epoxy was intended to verify the quality of adhesive bonds obtained with these specific alloys and surface preparations, and not for screening purposes. Lower temperature structural epoxy adhesives are better established than higher temperature structural adhesives.

To assess the performance of the adhesive selected from lap shear screening tests for bonding metal honeycomb core, sandwich panels were bonded using titanium honeycomb core and the aluminum alloys as skins. Specimens were tested in flatwise tension in which the face skins are pulled directly off of the core, and is a measure of the core/skin bond strength. Edgewise compression testing was also conducted because this mode of loading is important in P/A module designs.

Toughness is an important property of bonded structure, where catastrophic failure modes are unacceptable. In airplane structures, as well as other metal bonded structures, tear stoppers are frequently bonded to skins. Peel stresses are often present in bonded joints; therefore adhesives with good toughness are required for these joints. Laminating sheets of high-temperature aluminum alloys together is an attractive method of producing an aluminum structure with increased toughness (ref. 4). Toughness is also a desirable property for recoverable P/A modules that can experience repeated water landings (hydrodynamic impact).

The toughness characteristics of joints bonded with these high-performance aluminum alloys were assessed using test specimens that fail in two modes that are common in crack propagation through an adhesive joint. The double cantilever beam (DCB) specimen fails in mode I which is a crack opening mode. The end notched flexure (ENF) specimen fails in mode II which is a crack propagation mode associated with a pure shear displacement of the adherends.

Thermal cycling is a concern in both P/A module and HSCT designs. Selected test specimens were subjected to thermal cycling, and subsequently tested to assess any detrimental effects on adhesive bond strength. The thermal cycle selected was adapted from P/A module and HSCT flight profiles.

The effects of thermal aging are of concern for HSCT applications where structures are exposed to elevated temperatures for long periods during flight. Thermal aging can cause changes to occur in the adhesive resin microstructure, oxidation of the adhesive, and degradation of the adherend-adhesive interface. Thermal aging effects are often investigated by exposing test specimens to elevated temperatures in an air circulating oven for predetermined times, and comparing the aged specimen test results to unaged specimens. The lifetime HSCT thermal exposure would be for 60,000 hours; however, 1000 hours was selected for preliminary evaluation of the selected adhesives and to fit within the program schedule.

2.0 OBJECTIVES

The objective of this program was to investigate adhesives and bonding processes for high-temperature and high-performance aluminum alloys that would meet the requirements of aerospace vehicle designs such as the P/A module or HSCT airplane. This objective was accomplished by screening adhesives using single lap shear tests conducted at ambient, elevated, and low temperatures, consistent with the capabilities of the aluminum alloy face sheets. Sandwich and interlaminar fracture toughness specimens were then bonded and tested using the selected adhesives to assess the toughness and durability of bonded structure produced from these high-temperature aluminum alloys. Thermal cycling of some of these specimens was also performed to assess the effects of ground-air-ground cycles on bonded structures. The effects of prolonged elevated temperature exposure on the lap shear strength of the selected adhesives was also assessed.

3.0 PROGRAM PLAN

To accomplish the program objectives, single lap shear screening tests were conducted on candidate high-temperature adhesives (fig. 3.0-1), followed by testing of sandwich specimens and toughness specimens (fig. 3.0-2) bonded with the selected adhesives. Diagrams of the lap shear and sandwich specimens are shown in figure 3.0-3. Candidate adhesives for the high-temperature 8009 aluminum alloy and SiCp/8009 included polyimides for high operating temperatures and bismaleimides for slightly lower operating temperatures. An epoxy adhesive was used for the Weldalite and 8090 aluminum alloys because they would be used in lower temperature applications. Isothermal aging, followed by testing of single lap shear specimens, was also conducted (fig. 3.0-4) using the selected adhesives.

The bonding process used for each adhesive is outlined in Appendix A. Blanks measuring 6 in by 4 in were sheared, or machined from the brittle 8009 alloy, and bonded in fixtures to create a 1/2-in-long lap joint. All blanks were phosphoric acid anodized in accordance with the Boeing process specification (ref. 5) for aluminum. Blanks were primed after anodizing with a primer appropriate for the adhesive being used, and assembled in fixtures with adhesive tape between the bonding surfaces. The lap joint bonding surfaces were the areas where the upper and lower blanks overlapped. A shim of the same thickness as the lower blank was placed underneath the upper blank to support it during bonding.

The blank assemblies and bonding fixtures were vacuum bagged and bonded in an autoclave. Five 1-in-wide lap shear specimens were machined from each bonded assembly. The same procedure was followed with appropriately sized blanks to produce the toughness test specimens.

The sandwich test specimens (fig. 3.0-3) were prepared by anodizing and priming the face skins and assembled with adhesive tape and titanium honeycomb core. The titanium core was low-voltage chromic acid anodized (ref. 6) prior to priming. The same bonding processes were used with the sandwich and metal-to-metal bonded specimens.

Adherends	Test Temp. (°F)	Adhesives					
		XEA 9674 BMI	X2550 BMI	FM 680	PT Resin	LARC-TPI	AF191 Epoxy
8009 Al Sheet	-67	5	5	5	5	5	---
	72	5	5	5	5	5	---
	250	5	5	5	5	5	---
	350	5*	5*	5	5	5	---
2- Weldalite Sheet -T8	-67	---	---	---	---	---	5
	72	---	---	---	---	---	5
	225	---	---	---	---	---	5
	275	---	---	---	---	---	5
SiCp/8009	-67	---	---	---	---	---	---
	72	---	---	---	---	---	---
	250	5	---	5	5	5	---
	350	5*	---	5	5	5	---
SiCp/8090	-67	---	---	---	---	---	5
	72	---	---	---	---	---	5
	225	---	---	---	---	---	5
	275	---	---	---	---	---	5

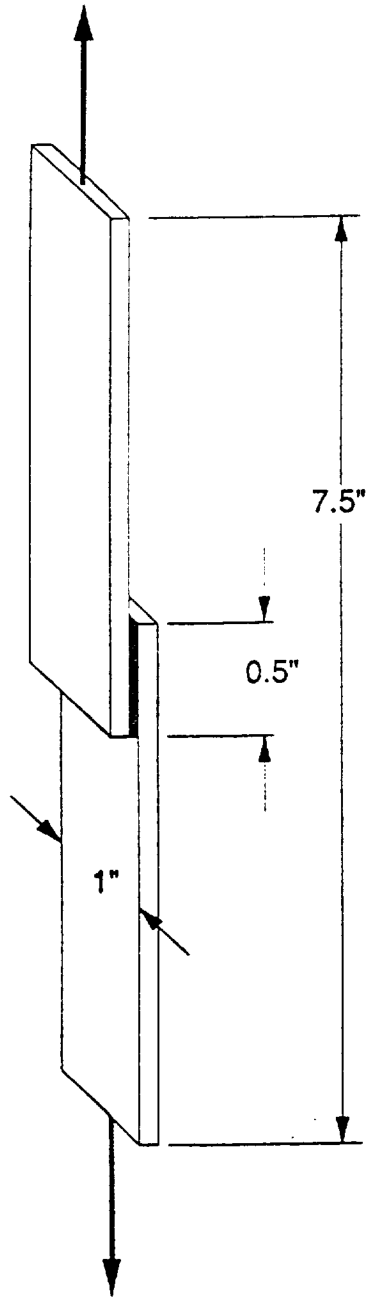
*Tested at 300°F.

Figure 3.0-1. Lap Shear Test Matrix for Adhesive Screening

Test Specimen	Face Sheets	Adhesive	Thermal Cycling*	Test Temperatures				Total No. of Test Specimens
				-67°F	72°F	275°F	300°F	
Flatwise Tension	8009	XEA 9674 BMI	no	3	3	--	3	9
	8009	XEA 9674 BMI	yes	3	3	--	3	9
	Weldalite	AF 191 Epoxy	no	3	3	3	--	9
	Weldalite	AF 191 Epoxy	yes	--	3	3	--	6
	SiC_p/8009	XEA 9674 BMI	no	--	3	--	3	6
	SiC_p/8009	XEA 9674 BMI	yes	--	3	--	3	6
	SiC_p/8090	AF 191 Epoxy	no	3	3	2	--	8
Edgewise Compression	8009	XEA 9674 BMI	no	--	3	--	3	6
	8009	XEA 9674 BMI	yes	--	3	--	2	5
	Weldalite	AF 191 Epoxy	no	--	3	3	--	6
	Weldalite	AF 191 Epoxy	yes	--	3	3	--	6
	SiC_p/8009	XEA 9674 BMI	no	--	3	--	3	6
	SiC_p/8009	XEA 9674 BMI	yes	--	2	--	2	4
	SiC_p/8090	AF 191 Epoxy	no	--	3	3	--	6
	SiC_p/8090	AF 191 Epoxy	yes	--	3	0	--	3
Double Cantilever Beam (G_{IC})	8009	XEA 9674 BMI	no	3	3	--	--	6
	8009	XEA 9674 BMI	yes	3	3	--	--	6
	Weldalite	AF 191 Epoxy	no	3	2	--	--	5
	Weldalite	AF 191 Epoxy	yes	3	1	--	--	4
	SiC_p/8009	XEA 9674 BMI	no	--	0	--	--	0
End Notched Flexure (G_{IIC})	8009	XEA 9674 BMI	no	3	3	--	--	6
	8009	XEA 9674 BMI	yes	3	3	--	--	6
							Total	128

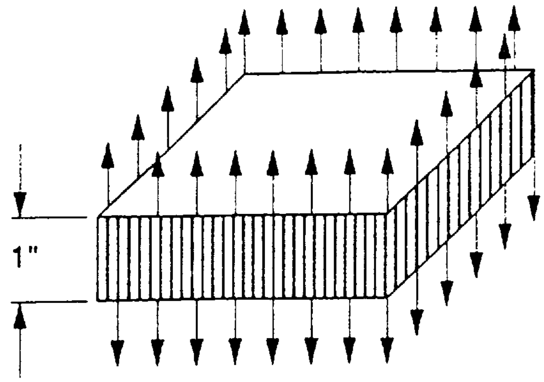
*50 cycles, -67°F to highest elevated test temperature (275° or 300°F).
BMI= Bismaleimide

Figure 3.0-2. Sandwich and Toughness Specimen Test Matrix to Determine Skin-Core Bond Strength and Toughness of Metal-to-Metal Bonds



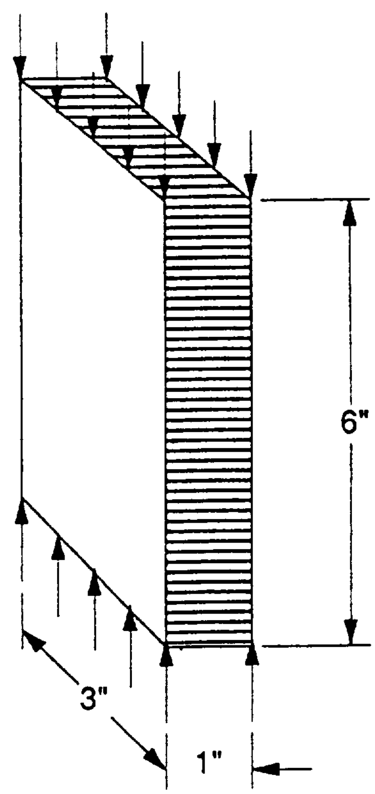
Lap Shear Test
(ASTM D1002 & D2295)

Objective: Validate adhesive strength and surface treatment of high-temp Al adherends.



Flatwise Tension Test
(ASTM C 297) (2"X2")

Objective: Validate capability of high-temp adhesives and aluminums in sandwich structure.



Edgewise Compression Test
(ASTM C 364)

Objective: Validate capability of high-temp adhesives and aluminums in sandwich structure.

Figure 3.0-3. High-Temperature Aluminum Lap Shear and Sandwich Test Specimens

Adherends	Adhesive	Test Temp. (°F)	Isothermal aging exposure (hours)		
			100	500	1000
8009 Al Sheet	XEA9674 BMI	-67	5	5	5
	XEA9674 BMI	72	5	5	5
	XEA9674 BMI	300	5	5	5
Weldalite Sheet -T8	AF 191 Epoxy	275	5	5	5
SiCp/8009	XEA9674 BMI	300	5	5	5
Total			25	25	25

BMI = Bismaleimide

Figure 3.0-4. Lap Shear Test Matrix to Determine Effects of Prolonged Elevated Temperature Exposure on Adhesive Strength

The elevated test temperatures were selected based on anticipated continuous-use temperatures for HSCT and other aerospace vehicle structures. Intermediate temperatures were selected to cover the temperature range of interest, and to determine the temperature range where property dropoffs occurred. The elevated test temperatures of 225°F and 275°F were selected for the Weldalite and the 8090 alloys to match the test temperatures being used in other NASA evaluations of these alloys. -67°F was selected as the low test temperature because it corresponds with the lowest temperatures experienced by aircraft structures in service, and is typically used as the lower limit for aircraft materials testing.

The thermal cycle profile was selected from a Boeing HSCT structural composites requirements study. The 50-cycle period was selected so that cycling and testing could be accomplished within the program schedule, and consistent with preliminary aircraft and space structural testing. The thermal cycling of the flatwise tension, compression, and toughness test specimens was performed between -67°F and 300°F for 50 cycles (fig. 3.0-5). The cycling was performed by manually transferring wire baskets of the specimens between an air circulating oven and a chest freezer.

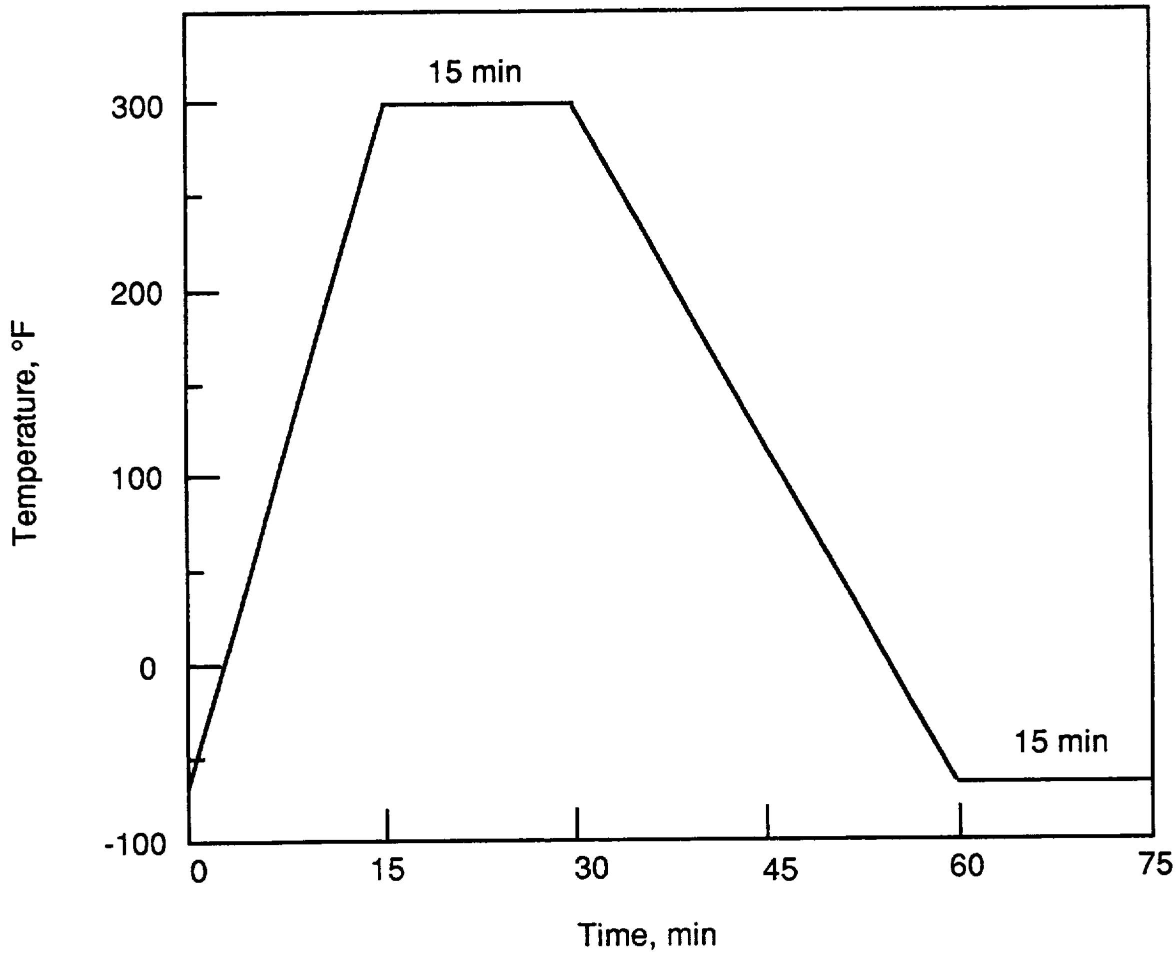


Figure 3.0-5. Thermal Cycle for Bonded Test Specimen Cycling

The 1000-hour exposure period was appropriate for preliminary testing and fit within the program schedule. The single lap shear specimens were placed freestanding in an air circulating oven at 300°F, and removed for testing after 100, 500, and 1000 hours of exposure.

4.0 TECHNICAL DISCUSSION

4.1 ADHESIVE SCREENING

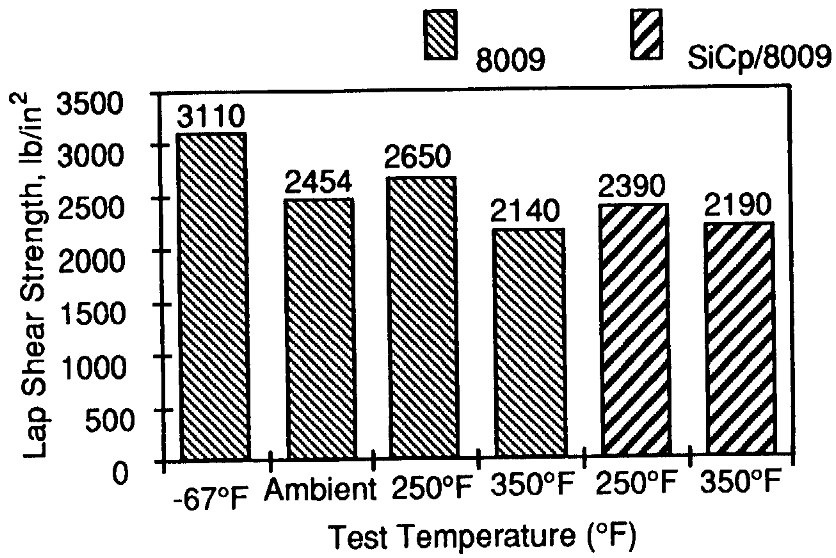
The average lap shear strengths obtained in screening tests are summarized in the bar charts of figures 4.1-1 and 4.1-2. Results of individual specimens appear in Appendix B. Of the high-temperature adhesives, the Dexter Hysol XEA 9674 bismaleimide (BMI) exhibited the highest lap shear strengths and was selected for further testing with the sandwich and toughness test specimens.

The bond strengths desired were obtained with the 3M AF 191 epoxy adhesive and the SiCp/8090 and Weldalite aluminum adherends. AF 191 epoxy was therefore used to bond the sandwich and toughness test specimens. Lap shear tests with this adhesive were conducted only to verify the quality of the adhesive, primer, and surface preparation system.

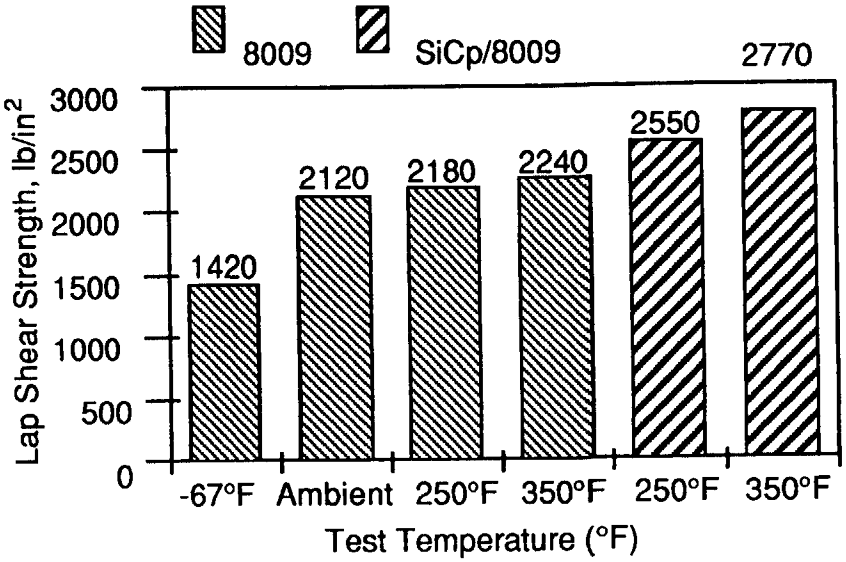
Some of the shear strengths as shown in the test data for the 8009 aluminum and the SiCp/8009 aluminum bonded with the XEA 9674 were unusually high compared with vendor and other Boeing data, and appeared off by a factor of two (fig. 4.1-1). Consequently, the elevated temperature tests were repeated, with the results shown for comparison in figure 4.1-3. The second round of tests (fig. 4.1-3) at 250°F and 300°F produced more reasonable values for this BMI adhesive. The higher test data at 250°F and 300°F are probably valid; however, subsequent analysis did not reveal why these shear strengths were so high.

The specimen fracture surfaces are shown in figure 4.1-4 and were predominantly cohesive, with adhesive remaining on both adherends. Cohesive failure surfaces are usually associated with high bond strengths. Adhesive failures, in which little or no adhesive remains on one adherend, usually occur with low bond strengths and may indicate a deficiency in the primer or surface preparation.

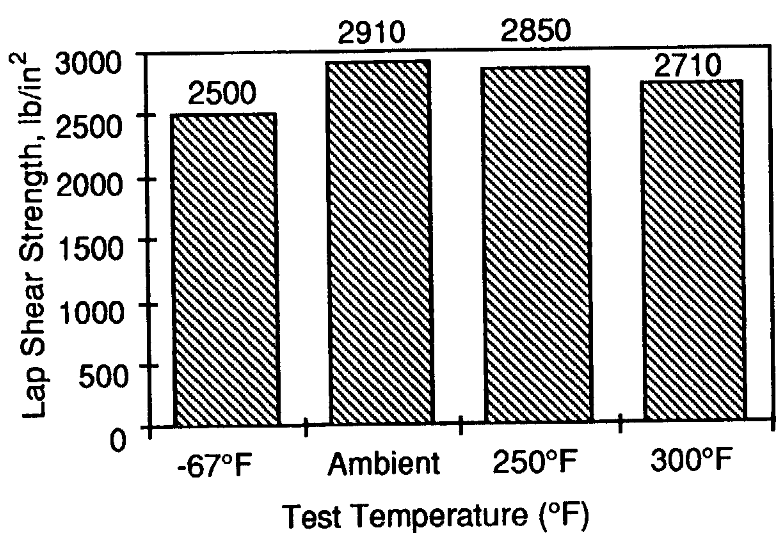
The test results with the 3M AF 191 epoxy were very good with both Weldalite and SiCp/8090 adherends; lap shear strengths were above 4000 lb/in^2 at temperatures up to 225°F. A total of five of the SiC_p/8090 lap shear adherends failed in tension during testing; two at -67°F and



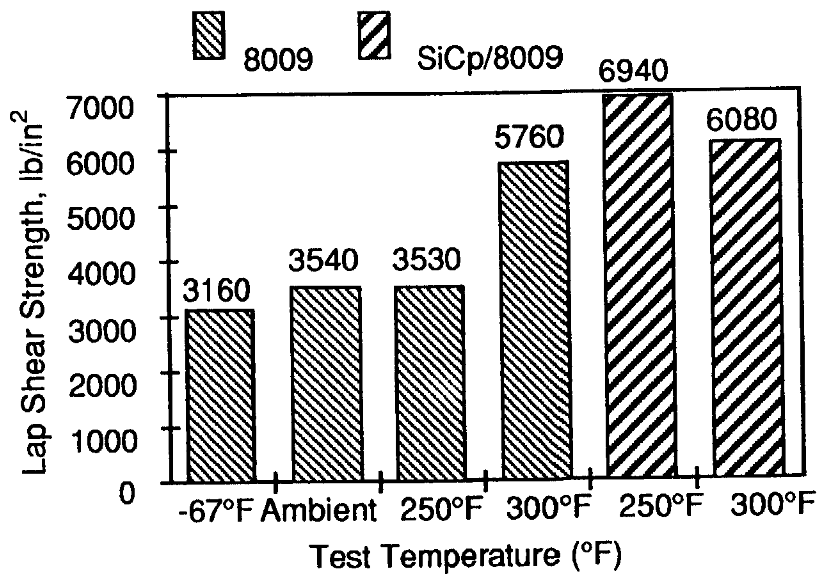
Lap Shear Strength of 8009 and SiCp/8009 Bonded with American Cyanamid FM 680 Polyimide Adhesive



Lap Shear Strength of 8009 and SiCp/8009 Bonded with Allied Signal Phenolic Triazine (PT) Resin

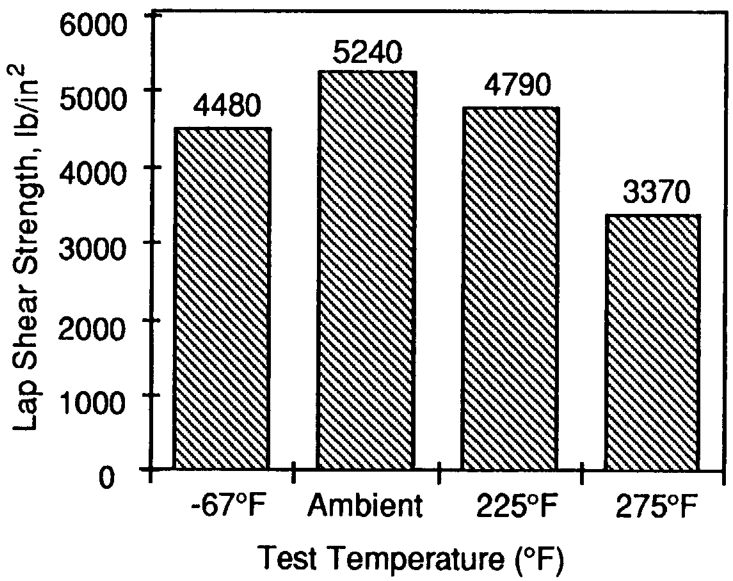


Lap Shear Strength of 8009 Bonded with BASF X2550 Bismaleimide Adhesive

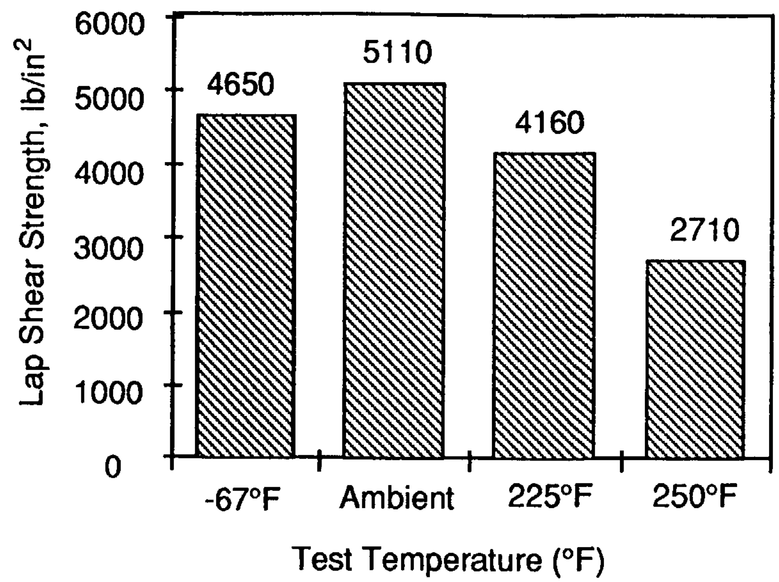


Lap Shear Strength of 8009 and SiCp/8009 Bonded with Dexter Hysol XEA 9674 Bismaleimide Adhesive

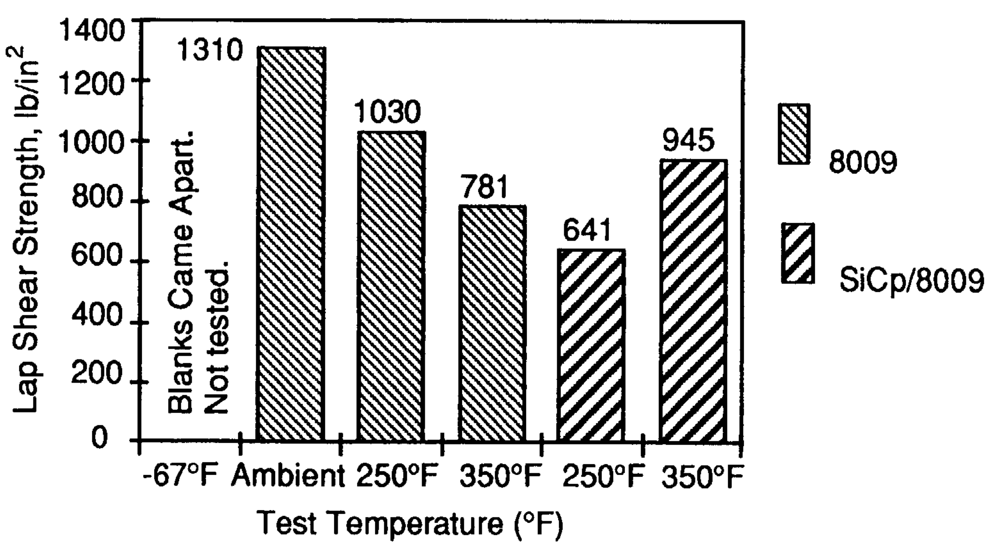
Figure 4.1-1. Summary of Average (of 5 specimens) Lap Shear Strength Data for High-Temperature Adhesives



Lap Shear Strength of Weldalite Bonded with 3M AF191 Epoxy Adhesive

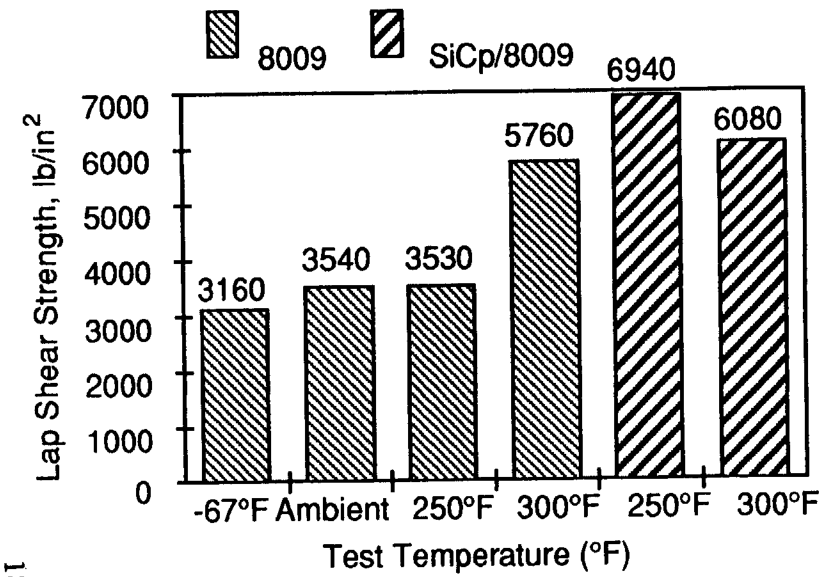


Lap Shear Strength of SiC/8090 Bonded with 3M AF191 Epoxy Adhesive

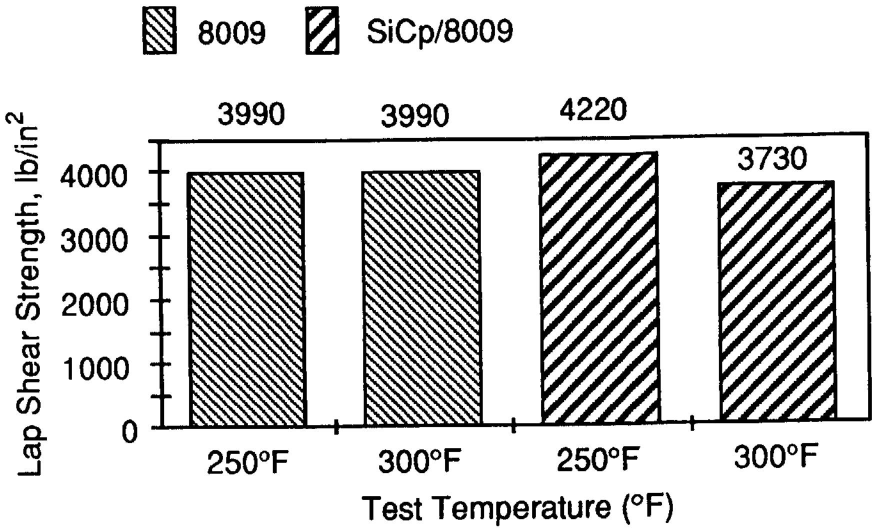


Lap Shear Strength of 8009 and SiCp/8009 Bonded with Mitsui Toatsu LARC-TPI Polyimide Adhesive

Figure 4.1-2. Summary of Average Lap Shear Strengths for AF 191 Epoxy and LARC-TPI Polyimide Adhesives



Lap shear strength of 8009 and SiCp/8009 bonded with Dexter Hysol XEA 9674 bismaleimide adhesive (Same bar chart in Figure 4.1-1)



Lap shear strength of 8009 and SiCp/8009 bonded with Dexter Hysol XEA 9674 bismaleimide adhesive, repeated tests, June, 1992

Figure 4.1-3. Comparison of Average Lap Shear Strength Data for Hysol XEA 9674 Bismaleimide Adhesive Specimens, Bonded and Tested at Two Different Times.

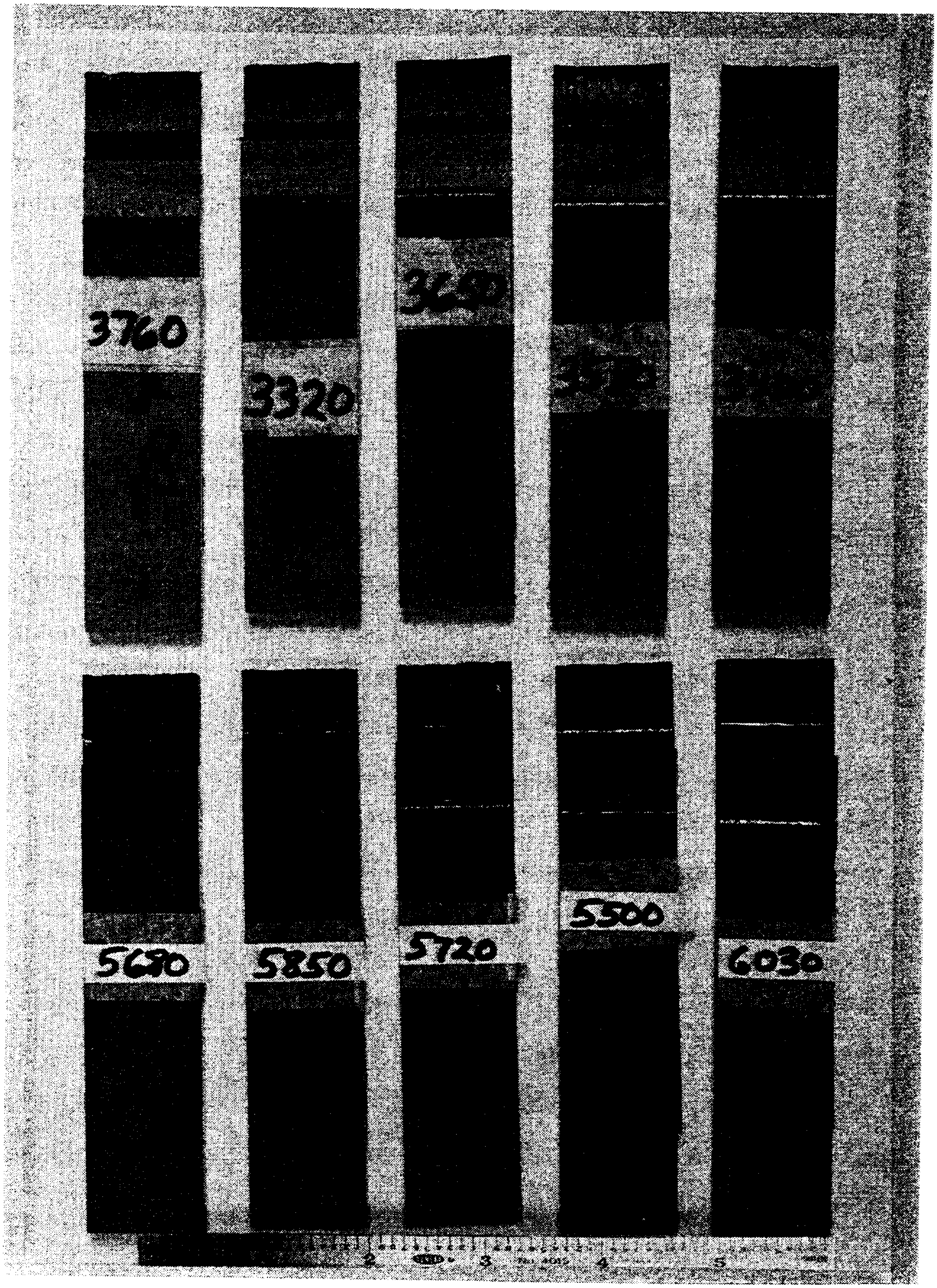


Figure 4.1-4. Photograph of Tested 8009 Single Lap Shear Specimens Bonded With XEA 9674 BMI

three at ambient temperature. The bonds of these specimens remained intact. Predominantly cohesive failures occurred in the AF 191 epoxy bonded lap shear specimens.

The results with LARC-TPI were disappointing and not representative of the capabilities of the LARC-TPI resin. Much higher titanium lap shear bond strengths (typically 4000 to 5000 lb/in^2) have been obtained with LARC-TPI adhesive tapes prepared in the past from LARC-TPI powder and resin solutions (ref. 7). The 8009 specimens were prepared with adhesive tapes supplied by the LARC-TPI manufacturer, Mitsui Toatsu Chemicals. This tape exhibited a moderate degree of flow of 7% and had a low volatile content of 2.7%. Bonding was performed in the autoclave at 700°F and 200 lb/in^2 for 15 min, and with a freestanding postcure at 600°F for 2 hours. The low lap shear strengths may have resulted from an inferior batch of resin. Uniform cohesive failures were obtained in all specimens.

The additional SiC_p/8090 sheet stock that was ordered was temporarily unavailable from the supplier, BP Metal Composites, due to production problems. As much testing as possible was performed with the SiC_p/8090 sheet stock that was purchased earlier.

To summarize: of the high temperature adhesives, the Dexter Hysol XEA 9674 bismaleimide (BMI) exhibited the highest lap shear strengths and was selected for further testing. Satisfactory results were obtained with the 3M AF 191 epoxy adhesive, and it was used to bond the sandwich and toughness test specimens from the Weldalite and SiCp/8090 adherends.

4.2 SANDWICH TESTING

4.2.1 Sandwich Test Specimens

The sandwich specimens tested (fig. 3.0-3) are listed in figure 3.0-2. The bonding procedures were the same as for the lap shear specimens (Appendix A). The titanium honeycomb core was chromic acid anodized (ref. 6) at low voltage (5 V).

The titanium honeycomb core specification was Boeing Material Specification (BMS) 4-12B SC6-35-NF, which is a welded titanium core having square cells (S), a corrugated (C) cell wall contour, a 3/8-in cell size (6/16 in), produced from 0.035-in-thick titanium foil (35), nonperforated (N) cell walls, with a finished cut (F) on the foil edges. The core had a density of 6.1 lb/ft^3.

4.2.2 Sandwich Test Results

The average flatwise tensile (FWT) test results are plotted in figures 4.2.2-1 through 4.2.2-4 for both uncycled and thermally cycled specimens. Photographs of some of the failed test specimens are shown in figure 4.2.2-5. Results of individual specimens appear in Appendix B.

The uncycled BMI bonded flatwise tensile specimens exhibited a relatively small drop in strength at elevated temperatures; however, the specimens bonded with AF 191 epoxy adhesive exhibited a large drop in strength, to about half the ambient temperature strength. Both the BMI and epoxy adhesives formed fillets with the titanium honeycomb core, and a portion of the fractured adhesive remained on the core (fig. 4.2.2-5), indicating that an optimum bond was achieved.

After thermal cycling there generally was a small drop in strength for all of the materials tested, usually 2% to 10% but not more than 17%; however, the FWT strengths were still high. Again, both the XEA 9674 BMI adhesive and the AF 191 epoxy adhesives formed good fillets with the core, and some of the fractured adhesive remained on the core.

Even after thermal cycling the FWT test results exceeded the requirements in BMS 5-104 for a 350°F structural adhesive having flatwise tensile strengths (minimum average) of 475 lb/in^2 at ambient and 220 lb/in^2 at 350°F. The aluminum honeycomb core used in BMS 5-104 sandwich test specimens is a 5052 aluminum alloy with a 3/8-in cell size, the same cell size as the titanium core used in the sandwich test specimens. Flatwise tensile strength is a function of core cell size, because smaller cells result in more bonding surface per unit area.

The results of the edgewise compression testing are shown in the barcharts of Figures 4.2.2-6 through 4.2.2-9. The edgewise compression specimens (figs. 3.0-3 and 4.2.2-10) were

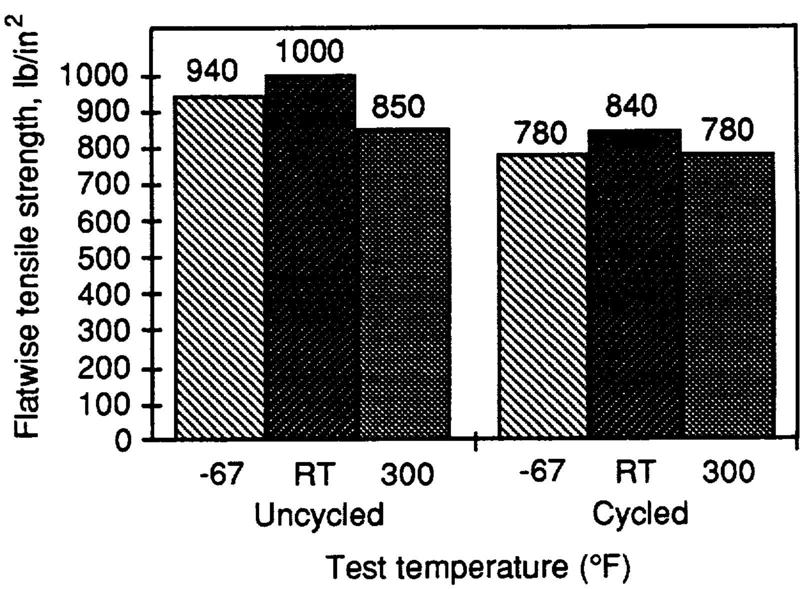


Figure 4.2.2-1. Average Flatwise Tensile Strength of 8009/XEA 9674/Titanium Honeycomb Core Sandwich Specimens, Uncycled and Cycled

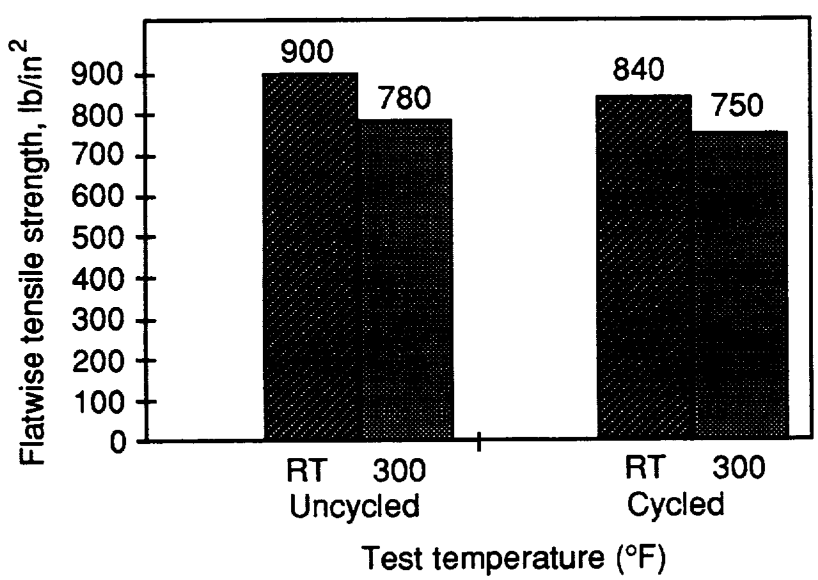


Figure 4.2.2-2. Average Flatwise Tensile Strength of SiCp/8009/XEA 9674/Titanium Honeycomb Core Sandwich Specimens, Uncycled and Cycled

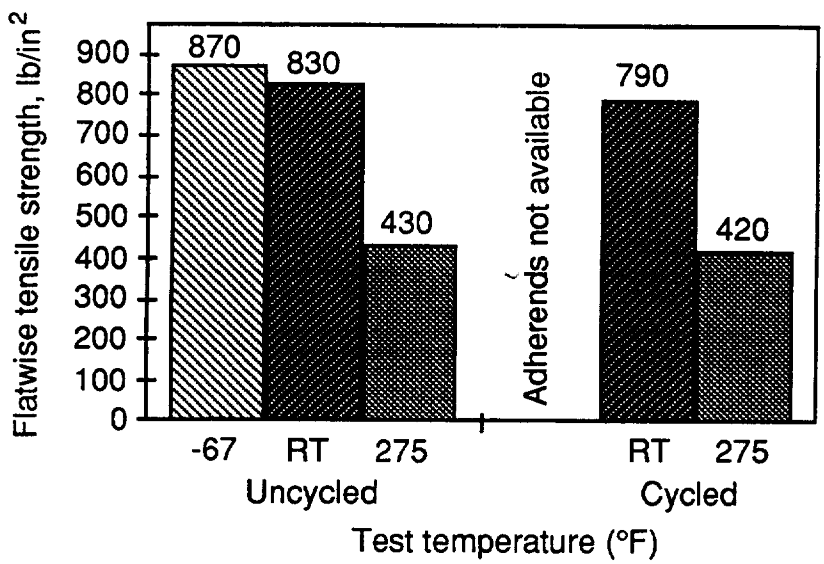


Figure 4.2.2-3. Average Flatwise Tensile Strength of Weldalite/AF 191/Titanium Honeycomb Core Sandwich Specimens, Uncycled and Cycled

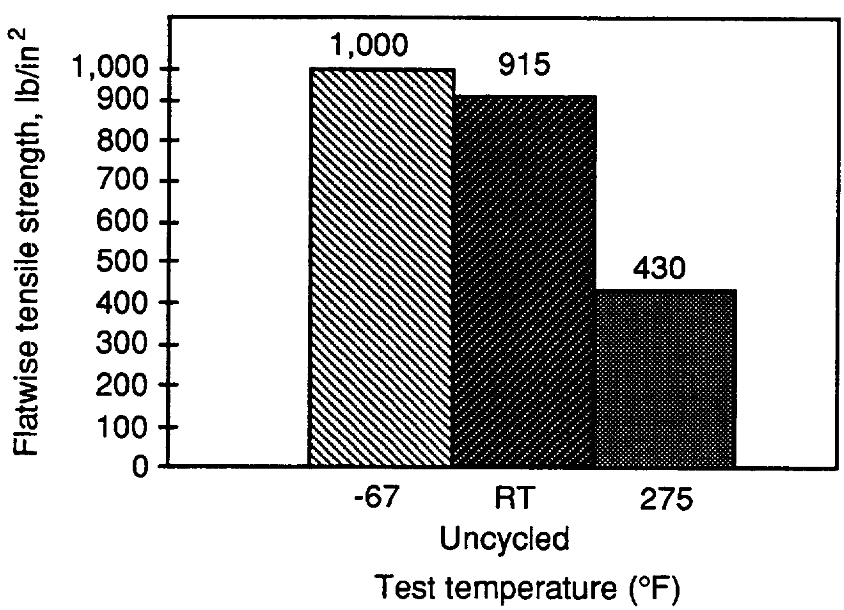


Figure 4.2.2-4. Average Flatwise Tensile Strength of SiCp/8090/AF 191/Titanium Honeycomb Core Sandwich Specimens, Uncycled Only

8009/XEA 9674

SiCp/8090/AF 191

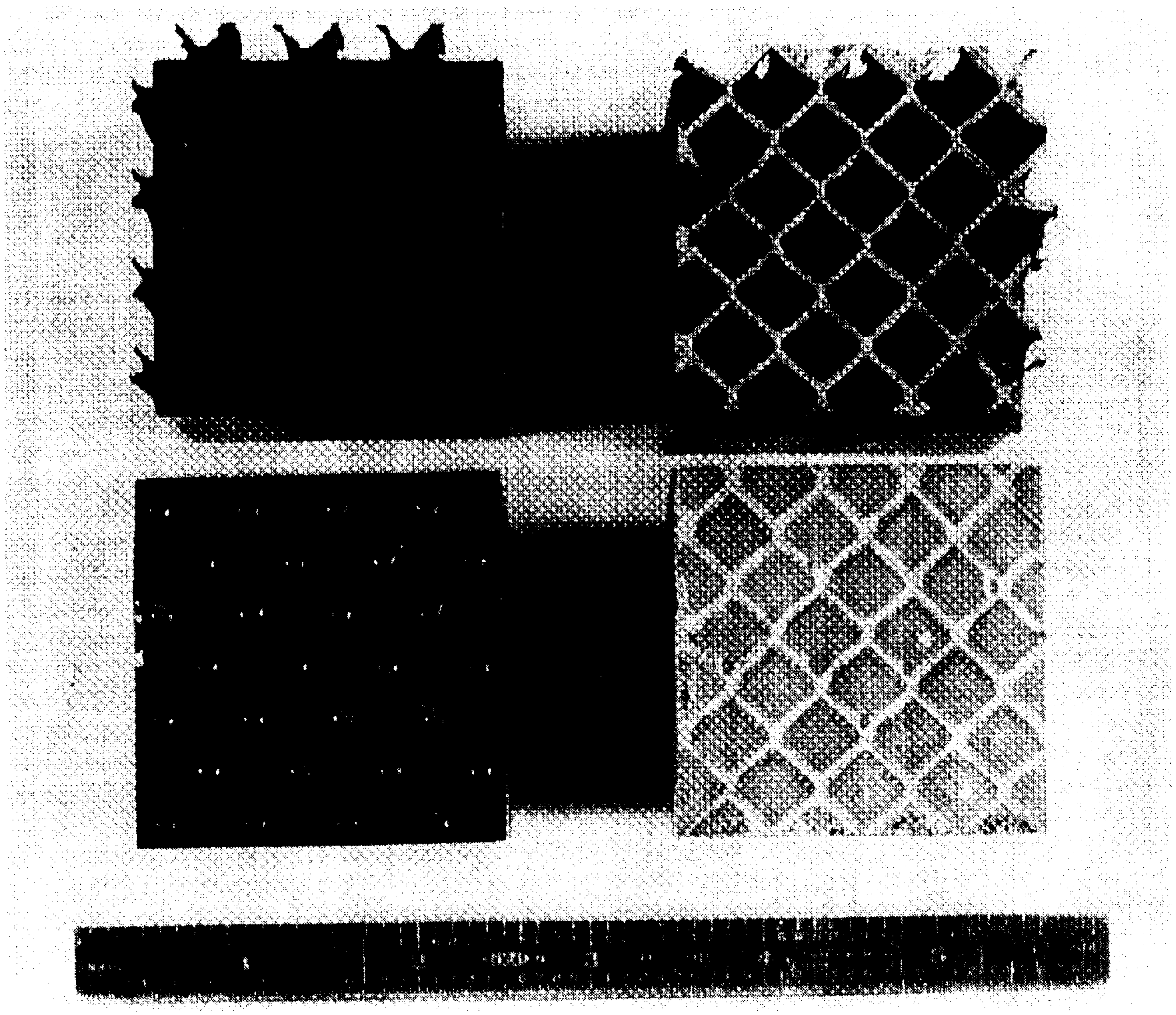


Figure 4.2.2-5. Photograph of Selected Flatwise Tensile Test Specimen Fracture Surfaces

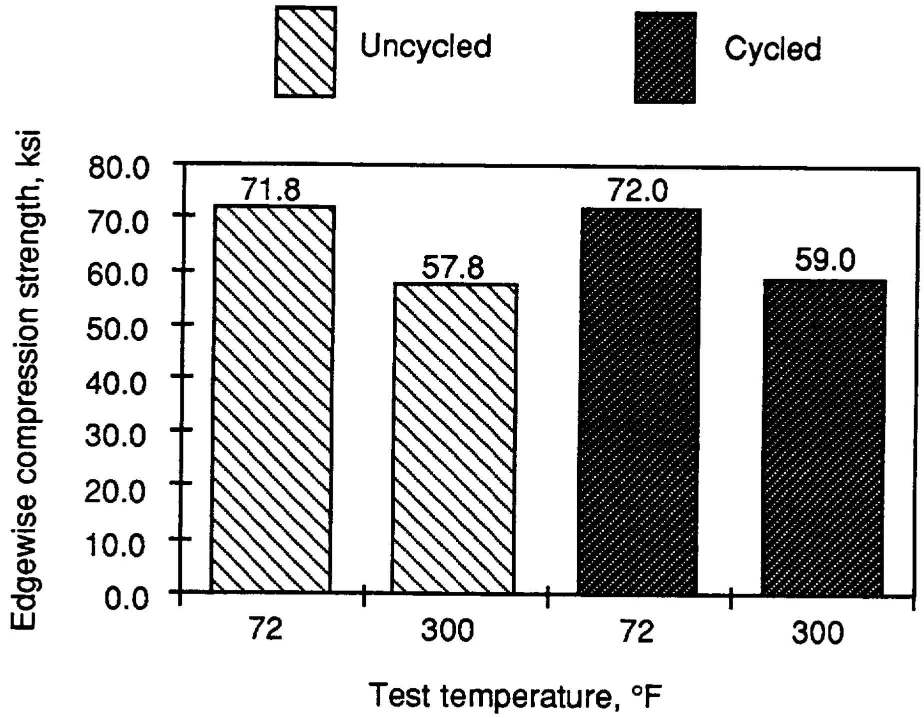


Figure 4.2.2-6. Average Edgewise Compression Strengths of 8009/XEA 9674 Sandwich Specimens

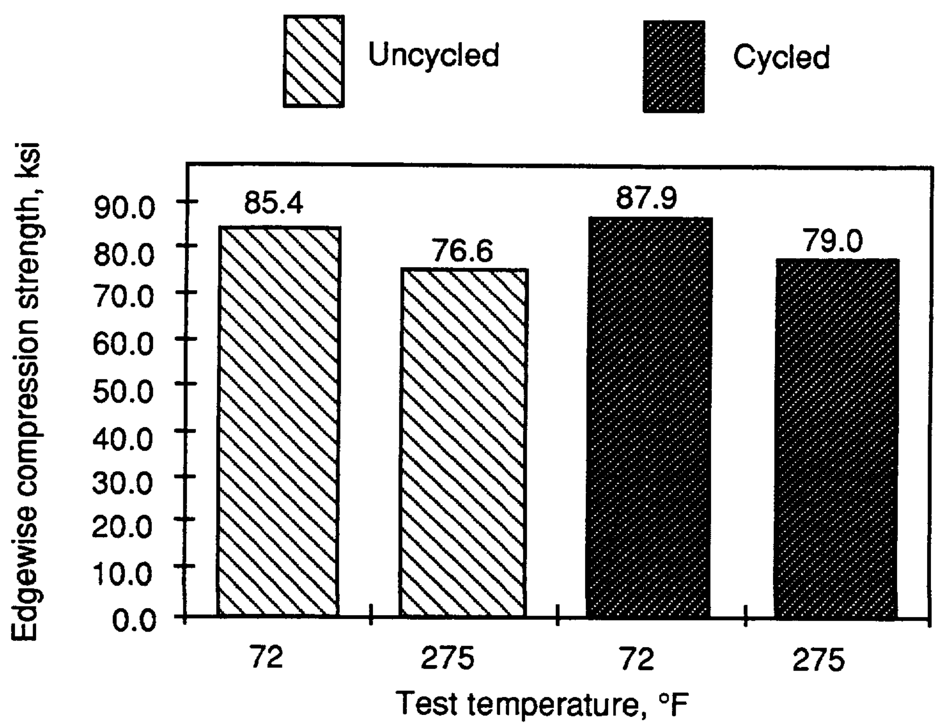


Figure 4.2.2-7. Average Edgewise Compression Strengths of Weldalite/AF 191 Epoxy Sandwich Specimens

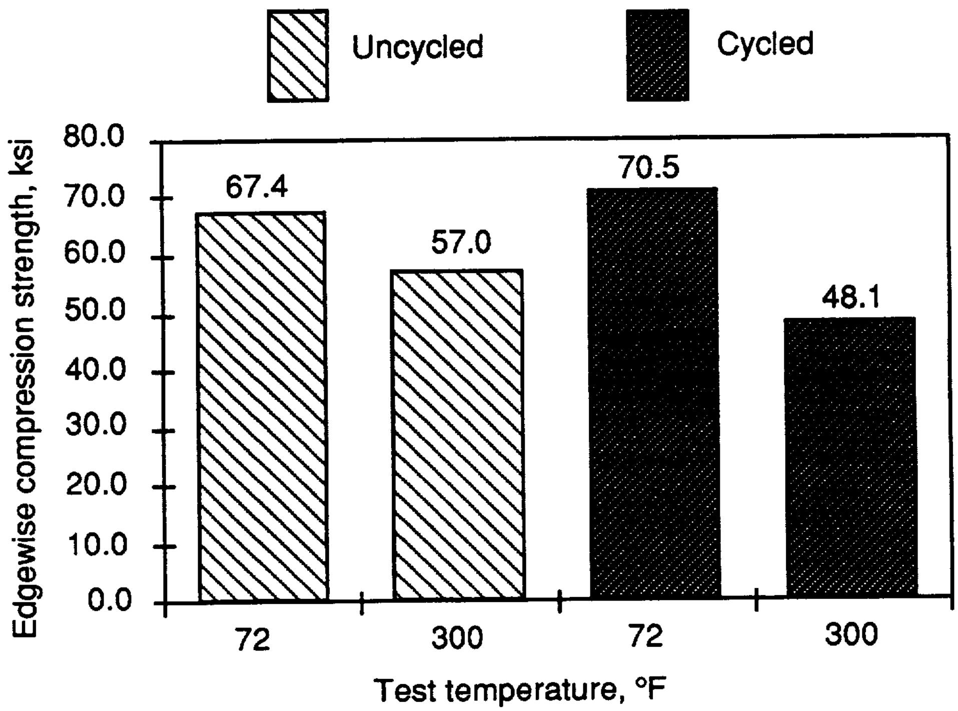


Figure 4.2.2-8. Average Edgewise Compression Strengths of SiCp/8009/XEA 9674 Sandwich Specimens

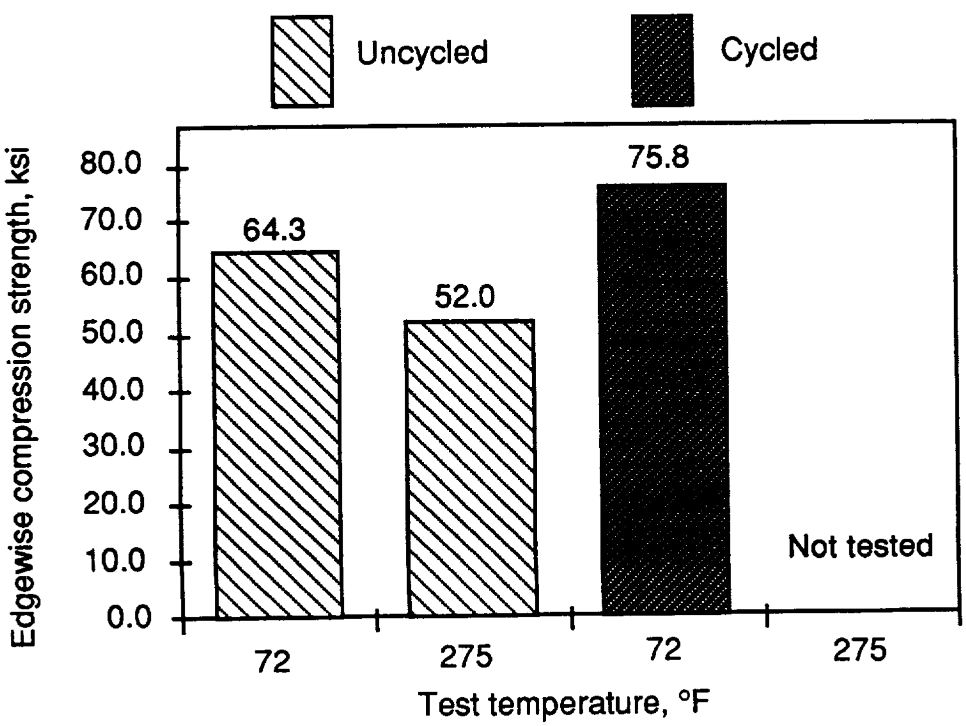


Figure 4.2.2-9. Average Edgewise Compression Strengths of SiCp/8090/AF191 Epoxy Sandwich Specimens

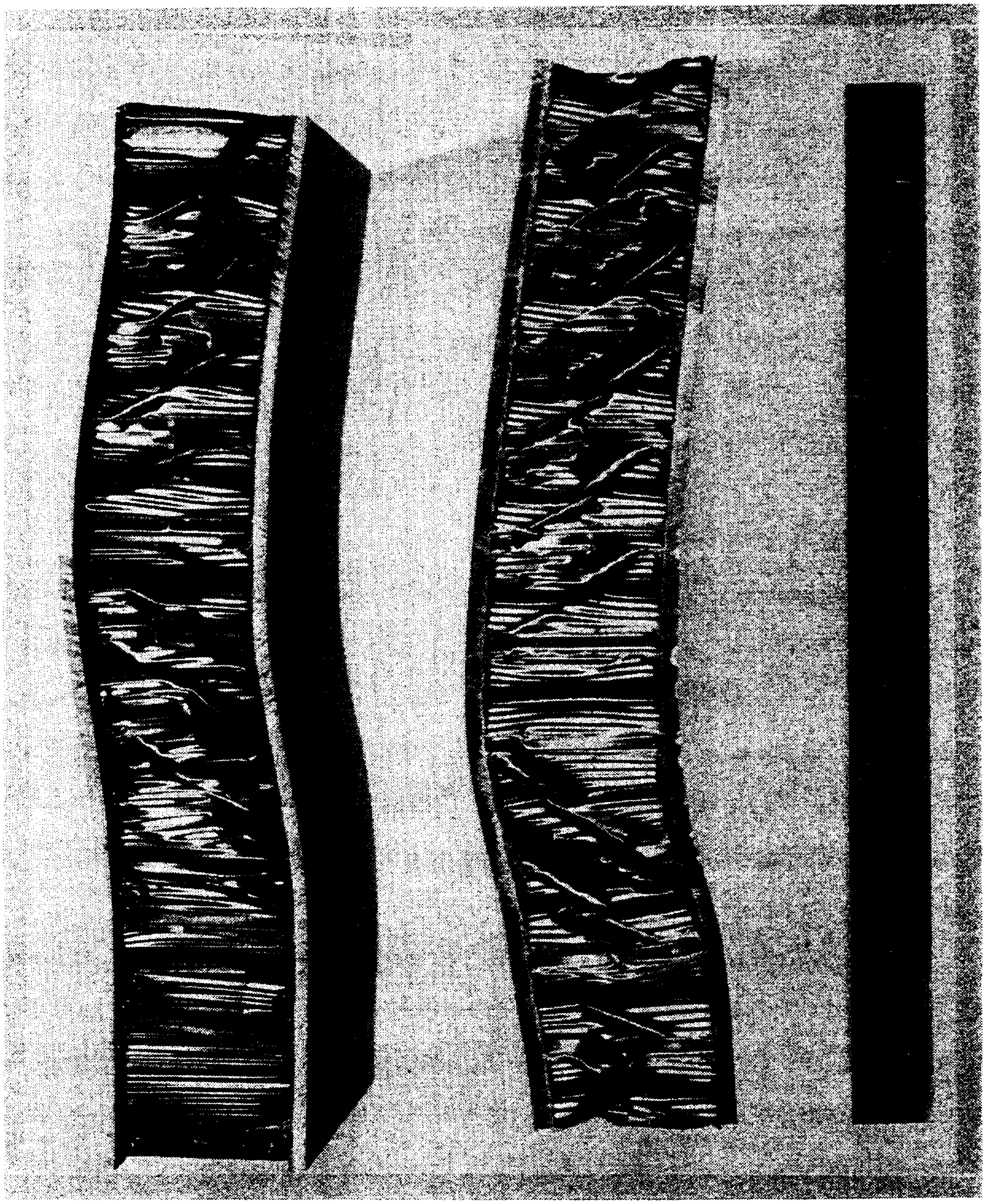


Figure 4.2.2-10. Photograph of Selected Edgewise Compression Specimens After Testing

placed in a test fixture that supported the ends for a distance of 1/2-in. The specimens were loaded on the ends at a crosshead speed of 0.02 in/min (ASTM C364).

Compression failure loads were predicted for the possible failure modes (fig. 4.2.2-11). The face sheet yielding failure mode occurred at the lowest load, and the actual failure loads compared favorably with these predicted loads. All of the specimens except one failed by column buckling (global instability, fig. 4.2.2-11) rather than face sheet yielding, however. There was a 15% to 32% drop in edgewise compression strength between the room temperature and elevated temperature tests; however, the 50 thermal cycles that some specimens were exposed to appeared to have no effect on strength. There was a 15% increase in edgewise compression strength of the SiC_p/8090 sandwich specimens with thermal cycling.

4.3 TOUGHNESS TESTING

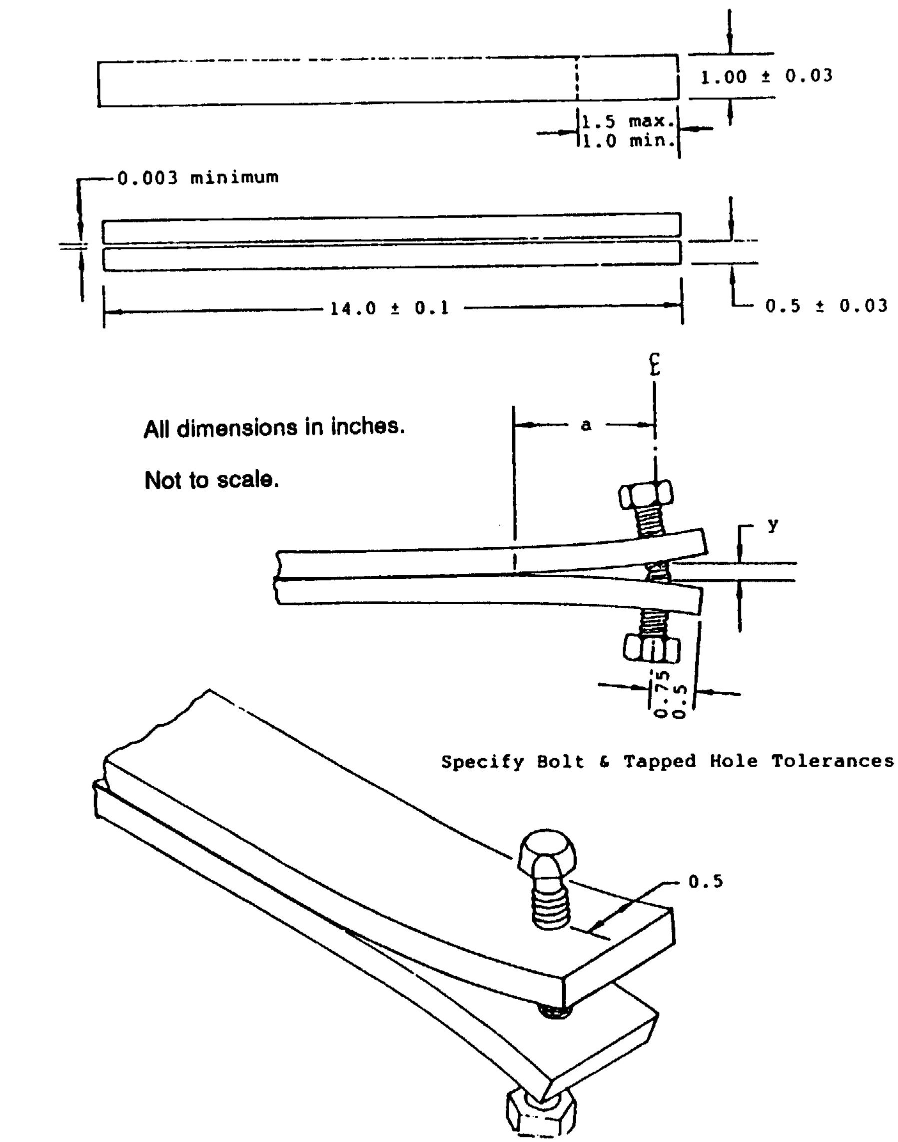
The toughness test specimens selected were the double cantilever beam (DCB) and end notched flexure (ENF) test specimens (ref 8). The specimens are sketched in figure 4.3-1. The specimens tested are listed in figure 3.0-2. Average values for mode I critical fracture toughness (G_{Ic}) and arrest fracture toughness (G_{Ia}) are plotted in figures 4.3-2 and 4.3-3. Mode II critical fracture toughness (G_{IIc}) values from the ENF specimens are plotted in figure 4.3-4. Results of individual specimens appear in Appendix B. Photographs of some of the failed DCB and ENF test specimens appear in figures 4.3-5 and 4.3-6, respectively.

Because plates of a nominal thickness of 0.5 in were not available for the aluminum alloys investigated, the DCB adherends were secondarily bonded to backup plates machined from 0.5-in-thick 7075 aluminum. The specimen assemblies were then machined to a uniform width over their length. When the load was applied to separate the adherends, some of the backup plates on the AF 191 specimens debonded after the first crack jump. Consequently, only one crack jump could be performed on several of the AF 191 epoxy bonded specimens.

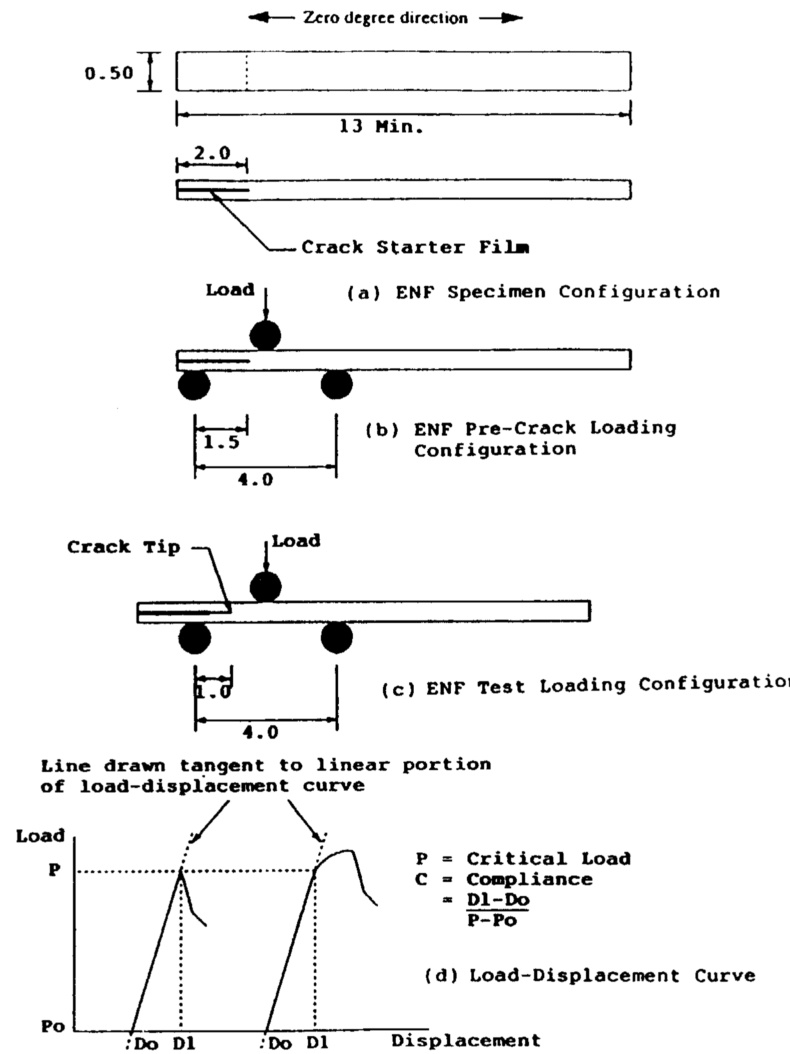
The DCB specimens were tested by propagating three crack jumps on each specimen using jacking screws, and measuring the crack length shortly after the jump and again 24 hours later.

		Aluminum Alloy Facesheets			
Measurements, in	Symbol	8009	Weldalite	SiCp/8009	SiCp/8090
Column Width	b	3	3	3	3
Column Length	L	6	6	6	6
Core Thickness	c	1	1	1	1
Core Cell Size	s	0.375	0.375	0.375	0.375
Facesheet Thickness	t	0.094	0.085	0.081	0.08
Facesheet Centroid Separation	d	1.094	1.085	1.081	1.08
Column Thickness	h	1.188	1.17	1.162	1.16
Column End Fixity Coefficient	cf	1	1	1	1
Effective Column Buckling Length	L'	6	6	6	6
Material Properties, lb/in^2					
Facesheet Elastic Modulus	E	1.28E+07	1.13E+07	1.40E+07	1.50E+07
Facesheet Poisson's Ratio	nu	0.33	0.33	0.33	0.33
Facesheet Yield Strength	Fty	6.00E+04	9.71E+04	5.50E+04	4.76E+04
Facesheet Core Shear Modulus	Gxz	8.40E+04	8.40E+04	8.40E+04	8.40E+04
Core Compression Modulus	Ecc	4.40E+05	4.40E+05	4.40E+05	4.40E+05
Failure Loads, kips					
by Facesheet Yield		33.8	49.5	26.7	22.8
by Global Instability		198.8	180.4	190.5	193.9
by Intracell Buckling		1674.7	1093.1	1172.0	1209.8
by Face Wrinkling		193.4	167.7	171.7	173.5
by Shear Crimping		226.2	222.5	220.9	220.4
Predicted Failure Load		**33.8**	**49.5**	**26.7**	**22.8**

Figure 4.2.2-11. Sandwich Column Analysis With Predicted Compression Failure Loads



Crack Extension Test Specimen - Constant Displacement, End Bolt Loaded



End Notch Flexure Testing

Figure 4.3-1. Double Cantilever Beam and End Notched Flexure Test Specimens

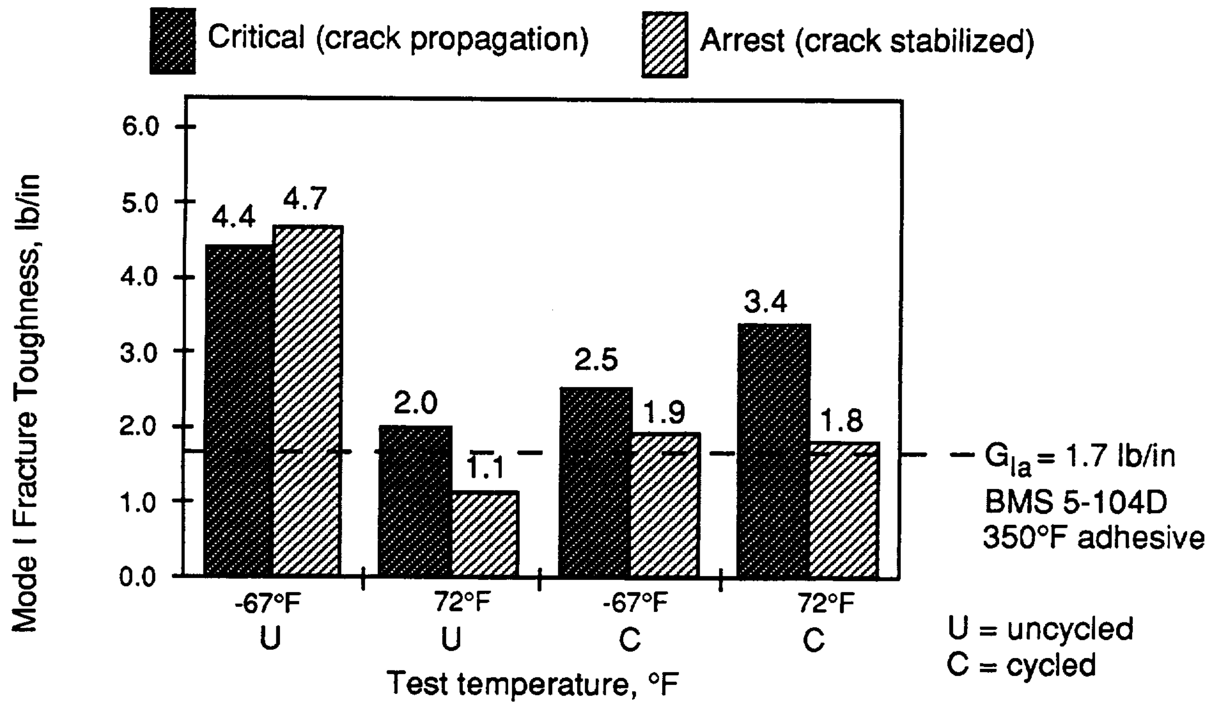


Figure 4.3-2. Average Mode I Fracture Toughness of 8009/XEA 9674 Bismaleimide Specimens

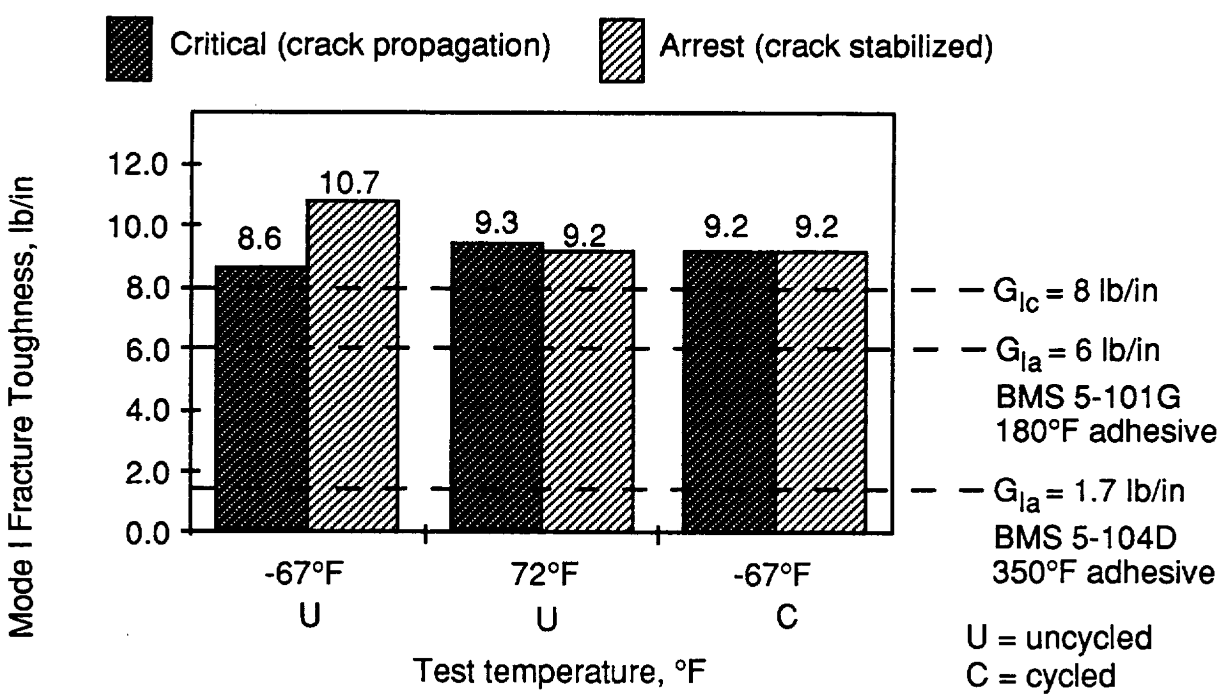


Figure 4.3-3. Average Mode I Fracture Toughness of Weldalite/AF 191 Epoxy Specimens

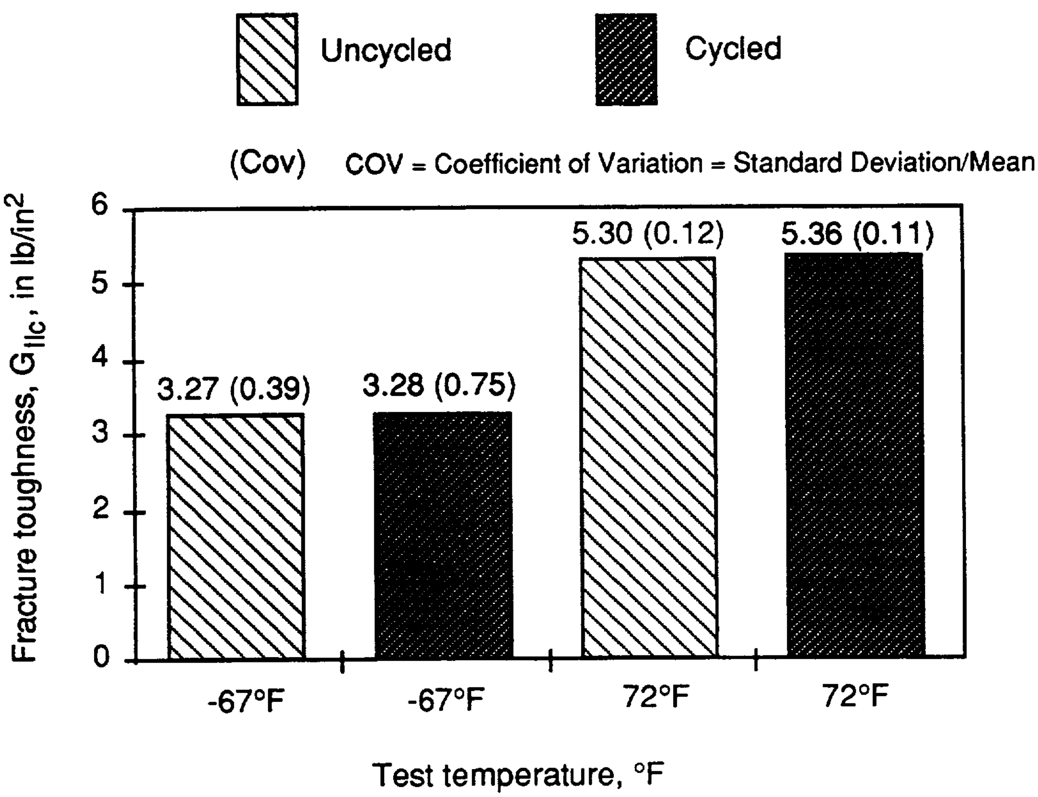


Figure 4.3-4. Mode II, G_{IIc} Fracture Toughness Test Results, 8009/XEA 9674

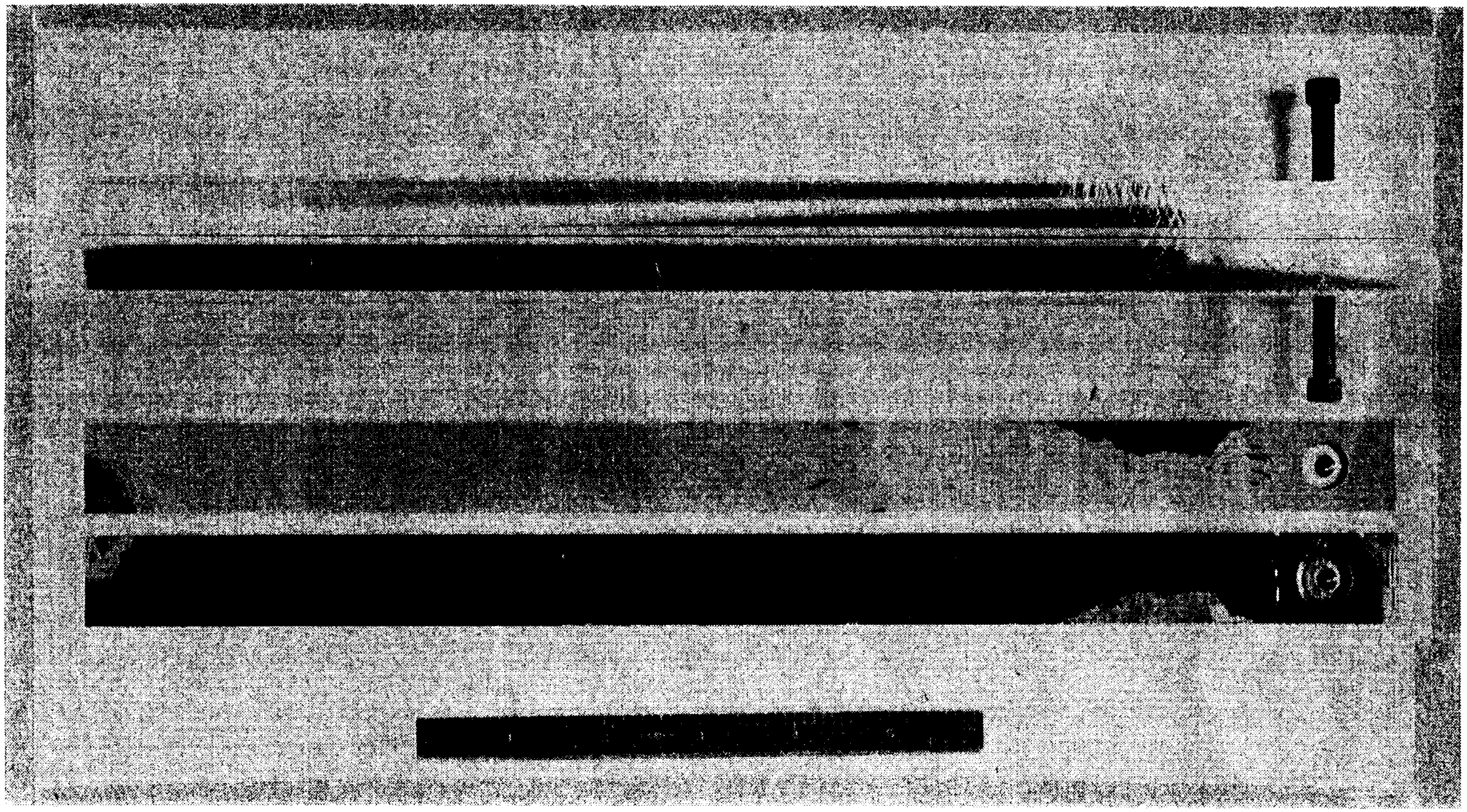


Figure 4.3-5. Photograph of Fracture Surfaces of Selected Double Cantilever Beam Test Specimens, Mode I Loading

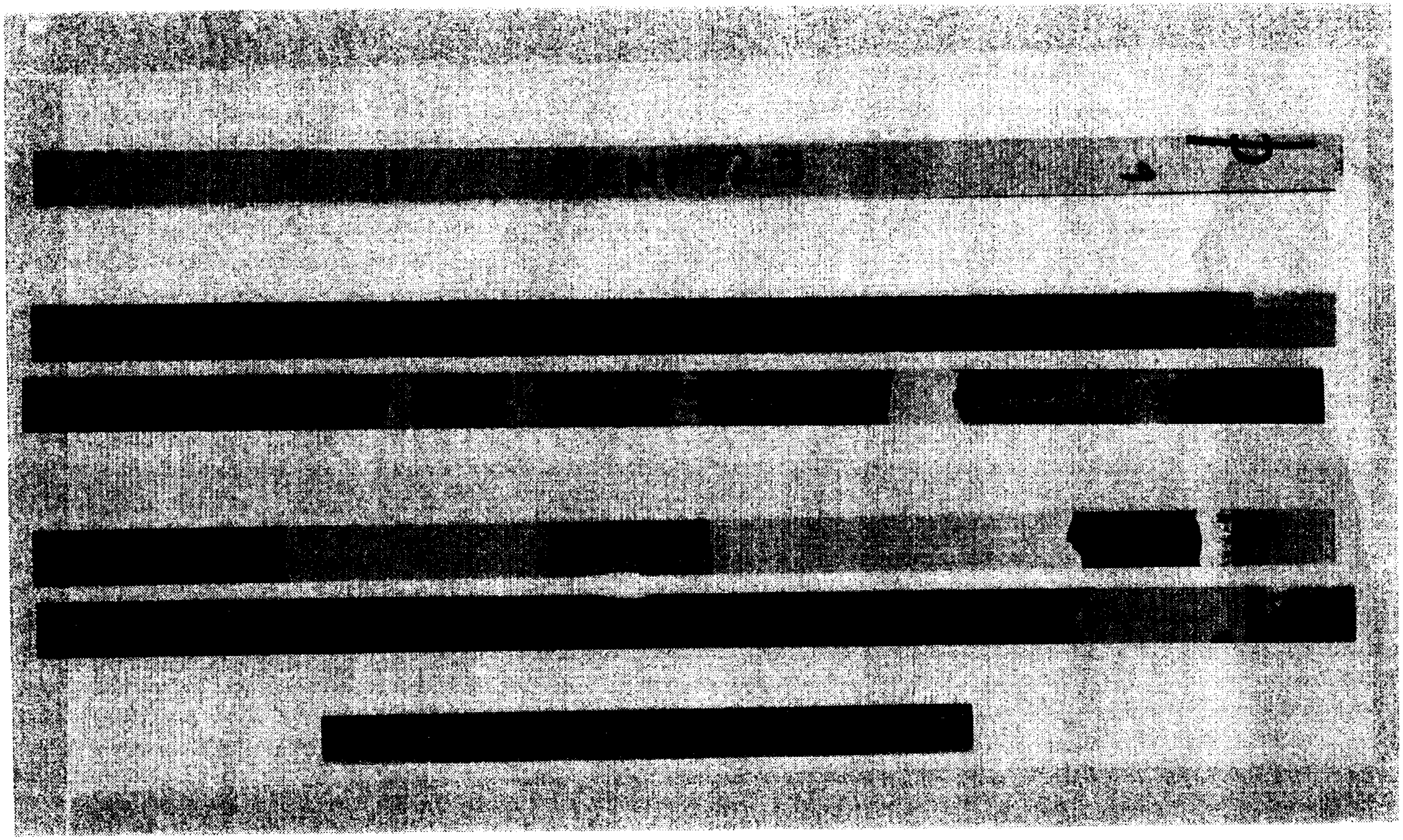


Figure 4.3-6. Photograph of Fracture Surfaces of Selected End Notch Flexure Test Specimens, Mode II Loading

The former was used to calculate the critical fracture toughness (G_{Ic}), and the latter to calculate the arrest fracture toughness (G_{Ia}). The crack opening displacement (y) or opening along the centerline of the jacking screws was also measured.

Data points more than two standard deviations from the mean were excluded from the averages shown in the plots (figures 4.3-2 and 4.3-3). The AF 191 epoxy resin was tougher than the XEA 9674 BMI, and its toughness was comparable to the requirements in Boeing epoxy adhesive specifications. The AF 191 epoxy exhibited more cohesive characteristic failures because the adhesive remained on both fracture surfaces, whereas the BMI exhibited more adhesive characteristic failures because the adhesive remained on only one fracture surface. Adhesive failure is associated with lower bond strengths and can be a result of primer or surface preparation problems and not necessarily the adhesive resin itself.

The mode I fracture toughness measurements compared favorably with the requirements in Boeing specifications for 180°F and 350°F structural adhesives (fig. 4.3-3). While the BMI adhesive met the 350°F requirements, it would not satisfy the 180°F requirements, although many of the fractures propagated at the adhesive/primer interface. Higher fracture toughness values might be obtained with a more suitable primer. The AF 191 epoxy adhesive met both the requirements for a 180°F and 350°F adhesive.

The thermal cycling that some specimens were subjected to did not appear to reduce the mode I fracture toughness, nor did toughness appear to be reduced at lower temperatures. Some of the scatter in the data can probably be attributed to the difficulty of locating the crack front precisely, because only the edges of the advancing crack are visible from the sides of the specimen. Mechanical test results of the individual specimens appear in Appendix B.

Only 8009 aluminum alloy was available for the end notched flexure test specimens. The specimens had a 1.0-in starter crack (teflon separator) at one end. The crack was initiated using a wedge (mode I crack), and the crack length increase was measured after loading in three-point bending (fig. 4.3-1) for three-crack jumps per specimen.

The mode II fracture toughness (G_{IIc}) was calculated from the crack length increase (refs. 8 and 9). The average fracture toughness was calculated over nine crack jumps (three per specimen for three specimens, fig. 4.3-4). Thermal cycling appeared to have no effect on the fracture toughness, as expected. The fracture toughness dropped to 60% of the room temperature value at -67°F. The mode II fracture toughness values are lower than the values in BMS 8-276 (ref. 9) for a toughened graphite epoxy (8.0 to 13.0 in-lb/in^2) as might be expected for a bismaleimide adhesive. However, the data may compare more favorably to other adhesively bonded metals.

4.4 ISOTHERMAL AGING OF SINGLE LAP SHEAR TEST SPECIMENS

Individual single lap shear specimens were isothermally aged in air circulating ovens at 300°F (275°F for the Weldalite) and tested after 100, 500, and 1,000 hours of aging (fig. 3.0-4). The average results are plotted in the bar chart of Figure 4.4-1. Results of individual specimens appear in Appendix B.

The isothermal aging exposures had only modest effects on joint strength. At -67°F and room temperature, the strength of the 8009/XEA 9674 system actually increases with longer exposure, possibly due to post-curing effects. At 300°F, the strength decreased slightly with longer exposure times. The Weldalite RX-818/AF 191 system also showed an increase in joint strength after 1000-hour exposure at 275°F.

Themal aging only affected the appearance of the AF 191 epoxy adhesive. The XEA 9674 BMI did not discolor with thermal aging. The AF 191 epoxy adhesive in the thermally aged lap shear specimens became slightly darker, and the adhesive squeeze-out at the bond edges changed from yellow to dark brown. There was no difference in the appearance of the AF 191 bonded specimens that had been aged for 100 hours versus 500 or 1000 hours, however.

The results demonstrate that good adhesive bond strengths can be obtained with advanced aluminum alloys and existing adhesive systems, and that these bond strengths are maintained for

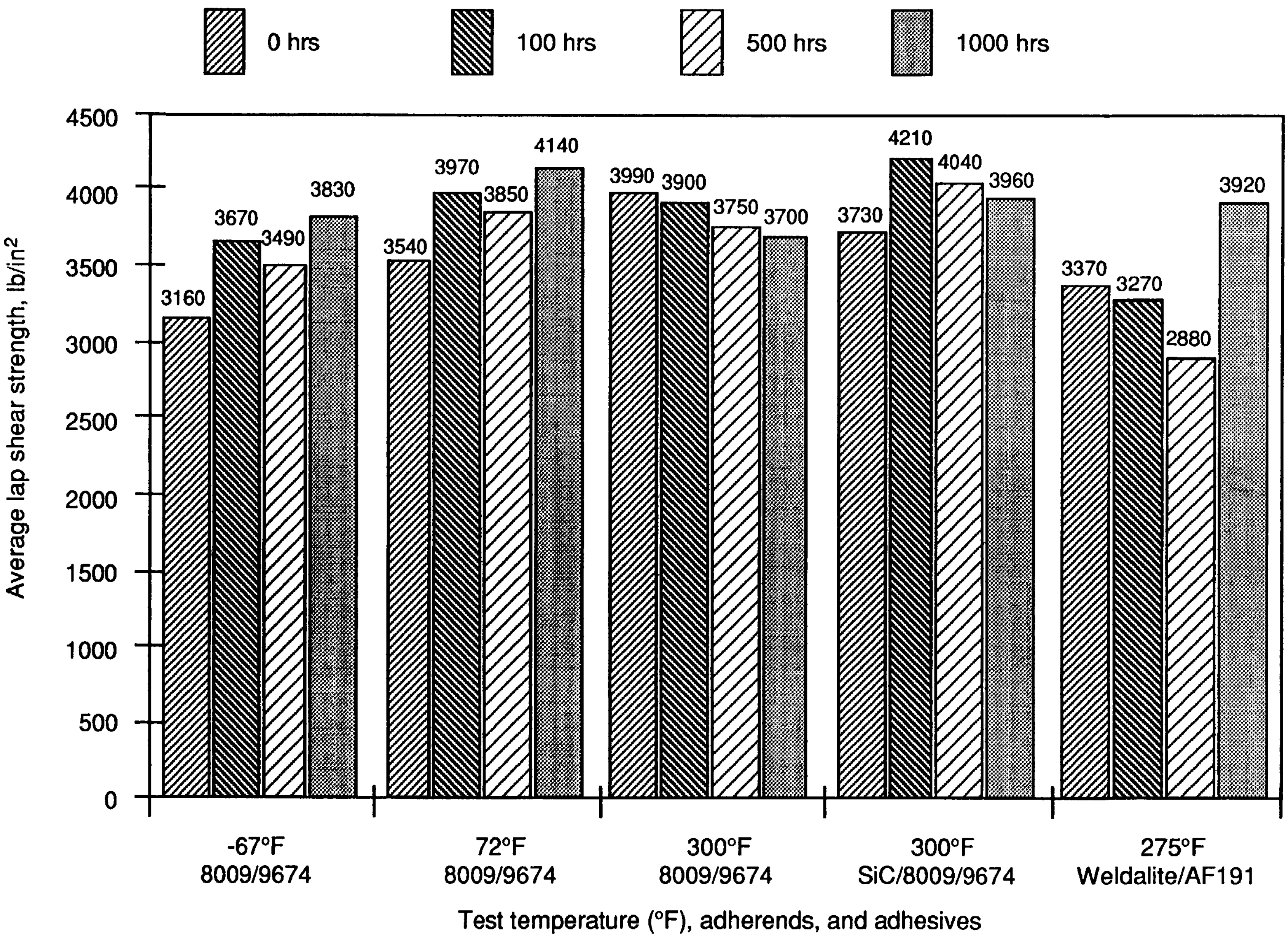


Figure 4.4-1. Average single lap shear strength of specimens aged for 0, 100, 500, and 1000 hours at 300°F (275°F for the Weldalite)

exposures up to 1000 hours at temperatures typical of those expected on the HSCT airframe structure.

4.5 COMPARISON OF TEST DATA WITH OTHER DATA AND REQUIREMENTS

Lap shear strengths from other Boeing tests, from vendor data, and from Boeing Material Specification (BMS) requirements are plotted for comparison with the data obtained under this program (Figs. 4.5-1, 4.5-2, and 4.5-3). The lap shear strengths of the selected BMI and epoxy adhesives compare very favorably with other data, and exceed the BMS specification requirements. With further process development the BMI shear strengths at -67°F and ambient temperature could possibly reach 4000 lb/in^2.

The flatwise tensile test results exceeded the requirements in BMS 5-104 for a 350°F structural adhesive having flatwise tensile strengths (minimum average) of 475 lb/in^2 at ambient and 220 lb/in^2 at 350°F. Tensile strengths exceeded 750 lb/in^2 at all test temperatures except 275°F for the AF 191 epoxy adhesive, which had average strengths of 430 lb/in^2 at that temperature. Both the BMI and epoxy adhesives formed fillets with the titanium honeycomb core, and a portion of the fractured adhesive remained on the core indicating that an optimum bond was achieved.

The Boeing HSCT program has not yet identified formal requirements for adhesive bond properties; however, the properties in Figure 4.5-4 are indicative of those requirements which have been used for design trade studies. These properties are design goals, and lower values may prove acceptable in HSCT designs.

The lap shear and flatwise tensile test specimens bonded with AF 191 epoxy exceeded these requirements with the exception of the elevated temperature values measured at 275°F which were slightly lower than the 350°F values in figure 4.5-4. The lap shear strengths of the BMI bonded specimens were below the values listed in figure 4.5-4; however, the flatwise tensile strengths exceeded the requirements of figure 4.5-4 by a significant margin. If the flatwise tension requirements in figure 4.5-4 were based on a 3/8-in cell size instead of 3/16-in the requirements

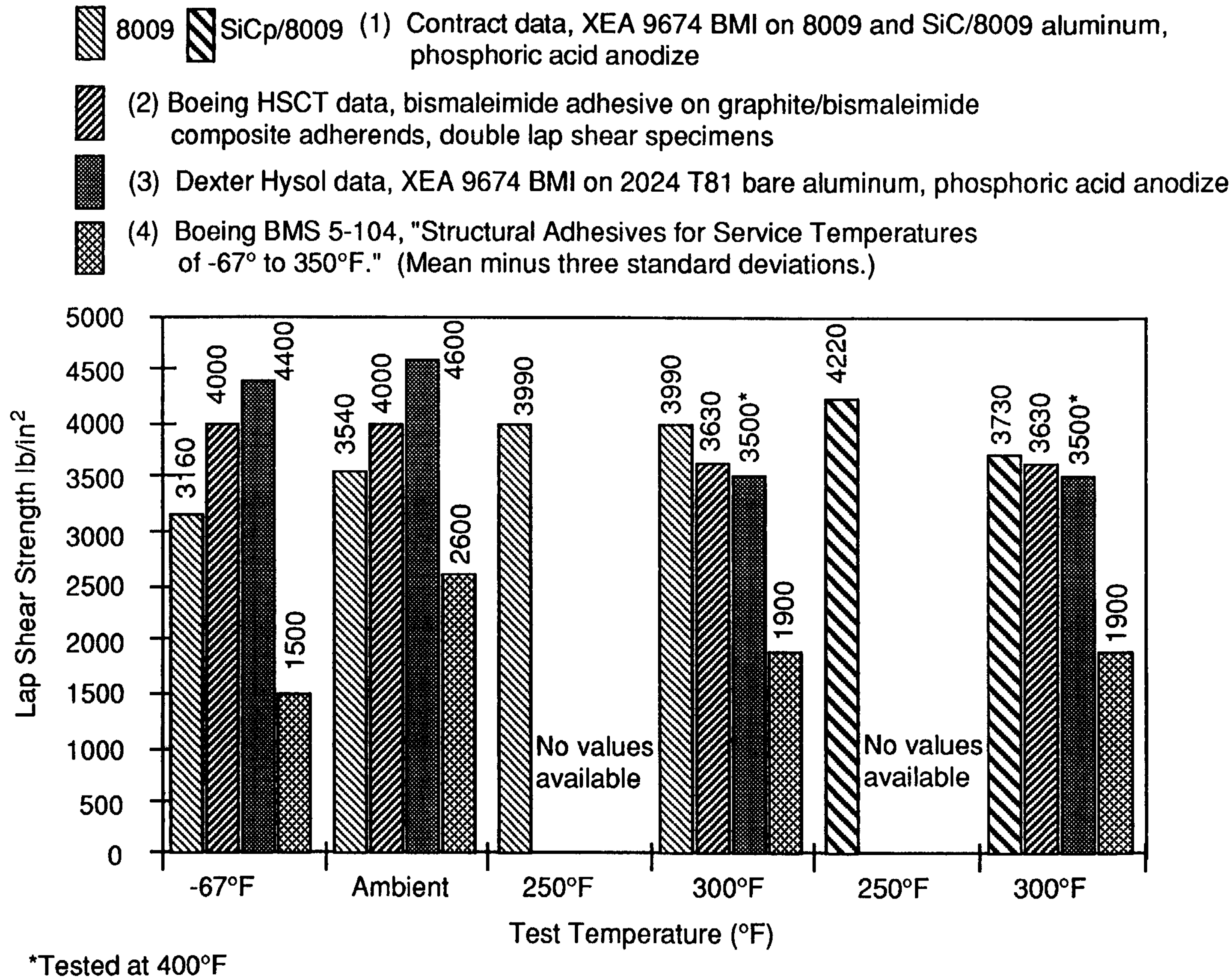


Figure 4.5-1. Comparison of Average Lap Shear Strength Data for Hysol XEA 9674 Bismaleimide Adhesive Specimens to Other Test Results and to Requirements of BMS 5-104, "Structural Adhesives for Service Temperatures of -67° to 350°F"

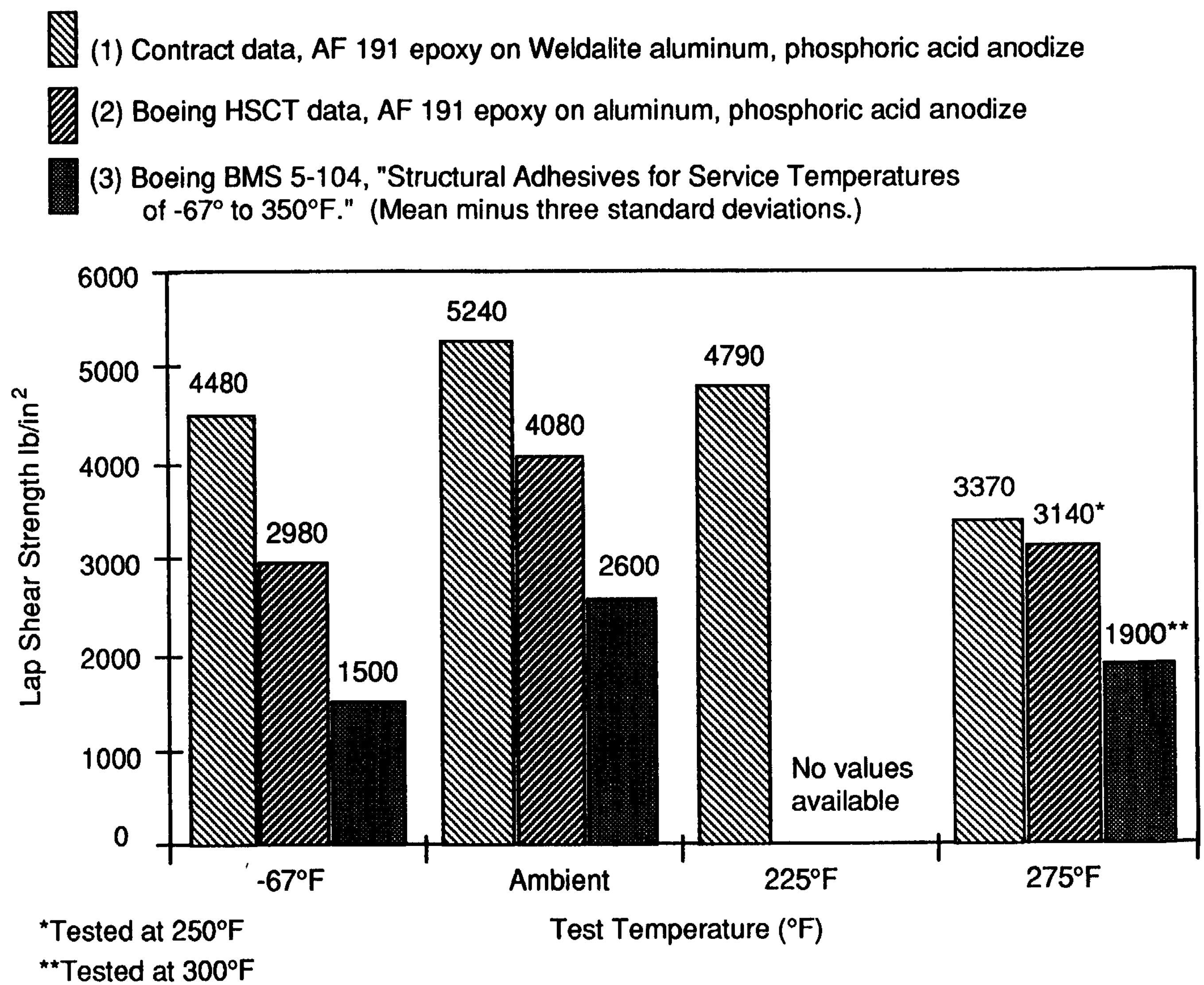


Figure 4.5-2. Comparison of Average Lap Shear Strength Data for Weldalite Bonded With 3M AF 191 Epoxy to Other Test Results and to Requirements of BMS 5-104, "Structural Adhesives for Service Temperatures of -67° to 350°F"

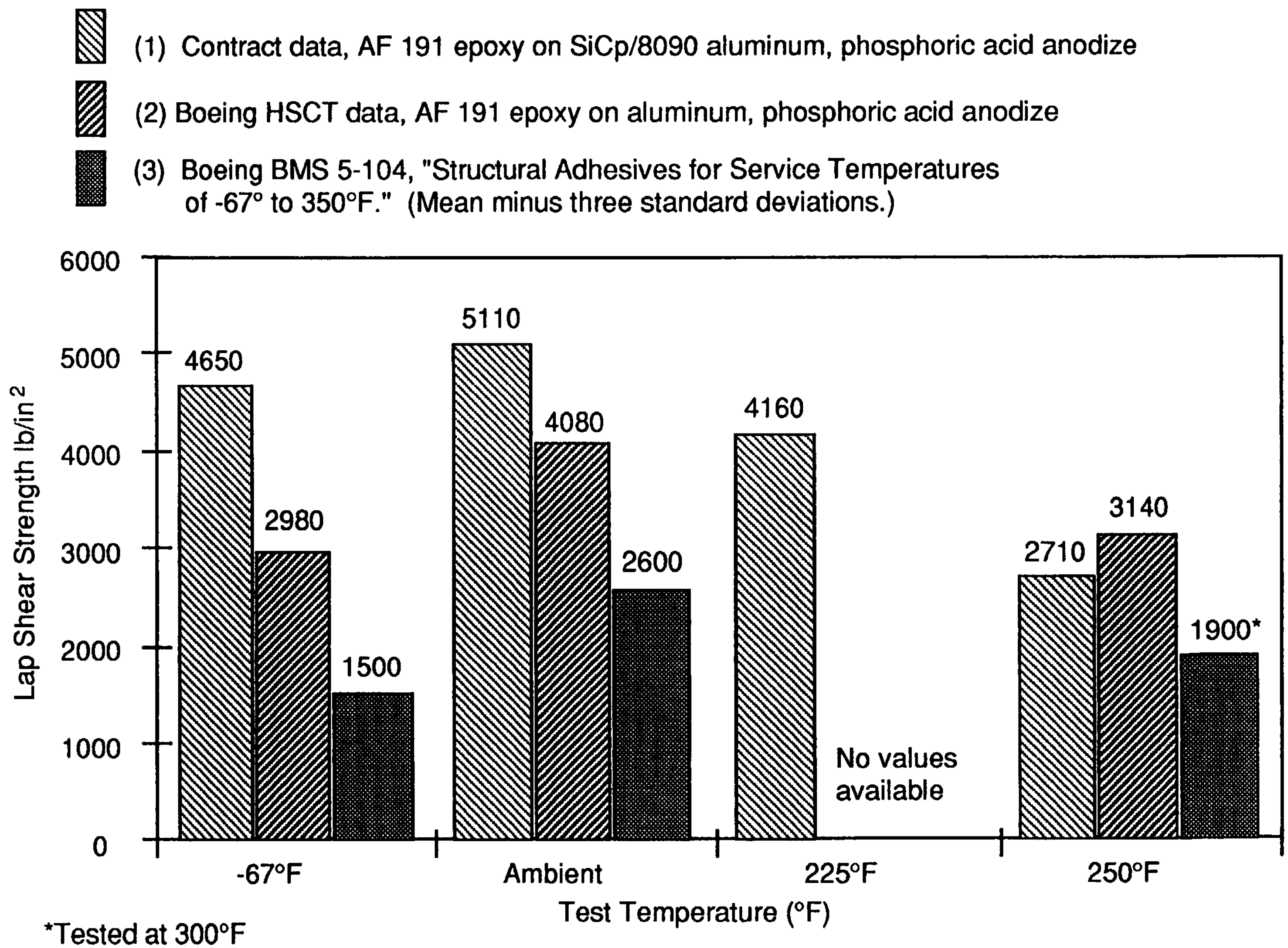


Figure 4.5-3. Comparison of Average Lap Shear Strength Data for SiCp/8090 Bonded with 3M AF 191 Epoxy to Other Test Results and to Requirements of BMS 5-104, "Structural Adhesives for Service Temperatures of -67° to 350°F"

would be even lower, and the margin of superiority of the BMI bonded honeycomb would be even greater.

Property	Temperature	Strength, mean
Single lap shear	-67°F	4,000 lb/in^2
Single lap shear	Ambient	4,000 lb/in^2
Single lap shear	350°F	2,750 lb/in^2
Flatwise tension*	-67°F	625 lb/in^2
Flatwise tension*	Ambient	625 lb/in^2
Flatwise tension*	350°F	480 lb/in^2

*3/16-in cell size.

Figure 4.5-4. Trade Study Design Properties for a High Speed Civil Transport Airplane

5.0 CONCLUDING REMARKS

Adhesive candidates were screened for bonding high-temperature and high-performance aluminum alloys which may find application in space launch vehicles and in high-speed civil transport aircraft. From the adhesives screening effort using single lap shear tests, the XEA 9674 bismaleimide exhibited the best mechanical performance of the elevated temperature adhesives tested. The AF 191 epoxy adhesive, which was selected based on favorable past experience for bonding the SiC_p/8090 and Weldalite test specimens and to avoid subjecting these alloys to temperatures above 350°F, also performed well. The mechanical test results from these adhesives are further discussed relative to existing requirements for subsonic transport airplanes, as well as to design goals for high speed civil transport (HSCT) airplanes.

Moderate to high adhesive bond strengths were obtained with the XEA 9674 bismaleimide (BMI) and AF 191 epoxy adhesives, and the four high-performance aluminum adherends. Single lap shear strengths over the temperature range tested (-67° to 275°F and 300°F) usually exceeded 3500 lb/in^2. A maximum decrease in lap shear strength of 7% was observed after isothermal aging of lap shear specimens (SiC_p/8009/XEA 9674). The standard aluminum bonding surface preparation, Boeing Airplane Company (BAC 5555) phosphoric acid anodize process, produced satisfactory primer and resin adhesion for all four of the aluminum alloys tested. The failure surfaces of the both the BMI and epoxy-bonded lap shear specimens were predominantly cohesive, in which fracture occurred through the adhesive layer and adhesive remained on both adherends. Cohesive failure surfaces are usually associated with high bond strengths, and can indicate that an optimum bond was achieved. Adhesive failures in which all or most of the adhesive remains on one adherend may indicate deficiencies in the primer or adherend surface preparation, and are usually associated with low bond strengths.

Using the XEA 9674 BMI and AF 191 epoxy adhesives selected through the screening tests, high flatwise tensile strengths were obtained with the four aluminum alloy skins bonded to titanium honeycomb core. The BMI bonded specimens exhibited a small drop in strength at elevated temperature, however, with AF 191 epoxy adhesive the elevated temperature strengths dropped to half their room temperature values. Even after thermal cycling the sandwich specimens exhibited acceptable flatwise tensile strengths. The flatwise tensile performance of both adhesives satisfied the requirements of a Boeing structural adhesive specification at the temperatures used for the testing.

Examination of the flatwise tensile specimen fracture surfaces revealed that both the BMI and epoxy adhesives formed well developed fillets between the core ribbon and aluminum face sheets. Cohesive failure occurred in which adhesive remained on both the core and face skins. The fracture surface morphology indicated that an optimum skin-core bond was achieved with both the BMI and epoxy adhesives. The quality of the skin-core bond was also indicated by the integrity of most of the bonds in the edgewise compression specimens after testing, despite the large permanent deformations these specimens were subjected to by the test.

The edgewise compression strengths of sandwich specimens compared favorably with predicted values. A 15% to 30% drop in compression strength of sandwich specimens at elevated temperature occurred with the alloys tested. The thermal cycling appeared to have little effect on sandwich edgewise compression strength. Despite the large deformations that occurred when the compression specimens failed, most of the face sheets remained bonded to the core indicating excellent adhesive strength and toughness.

In the toughness testing the AF 191 epoxy exhibited higher performance than the XEA 9674 in mode I, crack-opening fracture toughness; however, failure in the BMI bonded specimens occurred adhesively which indicated that higher fracture toughness values might be obtained with a more suitable primer. In mode II crack propagation under pure shear fracture toughness was measured with BMI-bonded 8009 aluminum alloy only, which as expected had lower values than a toughened graphite/epoxy composite. Bond toughness was usually lower at -67°F than at ambient temperature. Thermal cycling appeared to have no effect on the mode I or II fracture toughness values.

Isothermal aging up to 1000 hours had only modest effects on lap joint strength. Longer exposures will be needed to assess the aluminum oxide-primer-adhesive system performance with respect to the operating requirements of HSCT designs which require high durability over 60,000 hours of elevated temperature exposure.

HSCT airplane designs are one source of potential applications for the aluminum alloys and adhesives evaluated in this task. Boeing HSCT trade studies have included mach 2.0 and mach 2.4 concepts. In a mach 2.0 design for long-term operating temperatures of 225°F, Weldalite, discontinuous reinforced aluminum metal matrix composites (MMC), and elevated temperature aluminum (ETA) skins are bonded to aluminum honeycomb core on the wings and fuselage primary structure. For a mach 2.4 design with a higher long-term operating temperature of 300°F, ETA and ETA MMC skins are bonded to ETA core for the wing and fuselage panels.

The test results from this program indicate that the XEA 9674 BMI and the AF 191 epoxy are promising candidates for adhesively bonded advanced aluminum alloy structure for HSCT and space launch vehicle applications. The existing phosphoric acid anodize process for aluminum bonding surface preparation performed well in these evaluations with all of the aluminum alloys investigated. Future work should include developing an improved primer for the XEA 9674 BMI, and repeating the tests conducted in this program on specimens bonded using this primer. Longer term thermal aging tests of these adhesives would also be of interest to determine the property retention of bonded structure over time. Durability of the aluminum oxide-primer-adhesive systems under fluid exposures also needs to be assessed.

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APPENDIX A - BONDING PROCEDURES

A.1 Bonding Procedure for 8009 Aluminum and $dSiC_p$/8009 With Dexter Hysol XEA 9674 BMI

1. Phosphoric acid anodize blanks per BAC 5555.

2. Apply BASF X268-9 primer. Shake well prior to pouring into spray gun. Shake spray gun prior to spraying.

3. Spray on a thin uniform coat (1/10 of a mil). If too thick a coat is applied the primer will start to flow.

4. Dry and cure the primer after spray-coating by heating for one hour in at 350°F (± 10°F).

5. Assemble the coupon blanks with the XEA 9674 adhesive tape (warmed to room temperature) and vacuum bag for 350°F cure.

6. Heat to 350°F at between 2° and 7°F/min., with full vacuum to 125°F. At 125°F vent bag to atmosphere and apply 50 lb/in^2 bonding pressure.

7. Hold for one hour at 350°F. Cool assembly and remove bonding pressure below 150°F.

8. Postcure freestanding at 475°F for 3 hours.

A.2 Bonding Procedure for 8009 Aluminum and $dSiC_p$/8009 With Allied Signal/YLA Phenolic-Triazine (PT) Resin/PT Primer

1. Phosphoric acid anodize blanks per BAC 5555.

2. Apply phenolic-triazine (PT) resin primer and cure for one hour at 350°F.

3. Assemble the coupon blanks with the PT adhesive tape (warmed to room temperature) and vacuum bag for 350°F cure.

4. Heat to 350°F at between 2° and 10°F/min. and apply 50 lb/in^2 bonding pressure with slight vacuum pressure (starting at 200°F) for 2 hours at 350°F.

5. Cool assembly and remove bonding pressure below 150°F. Postcure freestanding at 525°F for 3 hours.

A.3 Bonding Procedure for 8009 Aluminum and $dSiC_p/8009$ With American Cyanamid FM 680/BR 680 Primer

1. Phosphoric acid anodize blanks per BAC 5555.
2. Apply American Cyanamid BR 680 primer with a spray gun. Do not dilute the primer. Since the primer is costly please try to minimize the amount that is used and wasted. Apply a thin coat (0.1 to 0.3 mils).
3. Dry the primer in air for 30 minutes at 75°F, at 300°F, at 400°F, and at 600°F in succession.
4. Assemble the coupon blanks with the American Cyanamid adhesive tape (warmed to room temperature) and vacuum bag for 600°F cure.
5. Apply 5 in. Hg. Heat at 2°F/min to 250°F. Apply full vacuum and 100 lb/in^2. Heat at 3.5°F per minute to 600°F. Cool at 5°F per minute to 200°F.
6. Remove bonding pressure and release vacuum below 200°F.
7. Postcure freestanding at 600°F for 16 hours, using a 5°F heat up and cool down rate.

A.4 Bonding Procedure for 8009 Aluminum and $dSiC_p/8009$ With BASF X2550 BMI Adhesive

1. Phosphoric acid anodize blanks per BAC 5555.
2. Apply BASF X268-9 primer. Shake well prior to pouring into spray gun. Shake spray gun prior to spraying.
3. Spray on a thin uniform coat (1/10 of a mil). If too thick a coat is applied the primer will start to flow.
4. Dry and cure the primer after spray-coating by heating for one hour in at 350°F ($\pm$ 10°F).
5. Assemble the coupon blanks with BASF X2550 BMI adhesive tape (warmed to room temperature) and vacuum bag for 350°F cure.
6. Autoclave cure for 4.0 hours at 350°F and 45 lb/in^2 in a bag vented to the atmosphere. Heat at 3° to 5°F/min and cool no faster than 5°F/min.
7. Postcure freestanding at 470°F for 6 hours.

A.5 Bonding Procedure for Weldalite Aluminum and dSiC/8090 With 3M AF 191 Epoxy Adhesive

1. Phosphoric acid anodize blanks per BAC 5555.

2. Apply EC 3960 (BMS 5-89, Type 1, Grade A) primer with spray gun. Spray on a thin uniform coat (0.15 to 0.40 mil - Ref. BAC 5514-589).

3. Dry and cure the primer 30 minutes after spray-coating by heating for one hour at 250°F.

5. Assemble the coupon blanks with AF191 epoxy adhesive tape (warmed to room temperature) and vacuum bag for 350°F cure.

6. Autoclave cure at 350°F and 50 lb/in^2 for 1.0 hour. No postcure is needed.

A.6 Phosphoric Acid Anodizing Procedure (Summary of BAC 5555)

1. Vapor, solvent, or emulsion degrease aluminum adherends.

2. Alkaline clean adherends.

3. Rinse for 5 min, deoxidize in chromic acid-sulfuric acid solution, and rinse again for 5 min.

4. Immerse parts in the phosphoric acid solution. Raise to a potential of 15$\pm$1 V. Maintain the potential for 20 to 25 min.

5. Remove details from anodize solution and rinse. Time interval from interruption of current to start of rinse shall not exceed 2-1/2 minutes for any part of the load. Water rinse for 5 to 15 minutes, 110°F maximum. Control pH of rinse water from 2.5 to 8.0.

6. Dry thoroughly at 160°F maximum.

7. Examine for presence of anodic coating.

8. Apply adhesive primer within 72 hours of drying.

A.7 Chromic Acid Anodizing Procedure (Summary of BAC 5890)

1. Emulsion or solvent degrease aluminum adherends.

2. Alkaline clean adherends, and rinse with hot water (110°F minimum) for 5 min.

3. Etch in nitric-hydrofluoric acid for 0.5 to 1.5 min.

4. Rinse in cold water for 5 min minimum.

5. Anodize in chromic acid solution by immersing adherends, and increasing the part voltage to 9 to 10 V within 5 min. Maintain 9 to 10 V for 18 to 22 min.

6. Remove adherends from anodize solution and begin rinsing within 2 min after current was stopped. Cold water rinse for 10 to 15 min.

7. Dry thoroughly at 160°F maximum.

8. Examine for presence of anodic coating.

9. Apply adhesive primer within 72 hours after drying.

APPENDIX B - MECHANICAL TEST DATA FOR INDIVIDUAL SPECIMENS

Adherends: 8009 Aluminum Single Lap Shear Test Data					Contract NAS1-18560			
Adhesive: American Cyanamid FM 680 Polyimide/BR 680 Primer								
Surface Preparation: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table I.			
Thermal Cycle: None					Averages Plotted in Figure 4.1-2			
Specimen No.	Test Temp.	Bondline Thickness (in.)	Ultimate Load (lbf)	Ultimate Stress (psi)	Fracture Surface	Overlap (in)	Adherend A (in)	Adherend B (in)
12S67U1-1	-67°F	0.005	1605	3210	Cohesive	0.191	0.093	0.093
12S67U1-2	-67°F	0.005	1610	3220	Cohesive	0.191	0.093	0.093
12S67U1-3	-67°F	0.005	1510	3020	Cohesive	0.191	0.093	0.093
12S67U1-4	-67°F	0.006	1520	3040	Cohesive	0.192	0.093	0.093
12S67U1-5	-67°F	0.006	1525	3050	Cohesive	0.192	0.093	0.093
Average				3108				
Standard Deviation				98				
Coefficient of Variation				0.03				
12S72U1-1	RT	0.005	1170	2340	Cohesive	0.193	0.094	0.094
12S72U1-2	RT	0.005	1245	2490	Cohesive	0.193	0.094	0.094
12S72U1-3	RT	0.005	1210	2420	Cohesive	0.193	0.094	0.094
12S72U1-4	RT	0.005	1250	2500	Cohesive	0.193	0.094	0.094
12S72U1-5	RT	0.005	1260	2520	Cohesive	0.193	0.094	0.094
Average				2454				
Standard Deviation				43				
Coefficient of Variation				0.02				
12S250U1-1	250°F	0.006	1380	2760	Cohesive	0.194	0.094	0.094
12S250U1-2	250°F	0.006	1380	2760	Cohesive	0.194	0.094	0.094
12S250U1-3	250°F	0.006	1225	2450	Cohesive	0.194	0.094	0.094
12S250U1-4	250°F	0.006	1360	2720	Cohesive	0.194	0.094	0.094
12S250U1-5	250°F	0.006	1280	2560	Cohesive	0.194	0.094	0.094
Average				2650				
Standard Deviation				139				
Coefficient of Variation				0.05				

Table B.1-1. Single Lap Shear Screening Test Results for 8009/FM 680

Adherends: 8009 Aluminum Single Lap Shear Test Data					Contract NAS1-18560			
Adhesive: American Cyanamid FM 680 Polyimide/BR 680 Primer								
Surface Preparation: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table I.			
Thermal Cycle: None					Averages Plotted in Figure 4.1-2			
Specimen No.	Test Temp.	Bondline	Ultimate	Ultimate		Overlap	Adherend A	Adherend B
	(°F)	Thickness (in.)	Load (lbf)	Stress (psi)		(in)	(in)	(in)
12S350U1-1	350°F	0.006	990	1980	Cohesive	0.194	0.094	0.094
12S350U1-2	350°F	0.006	1210	2420	Cohesive	0.194	0.094	0.094
12S350U1-3	350°F	0.006	1040	2080	Cohesive	0.194	0.094	0.094
12S350U1-4	350°F	0.006	1110	2220	Cohesive	0.194	0.094	0.094
12S350U1-5	350°F	0.006	1010	2020	Cohesive	0.194	0.094	0.094
Average				2144				
Standard Deviation				179				
Coefficient of Variation				0.08				

Table B.1-1. Single Lap Shear Screening Test Results for 8009/FM 680 (continued)

Adherends: SiCp/8009 Aluminum Single Lap Shear Test Data					Contract NAS1-18560			
Adhesive: American Cyanamid FM 680 Polyimide/BR 680 Primer								
Surface Preparation: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table I.			
Thermal Cycle: None		SiCp = silicon carbide particulate.			Averages Plotted in Figure 4.1-2			
Specimen No.	Test Temp.	Bondline Thickness (in.)	Ultimate Load (lbf)	Ultimate Stress (psi)	Fracture Surface	Overlap (in)	Adherend A (in)	Adherend B (in)
32S250U1-1	250°F	0.004	1160	2320	Cohesive	0.170	0.083	0.083
32S250U1-2	250°F	0.004	1100	2200	Cohesive	0.170	0.083	0.083
32S250U1-3	250°F	0.004	1260	2520	Cohesive	0.170	0.083	0.083
32S250U1-4	250°F	0.004	1260	2520	Cohesive	0.170	0.083	0.083
32S250U1-5	250°F	0.004	1200	2400	Cohesive	0.170	0.083	0.083
Average				2392				
Standard Deviation				137				
Coefficient of Variation				0.06				
32S350U1-1	350°F	0.006	1080	2160	Cohesive	0.168	0.081	0.081
32S350U1-2	350°F	0.006	1055	2110	Cohesive	0.168	0.081	0.081
32S350U1-3	350°F	0.006	1020	2040	Cohesive	0.168	0.081	0.081
32S350U1-4	350°F	0.006	1070	2140	Cohesive	0.168	0.081	0.081
32S350U1-5	350°F	0.006	1240	2480	Cohesive	0.168	0.081	0.081
Average				2186				
Standard Deviation				196				
Coefficient of Variation				0.09				

Table B.1-2. Single Lap Shear Screening Test Results for SiCp/8009/FM 680

Adherends: 8009 Aluminum, Single Lap Shear Test Data					Contract NAS1-18560			
Adhesive: Allied Signal Phenolic Triazine (PT) Resin/PT Resin Primer								
Surface Preparation: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table I.			
Thermal Cycle: None					Averages plotted in Figure 4.1-2			
Specimen No.	Test Temp.	Bondline	Ultimate	Ultimate	Fracture	Overlap	Adherend A	Adherend B
		Thickness	Load	Stress	Surface	(in)	(in)	(in)
		(in.)	(lbf)	(psi)				
13S67U1-1	-67°F	0.006	580	1160	80% Adhesive	0.192	0.093	0.093
13S67U1-2	-67°F	0.006	685	1370	80% Adhesive	0.192	0.093	0.093
13S67U1-3	-67°F	0.006	650	1300	80% Adhesive	0.192	0.093	0.093
13S67U1-4	-67°F	0.006	900	1800	80% Adhesive	0.192	0.093	0.093
13S67U1-5	-67°F	0.006	725	1450	80% Adhesive	0.192	0.093	0.093
Average				1416				
Standard Deviation				240				
Coefficient of Variation				0.17				
13S72U1-1	RT	0.005	1035	2070	80% Adhesive	0.193	0.094	0.094
13S72U1-2	RT	0.005	1270	2540	80% Adhesive	0.193	0.094	0.094
13S72U1-3	RT	0.005	1122	2244	80% Adhesive	0.193	0.094	0.094
13S72U1-4	RT	0.005	750	1500	80% Adhesive	0.193	0.094	0.094
13S72U1-5	RT	0.005	1110	2220	80% Adhesive	0.193	0.094	0.094
Average				2115				
Standard Deviation				442				
Coefficient of Variation				0.21				
13S250U1-1	250°F	0.005	1135	2270	80% Adhesive	0.193	0.094	0.094
13S250U1-2	250°F	0.005	965	1930	80% Adhesive	0.193	0.094	0.094
13S250U1-3	250°F	0.005	1165	2330	80% Adhesive	0.193	0.094	0.094
13S250U1-4	250°F	0.005	1160	2320	80% Adhesive	0.193	0.094	0.094
13S250U1-5	250°F	0.005	1020	2040	80% Adhesive	0.193	0.094	0.094
Average				2178				
Standard Deviation				182				
Coefficient of Variation				0.08				

Table B.1-3. Single Lap Shear Test Results for 8009/Phenolic Triazine

Adherends: 8009 Aluminum, Single Lap Shear Test Data					Contract NAS1-18560			
Adhesive: Allied Signal Phenolic Triazine (PT) Resin/PT Resin Primer								
Surface Preparation: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table I.			
Thermal Cycle: None					Averages plotted in Figure 4.1-2			
Specimen No.	Test Temp.	Bondline	Ultimate	Ultimate		Overlap	Adherend A	Adherend B
	(°F)	Thickness (in.)	Load (lbf)	Stress (psi)		(in)	(in)	(in)
13S300U1-1	350°F	0.006	1255	2510	80% Adhesive	0.194	0.094	0.094
13S300U1-2	350°F	0.006	1090	2180	80% Adhesive	0.194	0.094	0.094
13S300U1-3	350°F	0.006	990	1980	80% Adhesive	0.194	0.094	0.094
13S300U1-4	350°F	0.006	1135	2270	80% Adhesive	0.194	0.094	0.094
13S300U1-5	350°F	0.006	1140	2280	80% Adhesive	0.194	0.094	0.094
Average				2244				
Standard Deviation				191				
Coefficient of Variation				0.09				

Table B.1-3. Single Lap Shear Test Results for 8009/Phenolic Triazine (continued)

Adherends: SiCp/8009 Aluminum, Single Lap Shear Test Data					Contract NAS1-18560			
Adhesive: Allied Signal Phenolic Triazine (PT) Resin/PT Resin Primer								
Surface Preparation: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table I.			
Thermal Cycle: None		SiCp = silicon carbide particulate			Averages plotted in Figure 4.1-2			
Specimen No.	Test Temp.	Bondline Thickness (in.)	Ultimate Load (lbf)	Ultimate Stress (psi)	Fracture Surface	Overlap (in)	Adherend A (in)	Adherend B (in)
33S250U1-1	250°F	0.008	1355	2710	80% Adhesive	0.170	0.081	0.081
33S250U1-2	250°F	0.008	1300	2600	80% Adhesive	0.170	0.081	0.081
33S250U1-3	250°F	0.008	1222	2444	80% Adhesive	0.170	0.081	0.081
33S250U1-4	250°F	0.008	1240	2480	80% Adhesive	0.170	0.081	0.081
331S250U1-5	250°F	0.008	1245	2490	80% Adhesive	0.170	0.081	0.081
Average				2545				
Standard Deviation				109				
Coefficient of Variation				0.04				
33S350U1-1	350°F	0.008	1540	3080	80% Adhesive	0.168	0.080	0.080
33S350U1-2	350°F	0.010	1490	2980	80% Adhesive	0.170	0.080	0.080
33S350U1-3	350°F	0.012	1210	2420	80% Adhesive	0.172	0.080	0.080
33S350U1-4	350°F	0.011	1365	2730	80% Adhesive	0.171	0.080	0.080
33S350U1-5	350°F	0.011	1320	2640	80% Adhesive	0.171	0.080	0.080
Average				2770				
Standard Deviation				232				
Coefficient of Variation				0.08				

Table B.1-4. Single Lap Shear Test Results for SiCp/8009/Phenolic Triazine

Adherends: 8009 Aluminum, Single Lap Shear Test Data					Contract NAS1-18560			
Adhesive: BASF X2550 bismaleimide (BMI)/X268-9 BMI primer								
Surface Preparation: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table I.			
Thermal Cycle: None					Averages plotted in Figure 4.1-2			
Specimen No.	Test Temp.	Bondline Thickness (in.)	Ultimate Load (lbf)	Ultimate Stress (psi)	Fracture Surface	Overlap (in)	Adherend A (in)	Adherend B (in)
15S67U1-1	-67°F	0.006	1280	2560	50% Cohesive	0.192	0.093	0.093
15S67U1-2	-67°F	0.006	1310	2620	50% Cohesive	0.192	0.093	0.093
15S67U1-3	-67°F	0.006	1180	2360	50% Cohesive	0.192	0.093	0.093
15S67U1-4	-67°F	0.006	1240	2480	50% Cohesive	0.192	0.093	0.093
15S67U1-5	-67°F	0.006	1240	2480	50% Cohesive	0.192	0.093	0.093
Average				2500				
Standard Deviation				98				
Coefficient of Variation				0.04				
15S72U1-1	RT	0.005	1480	2960	50% Cohesive	0.193	0.094	0.094
15S72U1-2	RT	0.005	1440	2880	50% Cohesive	0.193	0.094	0.094
15S72U1-3	RT	0.005	1360	2720	50% Cohesive	0.193	0.094	0.094
15S72U1-4	RT	0.005	1430	2860	50% Cohesive	0.193	0.094	0.094
15S72U1-5	RT	0.005	1568	3136	50% Cohesive	0.193	0.094	0.094
Average				2911				
Standard Deviation				173				
Coefficient of Variation				0.06				
15S250U1-1	250°F	0.005	1420	2840	50% Cohesive	0.193	0.094	0.094
15S250U1-2	250°F	0.005	1480	2960	50% Cohesive	0.193	0.094	0.094
15S250U1-3	250°F	0.005	1340	2680	50% Cohesive	0.193	0.094	0.094
15S250U1-4	250°F	0.005	1520	3040	50% Cohesive	0.193	0.094	0.094
15S250U1-5	250°F	0.005	1360	2720	50% Cohesive	0.193	0.094	0.094
Average				2848				
Standard Deviation				153				
Coefficient of Variation				0.05				

Table B.1-5. Single Lap Shear Screening Test Results for 8009/X2550

Adherends: 8009 Aluminum, Single Lap Shear Test Data					Contract NAS1-18560			
Adhesive: BASF X2550 bismaleimide (BMI)/X268-9 BMI primer								
Surface Preparation: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table I.			
Thermal Cycle: None					Averages plotted in Figure 4.1-2			
Specimen No.	Test Temp.	Bondline Thickness (in.)	Ultimate Load (lbf)	Ultimate Stress (psi)		Overlap (in)	Adherend A (in)	Adherend B (in)
15S300U1-1	300°F	0.003	1400	2800	50% Cohesive	0.193	0.095	0.095
15S300U1-2	300°F	0.003	1422	2844	50% Cohesive	0.193	0.095	0.095
15S300U1-3	300°F	0.003	1360	2720	50% Cohesive	0.193	0.095	0.095
15S300U1-4	300°F	0.003	1280	2560	50% Cohesive	0.193	0.095	0.095
15S300U1-5	300°F	0.003	1310	2620	50% Cohesive	0.193	0.095	0.095
Average				2709				
Standard Deviation				119				
Coefficient of Variation				0.04				

Table B.1-5. Single Lap Shear Screening Test Results for 8009/X2550 (continued)

Adherends: 8009 Aluminum, Single Lap Shear Test Data

Contract NAS1-18560

Adhesive: Dexter Hysol XEA 9674 BMI/BASF X268-9 Primer

Surface Preparation: Phosphoric Acid Anodize per BAC 5555

Specimens in final report Table I.

Thermal Cycle: None

Averages plotted in Figure 4..1-2

Specimen No.	Test Temp.	Bondline Thickness (in.)	Ultimate Load (lbf)	Ultimate Stress (psi)	Fracture Surface	Overlap (in)	Adherend A (in)	Adherend B (in)
11S67U1-1	-67°F	0.002	1650	3300	Cohesive	0.184	0.091	0.091
11S67U1-2	-67°F	0.002	1645	3290	Cohesive	0.184	0.091	0.091
11S67U1-3	-67°F	0.003	1625	3250	Cohesive	0.185	0.091	0.091
11S67U1-4	-67°F	0.003	1620	3240	Cohesive	0.185	0.091	0.091
11S67U1-5	-67°F	0.003	1350	2700	Cohesive	0.185	0.091	0.091
Average				3156				
Standard Deviation				256				
Coefficient of Variation				0.08				
11S72U1-1	RT	0.004	1880	3760	Cohesive	0.192	0.094	0.094
11S72U1-2	RT	0.005	1660	3320	Cohesive	0.193	0.094	0.094
11S72U1-3	RT	0.004	1825	3650	Cohesive	0.192	0.094	0.094
11S72U1-4	RT	0.005	1790	3580	Cohesive	0.193	0.094	0.094
11S72U1-5	RT	0.004	1700	3400	Cohesive	0.192	0.094	0.094
Average				3542				
Standard Deviation				153				
Coefficient of Variation				0.04				
11S250U1-1	250°F	0.003	1720	3440	Cohesive	0.192	0.095	0.094
11S250U1-2	250°F	0.003	1775	3550	Cohesive	0.192	0.095	0.094
11S250U1-3	250°F	0.002	1730	3460	Cohesive	0.191	0.095	0.094
11S250U1-4	250°F	0.003	1740	3480	Cohesive	0.192	0.095	0.094
11S250U1-5	250°F	0.003	1860	3720	Cohesive	0.192	0.095	0.094
Average				3530				
Standard Deviation				114				
Coefficient of Variation				0.03				

Table B.1-6. Single Lap Shear Screening Test Results for 8009/XEA 9674

Adherends: 8009 Aluminum, Single Lap Shear Test Data - Continued					Contract NAS1-18560			
Adhesive: Dexter Hysol XEA 9674 BMI/BASF X268-9 Primer								
Surface Preparation: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table I.			
Thermal Cycle: None					Averages plotted in Figure 4..1-2			
Specimen No.	Test Temp.	Bondline	Ultimate	Ultimate	Fracture			
	(°F)	Thickness	Load	Stress	Surface	Overlap	Adherend A	Adherend B
		(in.)	(lbf)	(psi)		(in)	(in)	(in)
11S300U1-1	300°F	0.001	2840	5680	Cohesive	0.190	0.094	0.095
11S300U1-2	300°F	0.001	2925	5850	Cohesive	0.190	0.094	0.095
11S300U1-3	300°F	0.001	2860	5720	Cohesive	0.190	0.094	0.095
11S300U1-4	300°F	0.001	2750	5500	Cohesive	0.190	0.094	0.095
11S300U1-5	300°F	0.001	3015	6030	Cohesive	0.190	0.094	0.095
Average				5756				
Standard Deviation				198				
Coefficient of Variation				0.03				

Table B.1-6. Single Lap Shear Screening Test Results for 8009/XEA 9674 (continued)

Adherends: SiCp/8009 Aluminum Single Lap Shear Test Data					Contract NAS1-18560			
Adhesive: Dexter Hysol XEA 9674 BMI/BASF X268-9 Primer								
Surface Prep.: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table I.			
Thermal Cycle: None		SiCp = silicon carbide particulate			Averages plotted in Figure 4..1-2			
		Bondline	Ultimate	Ultimate	Fracture			
Specimen No.	Test Temp.	Thickness	Load	Stress	Surface	Overlap	Adherend A	Adherend B
		(in.)	(lbf)	(psi)		(in)	(in)	(in)
31S250U1-1	250°F	0.003	3575	7150	Cohesive	0.162	0.079	0.080
31S250U1-2	250°F	0.003	3500	7000	Cohesive	0.162	0.079	0.080
31S250U1-3	250°F	0.002	3345	6690	Cohesive	0.161	0.079	0.080
31S250U1-4	250°F	0.002	3350	6700	Cohesive	0.161	0.079	0.080
31S250U1-5	250°F	0.002	3575	7150	Cohesive	0.161	0.079	0.080
Average				6938				
Standard Deviation				230				
Coefficient of Variation				0.03				
31S300U1-1	300°F	0.004	3125	6250	Cohesive	0.169	0.082	0.083
31S300U1-2	300°F	0.004	3200	6400	Cohesive	0.169	0.082	0.083
31S300U1-3	300°F	0.003	3035	6070	Cohesive	0.168	0.082	0.083
31S300U1-4	300°F	0.003	3070	6140	Cohesive	0.168	0.082	0.083
31S300U1-5	300°F	0.002	2775	5550	Cohesive	0.167	0.082	0.083
Average				6082				
Standard Deviation				356				
Coefficient of Variation				0.06				

Table B.1-7. Single Lap Shear Screening Test Results for SiCp/8009/XEA 9674

Adherends: Weldalite Aluminum, Single Lap Shear Test Data					Contract NAS1-18560			
Adhesive: 3M AF191 Epoxy/EC 3960 primer (BMS 5-89, Type 1, Grade A)								
Surface Preparation: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table I.			
Thermal Cycle: None					Averages plotted in Figure 4.1-3			
Specimen No.	Test Temp.	Bondline Thickness (in.)	Ultimate Load (lbf)	Ultimate Stress (psi)	Fracture Surface	Overlap (in)	Adherend A (in)	Adherend B (in)
24S67U1-1	-67°F	0.004	2525	5050	50% Cohesive	0.178	0.087	0.087
24S67U1-2	-67°F	0.005	2345	4690	50% Cohesive	0.179	0.087	0.087
24S67U1-3	-67°F	0.005	2000	4000	50% Cohesive	0.179	0.087	0.087
24S67U1-4	-67°F	0.006	2160	4320	50% Cohesive	0.180	0.087	0.087
24S67U1-5	-67°F	0.005	2175	4350	50% Cohesive	0.179	0.087	0.087
Average				4482				
Standard Deviation				401				
Coefficient of Variation				0.09				
24S72U1-1	RT	0.008	2400	4800	Cohesive	0.182	0.087	0.087
24S72U1-2	RT	0.007	2390	4780	Cohesive	0.181	0.087	0.087
24S72U1-3	RT	0.007	2555	5110	Cohesive	0.181	0.087	0.087
24S72U1-4	RT	0.005	3100	6200	Cohesive	0.179	0.087	0.087
24S72U1-5	RT	0.007	2660	5320	Cohesive	0.181	0.087	0.087
Average				5242				
Standard Deviation				607				
Coefficient of Variation				0.12				
24S225U1-1	225°F	0.003	2425	4850	Cohesive	0.179	0.088	0.088
24S225U1-2	225°F	0.001	2400	4800	Cohesive	0.177	0.088	0.088
24S225U1-3	225°F	0.001	2260	4520	Cohesive	0.177	0.088	0.088
24S225U1-4	225°F	0.001	2465	4930	Cohesive	0.177	0.088	0.088
24S225U1-5	225°F	0.001	2425	4850	Cohesive	0.177	0.088	0.088
Average				4790				
Standard Deviation				158				
Coefficient of Variation				0.03				

Table B.1-8. Single Lap Shear Screening Test Results for Weldalite/AF 191

Adherends: Weldalite Aluminum, Single Lap Shear Test Data					Contract NAS1-18560			
Adhesive: 3M AF191 Epoxy/EC 3960 primer (BMS 5-89, Type 1, Grade A)								
Surface Preparation: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table I.			
Thermal Cycle: None					Averages plotted in Figure 4.1-3			
Specimen No.	Test Temp.	Bondline	Ultimate	Ultimate	Fracture	Overlap	Adherend A	Adherend B
		Thickness	Load	Stress	Surface	(in)	(in)	(in)
		(in.)	(lbf)	(psi)				
24S275U1-1	275°F	0.005	1750	3500	Cohesive	0.179	0.087	0.087
24S275U1-2	275°F	0.006	1690	3380	Cohesive	0.180	0.087	0.087
24S275U1-3	275°F	0.005	1650	3300	Cohesive	0.179	0.087	0.087
24S275U1-4	275°F	0.005	1675	3350	Cohesive	0.179	0.087	0.087
24S275U1-5	275°F	0.005	1650	3300	Cohesive	0.179	0.087	0.087
Average				3366				
Standard Deviation				82.3				
Coefficient of Variation				0.02				

Table B.1-8. Single Lap Shear Screening Test Results for Weldalite/AF 191 (continued)

Adherends: SiCp/8090 Aluminum, Single Lap Shear Test Data					Contract NAS1-18560			
Adhesive: 3M AF191 Epoxy/EC 3960 primer (BMS 5-89, Type 1, Grade A)								
Surface Preparation: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table I.			
Thermal Cycle: None		SiCp = silicon carbide particulate			Averages plotted in Figure 4.1-3			
Specimen No.	Test Temp.	Bondline Thickness (in.)	Ultimate Load (lbf)	Ultimate Stress (psi)	Fracture Surface	Overlap (in)	Adherend A (in)	Adherend B (in)
44S67U1-1	-67°F	<0.001	2010	4020	Adh. @ Primer	0.160	0.080	0.080
44S67U1-2	-67°F	<0.001	2360	4720	Adh. @ Primer	0.160	0.080	0.080
44S67U1-3	-67°F	<0.001	2090	4180	Adh. @ Primer	0.160	0.080	0.080
44S67U1-4	-67°F	<0.001	2625	5250	Adherend Failed	0.160	0.080	0.080
44S67U1-5	-67°F	<0.001	2545	5090	Adherend Failed	0.160	0.080	0.080
Average				4652				
Standard Deviation				542				
Coefficient of Variation				0.12				
44S72U1-1	RT	<0.001	2650	5300	Adherend Failed	0.157	0.080	0.080
44S72U1-2	RT	<0.001	2560	5120	Adherend Failed	0.155	0.080	0.080
44S72U1-3	RT	<0.001	2750	5500	Adherend Failed	0.156	0.080	0.080
44S72U1-4	RT	<0.001	2755	5510	Cohesive	0.156	0.080	0.080
44S72U1-5	RT	<0.001	2060	4120	Cohesive	0.158	0.080	0.080
Average				5110				
Standard Deviation				654				
Coefficient of Variation				0.13				
44S250U1-1	225°F	0.006	1865	3730	80% Cohesive	0.166	0.080	0.080
44S250U1-2	225°F	0.006	2125	4250	80% Cohesive	0.166	0.080	0.080
44S250U1-3	225°F	0.006	2100	4200	80% Cohesive	0.166	0.080	0.080
44S250U1-4	225°F	0.007	2125	4250	80% Cohesive	0.167	0.080	0.080
44S250U1-5	225°F	0.007	2175	4350	80% Cohesive	0.167	0.080	0.080
Average				4156				
Standard Deviation				244				
Coefficient of Variation				0.06				

Table B.1-9. Single Lap Shear Screening Test Results for SiCp/8090/AF 191

Adherends: SiCp/8090 Aluminum, Single Lap Shear Test Data					Contract NAS1-18560			
Adhesive: 3M AF191 Epoxy/EC 3960 primer (BMS 5-89, Type 1, Grade A)								
Surface Preparation: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table I.			
Thermal Cycle: None		SiCp = silicon carbide particulate			Averages plotted in Figure 4.1-3			
Specimen No.	Test Temp.	Bondline Thickness (in.)	Ultimate Load (lbf)	Ultimate Stress (psi)	Fracture Surface	Overlap (in)	Adherend A (in)	Adherend B (in)
44S300U1-2	250°F	0.006	1510	3020	80% Cohesive	0.166	0.080	0.080
44S300U1-3	250°F	0.008	1350	2700	80% Cohesive	0.168	0.080	0.080
44S300U1-4	250°F	0.007	1200	2400	80% Cohesive	0.167	0.080	0.080
44S300U1-5	250°F	0.007	1150	2300	80% Cohesive	0.167	0.080	0.080
Average				2605				
Standard Deviation				325				
Coefficient of Variation				0.12				

Table B.1-9. Single Lap Shear Screening Test Results for SiCp/8090/AF 191 (continued)

Adherends: 8009 Aluminum, Single Lap Shear Test Data					Contract NAS1-18560			
Adhesive: Mitsui Toatsu LARC-TPI Polyimide/LARC-TPI primer								
Surface Preparation: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table I.			
Thermal Cycle: None					Averages plotted in Figures 4.1-3			
Specimen No.	Test Temp.	Bondline Thickness (in.)	Ultimate Load (lbf)	Ultimate Stress (psi)	Fracture Surface	Overlap (in)	Adherend A (in)	Adherend B (in)
16S67U1-1	-67°F							
16S67U1-2	-67°F							
16S67U1-3	-67°F	Blanks came apart in handling. Not tested.						
16S67U1-4	-67°F							
16S67U1-5	-67°F							
Average				N/A				
Standard Deviation				N/A				
Coefficient of Variation				N/A				
16S72U1-1	RT	0.006	540	1080	Cohesive	0.192	0.093	0.093
16S72U1-2	RT	0.006	730	1460	Cohesive	0.192	0.093	0.093
16S72U1-3	RT	0.005	720	1440	Cohesive	0.191	0.093	0.093
16S72U1-4	RT	0.004	620	1240	Cohesive	0.190	0.093	0.093
16S72U1-5	RT	0.003	660	1320	Cohesive	0.189	0.093	0.093
Average				1308				
Standard Deviation				104				
Coefficient of Variation				0.08				
16S250U1-1	250°F	0.004	609	1218	Cohesive	0.190	0.093	0.093
16S250U1-2	250°F	0.006	550	1100	Cohesive	0.192	0.093	0.093
16S250U1-3	250°F	0.007	480	960	Cohesive	0.193	0.093	0.093
16S250U1-4	250°F	0.008	524	1048	Cohesive	0.194	0.093	0.093
16S250U1-5	250°F	0.009	418	836	Cohesive	0.195	0.093	0.093
Average				1032				
Standard Deviation				144				
Coefficient of Variation				0.14				

Table B.1-10. Single Lap Shear Screening Test Results for 8009/LARC-TPI

Adherends: 8009 Aluminum, Single Lap Shear Test Data					Contract NAS1-18560			
Adhesive: Mitsui Toatsu LARC-TPI Polyimide/LARC-TPI primer								
Surface Preparation: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table I.			
Thermal Cycle: None					Averages plotted in Figures 4.1-3			
Specimen No.	Test Temp.	Bondline	Ultimate	Ultimate		Overlap	Adherend A	Adherend B
	(°F)	Thickness (in.)	Load (lbf)	Stress (psi)		(in)	(in)	(in)
16S350U1-1	350°F	0.005	395	790	Cohesive	0.193	0.094	0.094
16S350U1-2	350°F	0.005	430	860	Cohesive	0.193	0.094	0.094
16S350U1-3	350°F	0.005	363	726	Cohesive	0.193	0.094	0.094
16S350U1-4	350°F	0.005	420	840	Cohesive	0.193	0.094	0.094
16S350U1-5	350°F	0.005	344	688	Cohesive	0.193	0.094	0.094
Average				781				
Standard Deviation				73				
Coefficient of Variation				0.09				

Table B.1-10. Single Lap Shear Screening Test Results for 8009/LARC-TPI (continued)

Adherends: SiCp/8009 Aluminum, Single Lap Shear Test Data					Contract NAS1-18560			
Adhesive: Mitsui Toatsu LARC-TPI Polyimide/LARC-TPI primer								
Surface Preparation: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table I.			
Thermal Cycle: None		SiCp = silicon carbide particulate			Averages plotted in Figures 4.1-3			
Specimen No.	Test Temp.	Bondline	Ultimate	Ultimate	Fracture	Overlap	Adherend A	Adherend B
		Thickness	Load	Stress	Surface	(in)	(in)	(in)
		(in.)	(lbf)	(psi)				
36S250U1-1	250°F	0.007	400	800	Cohesive	0.167	0.080	0.080
36S250U1-2	250°F	0.006	364	728	Cohesive	0.166	0.080	0.080
36S250U1-3	250°F	0.007	375	750	Cohesive	0.167	0.080	0.080
36S250U1-4	250°F	0.007	414	828	Cohesive	0.167	0.080	0.080
36S250U1-5	250°F	0.008	50	100	Cohesive	0.168	0.080	0.080
Average				641				
Standard Deviation				305				
Coefficient of Variation				0.48				
36S350U1-1	350°F	0.006	440	880	Cohesive	0.166	0.080	0.080
36S350U1-2	350°F	0.007	510	1020	Cohesive	0.167	0.080	0.080
36S350U1-3	350°F	0.006	470	940	Cohesive	0.166	0.080	0.080
36S350U1-4	350°F	0.007	460	920	Cohesive	0.167	0.080	0.080
36S350U1-5	350°F	0.007	483	966	Cohesive	0.167	0.080	0.080
Average				945				
Standard Deviation				43				
Coefficient of Variation				0.05				

Table B.1-11. Single Lap Shear Screening Test Results for SiCp/8009/LARC-TPI

Adherends: 8009 Aluminum, Single Lap Shear Test Data					Contract NAS1-18560				
Adhesive: Dexter Hysol XEA 9674 BMI/BASF X268-9 Primer					Repeated tests.				
Surface Preparation: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table I.				
Thermal Cycle: None					Averages plotted in Figure 4.1-4.				
Specimen No.	Test Temp.	Bondline	Bondline	Ultimate	Ultimate	Fracture	Overlap	Adherend A	Adherend B
		Thickness	Width	Load	Stress	Surface	(in)	(in)	(in)
		(in.)	(in.)	(lbf)	(psi)				
11S250U1A-1	250°F	0.002	0.996	1950	3916	Cohesive	0.188	0.093	0.093
11S250U1A-2	250°F	0.002	0.997	1960	3932	Cohesive	0.188	0.093	0.093
11S250U1A-3	250°F	0.001	0.999	2000	4004	Cohesive	0.187	0.093	0.093
11S250U1A-4	250°F	0.001	0.998	2025	4058	Cohesive	0.187	0.093	0.093
11S250U1A-5	250°F	0.001	0.993	2015	4058	Cohesive	0.187	0.093	0.093
Average					3994				
Standard Deviation					67.8				
Coefficient of Variation					0.02				
11S300U1B-1	300°F	0.003	0.999	2020	4044	Cohesive	0.189	0.093	0.093
11S300U1B-2	300°F	0.002	0.997	1950	3912	Cohesive	0.188	0.093	0.093
11S300U1B-3	300°F	0.001	0.995	1950	3920	Cohesive	0.187	0.093	0.093
11S300U1B-4	300°F	0.001	0.996	2000	4016	Cohesive	0.187	0.093	0.093
11S300U1B-5	300°F	0.002	0.992	2015	4063	Cohesive	0.188	0.093	0.093
Average					3991				
Standard Deviation					70.6				
Coefficient of Variation					0.02				

Table B.2-1. Repeated Single Lap Shear Screening Test Results for 8009/XEA 9674

Adherends: SiCp/8009 Aluminum, Single Lap Shear Test Data					Contract NAS1-18560				
Adhesive: Dexter Hysol XEA 9674 BMI/BASF X268-9 Primer					Repeated tests.				
Surface Preparation: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table I.				
Thermal Cycle: None		SiCp = silicon carbide particulate			Averages plotted in Figure 4.1-4.				
Specimen No.	Test Temp.	Bondline	Bondline	Ultimate	Ultimate	Fracture	Overlap	Adherend A	Adherend B
		Thickness	Width	Load	Stress	Surface	(in)	(in)	(in)
		(in.)	(in.)	(lbf)	(psi)				
31S250U1C-1	250°F	0	0.996	2075	4167	Cohesive	0.160	0.080	0.080
31S250U1C-2	250°F	0.001	0.999	2120	4244	Cohesive	0.161	0.080	0.080
31S250U1C-3	250°F	0.001	0.997	2125	4263	Cohesive	0.161	0.080	0.080
31S250U1C-4	250°F	0	1.002	2050	4092	Cohesive	0.160	0.080	0.080
31S250U1C-5	250°F	0	0.997	2150	4313	Cohesive	0.160	0.080	0.080
Average					4216				
Standard Deviation					87				
Coefficient of Variation					0.02				
31S300U1D-1	300°F	0.003	1.001	1890	3776	Cohesive	0.163	0.080	0.080
31S300U1D-2	300°F	0.003	0.995	1825	3668	Cohesive	0.163	0.080	0.080
31S300U1D-3	300°F	0.002	0.999	1905	3814	Cohesive	0.162	0.080	0.080
31S300U1D-4	300°F	0.003	1.003	1840	3669	Cohesive	0.163	0.080	0.080
31S300U1D-5	300°F	0.002	0.997	1855	3721	Cohesive	0.162	0.080	0.080
Average					3730				
Standard Deviation					68				
Coefficient of Variation					0.02				

Table B.2-2. Repeated Single Lap Shear Screening Test Results for SiCp/8009/XEA 9674

Adherends: 8009 Aluminum, Flatwise Tensile Test Data				Contract NAS1-18560	
Core: Titanium, 3/8 in square cell, corrugated cell wall.					
Adhesive: Dexter Hysol XEA 9674 BMI/BASF X268-9 Primer					
Surface Prep.: Phosphoric Acid Anodize per BAC 5555				Final report Table II.	
Thermal Cycle: None				Averages, Figure 4.2-1	
(U=uncycled)					
		Specimen	Specimen	Ultimate	Ultimate
Specimen No.	Test Temp.	Width (in)	Length (in)	Load (lbf)	Stress (psi)
11T67U-1	'-67°F	2.0	2.0	3890	972.5
11T67U-2	'-67°F	2.0	2.0	3670	917.5
11T67U-3	'-67°F	2.0	2.0	3725	931.3
Average					940
		Specimen	Specimen	Ultimate	Ultimate
Specimen No.	Test Temp.	Width (in)	Length (in)	Load (lbf)	Stress (psi)
11T72U-1	72°F	2.0	2.0	4040	1010.0
11T72U-2	72°F	2.0	2.0	3900	975.0
11T72U-3	72°F	2.0	2.0	4075	1018.8
Average					1001
		Specimen	Specimen	Ultimate	Ultimate
Specimen No.	Test Temp.	Width (in)	Length (in)	Load (lbf)	Stress (psi)
11T300U-1	300°F	2.0	2.0	3840	960.0
11T300U-2	300°F	2.0	2.0	2820	705.0
11T300U-3	300°F	2.0	2.0	3550	887.5
Average					851

Table B.3-1. Flatwise Tensile Test Data for 8009/XEA9674

Adherends: SiCp/8009 Al., Flatwise Tensile Test Data				Contract NAS1-18560	
Core: Titanium, 3/8 in square cell, corrugated cell wall.					
Adhesive: Dexter Hysol XEA 9674 BMI/BASF X268-9 Primer					
Surface Prep.: Phosphoric Acid Anodize per BAC 5555				Final report Table II.	
SiCp = silicon carbide particulate.					
Thermal Cycle: None				Averages, Figure 4.2-1	
(U=uncycled)					
		Specimen	Specimen	Ultimate	Ultimate
Specimen No.	Test Temp.	Width (in)	Length (in)	Load (lbf)	Stress (psi)
31T72U-1	72°F	2.0	2.0	4025	1006.3
31T72U-2	72°F	2.0	2.0	2840	710.0
31T72U-3	72°F	2.0	2.0	3950	987.5
Average					901
		Specimen	Specimen	Ultimate	Ultimate
Specimen No.	Test Temp.	Width (in)	Length (in)	Load (lbf)	Stress (psi)
31T300U-1	300°F	2.0	2.0	3400	850.0
31T300U-1	300°F	2.0	2.0	3165	791.3
31T300U-1	300°F	2.0	2.0	2815	703.8
Average					782

Table B.3-2. Flatwise Tensile Test Data for SiCp/8009/XEA9674

Adherends: Weldalite, Flatwise Tensile Test Data				Contract NAS1-18560	
Core: Titanium, 3/8 in square cell, corrugated cell wall.					
3M AF191 Epoxy/BMS 5-89, Type I, Grade A Primer					
Surface Prep.: Phosphoric Acid Anodize per BAC 5555				Final report Table II.	
Thermal Cycle: None				Averages, Figure 4.2-1	
(U=uncycled)					
		Specimen	Specimen	Ultimate	Ultimate
Specimen No.	Test Temp.	Width (in)	Length (in)	Load (lbf)	Stress (psi)
24T67U-1	'-67°F	2.0	2.0	3810	952.5
24T67U-2	'-67°F	2.0	2.0	3400	850.0
24T67U-3	'-67°F	2.0	2.0	3190	797.5
Average					867
		Specimen	Specimen	Ultimate	Ultimate
Specimen No.	Test Temp.	Width (in)	Length (in)	Load (lbf)	Stress (psi)
24T72U-1	72°F	2.0	2.0	3440	860.0
24T72U-2	72°F	2.0	2.0	2925	731.3
24T72U-3	72°F	2.0	2.0	3625	906.3
Average					833
		Specimen	Specimen	Ultimate	Ultimate
Specimen No.	Test Temp.	Width (in)	Length (in)	Load (lbf)	Stress (psi)
24T275U-1	275°F	2.0	2.0	1725	431.3
24T275U-2	275°F	2.0	2.0	1810	452.5
24T275U-3	275°F	2.0	2.0	1650	412.5
Average					432

Table B.3-3. Flatwise Tensile Test Data for Weldalite/AF 191

Adherends: SiCp/8090 Al., Flatwise Tensile Test Data				Contract NAS1-18560	
Core: Titanium, 3/8 in square cell, corrugated cell wall.					
Adh.: 3M AF191 Epoxy/BMS 5-89, Type I, Grade A Primer					
Surface Prep.: Phosphoric Acid Anodize per BAC 5555				Final report Table II.	
SiCp = silicon carbide particulate.					
Thermal Cycle: None				Averages, Figure 4.2-1	
(U=uncycled)					
		Specimen	Specimen	Ultimate	Ultimate
Specimen No.	Test Temp.	Width (in)	Length (in)	Load (lbf)	Stress (psi)
44T67U-1	'-67°F	2.0	2.0	4115	1028.8
44T67U-2	'-67°F	2.0	2.0	3590	897.5
44T67U-3	'-67°F	2.0	2.0	4245	1061.3
Average					996
		Specimen	Specimen	Ultimate	Ultimate
Specimen No.	Test Temp.	Width (in)	Length (in)	Load (lbf)	Stress (psi)
44T72U-1	72°F	2.0	2.0	4050	1012.5
44T72U-2	72°F	2.0	2.0	2900	725.0
44T72U-3	72°F	2.0	2.0	4035	1008.8
Average					915
		Specimen	Specimen	Ultimate	Ultimate
Specimen No.	Test Temp.	Width (in)	Length (in)	Load (lbf)	Stress (psi)
44T275U-1	275°F	2.0	2.0	1680	420.0
44T275U-2	275°F	2.0	2.0	1725	431.3
Average					426

Table B.3-4. Flatwise Tensile Test Data for SiCp/8090/AF 191

Adherends: 8009 Aluminum, Flatwise Tensile Test Data				Contract NAS1-18560	
Core: Titanium, 3/8 in square cell, corrugated cell wall.					
Adhesive: Dexter Hysol XEA 9674 BMI/BASF X268-9 Primer					
Surface Prep.: Phosphoric Acid Anodize per BAC 5555				Final report Table II.	
Thermal Cycle: -67°F to 300°F				Averages, Figure 4.2-1	
(C = cycled)					
		Specimen	Specimen	Ultimate	Ultimate
Specimen No.	Test Temp.	Width (in)	Length (in)	Load (lbf)	Stress (psi)
11T67C-1	'-67°F	2.0	2.0	3860	965.0
11T67C-2	'-67°F	2.0	2.0	2300	575.0
11T67C-3	'-67°F	2.0	2.0	3195	798.8
Average					780
		Specimen	Specimen	Ultimate	Ultimate
Specimen No.	Test Temp.	Width (in)	Length (in)	Load (lbf)	Stress (psi)
11T72C-1	72°F	2.0	2.0	3340	835.0
11T72C-2	72°F	2.0	2.0	3250	812.5
11T72C-3	72°F	2.0	2.0	3500	875.0
Average					841
		Specimen	Specimen	Ultimate	Ultimate
Specimen No.	Test Temp.	Width (in)	Length (in)	Load (lbf)	Stress (psi)
11T300C-1	300°F	2.0	2.0	3500	875.0
11T300C-2	300°F	2.0	2.0	2825	706.3
11T300C-3	300°F	2.0	2.0	2985	746.3
Average					776

Table B.3-5. Flatwise Tensile Test Data for Cycled 8009/XEA 9674

Adherends: SiCp/8009 Al., Flatwise Tensile Test Data				Contract NAS1-18560	
Core: Titanium, 3/8 in square cell, corrugated cell wall.					
Adhesive: Dexter Hysol XEA 9674 BMI/BASF X268-9 Primer					
Surface Prep.: Phosphoric Acid Anodize per BAC 5555				Final report Table II.	
SiCp = silicon carbide particulate.					
Thermal Cycle: -67°F to 300°F				Averages, Figure 4.2-2	
(C = cycled)					
		Specimen	Specimen	Ultimate	Ultimate
Specimen No.	Test Temp.	Width (in)	Length (in)	Load (lbf)	Stress (psi)
31T72C-1	72°F	2.0	2.0	3740	935.0
31T72C-2	72°F	2.0	2.0	3100	775.0
31T72C-3	72°F	2.0	2.0	3250	812.5
Average					841
		Specimen	Specimen	Ultimate	Ultimate
Specimen No.	Test Temp.	Width (in)	Length (in)	Load (lbf)	Stress (psi)
31T300C-1	300°F	2.0	2.0	3020	755.0
31T300C-1	300°F	2.0	2.0	3075	768.8
31T300C-1	300°F	2.0	2.0	2875	718.8
Average					748
Adherends: Weldalite, Flatwise Tensile Test Data				Contract NAS1-18560	
Core: Titanium, 3/8 in square cell, corrugated cell wall.					
3M AF191 Epoxy/BMS 5-89, Type I, Grade A Primer					
Surface Prep.: Phosphoric Acid Anodize per BAC 5555				Final report Table II.	
Thermal Cycle: -67°F to 300°F				Averages, Figure 4.2-3	
(C = cycled)					
		Specimen	Specimen	Ultimate	Ultimate
Specimen No.	Test Temp.	Width (in)	Length (in)	Load (lbf)	Stress (psi)
24T72C-1	72°F	2.0	2.0	2725	681.3
24T72C-2	72°F	2.0	2.0	3375	843.8
24T72C-3	72°F	2.0	2.0	3350	837.5
Average					788
		Specimen	Specimen	Ultimate	Ultimate
Specimen No.	Test Temp.	Width (in)	Length (in)	Load (lbf)	Stress (psi)
24T275C-1	275°F	2.0	2.0	1650	412.5
24T275C-2	275°F	2.0	2.0	1750	437.5
24T275C-3	275°F	2.0	2.0	1600	400.0
Average					417

Table B.3-7. Flatwise Tensile Test Data for Cycled SiCp/8009/XEA 9674 and Weldalite/AF 191

Appendix B.4 Edgewise Compression Test Data

BOEING MATERIALS TECHNOLOGY
MECHANICAL PROPERTIES LABORATORY

BMT WORK REQUEST TITLE: *HIGH TEMP Al ALLOY EDGEWISE COMP TESTS*

BMT WORK REQUEST NO: *92-03098*

DATE: *September 17, 1992*

REQUESTOR: *Anthony Falcone, 9-5571, 73-09*

SPECIFICATION: *MIL-STD-401B*

SPECIMENS: *Forty three edgewise compression specimens fabricated of various aluminum alloy face sheets bonded together with various adhesives to a metal honeycomb core.*

EQUIPMENT: *1) MTS 50 KIP Servohydraulic Load Frame (440020, certified until 9-25-92; & 30-064640, certified until 2-9-93).*
2) Hewlett Packard X-Y Axis Autographic Chart Recorders (30-064645, certified until 11-5-92; & 30-073760, certified until 1-8-93).
3) Edgewise Compression Test Fixture.
4) MTS 1.00" Extensometer (1X-483873, certified for use at room temperature until 12-19-92.)

OBJECTIVE: *To ascertain compression strength and mode of failure of submitted specimens.*

PROCEDURE: *The specimens were compression loaded to failure at a displacement rate of 0.020 inch/min. on a 50 KIP load frame. Load vs. stroke and, or, deflection curves were recorded on an X-Y recorder. Testing was performed at room temperature, 275F, and 300F.*

RESULTS & ANALYSIS: *See attachments. Load deflection charts are available from BMT Work Request File.*

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EDGEWISE COMPRESSION TEST DATA BASED ON FACESHEET AREA FOR BMT WORK REQUEST NUMBER 9203098 14-SEP-92

SPECIMEN ID EW-C	TEMP (F)	DIMENSIONS GROSS THICK (IN)	SHEET THICK (IN)	WIDTH (IN)	LOAD ULT (KIP)	STRESS SHEET ULT (KSI)	COMMENTS
8009 Al + XEA 9674 BMI ADHESIVE - UNCYCLED							
11C72-1	75	1.1820	0.1860	3.0000	40.830	73.172	_/1,_/2
11C72-2	75	1.1820	0.1860	3.0000	39.676	71.104	_/1,_/2
11C72-3	75	1.1820	0.1860	2.9960	39.620	71.099	_/1,_/2
average						71.792	
standard deviation						1.1954	
correlation value Cv %						1.665	
WELDALITE + AF 191 EPOXY - UNCYCLED							
24C72-1	75	1.1650	0.1740	2.9950	44.610	85.601	_/1,_/2
24C72-2	75	1.1660	0.1740	2.9920	45.441	87.284	_/1,_/2
24C72-3	75	1.1620	0.1740	2.9840	43.300	83.395	_/1,_/2
average						85.427	
standard deviation						1.9506	
correlation value Cv %						2.283	
8009/SiCp/11p + XEA 9674 BMI ADHESIVE - UNCYCLED							
31C72-1	75	1.1530	0.1600	3.0720	32.560	66.243	_/1,_/2
31C72-2	75	1.1580	0.1600	3.0600	33.050	67.504	_/1,_/2
31C72-3	75	1.1540	0.1600	3.0540	33.520	68.599	_/2,_/3
average						67.449	
standard deviation						1.1785	
correlation value Cv %						1.747	
8090/SiCp/20wp + AF 191 EPOXY ADHESIVE - UNCYCLED							
44C72-1	75	1.1570	0.1600	2.9750	32.106	67.449	_/1,_/2
44C72-2	75	1.1570	0.1600	2.9600	29.660	62.627	_/1,_/2
44C72-3	75	1.1600	0.1600	2.9870	29.980	62.730	_/1,_/2
average						64.269	
standard deviation						2.7550	
correlation value Cv %						4.287	

COMMENTS:
_/1 - SOME CORE ADHESIVE FAILURE
_/2 - COLUMN BUCKLING AND SHEAR
_/3 - SEPARATION OF ONE OR BOTH FACE SHEETS FROM CORE
_/5 - FACE SHEET FRACTURE
_/6 - PRIOR TO TEST SOME CORE CELL WALLS WERE NOTICABLY NONPERPENDICULAR TO THE FACE SHEET SURFACES

EDGEWISE COMPRESSION TEST DATA BASED ON FACESHEET AREA FOR BMT WORK REQUEST NUMBER 9203098 14-SEP-92

SPECIMEN ID EW-C	TEMP (F)	DIMENSIONS GROSS THICK (IN)	SHEET THICK (IN)	WIDTH (IN)	LOAD ULT (KIP)	STRESS SHEET ULT (KSI)	COMMENTS
WELDALITE + AF 191 EPOXY - UNCYCLED							
24C275-1	275	1.1660	0.1740	3.0020	39.930	76.443	_/1,_/2
24C275-2	275	1.1680	0.1740	2.9980	39.970	76.622	_/1,_/2
24C275-3	275	1.1660	0.1740	3.0070	40.220	76.870	_/1,_/2
average						76.645	
standard deviation						0.2145	
correlation value Cv %						0.280	
8090/SiCp/20wp + AF 191 EPOXY ADHESIVE - UNCYCLED							
44C275-1	275	1.1600	0.1600	2.9890	25.040	52.359	_/1,_/2
44C275-2	275	1.1540	0.1600	2.9750	23.030	48.382	_/1,_/2
44C275-3	275	1.1610	0.1600	2.9930	26.520	55.379	_/1,_/2
average						52.040	
standard deviation						3.5093	
correlation value Cv %						6.743	
8009 Al + XEA 9674 BMI ADHESIVE - UNCYCLED							
11C300-1	300	1.1820	0.1860	2.9850	31.640	56.987	_/1,_/2
11C300-2	300	1.1820	0.1860	2.9830	32.120	57.891	_/1,_/2
11C300-3	300	1.1820	0.1860	3.0070	32.810	58.662	_/1,_/2
average						57.847	
standard deviation						0.8383	
correlation value Cv %						1.449	
8009/SiCp/11p + XEA 9674 BMI ADHESIVE - UNCYCLED							
31C300-1	300	1.1620	0.1600	3.0550	0.000	0.000	_/7
31C300-2	300	1.1500	0.1600	3.0490	28.340	58.093	_/1,_/2,_/6
31C300-3	300	1.1480	0.1600	3.0550	27.350	55.953	_/1,_/2,_/6
average						57.023	
standard deviation						1.5128	
correlation value Cv %						2.653	

COMMENTS:

_/1 - SOME CORE ADHESIVE FAILURE
_/2 - COLUMN BUCKLING AND SHEAR
_/3 - SEPARATION OF ONE OR BOTH FACE SHEETS FROM CORE
_/5 - FACE SHEET FRACTURE
_/6 - PRIOR TO TEST SOME CORE CELL WALLS WERE NOTICABLY NONPERPENDICULAR TO THE FACE SHEET SURFACES
_/7 - MISSING, PERHAPS REMOVED DUE TO POOR PRETEST CONDITION

EDGEWISE COMPRESSION TEST DATA BASED ON FACESHEET AREA FOR BMT WORK REQUEST NUMBER 9203098 14-SEP-92

SPECIMEN ID EW-C	TEMP (F)	DIMENSIONS GROSS THICK (IN)	SHEET THICK (IN)	WIDTH (IN)	LOAD ULT (KIP)	STRESS SHEET ULT (KSI)	COMMENTS
8009 Al + XEA 9674 BMI ADHESIVE - CYCLED							
11C72C-1	75	0.0000	0.1860	2.9450	39.730	72.530	_/1,_/2,_/8
11C72C-2	75	0.0000	0.1860	2.9930	40.710	73.128	_/1,_/2,_/8
11C72C-3	75	0.0000	0.1860	2.9740	38.920	70.359	_/1,_/2,_/8
average						72.006	
standard deviation						1.4571	
correlation value Cv %						2.024	
WELDALITE + AF 191 EPOXY - CYCLED							
24C72C-1	75	1.1680	0.1740	2.9250	45.260	88.928	_/1,_/2
24C72C-2	75	1.1680	0.1740	2.9690	45.150	87.397	_/1,_/2
24C72C-3	75	1.1660	0.1740	2.9300	44.510	87.305	_/1,_/2,_/3
average						87.877	
standard deviation						0.9116	
correlation value Cv %						1.037	
8009/SiCp/11p + XEA 9674 BMI ADHESIVE - CYCLED							
31C72C-1	75	1.1460	0.1600	2.9980	33.500	69.838	_/1,_/2
31C72C-2	75	1.1520	0.1600	2.9910	34.100	71.255	_/1,_/2
average						70.547	
standard deviation						1.0021	
correlation value Cv %						1.420	
8090/SiCp/20wp + AF 191 EPOXY ADHESIVE - CYCLED							
44C72C-1	75	1.1590	0.1600	2.9150	35.620	76.372	_/1,_/2,_/5
44C72C-2	75	1.1570	0.1600	2.9550	36.850	77.940	_/1,_/2
44C72C-3	75	1.1570	0.1600	2.9300	34.220	72.995	_/1,_/2,_/5
average						75.769	
standard deviation						2.5271	
correlation value Cv %						3.335	

COMMENTS:

_/1 - SOME CORE ADHESIVE FAILURE
_/2 - COLUMN BUCKLING AND SHEAR
_/3 - SEPARATION OF ONE OR BOTH FACE SHEETS FROM CORE
_/5 - FACE SHEET FRACTURE
_/6 - PRIOR TO TEST SOME CORE CELL WALLS WERE NOTICABLY NONPERPENDICULAR TO THE FACE SHEET SURFACES
_/7 - MISSING, PERHAPS REMOVED DUE TO POOR PRETEST CONDITION
_/8 - NEGLECTED TO MEASURE GROSS THICKNESS PRIOR TO TEST

EDGEWISE COMPRESSION TEST DATA BASED ON FACESHEET AREA FOR BMT WORK REQUEST NUMBER 9203098 14-SEP-92

SPECIMEN ID EW-C	TEMP (F)	DIMENSIONS GROSS THICK (IN)	SHEET THICK (IN)	WIDTH (IN)	LOAD ULT (KIP)	STRESS SHEET ULT (KSI)	COMMENTS
8009 Al + XEA 9674 BMI ADHESIVE - CYCLED							
11C300C-1	300	1.1820	0.1860	2.9820	32.620	58.812	_/1,_/2
11C300C-2	300	1.1820	0.1860	2.9700	33.590	60.805	_/1,_/2,_/3
11C300C-3	300	1.1820	0.1860	2.9390	31.350	57.349	_/1,_/2
average						58.989	
standard deviation						1.7349	
correlation value Cv %						2.941	
WELDALITE + AF 191 EPOXY - CYCLED							
24C275C-1	275	1.1670	0.1740	2.9540	40.970	79.709	_/1,_/2
24C275C-2	275	1.1660	0.1740	2.9660	41.020	79.483	_/1,_/2
24C275C-3	275	1.1650	0.1740	2.9680	40.120	77.687	_/1,_/2
average						78.960	
standard deviation						1.1080	
correlation value Cv %						1.403	
8009/SiCp/11p + XEA 9674 BMI ADHESIVE - CYCLED							
31C300C-1	300	1.1520	0.1600	2.9880	20.150	42.148	_/1,_/2,_/6
31C300C-2	300	1.1530	0.1600	2.9930	25.910	54.105	_/1,_/2,_/6
average						48.127	
standard deviation						8.4553	
correlation value Cv %						17.569	

COMMENTS:

_/1 - SOME CORE ADHESIVE FAILURE
_/2 - COLUMN BUCKLING AND SHEAR
_/3 - SEPARATION OF ONE OR BOTH FACE SHEETS FROM CORE
_/5 - FACE SHEET FRACTURE
_/6 - PRIOR TO TEST SOME CORE CELL WALLS WERE NOTICABLY NONPERPENDICULAR TO THE FACE SHEET SURFACES
_/7 - MISSING, PERHAPS REMOVED DUE TO POOR PRETEST CONDITION

Adherends: 8009 Aluminum Double Cantilevered Beam - Fracture Toughness Test Data							Contract NAS1-18560	
Adhesive: Dexter Hysol XEA 9674 BMI/BASF X268-9 Primer								
Surface Prep.: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table II.			
Thermal Cycle: None			E1(7075) = 10.3 Msi		Averages plotted in Figure 4.3-2			
			E2(8009) = 12.6 Msi					
Specimen No.	Test Temp.	Adherend Thickness	Backup Plate Thickness	Specimen Width (b)	Crack Opening Displacement	Initial Crack Length (ac1)	Arrest Crack Length (aa1)	
Data:	(°F)	(in)	(in)	(in)	(Y1) (in)	(in)	(in)	Failure Surface
11DCB-67U-1	'-67°F	0.094	0.508	0.997	0.042	3.50	3.53	95% adhesive
11DCB-67U-2	'-67°F	0.094	0.509	0.998	0.033	2.20	2.40	50% cohesive
11DCB-67U-3	'-67°F	0.094	0.508	0.996	0.038	2.05	2.30	80% cohesive
Specimen No.	Test Temp.	Crack Opening Displacement	Initial Crack Length (ac2)	Arrest Crack Length (aa2)	Crack Opening Displacement	Initial Crack Length (ac3)	Arrest Crack Length (aa3)	
Data:	(°F)	(Y2) (in)	(in)	(in)	(Y3) (in)	(in)	(in)	
11DCB-67U-1	'-67°F	0.047	4.06	4.19	0.058	4.79	4.79	No growth
11DCB-67U-2	'-67°F	0.034	2.62	2.82	0.049	3.17	3.36	
11DCB-67U-3	'-67°F	0.039	2.48	2.73	0.043	3.04	3.25	
Specimen No.	Test Temp.	Equivalent Modulus (Eq)	Fracture Toughness (Glc1)	Fracture Toughness (Gla1)	Fracture Toughness (Glc2)	Fracture Toughness (Gla2)	Fracture Toughness (Glc3)	Fracture Toughness (Gla3)
Calculations:	(°F)	(Msi)	(lb/in)	(lb/in)	(lb/in)	(lb/in)	(lb/in)	(lb/in)
11DCB-67U-1	'-67°F	1.07E+07	3.34	3.24	2.45	2.19	2.04	2.04
11DCB-67U-2	'-67°F	1.07E+07	10.28	7.68	1.15	4.70	6.48	5.28
11DCB-67U-3	'-67°F	1.07E+07	17.15	11.71	1.69	6.89	5.76	4.55
Average		N/A	6.8	5.5	1.8	4.6	4.8	4.0
							Ave. Critical Fracture Toughness Glc (lb/in)	Ave. Arrest Fracture Toughness Gla (lb/in)
			Dropped 17.15 and 11.71 from averages.					
							2.6	2.5
							6.0	5.9
							8.2	7.7
							4.4	4.7
						Std. Deviation:	3.13	2.05

Table B.5-1 Double Cantilevered Beam Fracture Toughness Test Results for 8009/XEA 9674 BMI

Adherends: 8009 Aluminum Double Cantilevered Beam - Fracture Toughness Test Data							Contract NAS1-18560	
Adhesive: Dexter Hysol XEA 9674 BMI/BASF X268-9 Primer								
Surface Prep.: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table II.			
Thermal Cycle: None			E1(7075) = 10.3 Msi		Averages plotted in Figure 4.3-2.			
			E2(8009) = 12.6 Msi					
		Adherend	Backup Plate	Specimen	Crack Opening	Initial Crack	Arrest Crack	
Specimen No.	Test Temp.	Thickness	Thickness	Width (b)	Displacement	Length (ac1)	Length (aa1)	
Data:	(°F)	(in)	(in)	(in)	(Y1) (in)	(in)	(in)	Failure Surface
11DCB72U-1	72°F	0.094	0.5085	0.971	0.098	6.1406	6.3125	100% adhesive
11DCB72U-2	72°F	0.094	0.5085	0.978	0.103	6.8125	7.7813	100% adhesive
11DCB72U-3	72°F	0.094	0.5080	0.970	0.102	6.4531	8.5000	100% adhesive
		Crack Opening	Initial Crack	Arrest Crack	Crack Opening	Initial Crack	Arrest Crack	
Specimen No.	Test Temp.	Displacement	Length (ac2)	Length (aa2)	Displacement	Length (ac3)	Length (aa3)	
Data:	(°F)	(Y2) (in)	(in)	(in)	(Y3) (in)	(in)	(in)	
11DCB72U-1	72°F	0.200	Not Measured	10.60938	0.300	Not Measured	13.0000	
11DCB72U-2	72°F	0.200	Not Measured	10.82813	0.300	Not Measured	13.0000	
11DCB72U-3	72°F	0.200	Not Measured	10.70313	0.300	Not Measured	13.0000	
		Equivalent	Fracture	Fracture	Fracture	Fracture	Fracture	Fracture
	Test Temp.	Modulus (Eq)	Toughness (Glc1)	Toughness (Gla1)	Toughness (Glc2)	Toughness (Gla2)	Toughness (Glc3)	Toughness (Gla3)
Calculations:	(°F)	(Msi)	(lb/in)	(lb/in)	(lb/in)	(lb/in)	(lb/in)	(lb/in)
11DCB72U-1	72°F	1.07E+07	2.32	2.09		1.20		1.23
11DCB72U-2	72°F	1.07E+07	1.73	1.05		1.11		1.23
11DCB72U-3	72°F	1.07E+07	2.08	0.73		1.16		1.23
Average			2.04	0.89		1.16		1.23
			Dropped 2.09 from averages.				Ave. Critical	Ave. Arrest
							Fracture	Fracture
							Toughness	Toughness
							Glc (lb/in)	Gla (lb/in)
							2.3	1.5
							1.7	1.1
							2.1	1.0
							2.0	1.1
						Std. Deviation:	N/A	0.17

Table B.5-2 Double Cantilevered Beam Fracture Toughness Test Results for 8009/XEA 9674 BMI

Adherends: 8009 Aluminum Double Cantilevered Beam - Fracture Toughness Test Data							Contract NAS1-18560	
Adhesive: Dexter Hysol XEA 9674 BMI/BASF X268-9 Primer								
Surface Prep.: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table II.			
Thermal Cycle: 50 cycles			E1(7075) = 10.3 Msi		Averages plotted in Figure 4.3-2.			
			E2(8009) = 12.6 Msi					
		Adherend	Backup Plate	Specimen	Crack Opening	Initial Crack	Arrest Crack	
Specimen No.	Test Temp.	Thickness	Thickness	Width (b)	Displacement	Length (ac1)	Length (aa1)	
Data:	(°F)	(in)	(in)	(in)	(Y1) (in)	(in)	(in)	Failure Surface
11DCB-67C-1	'-67°F	0.094	0.509	0.970	0.012	1.46	1.73	60% cohesive
11DCB-67C-2	'-67°F	0.094	0.509	0.970	0.015	1.92	2.24	90% adhesive
11DCB-67C-3	'-67°F	0.094	0.508	0.977	0.019	2.40	2.50	95% adhesive
		Crack Opening	Initial Crack	Arrest Crack	Crack Opening	Initial Crack	Arrest Crack	
Specimen No.	Test Temp.	Displacement	Length (ac2)	Length (aa2)	Displacement	Length (ac3)	Length (aa3)	
Data:	(°F)	(Y2) (in)	(in)	(in)	(Y3) (in)	(in)	(in)	
11DCB-67C-1	'-67°F	0.025	2.86	3.31	0.040	3.77	4.06	
11DCB-67C-2	'-67°F	0.026	2.86	3.02	0.037	3.50	3.67	
11DCB-67C-3	'-67°F	0.034	3.47	3.66	0.046	4.34	4.51	
		Equivalent	Fracture	Fracture	Fracture	Fracture	Fracture	Fracture
Specimen No.	Test Temp.	Modulus (Eq)	Toughness (Glc1)	Toughness (Gla1)	Toughness (Glc2)	Toughness (Gla2)	Toughness (Glc3)	Toughness (Gla3)
Calculations:	(°F)	(Msi)	(lb/in)	(lb/in)	(lb/in)	(lb/in)	(lb/in)	(lb/in)
11DCB-67C-1	'-67°F	1.07E+07	5.02	2.97	2.42	1.45	2.33	1.78
11DCB-67C-2	'-67°F	1.07E+07	3.32	2.00	2.62	2.16	2.60	2.20
11DCB-67C-3	'-67°F	1.07E+07	2.54	2.21	2.26	1.87	1.84	1.60
Average		N/A	2.93	2.10	2.43	1.83	2.26	1.86
							Ave. Critical	Ave. Arrest
			Dropped 5.02 from averages.				Fracture	Fracture
							Toughness	Toughness
				Dropped 2.97 from averages.			Glc (lb/in)	Gla (lb/in)
							3.3	2.1
							2.8	2.1
							2.2	1.9
							2.5	1.9
						Std. Deviation:	0.42	0.29

Table B.5-3 Double Cantilevered Beam Fracture Toughness Test Results for 8009/XEA 9674 BMI

Adherends: 8009 Aluminum Double Cantilevered Beam - Fracture Toughness Test Data							Contract NAS1-18560	
Adhesive: Dexter Hysol XEA 9674 BMI/BASF X268-9 Primer								
Surface Prep.: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table II.			
Thermal Cycle:	50 cycles		E1(7075) = 10.3 Msi		Averages plotted in Figure 4.3-2.			
			E2(8009) = 12.6 Msi					
Specimen No.	Test Temp.	Adherend Thickness	Backup Plate Thickness	Specimen Width (b)	Crack Opening Displacement	Initial Crack Length (ac1)	Arrest Crack Length (aa1)	
Data:	(°F)	(in)	(in)	(in)	(Y1) (in)	(in)	(in)	Failure Surface
11DCB72C-1	72°F	0.094	0.509	0.969	0.025	2.64	3.08	50% cohesive
11DCB72C-2	72°F	0.094	0.509	0.969	0.015	1.65	1.99	80% cohesive
11DCB72C-3	72°F	0.094	0.508	0.973	0.015	1.75	2.26	100% adhesive
Specimen No.	Test Temp.	Crack Opening Displacement	Initial Crack Length (ac2)	Arrest Crack Length (aa2)	Crack Opening Displacement	Initial Crack Length (ac3)	Arrest Crack Length (aa3)	
Data:	(°F)	(Y2) (in)	(in)	(in)	(Y3) (in)	(in)	(in)	
11DCB72C-1	72°F	0.042	4.10	4.52	0.056	4.68	5.19	
11DCB72C-2	72°F	0.033	3.00	3.49	0.044	3.85	4.20	
11DCB72C-3	72°F	0.038	2.99	3.81	0.051	4.12	4.73	
	Test Temp.	Equivalent Modulus (Eq)	Fracture Toughness (Glc1)	Fracture Toughness (Gla1)	Fracture Toughness (Glc2)	Fracture Toughness (Gla2)	Fracture Toughness (Glc3)	Fracture Toughness (Gla3)
Calculations:	(°F)	(Msi)	(lb/in)	(lb/in)	(lb/in)	(lb/in)	(lb/in)	(lb/in)
11DCB72C-1	72°F	1.07E+07	3.19	1.87	1.90	1.33	2.08	1.42
11DCB72C-2	72°F	1.07E+07	5.38	2.96	3.57	2.09	2.62	1.91
11DCB72C-3	72°F	1.07E+07	4.45	1.93	4.77	2.02	2.74	1.65
Average			4.34	1.90	3.41	1.81	2.48	1.66
							Ave. Critical Fracture Toughness Glc (lb/in)	Ave. Arrest Fracture Toughness Gla (lb/in)
				Dropped 2.96 from averages.				
							2.4	1.5
							3.9	2.3
							4.0	1.9
							3.4	1.8
						Std. Deviation:	1.23	0.28

Table B.5-4 Double Cantilevered Beam Fracture Toughness Test Results for 8009/XEA 9674 BMI

Adherends: Weldalite Aluminum Double Cantilevered Beam - Fracture Toughness Test Data							Contract NAS1-18560	
Adhesive: 3M AF 191 Epoxy/EC 3960 primer (BMS 5-89, Type 1, Grade A)								
Surface Prep.: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table II.			
Thermal Cycle: None			E1(7075) = 10.3 Msi		Averages plotted in Figure 4.3-3.			
			E2(Weldalite) = 11.3 Msi					
		Adherend	Backup Plate	Specimen	Crack Opening	Initial Crack	Arrest Crack	
Specimen No.	Test Temp.	Thickness	Thickness	Width (b)	Displacement	Length (ac1)	Length (aa1)	
Data:	(°F)	(in)	(in)	(in)	(Y1) (in)	(in)	(in)	Failure Surfaces
24DCB-67U-1	'-67°F	0.094	0.509	0.971	0.037	1.58	1.69	100% cohesive
24DCB-67U-2	'-67°F	0.094	0.507	0.972	0.011	1.08	1.08	100% cohesive
24DCB-67U-3	'-67°F	0.094	0.509	0.971	0.013	1.22	1.22	100% cohesive
		Crack Opening	Initial Crack	Arrest Crack	Crack Opening	Initial Crack	Arrest Crack	
Specimen No.	Test Temp.	Displacement	Length (ac2)	Length (aa2)	Displacement	Length (ac3)	Length (aa3)	
Data:	(°F)	(Y2) (in)	(in)	(in)	(Y3) (in)	(in)	(in)	
24DCB-67U-1	'-67°F	*Not measure	*Not measured.	*Not measured.	*Not measured.	*Not measured.	*Not measured.	
24DCB-67U-2	'-67°F	*Not measure	*Not measured.	*Not measured.	*Not measured.	*Not measured.	*Not measured.	
24DCB-67U-3	'-67°F	0.023	1.87	1.88	0.037	2.57	2.57	Some disbond.
		Equivalent	Fracture	Fracture	Fracture	Fracture	Fracture	Fracture
Specimen No.	Test Temp.	Modulus (Eq)	Toughness (GIc1)	Toughness (GIa1)	Toughness (GIc2)	Toughness (GIa2)	Toughness (GIc3)	Toughness (GIa3)
Calculations:	(°F)	(Msi)	(lb/in)	(lb/in)	(lb/in)	(lb/in)	(lb/in)	(lb/in)
24DCB-67U-1	'-67°F	1.05E+07	36.73	29.53				
24DCB-67U-2	'-67°F	1.05E+07	9.90	9.74				
24DCB-67U-3	'-67°F	1.05E+07	9.84	9.71	8.34	8.20	7.51	7.51
Average		N/A	9.9	16.3	8.3	8.2	7.5	7.5
*Due to separation of adherends from backup plates.								
							Ave. Critical	Ave. Arrest
							Fracture	Fracture
	Adherend separation (disbond) observed on all specimens.						Toughness	Toughness
							GIc (lb/in)	GIa (lb/in)
			Dropped 36.73 from averages.				36.7	29.5
							9.9	9.7
							8.6	8.5
							8.6	10.7
						Std. Deviation:	1.17	9.33

Table B.5-5 Double Cantilevered Beam Fracture Toughness Test Results for Weldalite/AF 191 Epoxy

Adherends: Weldalite Aluminum Double Cantilevered Beam - Fracture Toughness Test Data							Contract NAS1-18560	
Adhesive: 3M AF 191 Epoxy/EC 3960 primer (BMS 5-89, Type 1, Grade A)								
Surface Prep.: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table II.			
Thermal Cycle: None			E1(7075) = 10.3 Msi		Averages plotted in Figure 4.3-3			
			E2(Weldlite) = 11.3 Msi					
		Adherend	Backup Plate	Specimen	Crack Opening	Initial Crack	Arrest Crack	
Specimen No.	Test Temp.	Thickness	Thickness	Width (b)	Displacement	Length (ac1)	Length (aa1)	
Data:	(°F)	(in)	(in)	(in)	(Y1) (in)	(in)	(in)	Failure Surfaces
24DCB72U-1	72°F	0.094	0.5090	0.973	0.025	1.92	1.93	100% cohesive
24DCB72U-2	72°F	0.094	0.5080	0.973	0.019	1.57	1.57	100% cohesive
		Crack Opening	Initial Crack	Arrest Crack	Crack Opening	Initial Crack	Arrest Crack	
Specimen No.	Test Temp.	Displacement	Length (ac2)	Length (aa2)	Displacement	Length (ac3)	Length (aa3)	
Data:	(°F)	(Y2) (in)	(in)	(in)	(Y3) (in)	(in)	(in)	
24DCB72U-1	72°F	0.040	2.52	2.52	0.060	3.21	3.21	Slight disbond.
24DCB72U-2	72°F	0.036	2.34	2.34	0.057	3.19	3.19	No disbond.
		Equivalent	Fracture	Fracture	Fracture	Fracture	Fracture	Fracture
	Test Temp.	Modulus (Eq)	Toughness (Glc1)	Toughness (Gla1)	Toughness (Glc2)	Toughness (Gla2)	Toughness (Glc3)	Toughness (Gla3)
Calculations:	(°F)	(Msi)	(lb/in)	(lb/in)	(lb/in)	(lb/in)	(lb/in)	(lb/in)
24DCB72U-1	72°F	1.05E+07	9.05	8.90	9.39	9.39	9.12	9.12
24DCB72U-2	72°F	1.05E+07	9.88	9.88	9.77	9.77	8.42	8.42
Average		N/A	9.46	9.39	9.58	9.58	8.77	8.77
	Disbond refers to separation of an adherend from the backup plates.						Ave. Critical	Ave. Arrest
							Fracture	Fracture
							Toughness	Toughness
							Glc (lb/in)	Gla (lb/in)
							(lb/in)	(lb/in)
							9.2	9.1
							9.4	9.4
							9.3	9.2
						Std. Deviation:	0.53	0.55

Table B.5-6 Double Cantilevered Beam Fracture Toughness Test Results for Weldalite/AF 191 Epoxy

Adherends: Weldalite Aluminum Double Cantilevered Beam - Fracture Toughness Test Data							Contract NAS1-18560	
Adhesive: 3M AF 191 Epoxy/EC 3960 primer (BMS 5-89, Type 1, Grade A)								
Surface Prep.: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table II.			
Thermal Cycle: 50 cycles			E1(7075) = 10.3 Msi		Averages plotted in Figure 4.3-3.			
			E2Weldalite) = 11.3 Msi					
		Adherend	Backup Plate	Specimen	Crack Opening	Initial Crack	Arrest Crack	
Specimen No.	Test Temp.	Thickness	Thickness	Width (b)	Displacement	Length (ac1)	Length (aa1)	
Data:	(°F)	(in)	(in)	(in)	(Y1) (in)	(in)	(in)	Failure Surfaces
24DCB-67C-1	'-67°F	0.094	0.509	0.969	0.016	1.33	1.33	70% cohesive
24DCB-67C-2	'-67°F	0.094	0.509	0.969	0.016	1.30	1.30	100% cohesive
24DCB-67C-3	'-67°F	0.094	0.509	0.967	0.048	2.76	2.76	90% cohesive
		Crack Opening	Initial Crack	Arrest Crack	Crack Opening	Initial Crack	Arrest Crack	
Specimen No.	Test Temp.	Displacement	Length (ac2)	Length (aa2)	Displacement	Length (ac3)	Length (aa3)	
Data:	(°F)	(Y2) (in)	(in)	(in)	(Y3) (in)	(in)	(in)	
24DCB-67C-1	'-67°F	0.051	1.87	1.87	0.070	2.19	2.19	Large disbond
24DCB-67C-2	'-67°F	0.028	2.04	2.04	0.042	2.81	2.81	Disbond
24DCB-67C-3	'-67°F	*Not measured	*Not measured	*Not measured	*Not measured	*Not measured	*Not measured	Large disbond
		Equivalent	Fracture	Fracture	Fracture	Fracture	Fracture	Fracture
Specimen No.	Test Temp.	Modulus (Eq)	Toughness (Glc1)	Toughness (Gla1)	Toughness (Glc2)	Toughness (Gla2)	Toughness (Glc3)	Toughness (Gla3)
Calculations:	(°F)	(Msi)	(lb/in)	(lb/in)	(lb/in)	(lb/in)	(lb/in)	(lb/in)
24DCB-67C-1	'-67°F	1.05E+07	11.57	11.57	40.99	40.99	46.08	46.08
24DCB-67C-2	'-67°F	1.05E+07	12.38	12.38	9.32	9.32	7.12	7.12
24DCB-67C-3	'-67°F	1.05E+07	9.89	9.89				
Average			11.3	11.3	9.3	9.3	7.1	7.1
*Adherends began to separate from backup plates.							Ave. Critical	Ave. Arrest
							Fracture	Fracture
	Disbond refers to separation of an adherend from the backup plates.						Toughness	Toughness
							Glc (lb/in)	Gla (lb/in)
Specimen no. 1 data from second and third crack jumps excluded from averages due to formation of disbond.							32.9	32.9
							9.6	9.6
							9.9	9.9
							9.2	9.2
						Std. Deviation:	2.06	2.06

Table B.5-7 Double Cantilevered Beam Fracture Toughness Test Results for Weldalite/AF 191 Epoxy

Adherends: Weldalite Aluminum Double Cantilevered Beam - Fracture Toughness Test Data							Contract NAS1-18560	
Adhesive: 3M AF 191 Epoxy/EC 3960 primer (BMS 5-89, Type 1, Grade A)								
Surface Prep.: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table II.			
Thermal Cycle: 50 cycles			E1(7075) = 10.3 Msi		Averages not plotted. Data invalid due to adherend-backup plate dis			
			E2 (Weldalite) = 11.3 Msi					
		Adherend	Backup Plate	Specimen	Crack Opening	Initial Crack	Arrest Crack	
Specimen No.	Test Temp.	Thickness	Thickness	Width (b)	Displacement	Length (ac1)	Length (aa1)	
Data:	(°F)	(in)	(in)	(in)	(Y1) (in)	(in)	(in)	Failure Surface
24DCB72C-1	72°F	0.094	0.5080	0.971	0.080	1.73	1.80	100% cohesive
		Crack Opening	Initial Crack	Arrest Crack	Crack Opening	Initial Crack	Arrest Crack	
Specimen No.	Test Temp.	Displacement	Length (ac2)	Length (aa2)	Displacement	Length (ac3)	Length (aa3)	
Data:	(°F)	(Y2) (in)	(in)	(in)	(Y3) (in)	(in)	(in)	
24DCB72C-1	72°F	0.200	*Not measured	*Not measured	*Not measured	*Not measured	*Not measured	Large disbond
		Equivalent	Fracture	Fracture	Fracture	Fracture	Fracture	Fracture
	Test Temp.	Modulus (Eq)	Toughness (Glc1)	Toughness (Gla1)	Toughness (Glc2)	Toughness (Gla2)	Toughness (Glc3)	Toughness (Gla3)
Calculations:	(°F)	(Msi)	(lb/in)	(lb/in)	(lb/in)	(lb/in)	(lb/in)	(lb/in)
24DCB72C-1	72°F	1.05E+07	128.82	113.57				
*Adherends began to separate from backup plates.								
	Disbond refers to separation of an adherend from the backup plates.							

Table B.5-8 Double Cantilevered Beam Fracture Toughness Test Results for Weldalite/AF 191 Epoxy

C-2

Appendix B.6 End Notch Flexure (G_{IIc}) Test Data

BOEING MATERIALS TECHNOLOGY
MECHANICAL PROPERTIES LABORATORY

BMT WORK REQUEST TITLE: 8009/XEA9674 END NOTCHED FLEXURE

BMT WORK REQUEST NO: 92-03098

DATE: September 17, 1992

REQUESTOR: Anthony Falcone, 9-5571, 73-09

SPECIFICATION: BMS 8-276

SPECIMENS: Twelve each end notch flexure specimens fabricated of 8009 Aluminum bonded with BMI adhesive.

EQUIPMENT: 1) MTS 50 KIP Servohydraulic Load Frame (30-069457, certified until 10-8-92).
2) Hewlett Packard X-Y Axis Autographic Chart Recorder (30-064646, certified until 11-13-92).

OBJECTIVE: To ascertain Mode II interlaminar fracture toughness of submitted material matrix.

PROCEDURE: The ENF specimens were precracked in mode I with the aid of a vice and a specially designed wedge. The newly generated crack front was then located and marked on side of specimen. An "a" value of 0.50" was measured from the precrack tip backward to the reaction point. The following procedure was used to generate a mode II crack jump on each specimen: the specimen was mounted on a specified three point bending fixture, with the precrack front located 0.50 inch inward from a chosen outer support, and compression loaded at a crosshead speed of 0.10 in./min. until a critical load was reached and a crack jump occurred. Loading was halted, the crack front was marked on the side of the specimen, and the applied load was removed. Actual crack propagation was measured by physically pulling apart specimen top laminates from bottom laminates and measuring the mode I crack surface length. To derive compliance, crosshead displacement from the initial loading point to the critical loading point was used. The following equation was used to calculate GIIc:

$$GIIc = \frac{9A^2 P^2 C}{2W \left[2L^3 + 3A^3 \right]}$$

Where P = critical load
W = specimen width
C = compliance
A = crack length
L = half span (1.0 in.)

Loading was performed at 0.10 in./min. on a 50 KIP MTS servohydraulic load frame and load versus stroke was recorded on an autographic X-Y chart recorder. Six each specimens were tested at room temperature and six each were tested at -67F.

Continued on next page -

RESULTS & ANALYSIS: See attachments.

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ENF – 8009/XEA9674, WR 92–03098

SPECIMEN NUMBER	WIDTH (IN.)	CRACK (IN.)	COMPLIANCE IN/LB	LOAD CRITICAL	PER JUMP GIIc in-lb/in^2	SPECIMEN avg. GIIc in-lb/in^2
11ENF72-1	0.5040	0.50	6.72E-05	274.00	4.74	
11ENF72-1	0.5040	0.50	7.08E-05	281.00	5.25	
11ENF72-1	0.5040	0.50	7.16E-05	303.00	6.18	5.39
AVERAGE				286.00	5.39	
STD.DEV				15.13	0.73	
CV %				5.29	13.50	
11ENF72-2	0.5040	0.60	7.64E-05	249.00	5.69	
11ENF72-2	0.5040	0.56	7.08E-05	240.00	4.52	
11ENF72-2	0.5040	0.62	7.56E-05	220.00	4.63	4.94
AVERAGE				236.33	4.94	
STD.DEV				14.84	0.65	
CV %				6.28	13.08	
11ENF72-3	0.5040	0.54	6.88E-05	259.00	4.86	
11ENF72-3	0.5040	0.58	7.48E-05	262.00	5.97	
11ENF72-3	0.5040	0.56	7.28E-05	270.00	5.88	5.57
AVE./GRAND AVE.				263.67	5.57	5.30
STD.DEV/GRAND STD.DEV				5.69	0.62	0.32
CV %/GRAND CV%				2.16	11.05	6.07

ENF – 8009/XEA9674, WR 92–03098

SPECIMEN NUMBER	WIDTH (IN.)	CRACK (IN.)	COMPLIANCE IN/LB	LOAD CRITICAL	PER JUMP GIIc in–lb/in^2	SPECIMEN avg. GIIc in–lb/in^2
11ENF72C–1	0.5040	0.59	7.52E–05	234.00	4.89	
11ENF72C–1	0.5040	0.59	7.32E–05	220.00	4.21	
11ENF72C–1	0.5040	0.59	7.50E–05	244.00	5.30	4.80
AVERAGE				232.67	4.80	
STD.DEV				12.06	0.55	
CV %				5.18	11.52	
11ENF72C–2	0.5050	0.51	7.16E–05	296.00	6.06	
11ENF72C–2	0.5050	0.59	7.32E–05	250.00	5.42	
11ENF72C–2	0.5050	0.56	7.08E–05	264.00	5.46	5.65
AVERAGE				270.00	5.65	
STD.DEV				23.58	0.36	
CV %				8.73	6.37	
11ENF72C–3	0.5030	0.58	7.62E–05	246.00	5.37	
11ENF72C–3	0.5030	0.56	7.12E–05	282.00	6.29	
11ENF72C–3	0.5030	0.56	6.92E–05	262.00	5.27	5.64
AVE./GRAND AVE.				263.33	5.64	5.36
STD.DEV/GRAND STD.DEV				18.04	0.56	0.49
CV %/GRAND CV%				6.85	9.91	9.19

ENF – 8009/XEA9674, WR 92–03098

SPECIMEN NUMBER	WIDTH (IN.)	CRACK (IN.)	COMPLIANCE IN/LB	LOAD CRITICAL	PER JUMP GIIc in–lb/in^2	SPECIMEN avg. GIIc in–lb/in^2
11ENF67–1	0.5030	0.52	6.16E–05	260.00	4.16	
11ENF67–1	0.5030	0.54	5.90E–05	243.00	3.68	
11ENF67–1	0.5030	0.63	7.18E–05	180.00	2.98	3.60
AVERAGE				227.67	3.60	
STD.DEV				42.15	0.60	
CV %				18.51	16.52	
11ENF67–2	0.5040	0.60	6.08E–05	200.00	2.97	
11ENF67–2	0.5040	0.57	6.80E–05	156.00	1.88	
11ENF67–2	0.5040	0.59	6.48E–05	150.00	1.73	2.19
AVERAGE				168.67	2.19	
STD.DEV				27.30	0.68	
CV %				16.19	30.85	
11ENF67–3	0.5020	0.53	6.04E–05	250.00	3.89	
11ENF67–3	0.5020	0.56	6.12E–05	185.00	2.33	
11ENF67–3	0.5020	0.54	6.72E–05	285.00	5.77	4.00
AVE./GRAND AVE.				240.00	4.00	3.26
STD.DEV/GRAND STD.DEV				50.74	1.72	2.67
CV %/GRAND CV%				21.14	43.12	81.76

ENF – 8009/XEA9674, WR 92–03098

SPECIMEN NUMBER	WIDTH (IN.)	CRACK (IN.)	COMPLIANCE IN/LB	LOAD CRITICAL	PER JUMP GIIc in–lb/in^2	SPECIMEN avg. GIIc in–lb/in^2
11ENF67C–1	0.5050	0.51	5.68E–05	279.00	4.27	
11ENF67C–1	0.5050	0.54	6.76E–05	157.00	1.75	
11ENF67C–1	0.5050	0.56	6.16E–05	87.00	0.52	2.18
AVERAGE				174.33	2.18	
STD.DEV				97.17	1.92	
CV %				55.74	87.85	
11ENF67C–2	0.5010	0.52	6.84E–05	362.00	8.99	
11ENF67C–2	0.5010	0.54	6.68E–05	230.00	3.74	
11ENF67C–2	0.5010	0.53	6.80E–05	230.00	3.71	5.48
AVERAGE				274.00	5.48	
STD.DEV				76.21	3.04	
CV %				27.81	55.44	
11ENF67C–3	0.5020	0.54	5.68E–05	177.00	1.88	
11ENF67C–3	0.5020	0.52	6.40E–05	204.00	2.67	
11ENF67C–3	0.5020	0.56	6.88E–05	160.00	1.96	2.17
AVE./GRAND AVE.				180.33	2.17	3.28
STD.DEV/GRAND STD.DEV				22.19	0.43	3.13
CV %/GRAND CV%				12.30	19.92	95.52

ENF – 8009/XEA9674, WR 92–03098

COMMENTS:

1. SUPPORT SPAN WAS 2.00" AND THE "a" VALUE WAS 0.50" AS MEASURED FROM SIDE OF SPECIMEN, – HOWEVER, DUE TO THE IMPOSSIBILITY OF DIRECT VISUAL MEASUREMENT OF THE PRECRACK FRONT THE SPECIMEN WAS SEPARATED IN ORDER TO MEASURE THE ACTUAL VALUE OF "a".

2. ADHESIVE FAILURE WAS NOTED ON ALL SPECIMENS.

3. ALL MODE II CRACK JUMPS WERE PRECEDED BY A MANUALLY INDUCED MODE I PRECRACK WITH THE EXCEPTION OF SPECIMEN 11ENF72–1 WHICH WAS TESTED IN MODE II THROUT.

4. CONCERNING THE –67F SPECIMENS, – A DWELL TIME OF 10 MINUTES WAS USED PRIOR TO INITIATION OF FIRST CRACK JUMP. ON SUBSEQUENT JUMPS THE SPECIMENS WAS REMOVED FROM THE ENVIRONMENTAL CHAMBER ONLY LONG ENOUGH TO PRECRACK AND MARK "A" LOCATION (< 1 MIN.). UPON REINTRODUCTION TO THE CHAMBER ENOUGH TIME(AT LEAST 3 MIN.) WAS ALLOWED TO REACH A STABLE –67F.

Adherends: 8009 Aluminum, Single Lap Shear Test Data					Contract NAS1-18560				
Adhesive: Dexter Hysol XEA 9674 BMI/BASF X268-9 Primer									
Surface Preparation: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table III.				
Thermal Cycle: None		IA=isothermal aging			Averages plotted in Figure 4.4-1				
(U = uncycled)		100 hrs @ 300°F							
Specimen No.	Test Temp.	Bondline	Bondline	Ultimate	Ultimate	Fracture	Overlap	Adherend A	Adherend B
		Thickness	Width	Load	Stress	Surface	(in)	(in)	(in)
100 hrs @ 300°F		(in.)	(in.)	(lbf)	(psi)				
11S67IA(100)-1	'-67°F	0.005	1.004	1820	3625	Cohesive	0.193	0.094	0.094
11S67IA(100)-2	'-67°F	0.005	0.998	1770	3547	Cohesive	0.193	0.094	0.094
11S67IA(100)-3	'-67°F	0.005	0.998	1900	3808	Cohesive	0.193	0.094	0.094
11S67IA(100)-4	'-67°F	0.004	0.998	1895	3798	Cohesive	0.192	0.094	0.094
11S67IA(100)-5	'-67°F	0.004	0.998	1775	3557	Cohesive	0.192	0.094	0.094
Average					3667				
Standard Deviation					127.5				
Coefficient of Variation					0.03				
11S72IA(100)-1	RT	0.002	1.000	1975	3950	Cohesive	0.190	0.094	0.094
11S72IA(100)-2	RT	0.002	0.996	1990	3996	Cohesive	0.190	0.094	0.094
11S72IA(100)-3	RT	0.002	0.999	2000	4004	Cohesive	0.190	0.094	0.094
11S72IA(100)-4	RT	0.002	1.007	1985	3942	Cohesive	0.190	0.094	0.094
11S72IA(100)-5	RT	0.003	0.998	1980	3968	Cohesive	0.191	0.094	0.094
Average					3972				
Standard Deviation					27.3				
Coefficient of Variation					0.01				
11S300IA(100)-1	300°F	0.002	0.998	1975	3958	Cohesive	0.190	0.094	0.094
11S300IA(100)-2	300°F	0.002	1.000	1965	3930	Cohesive	0.190	0.094	0.094
11S300IA(100)-3	300°F	0.002	0.998	1950	3908	Cohesive	0.190	0.094	0.094
11S300IA(100)-4	300°F	0.001	1.007	1930	3833	Cohesive	0.189	0.094	0.094
11S300IA(100)-5	300°F	0.001	0.997	1925	3862	Cohesive	0.189	0.094	0.094
Average					3898				
Standard Deviation					50.6				
Coefficient of Variation					0.01				

Table B.7-1. Single Lap Shear Isothermal Aging Test Data for 8009/XEA 9674

Adherends: 8009 Aluminum, Single Lap Shear Test Data					Contract NAS1-18560				
Adhesive: Dexter Hysol XEA 9674 BMI/BASF X268-9 Primer									
Surface Preparation: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table III.				
Thermal Cycle: None		IA=isothermal aging			Averages plotted in Figure 4.4-2				
(U = uncycled)		500 hrs @ 300°F							
Specimen No.	Test Temp.	Bondline	Bondline	Ultimate	Ultimate	Fracture	Overlap	Adherend A	Adherend B
		Thickness	Width	Load	Stress	Surface	(in)	(in)	(in)
500 hrs @ 300°F		(in.)	(in.)	(lbf)	(psi)				
11S67IA(500)-1	'-67°F	0.004	0.992	1750	3528	Adhesive	0.192	0.094	0.094
11S67IA(500)-2	'-67°F	0.005	1.000	1690	3380	Adhesive	0.193	0.094	0.094
11S67IA(500)-3	'-67°F	0.005	1.003	1725	3440	Adhesive	0.193	0.094	0.094
11S67IA(500)-4	'-67°F	0.004	0.996	1750	3514	Adhesive	0.192	0.094	0.094
11S67IA(500)-5	'-67°F	0.004	1.003	1800	3589	Adhesive	0.192	0.094	0.094
Average					3490				
Standard Deviation					81.4				
Coefficient of Variation					0.02				
11S72IA(500)-1	RT	0.003	1.000	2000	4000	Adhesive	0.191	0.094	0.094
11S72IA(500)-2	RT	0.003	1.000	1975	3950	Adhesive	0.191	0.094	0.094
11S72IA(500)-3	RT	0.004	1.005	1850	3682	Adhesive	0.192	0.094	0.094
11S72IA(500)-4	RT	0.004	0.998	1875	3758	Adhesive	0.192	0.094	0.094
11S72IA(500)-5	RT	0.004	0.997	1930	3872	Adhesive	0.192	0.094	0.094
Average					3852				
Standard Deviation					132.2				
Coefficient of Variation					0.03				
11S300IA(500)-1	300°F	0.003	1.000	1820	3640	Cohesive	0.191	0.094	0.094
11S300IA(500)-2	300°F	0.003	0.997	1770	3551	Cohesive	0.191	0.094	0.094
11S300IA(500)-3	300°F	0.003	0.999	1970	3944	Cohesive	0.191	0.094	0.094
11S300IA(500)-4	300°F	0.003	1.007	2000	3972	Cohesive	0.191	0.094	0.094
11S300IA(500)-5	300°F	0.003	0.997	1820	3651	Cohesive	0.191	0.094	0.094
Average					3752				
Standard Deviation					192.8				
Coefficient of Variation					0.05				

Table B.7-2. Single Lap Shear Isothermal Aging Test Data for 8009/XEA 9674

Adherends: 8009 Aluminum, Single Lap Shear Test Data					Contract NAS1-18560				
Adhesive: Dexter Hysol XEA 9674 BMI/BASF X268-9 Primer									
Surface Preparation: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table III.				
Thermal Cycle: None		IA=isothermal aging			Averages plotted in Figure 4.4-1				
(U=uncycled)		1000 hrs @ 300°F							
Specimen No.	Test Temp.	Bondline	Bondline	Ultimate	Ultimate	Fracture	Overlap	Adherend A	Adherend B
		Thickness	Width	Load	Stress	Surface	(in)	(in)	(in)
1000 hrs @ 300°F		(in.)	(in.)	(lbf)	(psi)				
11S67UIA(1000)-1	'-67°F	0.002	1.000	1945	3890	Adhesive	0.190	0.094	0.094
11S67UIA(1000)-2	'-67°F	0.003	0.996	1950	3916	Adhesive	0.191	0.094	0.094
11S67UIA(1000)-3	'-67°F	0.003	0.999	1960	3924	Adhesive	0.191	0.094	0.094
11S67UIA(1000)-4	'-67°F	0.003	1.003	1950	3888	Adhesive	0.191	0.094	0.094
11S67UIA(1000)-5	'-67°F	0.003	0.998	1750	3507	Adhesive	0.191	0.094	0.094
Average					3825				
Standard Deviation					178.4				
Coefficient of Variation					0.05				
11S72UIA(1000)-1	RT	0.003	0.997	2075	4162	Adhesive	0.191	0.094	0.094
11S72UIA(1000)-2	RT	0.003	1.008	2100	4167	Adhesive	0.191	0.094	0.094
11S72UIA(1000)-3	RT	0.003	0.998	2070	4148	Adhesive	0.191	0.094	0.094
11S72UIA(1000)-4	RT	0.002	1.000	2060	4120	Adhesive	0.190	0.094	0.094
11S72UIA(1000)-5	RT	0.003	0.999	2060	4124	Adhesive	0.191	0.094	0.094
Average					4144				
Standard Deviation					21.5				
Coefficient of Variation					0.01				
11S300UIA(1000)-1	300°F	0.009	1.000	1825	3650	Cohesive	0.197	0.094	0.094
11S300UIA(1000)-2	300°F	0.009	0.999	1875	3754	Cohesive	0.197	0.094	0.094
11S300UIA(1000)-3	300°F	0.010	0.998	1870	3747	Cohesive	0.198	0.094	0.094
11S300UIA(1000)-4	300°F	0.012	1.007	1890	3754	Cohesive	0.200	0.094	0.094
11S300UIA(1000)-5	300°F	0.010	1.003	1800	3589	Cohesive	0.198	0.094	0.094
Average					3699				
Standard Deviation					75.5				
Coefficient of Variation					0.02				

Table B.7-3. Single Lap Shear Isothermal Aging Test Data for 8009/XEA 9674

NASA-SIDARS SiC/8009 Aluminum Single Lap Shear Test Data					Contract NAS1-18560				
Dexter Hysol XEA 9674 BMI/BASF X268-9 Primer									
Surface Prep.: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table III.				
Thermal Cycle: None		IA=isothermal aging			Averages plotted in Figure 4.4-1.				
(U=uncycled)		100, 500, and 1000 hrs @ 300°F							
SiCp = silicon carbide particulate									
Specimen No.	Test Temp.	Bondline Thickness (in.)	Bondline Width (in.)	Ultimate Load (lbf)	Ultimate Stress (psi)	Fracture Surface	Overlap (in)	Adherend A (in)	Adherend B (in)
100 hrs @ 300°F									
31S300UIA(100)-1	300°F	0.001	0.997	2125	4263	Cohesive	0.163	0.081	0.081
31S300UIA(100)-2	300°F	0.002	0.998	2150	4309	Cohesive	0.164	0.081	0.081
31S300UIA(100)-3	300°F	0.001	1.006	2125	4225	Cohesive	0.163	0.081	0.081
31S300UIA(100)-4	300°F	0.001	1.000	2060	4120	Cohesive	0.163	0.081	0.081
31S300UIA(100)-5	300°F	<1mil	1.000	2075	4150	Cohesive	0.162	0.081	0.081
Average					4213				
Standard Deviation					78.1				
Coefficient of Variation					0.02				
500 hrs @ 300°F									
31S300UIA(500)-1	300°F	0.002	1.000	1990	3980	Cohesive	0.164	0.081	0.081
31S300UIA(500)-2	300°F	0.003	1.008	2020	4008	Cohesive	0.165	0.081	0.081
31S300UIA(500)-3	300°F	0.004	0.998	2075	4158	Cohesive	0.166	0.081	0.081
31S300UIA(500)-4	300°F	0.004	1.003	1975	3938	Cohesive	0.166	0.081	0.081
31S300UIA(500)-5	300°F	0.004	0.997	2050	4112	Cohesive	0.166	0.081	0.081
Average					4039				
Standard Deviation					92.5				
Coefficient of Variation					0.02				
1000 hrs @ 300°F									
31S300UIA(1000)-1	300°F	<0.001	0.998	1975	3958	Cohesive	0.162	0.081	0.081
31S300UIA(1000)-2	300°F	0.001	1.003	1845	3679	Cohesive	0.163	0.081	0.081
31S300UIA(1000)-3	300°F	0.001	0.998	1950	3908	Cohesive	0.163	0.081	0.081
31S300UIA(1000)-4	300°F	<0.001	1.005	2000	3980	Cohesive	0.162	0.081	0.081
31S300UIA(1000)-5	300°F	<0.001	1.003	2150	4287	Cohesive	0.162	0.081	0.081
Average					3962				
Standard Deviation					217.4				

Table B.7-4. Single Lap Shear Isothermal Aging Test Data for SiCp/8009/XEA 9674

Adherends: Weldalite Aluminum, Single Lap Shear Test Data					Contract NAS1-18560				
Adhesive: 3M AF191 Epoxy/BMS 5-89 Type I, Grade A Primer									
Surface Preparation: Phosphoric Acid Anodize per BAC 5555					Specimens in final report Table III.				
Thermal Cycle: None		IA=isothermal aging			Averages plotted in Figure 4.4-1				
(U=uncycled)		100, 500, and 1000 hrs. @ 275°F							
Specimen No.	Test Temp.	Bondline Thickness (in.)	Bondline Width (in.)	Ultimate Load (lbf)	Ultimate Stress (psi)	Fracture Surface	Overlap (in)	Adherend A (in)	Adherend B (in)
100 hrs @ 275°F									
24S275UIA(100)-1	275°F	0.004	0.999	1940	3884	Cohesive	0.174	0.085	0.085
24S275UIA(100)-2	275°F	0.004	0.999	2040	4084	Cohesive	0.174	0.085	0.085
24S275UIA(100)-3	275°F	0.003	1.007	2100	4171	Cohesive	0.173	0.085	0.085
24S275UIA(100)-4	275°F	0.005	1.003	900	1795	Adhesive	0.175	0.085	0.085
24S275UIA(100)-5	275°F	0.004	1.001	1200	2398	Adhesive	0.174	0.085	0.085
Average					3266				
Standard Deviation					1094.2				
Coefficient of Variation					0.33				
500 hrs @ 275°F									
24S275UIA(500)-1	275°F	0.006	1.001	1060	2118	Cohesive	0.176	0.085	0.085
24S275UIA(500)-2	275°F	0.006	0.997	1660	3330	Adhesive	0.176	0.085	0.085
24S275UIA(500)-3	275°F	0.008	0.999	1710	3423	Adhesive	0.178	0.085	0.085
24S275UIA(500)-4	275°F	0.007	1.009	1775	3518	Adhesive	0.177	0.085	0.085
24S275UIA(500)-5	275°F	0.007	0.998	990	1984	Cohesive	0.177	0.085	0.085
Average					2875				
Standard Deviation					756.4				
Coefficient of Variation					0.26				
1000 hrs @ 275°F									
24S275UIA(1000)-1	275°F	0.006	1.000	2120	4240	Cohesive	0.176	0.085	0.085
24S275UIA(1000)-2	275°F	0.006	0.999	2175	4354	Adhesive	0.176	0.085	0.085
24S275UIA(1000)-3	275°F	0.006	0.998	2180	4369	Adhesive	0.176	0.085	0.085
24S275UIA(1000)-4	275°F	0.005	1.007	1675	3327	Adhesive	0.175	0.085	0.085
24S275UIA(1000)-5	275°F	0.006	0.999	1660	3323	Cohesive	0.176	0.085	0.085
Average					3923				
Standard Deviation					547.8				
Coefficient of Variation					0.14				

Table B.7-5. Single Lap Shear Isothermal Aging Test Data for Weldalite/AF 191

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Adhesive bonding materials and processes were evaluated for assembly of future high-temperature aluminum alloy structural components such as may be used in high-speed civil transport aircraft and space launch vehicles. A number of candidate high-temperature adhesives were selected and screening tests were conducted using single lap shear specimens. The selected adhesives were then used to bond sandwich (titanium core) test specimens, adhesive toughness test specimens, and isothermally aged lap shear specimens. Moderate-to-high lap shear strengths were obtained from bonded high-temperature aluminum and silicon carbide particulate-reinforced (SiC_p) aluminum specimens. Shear strengths typically exceeded 3500 to 4000 lb/in^2 and flatwise tensile strengths exceeded 750 lb/in^2 even at elevated temperatures (300°F) using a bismaleimide adhesive. All faceskin-to-core bonds displayed excellent tear strength. The existing production phosphoric acid anodize surface preparation process developed at Boeing was used, and gave good performance with all of the aluminum and silicon carbide particulate-reinforced aluminum alloys investigated. The results of this program support using bonded assemblies of high-temperature aluminum components in applications where bonding is often used (e.g., secondary structures and tear stoppers).

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