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LOW-COST FORMING INFLUENCE ON REINFORCED THERMOPLASTIC MECHANICAL PROPERTIES

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This report describes a study of the influence of low-cost forming methods on the mechanical properties of reinforced thermoplastics. Two tasks comprise the main body of the study; one establishes a relationship between processing parameters (time/pressure/temp-variables) and selected material properties (modulus, flex strength, inter-laminar shear strength); the other determines the effects (measured by the change in material flexural properties) of simulated R&M solvent attack on

(over)

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painted and unpainted laminates. Two secondary tasks complete the study: a review of the available literature on industrial and government-sponsored reinforced thermoplastic materials, material properties, and fabrication methods. The other task required the manufacture of four, 16" x 20", five ply Kevlar 49 style 285 fabric, polysulfone, laminated panels for AMMRC testing. Test data (with respect to processing parameters) indicates a decrease in flexural strength as thermoforming temperature increases with highest strength readings coming at the 450°F thermoforming temperature. Modulus values are highest in the 500°F - 550°F thermoforming temperature range. Interlaminar shear strength values also tend to decrease as thermoforming temperature increases. Regarding solvent attack, test data indicates generally higher flexural strength with polyphenylsulfone than with polysulfone sandwich beams. Conversely higher "EI" values occurred in the polysulfone than in the polyphenylsulfone sandwich beams. Data also suggests no degradation in material flexural properties when specimens are exposed to acetone and methyl-ethyl-ketone solvents.

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FOREWORD

This final technical report concludes the study of low-cost forming influence on reinforced thermoplastic mechanical properties contract for the Army Materials & Mechanics Research Center (AMMRC), Watertown, Massachusetts, by the Boeing Vertol Company under Contract DAAG46-79-C-0092.

Mr. Peter Dehmer was the Army Contracting Officer's Technical Representative. The program was conducted at the Boeing Vertol Company under the technical direction of Mr. Thomas W. Griffith, Program Manager. Principal contributors were Donald J. Hoffstedt, Project Engineer; Donald J. Toto; Lawrence C. Ritter; and Erwin Durchlaub.

SUMMARY

The following is a general summary of results for each of the tasks comprising this study program.

1. Task I — Literature Review and Oral Presentation

Development of hot melt preimpregnation has shown encouraging results with Udel polysulfone P-1700 and CM-1 polyarylsulfone.

Emergence of hot roll continuous impregnation from film and continuous fiber materials make highly solvent resistant polymers candidates for further development.

Hot melt development is recommended with candidates offered by suppliers in film form.

2. Task II — Establish Relationship Between Processing Parameters and Selected Material Properties

Time/Temperature/Pressure Variables — Utilizing a polysulfone matrix and Kevlar 49 aramid fabric, specimens were fabricated to determine the experimental relationship between preconsolidated laminate flexure strength versus postformed laminate flexure strength when exposed to the forming parameters in Table 1. This relationship is described by:

(a) Flexural strength
(b) Modulus
(c) Interlaminar shear strength

Flexural Strength — Only those specimens postformed at the 450°F thermoforming temperature had increased flexural strength readings (up 5%) over the nonpostformed control group. The group having the highest flexural strength readings below those of the control (10% under control) were postformed at 500°F. All other higher temperature postformed groups (550°F, 600°F, 650°F) had flexural strength readings a minimum of 28% under the nonpostformed control group. (NOTE: All percentage differences are based on "group average" values.)

Generally, the test data indicated a definite decrease in flexural strength as thermoforming (postforming) temperatures increase. This trend was unaffected by variations in post forming pressure (vacuum only or vacuum plus light die pressure).

Modulus — Specimens postformed at the 500°F postforming temperatures had the highest percentage increase (+23%) over the control group modulus values. Two other groups had higher modulus values than the control group: 450°F postforming (+6.5%), 550°F postforming (+15.5%). The two remaining postformed specimen groups had modulus values lower than those of the nonpostformed control group: Postformed at 600°F (−1.8%), postformed at 650°F (−21.4%). (NOTE: All percentage differences were based on "group average" values.)

TABLE 1. THERMOFORMING PROCESSING CONDITIONS

SPECIMEN GROUP	MATERIAL (POLYSULFONE P-1700 RESIN)	POST-FORMING TEMPERATURE (^{0}F)					PRESSURE DURING HEAT CYCLE (PSI)	POST-FORMING PRESSURE (PSI)	
		450	500	550	600	650		VAC ONLY	VLOP *
CONTROL (NO POST-FORMING)	5-PLY KEVLAR 285	–	–	–	–	–	–	–	–
1	5-PLY KEVLAR 285	X					0	X	
2	5-PLY KEVLAR 285		X				0	X	
3	5-PLY KEVLAR 285			X			0	X	
4	5-PLY KEVLAR 285				X		0	X	
5	5-PLY KEVLAR 285					X	0	X	
6	5-PLY KEVLAR 285	X					0		X
7	5-PLY KEVLAR 285		X				0		X
8	5-PLY KEVLAR 285			X			0		X
9	5-PLY KEVLAR 285				X		0		X
10	5-PLY KEVLAR 285					X	0		X

* VLDP = VACUUM PLUS LIGHT DIE PRESSURE

VAC ONLY = VACUUM ONLY

Interlaminar Shear Strength — Those specimens postformed at 450°F and using vacuum only as the postforming pressure comprised the only group to attain higher interlaminar shear strength readings than that of the nonpostformed control group. All other specimen groups had shear strength readings a minimum of 15% under that of the control group. Although 9 out of the 10 specimen groups had shear strength readings less than those of the control group, a trend of decreasing interlaminar shear strength with increasing thermoforming temperature, regardless of postforming pressure, became evident in the data compilation.

3. Task III — Determination of Simulated Repair and Maintenance (R&M) Solvent Effects on Protected and Unprotected Laminates

Composite honeycomb sandwich test specimens were fabricated from thermoformed 2 ply Kevlar 49 style 285 fabric/polysulfone and 2 ply Kevlar 49 type 285 fabric/polyphenylsulfone using 1/2-inch thick Nomex honeycomb as the core material as outlined in Table 2. These specimens were used to determine the solvent resistance of painted and unpainted laminates as described by the effects on their flexure properties (flexural strength and stiffness "EI").

Four-point flex testing of Udel (Polysulfone) and Radel (Polyphenylsulfone) sandwich beams indicates higher overall flexure strength readings with Radel beams than Udel beams by some 14-15% regardless of paint and solvent effects. Conversely, stiffness "EI" values are 25-30% higher in the Udel beams than the Radel beams, again ignoring paint and solvent effects.

Realistic exposure (application of a solvent soaked rag for two hours or until dry) had no degrading effects on specimen flexural properties.

4. Task IV — Panel Fabrication

Six (6) 17.75" x 18.0" panels of 5 ply Kevlar 49 style 285 fabric (preimpregnated with P1700 polysulfone using methylene chloride solvent dispersal) were fabricated for testing by AMMRC. One of the six panels is to be used as a control specimen, therefore, it had no postforming operation. Each of the remaining five panels were thermoformed (postformed) at different temperatures (450°F, 500°F, 550°F, 600°F, 650°F), but with the same postforming pressure (Vacuum Plus Light Die Pressure).

TABLE 2. SOLVENT TESTING MATRIX

COMPOSITE MATERIAL	SOLVENTS		
	* CONTROL	MEK	ACETONE
	SPECIMEN QTY.	SPECIMEN QTY.	SPECIMEN QTY.
KEVLAR/POLYSULFONE			
PAINTED	3	3	3
UNPAINTED	3	3	3
KEVLAR/POLYPHENYLSULFONE			
PAINTED	3	3	3
UNPAINTED	3	3	3

*CONTROL - NO SOLVENT EXPOSURE

INTRODUCTION

Lightweight composite structure research and development for U.S. Army helicopter applications has centered largely around fiber-reinforced epoxy structures. The raw materials are more expensive than current metallic raw materials and cost parity can only be achieved through reduction in manufacturing costs of the details and assemblies. One promising approach for helicopter structures is the use of reinforced thermoplastics rather than reinforced epoxy, since investigations to date indicate that reduction in fabrication cost may be achieved with little loss in mechanical properties.

This program attempts to define and evaluate the most suitable materials for application of low elongation fiber reinforced thermoplastic laminates to helicopter secondary structures, (adapting low cost commercial techniques currently used for unreinforced, chopped-fiber-reinforced, and high elongation continuous fiber reinforced thermoplastics such as polyesters, acrylics and polycarbonates) by determining the correlation between the mechanical properties of selected fiber-reinforced thermoplastics and processing parameters in variants of vacuum-forming.

This program studies only the mechanical properties aspects of continuous fiber reinforced thermoplastics and not the suitability of the material for thermoforming shapes other than two dimensional forms.

TASK I
LITERATURE REVIEW AND ORAL PRESENTATION

This literature review is organized in the order of: definition of the areas of consideration, general review of base polymer characteristics, review of existing data on low elongation continuous fiber reinforced thermoplastic R&D, and recommendations for current and future material utilization and development.

1. MATERIAL AND FABRICATION CONSIDERATIONS

The areas of interest to this technology include matrix thermoplastic candidate systems, fibrous reinforcements of interest, the processability of component systems into a total material system, and the resulting physical and mechanical properties.

Some of the major attributes sought include low cost of base materials, good chemical resistance to solvents encountered in military helicopter environment and depot maintenance actions, low flammability smoke and toxicity hazard, low energy consumption in laminate consolidation, adaptability to low cost postforming methods, and ability to reprocess formed parts if unsatisfactory. Mechanical properties would be required to compare well with epoxy matrix reinforced with similar fibers.

Matrix Materials

Specific task assignment is the review of matrix resin systems to include those listed below.

Polysulfone
Polyphenylsulfone
PKXA
Nylon
Polybutylene Terephthalate

Fibrous Reinforcements

The continuous fiber reinforcements listed below are of specific interest in this technology:

Kevlar 49 Tape
Kevlar 49 Fabric
E-Glass Fabric
E-Glass Tape
AS Graphite Tape
HMS Graphite Tape
HTS Graphite Tape
T300 Graphite Tape
T300 Graphite Fabric

Fabrication Cycle

The fabrication stages outlined below are of specific interest in this fabrication technology:

- Preimpregnation Method
  - Dispersion Coating
  - Solution Coating
    - N-Methyl Pyrrolidone
    - Dimethyl Formamide
    - Methylene Chloride
    - Other
  - Hot Melt (Film)
- Solvent Dispersal/Drying
  - Cycle Time
  - Temperature
- Consolidation Methods
  - Temperature Range
  - Pressure Range
  - Dwell Time
- Thermoforming
  - Vacuum Forming
  - Vacuum and Plug
  - Vacuum and Matched Dies

Material System Properties

The material properties desired after prepregging, consolidating and postforming the reinforced laminates are listed below:

- Physical Properties
  - Fiber Volume
  - Density
  - Coefficient of Linear Thermal Expansion
  - Heat Distortion Temperature @ 264 psi
- Mechanical Properties
  - Tensile Strength
  - Tensile Modulus
  - Compressive Strength

Compressive Modulus
Flexural Strength
Flexural Modulus
Interlaminar Shear
In-Plane Shear
Shear Modulus

2. GENERAL SCREENING, BASE POLYMERS

Basic polymers and their specific products have been reviewed in a general sense and the advantages and disadvantages of each are noted in Table 3.

3. SPECIFIC DATA SOURCE REVIEW

Previous investigators have selected one or more thermoplastic resin system and reinforced them with one or more continuous fiber reinforcement system and performed processing trials, measured mechanical properties and evaluated the effects of environmental exposure on the mechanical properties. Most of the work has been performed using high pressure post-forming methods.

Matrix Material Evaluations

Materials were reviewed and compared by prior investigators in selecting best candidates for process evaluation and engineering property measurement when reinforced with low elongation continuous fibers. Resins evaluated and systems selected are shown in Table 4, with reasons for rejection, when known.

Matrix/Fiber System Evaluations

The selected candidate matrices have been used in preimpregnation, processing, postforming and mechanical properties evaluation. Material system evaluation results are presented in Table 5.

TABLE 3. GENERAL SCREENING OF BASE POLYMERS

BASE POLYMER	MATERIAL TYPE OR DESIGNATION	PRO	CON
"Styrenics"	ABS	Good Process-ability Low Cost	Low Softening Point Low Strength Attacked by Organic Sol-vents
	Styrene-Acrylo-Nitrile	Good Process-ability Low Cost	Low Softening Point Low Strength Attacked by Solvents Hard & Rigid Trim Problems
Fluorocarbon Polymers	Ethylene-Tetra-Fluoroethylene Copolymer Tefzel 200	Exceptional Chemical Resistance	High Cost (?) Creep
Polyvinylchloride	Rigid PVC	Nonflammable Relatively Low Cost	Low Softening Temperature Solvent Attack by Ketones, Some Chlorin-ated & Aromat-ic Compounds, Esters
Sulfones	Polysulfone Udel	Good Engineer-ing Properties Low Creep High Impact	Attacked by Ketones, Chlor-inated and Aromatic HydroCarbons
	Polyphenyl-Sulfone Radel	Good Engineer-ing Properties Low Creep	" (Improved)
	Polyethersul-fone Viltrex	Good Engineer-ing Properties Low Creep	Attacked by Ketones, Some Halogenated & Aromatic Hydro-Carbons
	Polyarylsulfone HC3601		

TABLE 3. GENERAL SCREENING OF BASE POLYMERS — Continued

BASE POLYMER	MATERIAL TYPE OR DESIGNATION	PRO	CON
Polyphenylene Sulfide	PPS Ryton	Good Wetting Good Chemical Resistance Nonflammable	High Consolidation Temp (>700°F) Difficult to Process
PolyPhenylene Oxide	PPO Noryl	Toughened Polystyrene Added Good Mechanical Properties	Attacked by Chlorinated Hydrocarbon Solvents and Ketones
Polyamide	Nylon 6/6 Nylon 6 Nylon 6/10 Nylon 6/12 Nylon 11 Nylon 12	Good Chemical Resistance	Reduced High Temperature Properties High Water Absorption Rate and Plasticization
Acetal Polymers & Co-Polymers	Acetal Co-Polymer	Good Chemical Resistance	Fiber-Matrix Adhesion Problems
	Celcon M90 Kematal	Good Mechanical Properties	
	Acetal Homopolymer Delrin	Good Mechanical Properties	Fiber-Matrix Adhesion Problems
Polyolefins	Polyethylene Hostalen Alathon Polypropylene	Good Processability	Low Strength (vs Epoxy)
		Good Chemical Resistance	Attacked by Hydro-Carbons. Limited Useful Temperature Range.
	Ethylene Co-Polymer with Ionic Inter-Chain Links Surlyn		Poor Properties
Thermoplastic Polyesters	Polybutylene Terephthalate Tenite 6 PRO Celanex 2001 Valox 310 Deroton Tap 10 Dular Hytrel	Good Water Resistance Good Mechanical Properties	Low Deflection Temperature Under Load Attacked by partly halogenated Hydrocarbon Solvents Flammability Problem on Some

TABLE 3. GENERAL SCREENING OF BASE POLYMERS — Continued

BASE POLYMER	MATERIAL TYPE OR DESIGNATION	PRO	CON
Polycarbonate	Lexan	Good Mechanical Properties	Attacked by Chlorinated Hydrocarbon and Ketone Solvents
Polyimides	NR150A 150B 150C Sablon 1010 Sablon 055 66-1-2	Excellent High Temperature Properties Film Castable from DMF	Cost Consolidation Process is High Tempera-ture
Alloys	PVC/Acrylic DKE 450 KYDEX	Melt Extrudes or Solvent Coats Self Extin-guishes	Relatively Low Useful Temper-ature (200°F) Soluble in THF and Cyclohexa-none
Phenoxy	PKHS	Low Cost Good Process-ing	Attacked by Ketones, Chlor-inated Hydro-Carbon Solvents

TABLE 4. MATRIX MATERIAL INVESTIGATIONS

BASIC POLYMER	MANUFACTURER AND/OR RESIN DESIGNATION	REFERENCE REPORT PAGES 87, 88 (17)	(20)	(9)	(18)	(14)	INVESTIGATOR'S STATED OR PROBABLE REASON FOR NOT SELECTING
ACETAL CO-POLYMER	CELANESE						
	CELCON		X		X		LOW USEFUL TEMPERATURE RANGE. CREEP.
ACETAL HOMO-POLYMER	DUPONT						
	DELRIN				X		LOW USEFUL TEMPERATURE RANGE. CREEP.
ACRYLIC	ROHM & HAAS						
	PLEXIGLASS		X				LOW USEFUL TEMPERATURE, SOLVENT RESISTANCE. CREEP.
ACRYLIC/PVC	DUPONT						
	DKE				X		SELECTED FOR SCREENING. 200°F MAX TEMPERATURE ILS LOW
ACRYLONITRILE BUTADIENE-STYRENE	BORG WARNER						
	CYCOLAC		X				CREEP. SOLVENT RESISTANCE.
BIS-A-PHENYL	UNION CARBIDE			X			COST/NOT COMMERCIAL PRODUCT UNAVAILABLE FOR TESTS
FLUOROCARBONS	MANY						
	PTFE		X				LOW STRENGTH, HIGH Tg, POOR WEAR & CREEP PROPERTIES
	ALLIED CHEMICAL						
	CM-1			X			SOME TESTING - PROMISING

TABLE 4. MATRIX MATERIAL INVESTIGATIONS – Continued

BASIC POLYMER	MANUFACTURER AND/OR RESIN DESIGNATION	REFERENCE REPORT PAGES 87,88 (17)	(20)	(9)	(18)	(14)	INVESTIGATOR'S STATED OR PROBABLE REASON FOR NOT SELECTING
NYLON(S)	MANY						
	NYLON 66	X	X				123°F Tg - LOSS OF HIGH STRENGTH ABOVE 120°F CREEP, WATER ABSORPTION
PHENOXY	UNION CARBIDE						
	PKHS		X				
	PKHS-1		X				SELECTED
POLYALLOMER			X				SOLVENT RESISTANCE IS POOR
POLYARYLSULFONE	3M						
	HC 5601	X					COST
	UNITIKA,LTD,UC						
	ARDEL			X			SOLUBLE IN METHYLENE CHLORIDE
POLYCARBONATE	G.E.						
	LEXAN		X		X		< 280°F USEFUL TEMPERATURE ATTACKED BY STRONG ALKALIS
POLYESTER	DUPONT						
	DULAR HYTREL				X		MELT EXTRUDES - NO CONVENIENT SOLVENT
POLYETHERSULFONE	ICI						
	100P				X		INADEQUATE HI-TEMP PROPERTIES LOW RESISTANCE TO CHLORINATED SOLVENTS

TABLE 4. MATRIX MATERIAL INVESTIGATIONS — Continued

BASIC POLYMER	MANUFACTURER AND/OR RESIN DESIGNATION	REFERENCE REPORT PAGES 87, 88 (17)	(20)	(9)	(18)	(14)	INVESTIGATOR'S STATED OR PROBABLE REASON FOR NOT SELECTING
POLYETHERSULFONE CONTINUED	ICI (Continued)						
	200P					X	EVALUATED
	300P			X		X	SELECTED
	720P					X	EVALUATED
	KM-1 (600P)			X			SELECTED
POLYETHER, CHLORINATED			X				NOT KNOWN NO CURRENT PRODUCT - "PENTON" FROM HERCULES OFF MARKET
POLYETHYLENE (CO-POLYMER WITH IONIC INTERCHAIN LINKS)	DUPONT						
	SURLYN		X		X		< 120°F USEFUL TEMPERATURE SOLVENT RESISTANCE IS POOR
POLYIMIDE	DUPONT						
	NR150A	X				X	COST/EXPERIMENTAL EVALUATED
	NR150B	X					COST/EXPERIMENTAL
	NR150C	X					COST/EXPERIMENTAL
	SOLAR						
	66-1-2		X				HIGH PROCESSING TEMPERATURE
	SABLON 1010		X				HIGH PROCESSING TEMPERATURE
	SABLON 055		X				HIGH PROCESSING TEMPERATURE
	UPJOHN 2030	X					SELECTED

TABLE 4. MATRIX MATERIAL INVESTIGATIONS – Continued

BASIC POLYMER	MANUFACTURER AND/OR RESIN DESIGNATION	REFERENCE REPORT PAGES 87, 88 (17)	(20)	(9)	(18)	(14)	INVESTIGATOR'S STATED OR PROBABLE REASON FOR NOT SELECTING
POLY (AMIDE/IMIDE)	AMOCO						
	TORLON 4000					X	EVALUATED-PROPERTIES < POLYIMIDE - PROMISING
POLYPARABONIC ACID	EXXON						NOT COMMERCIALLY AVAILABLE
POLYPHENYLENE	GENERAL ELECTRIC						
OXIDE	NORYL		X				SOLVENT RESISTANCE IS POOR
POLYPHENYLENE SULFIDE	PHILLIPS	X	X				
POLYPHENYL SULFONE	UNION CARBIDE						
	RADEL 5000					X	EVALUATED
POLYPHENYL-QUINOXALINE			X				
POLYPROPYLENE		X					SOLVENT RESISTANCE IS POOR
POLYSULFONE	UNION CARBIDE						
	UDEL P-1700	X	X	X	X		
	MINN. MINING MFG.						
	ASTREL 360					X	EVALUATED - LAMINATING DIFFICULTIES

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TABLE 4. MATRIX MATERIAL INVESTIGATIONS – Continued

BASIC POLYMER	MANUFACTURER AND/OR RESIN DESIGNATION	REFERENCE REPORT PAGES 87, 88 (17)	(20)	(9)	(18)	(14)	INVESTIGATOR'S STATED OR PROBABLE REASON FOR NOT SELECTING
POLYSULFONE (MODIFIED) ACETYLENE TERMINATED	AFML			X			NOT AVAILABLE IN TIME FOR EVALUATION
SILANE END-CAPPED	UNION CARBIDE						
	PKXA-24			X			EVALUATED
	PKXA 41			X			EVALUATED
POLYVINYLCHLORIDE	UNION CARBIDE						
	BAKELITE		X				
	ETHYL CORP.						
	ETHYL 7042						
STYRENE-ACRYLONITRILE	DOW						
	TYRIL 867		X				SOLVENT RESISTANCE CREEP
UNIDENTIFIED	DUPONT						
	RP-200				X		SELECTED FOR SCREENING, NOT COMMERCIALLY AVAILABLE SCREENED ILS < PHENOXY
	NR-140				X		NOT COMMERCIALLY AVAILABLE

TABLE 5. FIBER/MATRIX SYSTEMS – THERMOPLASTIC INVESTIGATIONS

REF.	PROJECT CONTRACT	RESIN	FIBER	METHOD OF PREPREG	TESTS CONDUCTED	PARTS FABRICATED	NOTES
20	D180-17531-1 N00019-72-C-0526	P-1700	181 E-GLASS	SOLVENT METHYLCHLORIDE	*MECHANICAL PROP @ -65°F +70°F, and +180°F	FLAT LAMINATES CORRUGATED PANELS	LARGE DATA SAMPLE
		PKHS-1	181 E-GLASS	SOLVENT MEK	TENSION,COMP., FLEX,ILS,IZOD IMPACT, CREEP FATIGUE *FLEX TESTS IN ADVERSE INVIRON-MENT AND FLUIDS		
		PKHS-1	"AS" GRAPHITE	SOLVENT MEK	*MECHANICAL PROP @-65°F, +70°F, +180°F	PRESS/TEMP VARIA-TIONS FLAT LAMINATES	SMALL DATA SAMPLE
		P-1700	3004-AS	HERCULES	FLEX, ILS IZOD IMPACT +70°F TENSION,COMP. THERMAL SHOCK	CORRUGATED PANEL	
17	GD/CONVAIR IR&D 1974	UPJOHN 2080 U/C P-1700 MMM 5601	"AS" GRAPHITE		*MECHANICAL PROP FLEX, SBS @ 70°F	HATS, CHANNELS, BEADED PANEL, DISH, PAN	LIMITED DATA SAMPLE
		P-1700	"AS" GRAPHITE	HERCULES	*MECHANICAL PROP @ RT, +150°F, +225°F, +250°F FLEX, SBS, TEN-SILE CREEP		LIMITED DATA SAMPLE

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TABLE 5. FIBER/MATRIX SYSTEMS – THERMOPLASTIC INVESTIGATIONS – Continued

REF.	PROJECT/ CONTRACT	RESIN	FIBER	METHOD OF PREPREG	TESTS CONDUCTED	PARTS FABRICATED	NOTES
16	D180-18034-1 N00019-73-C-0414 FEB, 1974	P-1700	"AS" GRAPHITE	BATCH METHYLENE CHLORIDE SOLUTION	*EFFECT OF RESIN CONT. (FLEX, TENS, ILS RT)	LAMINATES	LIMITED DATA SAMPLE
		P-1700	AS, HMS, T300, MOD I, MOD II	BATCH METHYLENE CHLORIDE SOLUTION	*FIBER/RESIN COMPAT. (TENS, FLEX, ILS, WATER BOIL) (70°F, 300°F)	LAMINATES	LIMITED DATA SAMPLE
		P-1700	"AS" GRAPHITE	BATCH METHYLENE CHLORIDE SOLUTION	*MECH. PROP, 0°, ±45°, 0/90°, 90° TENS -65°, RT, 180°, 300°F FLEX " COMP " ILS " CREEP, IZOD IMPACT FATIGUE *ENVIRONMENTAL RESISTANCE (ISOTHERMAL AGING ARTIFICIAL WEA-THERING, FLUID RESISTANCE	LAMINATES HALF ROUND HAT STIFFENER CORRUGATION FORMED PANEL "Z" STIFFENER TAPERED RADII CURVED PANEL H/C PANEL FORMED H/C PANEL	SMALL DATA SAMPLE GOOD FORMING RESULTS FINISHING EVALUATED
15	IR-417-4(III) F33615-74-C-5086	P-1700	"AS" GRAPHITE	NMP, METHYLENE CHLORIDE	*MECH.PROP. @ 0°, 90°, 0°±60°, @RT, +270°F TENS, COMP *SOLVENT COMPARI-SON FLEX, COMP, SBS *FAB CYCLE EFFECTS FLEX, TENS, SBS	YF-16 STRAKE	TOOLING EVALU'TN CERAMIC CHOSEN LIMITED DATA SAMPLE

TABLE 5. FIBER/MATRIX SYSTEMS – THERMOPLASTIC INVESTIGATIONS – Continued

REF	PROJECT CONTRACT	RESIN	FIBER	METHOD OF PREPREG	TESTS CONDUCTED	PARTS FABRICATED	NOTES
14	D180-17503-3 N00019-74-C-0226	P-1700	181 KEVLAR 49	BATCH METHYLENE CHLORIDE SOLVENT	*PROCESSING CONDITIONS FLEX, ILS +70°, +250°F *MECH PROP. @ RT +250°F, TENSION, FLEX, ILS *IZOD IMPACT, BALLISTIC, CREEP, ELECTRICAL PROP. *ENVIRONMENTAL RESIST. FLEX TESTS. THERMAL AGING, WEATHERING, SALT, WATER, AIRCRAFT FLUIDS	LAMINATES	POOR RESIN FIBER BOND SMALL DATA SAMPLE
		(HI-TEMP) POLYIMIDE POLYETHERSULFONE POLY (AMIDE/IMIDE) POLYARYLSULFONE	"AS" GRAPHITE	SOLVENTS NMP DMF AMICACID	*FLEX, ILS (RT)	LAMINATES	LIMITED DATA SAMPLE
		POLYETHERSULFONE POLYIMIDE	"	DMF NMP	*PROCESS STUDIES FLEX, ILS *MECH. PROP @ RT to 450°F, TENS. COMP., FLEX, ILS	LAMINATES	SMALL DATA
13	D180-18236-5 N62269-74-C-0368	P-1700	"AS" GRAPHITE 181 S-GLASS	PURCHASED	*MAT'L QUAL TESTS TO BOEING PREL. MAT'L SPEC D180-18236-4 (6/74)	BQM-34E FULL SCALE CENTERBODY	SUCCESSFUL DEMONSTRATION, FULL SCALE TESTS

TABLE 5. FIBER/MATRIX SYSTEMS – THERMOPLASTIC INVESTIGATIONS – Continued

REF.	PROJECT CONTRACT	RESIN	FIBER	METHOD OF PREPREG	TESTS CONDUCTED	PARTS FABRICATED	NOTES
12	D180-18752-3 N00019-76-C-0170 3-77	P-1700 PKXA.24 PKXA.41	HM-S A-S	BATCH METHYLENE CHLORIDE	*MECH. PROP, FLEX, ILS @ -65, RT +300°F	LAMINATES	LIMITED DATA SAMPLE
		P-1700	"AS" GRAPHITE	"	*NON-CLAD VS ALUM. METAL CLAD VS EPOXY CLAD STRESS CRACKING (FLEX) AFTER WEATHERING, MOIS-TURE, SALT WATER, AIRCRAFT FLUID EXPOSURE	LAMINATES	MIL-H-83306 HYD. FLUID ATTACK LIMITED DATA SAMPLE
		P-1700	GRAPHITE 181(T300) 181S-GLASS 181 KEVLAR 49	BATCH METHYLENE CHLORIDE	*MECH.PROP.@ -65°F RT, +300°F TENS. FLEX, ILS *RT IZOD IMPACT	10 PLY HYBRID LAMINATES	LIMITED DATA NO STRUC-TURAL PROBLEMS IN HYBRID-IZING
10	NADC-77231-30 N62269-74-C-0369 10-77	P-1700	"AS" GRAPHITE	VENDOR NMP-TROUBLE METHYLENE CHLORIDE USED	*MATL INSPECTION FLEX, COMP. SBS (RT)	MAIN LANDING GEAR DOOR-(STUDY A/C)	KIRKSITE DIES PASSED ALL STRUCTURAL TESTS
11	NADC-77187-30 N62269-75-C-0386 5-77	P-1700	"AS" GRAPHITE	HERCULES AS-3004 PROCURED	*PROCESS VARIABLES FLEX @ RT	CORRUGATED PANELS CURVED CHANNELS AMMO BAY DOOR	TOOLING EVALUATION JOINING STUDY

TABLE 5. FIBER/MATRIX SYSTEMS – THERMOPLASTIC INVESTIGATIONS – Continued

REF.	PROJECT CONTRACT	RESIN	FIBER	METHOD OF PREPREG	TESTS CONDUCTED	PARTS FABRICATED	NOTES
8	AFRTP IND. REVIEW F33615-76-C-3048 7-79	P-1700	"AS" GRAPHITE TAPE 3", 6" 181 T-300 GRAPHITE T300-12" TAPE	VENDOR SUPPLIED	*WIDE RANGE OF STRUC-INTEG-VERIFICATION TESTS MAT'L QUAL TESTS TO D180-18236-4 D180-19348-3 ENV., WEATHERING, FLUIDS, FUELS, LUBES	FULL SCALE YC-14 OUTBOARD ELEVATOR FAB PROCESS PARTS/ TRADE STUDIES	FULL SCALE STATIC TESTING PERFORMED
9	N00019-77-C-0561 MAY, 1979	POLYPHEN-YLSUL-FONE PKXA.41 PKXA.517 POLYETH-ERSUL-FONE	T300 GRAPHITE FABRIC	BATCH DMF METHYLENE CHLORIDE HOT MELT	*RESIN & COMPOSITE CHARACTERIZATION *MECH. PROP. TENS., ILS, FLEX, COMPRES-SION AT RT, 250, 350, 400°F. *ENVIRONMENTAL RESISTANCE AIRCRAFT FLUIDS SALT WATER *METAL CLAD MECH. PROP.	PROCESS DEVELOP. LAMINATES (7 PLY) TITANIUM CLADDING	LIMITED DATA STRESSED AND UNSTRESS-ED RESIDUAL STRESSES NO IMPROVE-MENT

TASK II
ESTABLISH RELATIONSHIP BETWEEN PROCESSING PARAMETERS AND SELECTED MATERIAL PROPERTIES

Work performed by Boeing Aerospace[1] has identified a strength reduction associated with heating preconsolidated laminates to forming temperatures and forming with vacuum/air assist. Table 1 establishes a test matrix to determine whether a correlation exists between postforming temperature and pressure on consolidated blanks during heat-up and postforming pressure with respect to flexural strength of the resulting laminate. Figure 1 is a photograph showing the attachment of a thermocouple to a 5-ply laminate. Figure 2 is a photograph showing a consolidated blank during the thermoforming process.

Flexural testing was performed in accordance with ASTM D790-71 (reapproved 1978), "Standard Test Methods for Flexural Properties of Plastics and Electrical Insulating Materials", except that four specimens were tested from each laminate for this screening program.

For the required short-beam shear testing, specimens were built up by (250°F cure) film adhesive bonding of three thicknesses (see Appendix "A") and tested in horizontal shear by the standard test method ASTM D2344-76, "Apparent Interlaminar Shear Strength of Parallel Fiber Composites by Short-Beam Method", except that the laminates were prepared for test using the processed postformed material, not ring-type specimens. This approach has been used by previous investigators since NOL rings are not representative of the process.

Four Point Flexural Tests

Flexural testing was accomplished under the standard test procedure stated above in accordance with Method II — a four point loading system utilizing two load points equally spaced from their adjacent support points, with a distance between load points of one third of the support span (Figure 3). All specimens had commonality in these values:

Fiber orientation	0°, 90°
Specimen length	2.0 In. (Nom)
Specimen width	0.50 In. ± 0.02
Support Span	1.00 In.
Load Span	0.33 In.
Rate of cross lead motion	0.05 In./Min
Hexcel Prepreg 5 ply laminate consolidation conditions	600°F, 100 Psig — for 30 minutes

Results of four point flex testing on 5 ply Kevlar 49 type 285 fabric/polysulfone (P1700) are summarized in Table 6. Individual specimen dimensions and test results are given in Table 7.

When a beam is loaded in flexure at two central points (1/3-span) and supported at two outer points, the maximum stress in the outer fibers occurs between the two central loading points that define the load span. This stress may be calculated for any point on the load-deflection curve for relatively small deflections by the following equation:

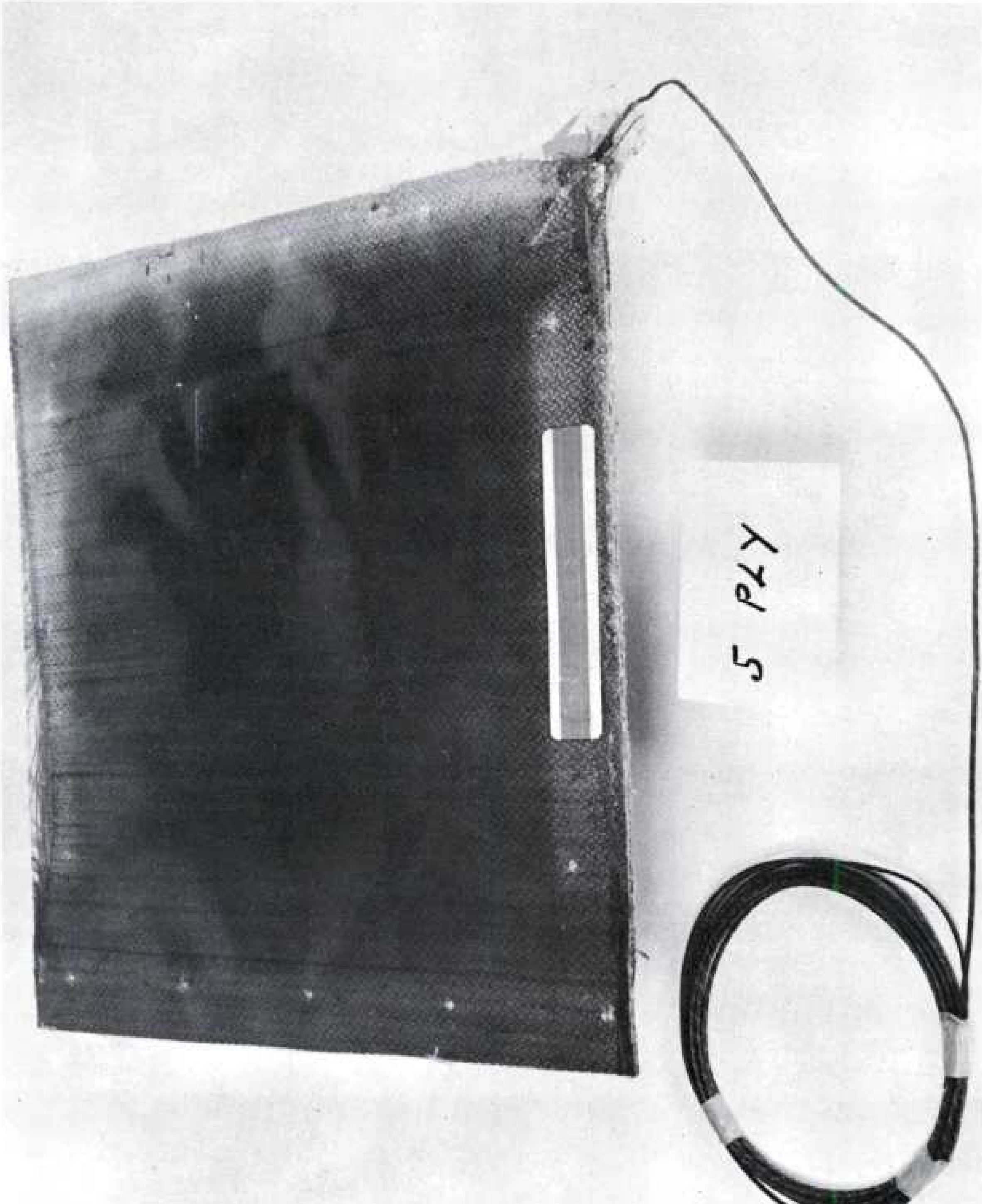

Figure 1. Kevlar 49/Polysulfone Consolidated Blank, With Thermocouple

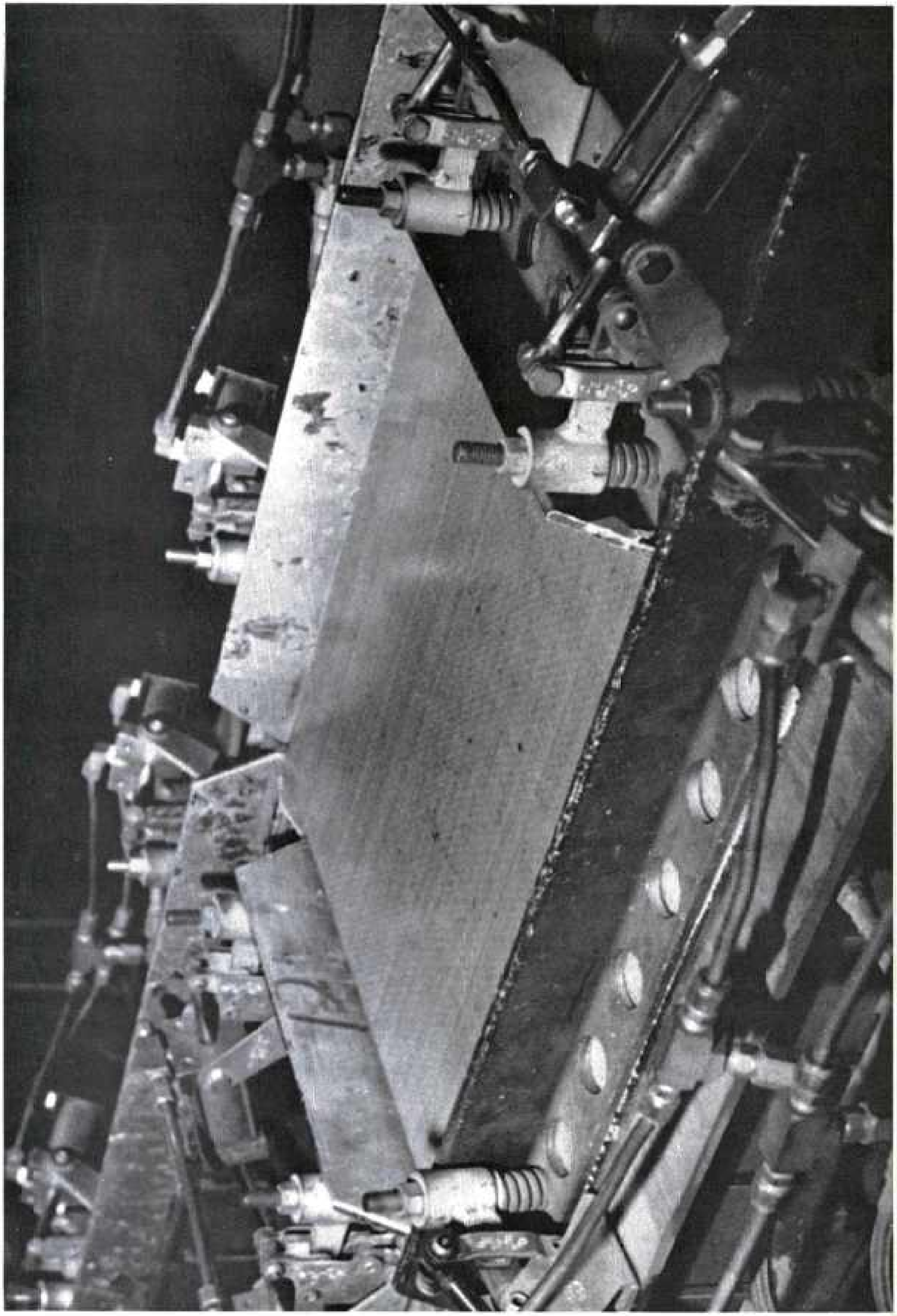

Figure 2. Consolidated Blank Thermoforming Process

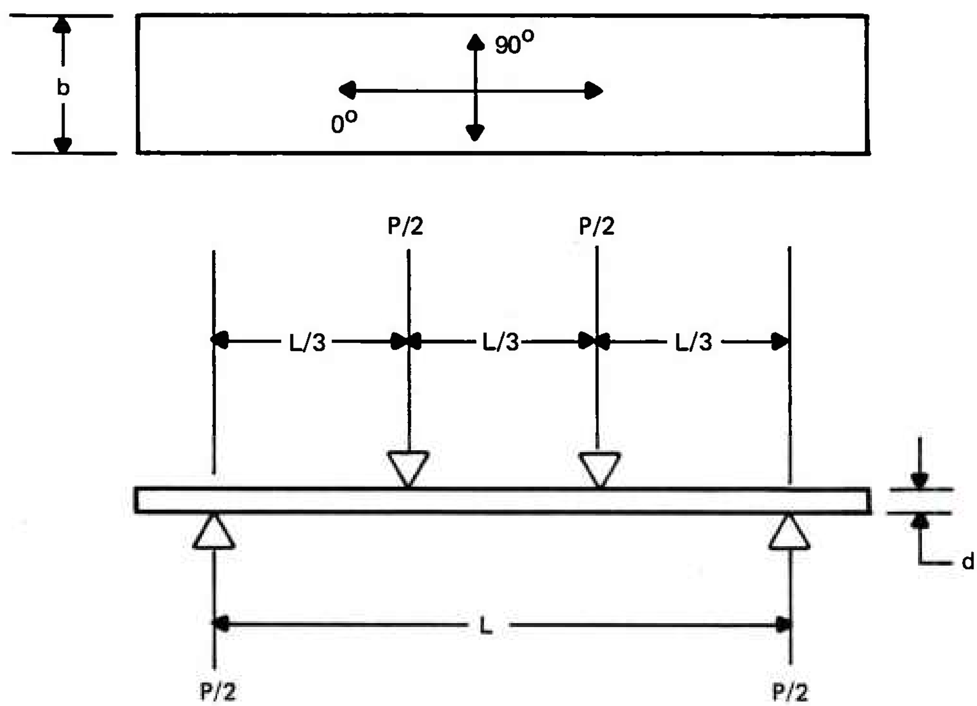

Figure 3. Four-Point Loading System for Flexural Testing of 5-Ply Laminate

TABLE 6. FOUR POINT FLEX TEST (1) – SUMMARY

Specimens Group I.D.	Specimens Qty	Postforming Temp (^oF)	Postforming Pressure VAC (2)	Postforming Pressure VLDP (3)	Flexural Strength (psi) Group Avg	Flexural Strength (psi) σ (4)	Modulus (psi x 10^6) Group Avg	Modulus (psi x 10^6) σ (4)
Control	4	NO POSTFORMING			43453	2379	3.54	0.36
1	4	450	X		47402	728	4.15	0.06
2	4	500	X		38031	4391	4.65	0.22
3	4	550	X		32745	4768	4.51	0.59
4	4	600	X		30404	7467	3.30	0.12
5	4	650	X		26787	4563	2.29	0.35
6	4	450		X	43575	1270	3.39	0.07
7	4	500		X	39900	1919	4.07	0.12
8	4	550		X	29981	12891	3.67	0.45
9	6	600		X	28664	2590	3.64	0.31
10	4	650		X	29358	6585	3.30	0.21

(1) All testing was done at room temperature.

(2) VAC = Vacuum Pressure Only.

(3) VLDP = Vacuum Plus Light Die Pressure.

(4) σ = Standard Deviation (with N-1 weighting).

$$S = PL/bd^2$$

where:

- S = stress in the outer fiber throughout load span (psi)
- P = load at a given point on the load-deflection curve (LbF)
- L = support span (In.)
- b = width of beam (In.)
- d = depth of beam (In.)

The tangent modulus of elasticity is the ratio, within the elastic limit of stress to corresponding strain and will be expressed in pounds per square inch. It is calculated by drawing a tangent to the steepest initial straight-line portion of the load-deflection curve and using the following equation:

$$E_b = 0.21\, L^3 m/bd^3$$

where:

- E_b = modulus of elasticity in bending (psi)
- L = support span (In.)
- b = width of beam (In.)
- d = depth of beam (In.)
- m = slope of the tangent to the initial straight-line portion of the load-deflection curve, lb/in. of deflection.

Shown in Figure 4 are photographs of thermoforming molds used in the postforming of consolidated Kevlar 49/Polysulfone blanks.

Figure 5 is a photograph showing the finished blank number 10 after the postforming process, with water-jet cutting lines marked on it. All testing in Task II for specimens processed under these postforming conditions (650^{o}F and vacuum plus light die pressure) were cut from the blank shown in Figure 5.

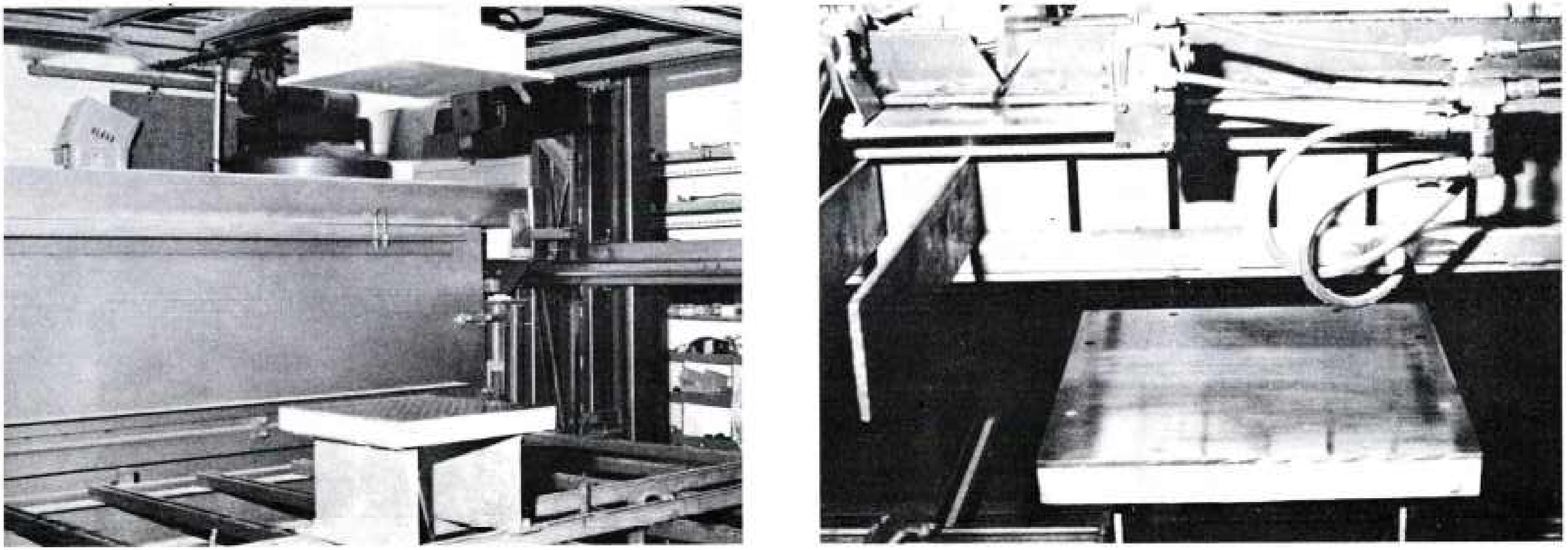

Figure 4. Thermoforming Molds

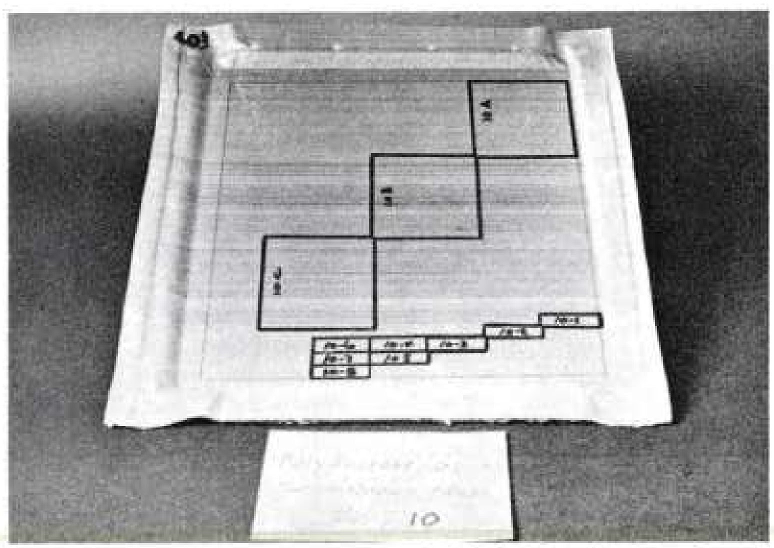

Figure 5. Postformed Blank No. 10, From Which the Smaller Test Specimens Were Cut

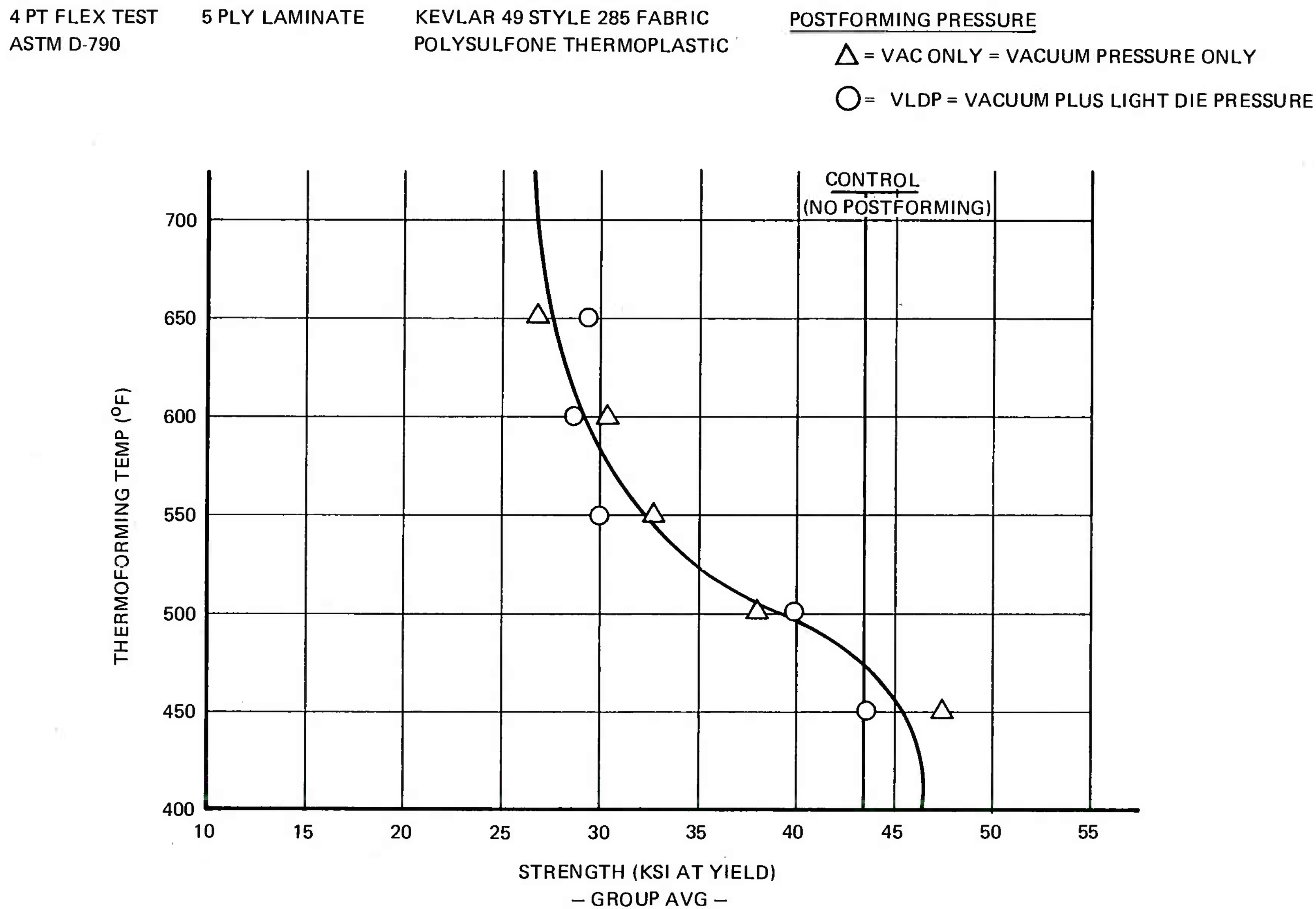

Figure 6. Flexural Strength vs Thermoforming Temperature

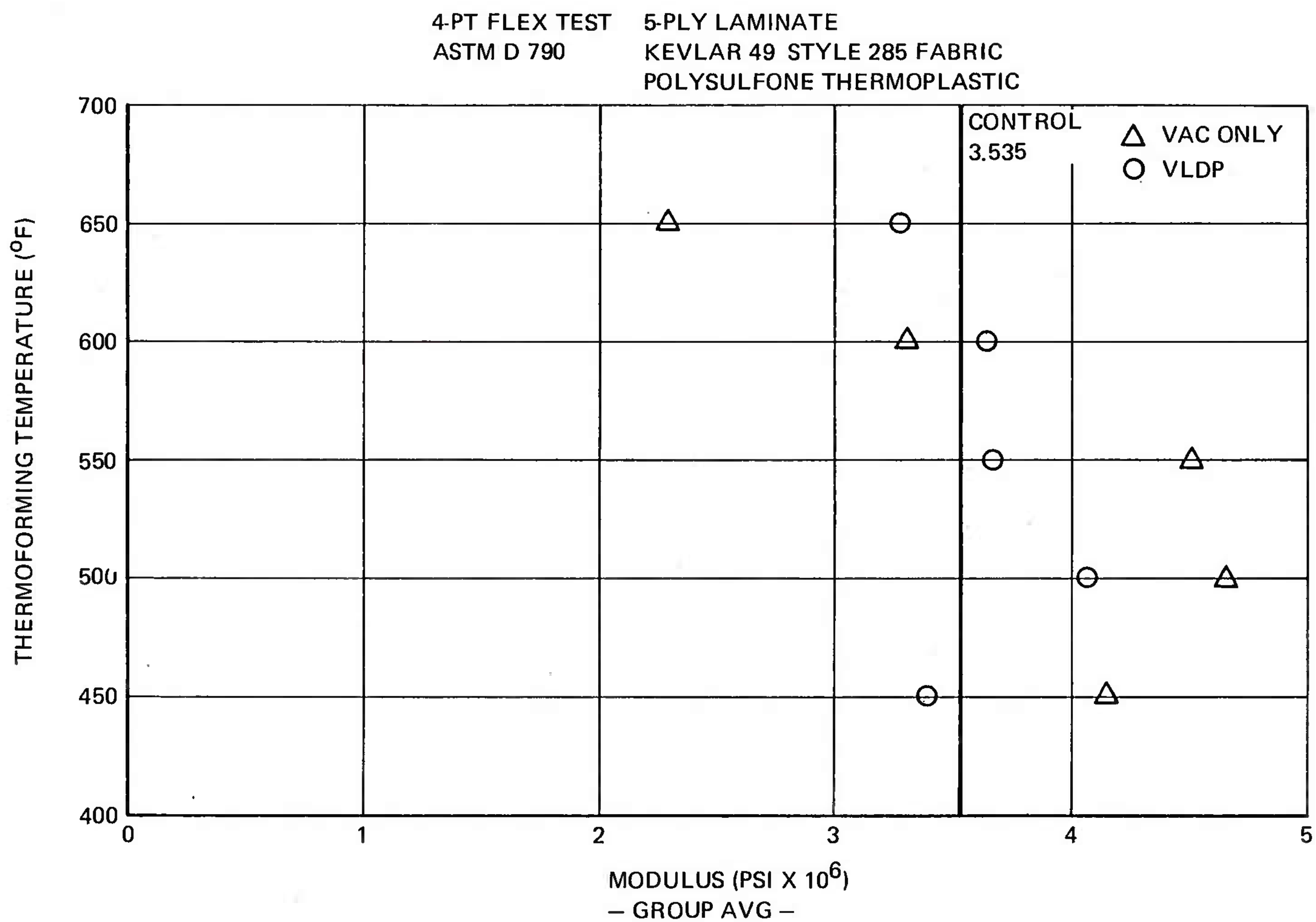

Figure 7. Flexural Stiffness vs Thermoforming Temperature

TABLE 7. FOUR POINT FLEX TEST – THERMOPLASTIC SPECIMEN BREAKDOWN

Specimen Group – Control
No Postforming Operation
Tested per ASTM D790,

Specimen Length = 2.0 in.
Support Span = 1.0 in.
Load Span = 0.33 in.
Rate of Cross Head Motion = 0.05 in./min
5 Ply Laminated Kevlar 49
Style 285 Fabric/P1700 Polysulfone

Specimen No.	t (in.)	w (in.)	Max Deflection Before Load Dropoff (in.)	Max Load (lbs)	Strength (psi)	Modulus (psi x 10^6)
C–1	0.039	0.5110	0.15	32	41,172	3.05
C–2	0.039	0.5158		VOID		
C–3	0.040	0.5158	0.125	36	43,622	3.56
C–4	0.039	0.5210	0.15	36	46,691	3.62
C–5	0.041	0.5200	0.125	37	42,328	3.91
				Avg	43,453	3.54
				σ*	2,379	0.36

*σ = Standard Deviation (with N-1 weighting)

TABLE 7. FOUR POINT FLEX TEST – THERMOPLASTIC SPECIMEN BREAKDOWN (Continued)

Specimen Group – No. 1
450°F, Vacuum Only
Tested per ASTM D790,

Specimen Length = 2.0 in.
Support Span = 1.0 in.
Load Span = 0.33 in.
Rate of Cross Head Motion = 0.05 in./min
5 Ply Laminated Kevlar 49
Style 285 Fabric/P1700 Polysulfone

Specimen No.	t (in.)	w (in.)	Max Deflection Before Load Dropoff (in.)	Max Load (lbs)	Strength (psi)	Modulus (psi x 10^6)
1–1	0.044	0.5178	0.1375	47	46,885	4.19
1–2	0.044	0.5202	0.125	47	46,668	4.17
1–3	0.043	0.5180	0.1375	46	48,028	N/A
1–4	0.043	0.5190		VOID		
1–5	0.043	0.5180	0.1375	46	48,028	4.08
				Avg	47,402	4.15
				σ*	728	0.06

*σ = Standard Deviation (with N-1 weighting)

TABLE 7. FOUR POINT FLEX TEST – THERMOPLASTIC SPECIMEN BREAKDOWN (Continued)

Specimen Group – No. 2
500°F, Vacuum Only
Tested per ASTM D790,

Specimen Length = 2.0 in.
Support Span = 1.0 in.
Load Span = 0.33 in.
Rate of Cross Head Motion = 0.05 in./min
5 Ply Laminated Kevlar 49
Style 285 Fabric/P1700 Polysulfone

Specimen No.	t (in.)	w (in.)	Max Deflection Before Load Dropoff (in.)	Max Load (lbs)	Strength (psi)	Modulus (psi x 10^6)
2–1	0.043	0.5210	0.125	40	41,523	4.46
2–2	0.043	0.5242	0.150	38	38,206	4.84
2–3	0.043	0.5234	0.125	38.5	39,782	4.84
2–4	0.043	0.5218	0.175	30.5	31,613	4.45
				Avg	38,031	4.65
				σ*	4,391	0.22

*σ = Standard Deviation (with N-1 weighting)

TABLE 7. FOUR POINT FLEX TEST – THERMOPLASTIC SPECIMEN BREAKDOWN (Continued)

Specimen Group – No. 3
550°F, Vacuum Only
Tested per ASTM D790,

Specimen Length = 2.0 in.
Support Span = 1.0 in.
Load Span = 0.33 in.
Rate of Cross Head Motion = 0.05 in./min
5 Ply Laminated Kevlar 49
Style 285 Fabric/P1700 Polysulfone

Specimen No.	t (in.)	w (in.)	Max Deflection Before Load Dropoff (in.)	Max Load (lbs)	Strength (psi)	Modulus (psi x 10^6)
3–1	0.044	0.5078	0.100	26	26,447	3.73
3–2	0.043	0.5092	0.125	32	33,988	4.40
3–3	0.043	0.5132	0.125	36	37,938	4.94
3–4	0.043	0.5142	0.1125	31	32,606	4.93
				Avg	32,645	4.51
				σ*	4,768	0.59

*σ = Standard Deviation (with N-1 weighting)

TABLE 7. FOUR POINT FLEX TEST – THERMOPLASTIC SPECIMEN BREAKDOWN (Continued)

Specimen Group – No. 4
600°F, Vacuum Only
Tested per ASTM D790,

Specimen Length = 2.0 in.
Support Span = 1.0 in.
Load Span = 0.33 in.
Rate of Cross Head Motion = 0.05 in./min
5 Ply Laminated Kevlar 49
Style 285 Fabric/P1700 Polysulfone

Specimen No.	t (in.)	w (in.)	Max Deflection Before Load Dropoff (in.)	Max Load (lbs)	Strength (psi)	Modulus (psi x 10^6)
4–1	0.047	0.5180	0.100	22	19,226	3.44
4–2	0.046	0.5180	0.1125	38	34,669	3.33
4–3	0.047	0.5160	0.100	39	34,215	3.14
4–4	0.047	0.5202	0.125	38.5	33,504	3.30
				Avg	30,404	3.3
				σ*	7,467	0.12

*σ = Standard Deviation (with N-1 weighting)

TABLE 7. FOUR POINT FLEX TEST – THERMOPLASTIC SPECIMEN BREAKDOWN (Continued)

Specimen Group – No. 5
650°F, Vacuum Only
Tested per ASTM D790,

Specimen Length = 2.0 in.
Support Span = 1.0 in.
Load Span = 0.33 in.
Rate of Cross Head Motion = 0.05 in./min
5 Ply Laminated Kevlar 49
Style 285 Fabric/P1700 Polysulfone

Specimen No.	t (in.)	w (in.)	Max Deflection Before Load Dropoff (in.)	Max Load (lbs)	Strength (psi)	Modulus (psi x 10^6)
5–1	0.054	0.5098	0.100	49	32,962	2.02
5–2	0.052	0.5070	0.0875	31	22,612	2.22
5–3	0.052	0.5138	0.100	38	27,352	2.79
5–4	0.053	0.5144	0.100	35	24,222	2.11
				Avg	26,787	2.29
				σ*	4,563	0.35

*σ = Standard Deviation (with N-1 weighting)

TABLE 7. FOUR POINT FLEX TEST – THERMOPLASTIC SPECIMEN BREAKDOWN (Continued)

Specimen Group – No. 6
450°F, Vacuum Plus Light Die Pressure
Tested per ASTM D790,

Specimen Length = 2.0 in.
Support Span = 1.0 in.
Load Span = 0.33 in.
Rate of Cross Head Motion = 0.05 in./min
5 Ply Laminated Kevlar 49
Style 285 Fabric/P1700 Polysulfone

Specimen No.	t (in.)	w (in.)	Max Deflection Before Load Dropoff (in.)	Max Load (lbs)	Strength (psi)	Modulus (psi x 10^6)
6–1	0.051	0.5114	0.125	57	42,852	3.47
6–2	0.052	0.5120	0.100	58.5	42,255	3.41
6–3	0.054	0.5132	0.100	66	44,103	3.38
6–4	0.053	0.5132	0.100	65	45,090	3.30
				Avg	43,575	3.39
				σ*	1,270	0.07

*σ = Standard Deviation (with N-1 weighting)

TABLE 7. FOUR POINT FLEX TEST – THERMOPLASTIC SPECIMEN BREAKDOWN (Continued)

Specimen Group – No. 7
500°F, Vacuum Plus Light Die Pressure
Tested per ASTM D790,

Specimen Length = 2.0 in.
Support Span = 1.0 in.
Load Span = 0.33 in.
Rate of Cross Head Motion = 0.05 in./min
5 Ply Laminated Kevlar 49
Style 285 Fabric/P1700 Polysulfone

Specimen No.	t (in.)	w (in.)	Max Deflection Before Load Dropoff (in.)	Max Load (lbs)	Strength (psi)	Modulus (psi x 10^6)
7–1	0.043	0.5074	0.1375	39.5	42,103	4.16
7–2	0.043	0.5140	0.125	36.5	38,405	4.11
7–3	0.043	0.5156	0.1375	39	40,909	3.93
7–4	0.043	0.5170	0.100	36.5	38,183	N/A
				Avg	39,900	4.07
				σ*	1,919	0.12

*σ = Standard Deviation (with N-1 weighting)

TABLE 7. FOUR POINT FLEX TEST – THERMOPLASTIC SPECIMEN BREAKDOWN (Continued)

Specimen Group – No. 8
550°F, Vacuum Plus Light Die Pressure
Tested per ASTM D790,

Specimen Length = 2.0 in.
Support Span = 1.0 in.
Load Span = 0.33 in.
Rate of Cross Head Motion = 0.05 in./min
5 Ply Laminated Kevlar 49
Style 285 Fabric/P1700 Polysulfone

Specimen No.	t (in.)	w (in.)	Max Deflection Before Load Dropoff (in.)	Max Load (lbs)	Strength (psi)	Modulus (psi x 10^6)
8–1	0.040	0.5100	0.1375	39.5	48,407	3.69
8–2	0.042	0.5100		VOID		
8–3	0.043	0.5156	0.100	28	28,370	4.10
8–4	0.045	0.5170	0.075	22	21,014	N/A
8–5	0.045	0.5164	0.100	22.1	21,134	3.21
				Avg	29,981	3.67
				σ*	12,891	0.63

*σ = Standard Deviation (with N-1 weighting)

TABLE 7. FOUR POINT FLEX TEST – THERMOPLASTIC SPECIMEN BREAKDOWN (Continued)

Specimen Group – No. 9
600°F, Vacuum Plus Light Die Pressure
Tested per ASTM D790,

Specimen Length = 2.0 in.
Support Span = 1.0 in.
Load Span = 0.33 in.
Rate of Cross Head Motion = 0.05 in./min
5 Ply Laminated Kevlar 49
Style 285 Fabric/P1700 Polysulfone

Specimen No.	t (in.)	w (in.)	Max Deflection Before Load Dropoff (in.)	Max Load (lbs)	Strength (psi)	Modulus (psi x 10^6)
9–1	0.044	0.5100	0.100	32	32,410	3.79
9–2	0.044	0.5082	0.100	28	28,459	3.88
9–3	0.045	0.5086	0.125	30	29,129	3.62
9–4	0.047	0.5090	0.100	28	24,903	3.18
9–5	0.046	0.5086	0.070	29	26,947	3.39
9–6	0.045	0.5080	0.100	31	30,135	3.99
				Avg	28,664	3.64
				σ*	2,590	0.31

*σ = Standard Deviation (with N-1 weighting)

TABLE 7. FOUR POINT FLEX TEST – THERMOPLASTIC SPECIMEN BREAKDOWN (Continued)

Specimen Group – No. 10
650°F, Vacuum Plug Light Die Pressure
Tested per ASTM D790,

Specimen Length = 2.0 in.
Support Span = 1.0 in.
Load Span = 0.33 in.
Rate of Cross Head Motion = 0.05 in./min
5 Ply Laminated Kevlar 49
Style 285 Fabric/P1700 Polysulfone

Specimen No.	t (in.)	w (in.)	Max Deflection Before Load Dropoff (in.)	Max Load (lbs)	Strength (psi)	Modulus (psi x 10^6)
10–1	0.040	0.5112	0.175	32	39,124	3.59
10–2	0.043	0.5114	0.0875	26	27,496	3.14
10–3	0.043	0.5118	0.100	24	25,361	3.14
10–4	0.043	0.5100	0.100	24	25,451	3.23
				Avg	29,358	3.3
				σ*	6,585	0.21

*σ = Standard Deviation (with N-1 weighting)

Horizontal Shear Tests

The horizontal shear test specimen is center-loaded as shown in Figure 8. The specimen ends rest on two supports which allow lateral motion, the load being applied by means of a loading nose directly centered on the midpoint of the test specimen. Although the apparent shear strength obtained by this method cannot be used as a design criteria, it can be utilized for comparative testing of composite materials. This apparent shear strength may be calculated by the following equation:

$$S_H = 0.75\ P_B/bd$$

where:

S_H = shear strength (psi)

P_B = breaking load (lbF)

b = width of specimen (in.)

d = thickness of specimen (in.)

The horizontal shear test specimens were fabricated utilizing 3M AF163 film adhesive (250^oF cure) to "stack-up" three five-ply laminates of Kevlar 49, Style 285 fabric/P1700 polysulfone with the fiber orientation being in the 0^o, 90^o direction (see Appendix A). This three-laminate "stack-up" procedure was accomplished subsequent to the five-ply laminate thermoforming (postforming) operation. Other areas common to all specimens were:

Specimen width	0.250 ± 0.010
Specimen length	7 x thickness, as prescribed by (3)
Support span	5 x thickness, as prescribed by (3)
Rate of crosshead motion	0.05 In./Min
Hexcel prepreg 5-ply laminate consolidation conditions	600^oF, 100 PSIG – for 30 minutes

Results of three point interlaminar shear tests are summarized in Table 8. Individual specimen dimensions, and test results are given in Table 9. NOTE: Not all specimens exhibited the classical midthickness horizontal shear failure mode; however, a comparison of the maximum load levels achieved by those that did fail in the classical manner with the maximum load levels achieved by those specimens that did not exhibit the classical failure mode, demonstrates values commensurate with each other. Therefore, it is assumed that all failures are valid interlaminar shear failures. Prior experience with Kevlar fabrics with epoxy and thermoplastic resins also has demonstrated similar nonclassical failure modes.

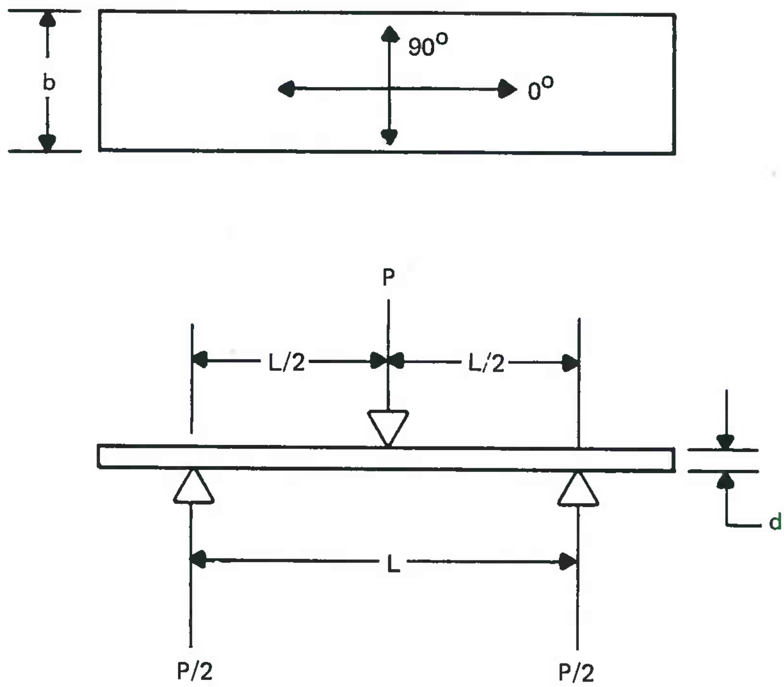

Figure 8. Three Point Loading System for Interlaminar Shear Testing

TABLE 8. THREE POINT INTERLAMINAR SHEAR TEST (4) – SUMMARY

Specimens Group I.D.	Qty	Postforming Temp (^oF)	Postforming Pressure VAC (1)	VLDP (2)	Interlaminar Shear Strength (psi) Group Avg	σ (3)
Control	5	No Postforming			2217	77.65
1	5	450	X		2469	35.85
2	5	500	X		1719	32.92
3	5	550	X		1655	19.95
4	5	600	X		1357	59.15
5	5	650	X		1917	215.37
5A	5	650	X		1799	62.00
6	5	450		X	1725	68.63
6A	6	450		X	1835	110.66
7	5	500		X	1851	52.14
8	5	550		X	1547	48.90
9	5	600		X	1441	46.57
10	5	650		X	1438	27.50

(1) VAC = Vacuum Pressure Only.

(2) VLDP = Vacuum Plus Light Die Pressure.

(3) σ = Standard Deviation (with N-1 weighting).

(4) All testing was done at room temperature.

NOTE – Strength values exhibited herein are to be used for comparative purposes only and not as design criteria.

3-PT ILS TEST 5-PLY LAMINATE – 3 LAMINATE STACKUP (USING FM163 FILM ADHESIVE)
ASTM D2344-76 KEVLAR 49 STYLE 285 FABRIC
POLYSULFONE THERMOPLASTIC

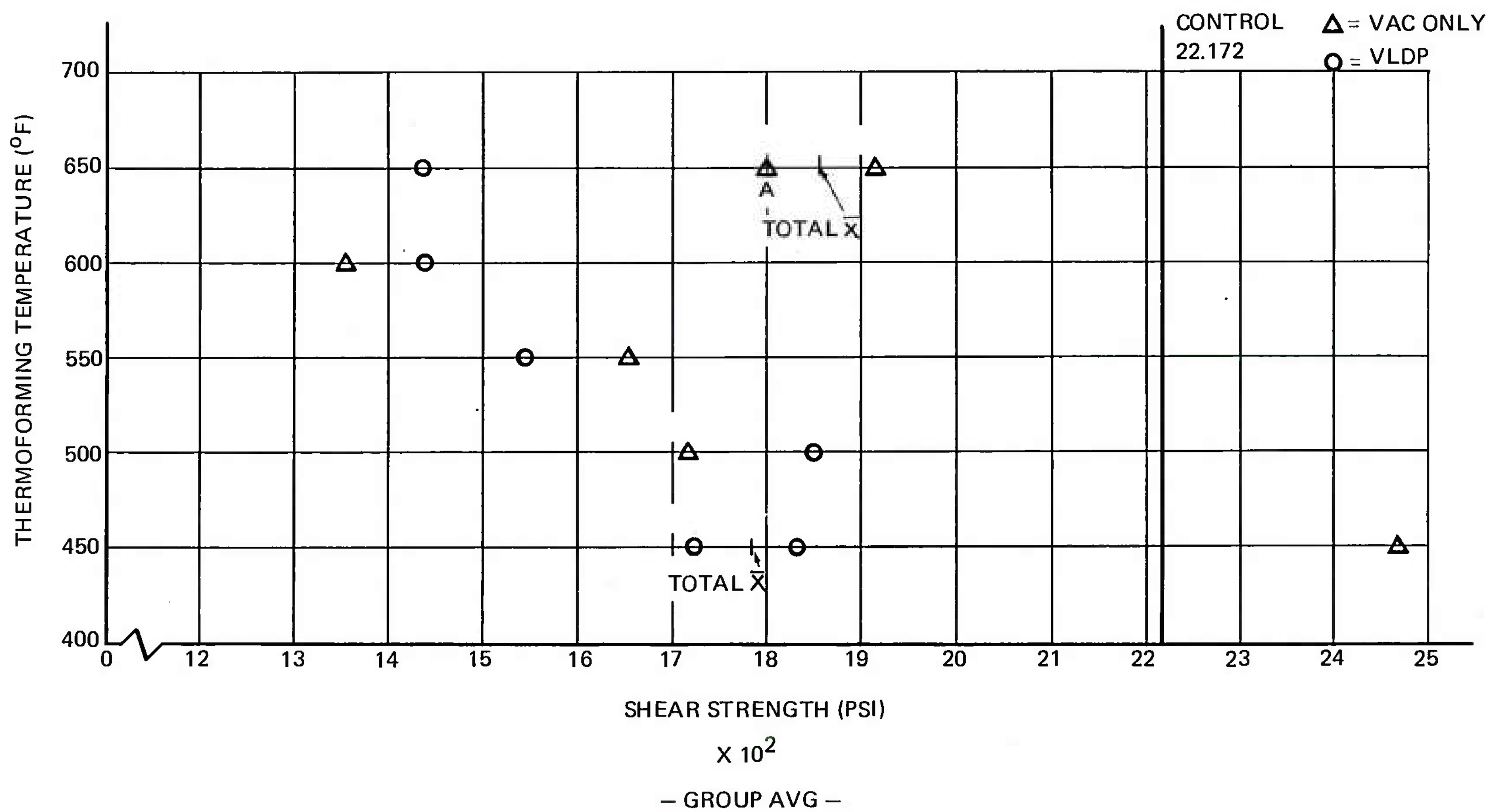

Figure 9. Interlaminar Shear Strengths vs Thermoforming Temperature

NOTE: USE FOR COMPARATIVE PURPOSES ONLY, NOT DESIGN CRITERIA

TABLE 9. THREE POINT INTERLAMINAR SHEAR TEST SPECIMEN BREAKDOWN

Specimen Group — CONTROL
(No Thermoforming)

Tested Per ASTM D2344-76:
Recommended Support Span = 5t
Recommended Specimen Length = 7t
Recommended Rate of Cross Head Motion = 0.05 in./min

Specimen No.	t (in.)	w (in.)	Load (lbf)	Shear Strength (psi) (1)
C–1	0.133	0.255	95	2101
C–2	0.132	0.256	101	2242
C–3	0.132	0.254	99	2215
C–4	0.132	0.257	100	2211
C–5	0.132	0.255	104	2317
			Avg	2217
			σ*	77.65

*σ = Standard Deviation (with N-1 weighting)

(1) NOTE: Use for comparative purposes only, not design criteria.

TABLE 9. THREE POINT INTERLAMINAR SHEAR TEST SPECIMEN BREAKDOWN (Continued)

Specimen Group — NO. 1
450°F, Vacuum Pressure Only

Tested Per ASTM D2344-76:
Recommended Support Span = 5t
Recommended Specimen Length = 7t
Recommended Rate of Cross Head Motion = 0.05 in./min

Specimen No.	t (in.)	w (in.)	Load (lbf)	Shear Strength (psi) (1)
1–1	0.130	0.254	107	2430
1–2	0.130	0.254	108	2453
1–3	0.131	0.254	112	2524
1–4	0.131	0.249	108	2483
1–5	0.131	0.254	109	2457
			Avg	2469
			σ*	35.85

*σ = Standard Deviation (with N-1 weighting)

(1) NOTE: Use for comparative purposes only, not design criteria.

TABLE 9. THREE POINT INTERLAMINAR SHEAR TEST SPECIMEN BREAKDOWN (Continued)

Specimen Group — NO. 2
500°F, Vacuum Pressure Only

Tested Per ASTM D2344-76:
Recommended Support Span = 5t
Recommended Specimen Length = 7t
Recommended Rate of Cross Head Motion = 0.05 in./min

Specimen No.	t (in.)	w (in.)	Load (lbf)	Shear Strength (psi) (1)
2–1	0.133	0.255	79	1747
2–2	0.134	0.255	78	1712
2–3	0.134	0.256	78	1705
2–4	0.134	0.254	76	1675
2–5	0.134	0.255	80	1756
			Avg	1719
			σ*	32.92

*σ = Standard Deviation (with N-1 weighting)

(1) NOTE: Use for comparative purposes only, not design criteria.

TABLE 9. THREE POINT INTERLAMINAR SHEAR TEST SPECIMEN BREAKDOWN (Continued)

Specimen Group — NO. 3

550°F, Vacuum Pressure Only

Tested Per ASTM D2344-76:
Recommended Support Span = 5t
Recommended Specimen Length = 7t
Recommended Rate of Cross Head Motion = 0.05 in./min

Specimen No.	t (in.)	w (in.)	Load (lbf)	Shear Strength (psi) (1)
3–1	0.133	0.254	75	1665
3–2	0.134	0.254	74	1631
3–3	0.134	0.249	74	1663
3–4	0.134	0.253	74	1637
3–5	0.136	0.253	77	1678
			Avg	1655
			σ*	19.96

*σ = Standard Deviation (with N-1 weighting)

(1) NOTE: Use for comparative purposes only, not design criteria.

TABLE 9. THREE POINT INTERLAMINAR SHEAR TEST SPECIMEN BREAKDOWN (Continued)

Specimen Group — NO. 4

600^{o}F, Vacuum Pressure Only

Tested Per ASTM D2344-76:
Recommended Support Span = 5t
Recommended Specimen Length = 7t
Recommended Rate of Cross Head Motion = 0.05 in./min

Specimen No.	t (in.)	w (in.)	Load (lbf)	Shear Strength (psi) (1)
4–1	0.141	0.255	61	1272
4–2	0.141	0.256	65	1351
4–3	0.141	0.256	67	1392
4–4	0.140	0.255	68	1429
4–5	0.140	0.256	64	1339
			Avg	1357
			σ*	59.15

*σ = Standard Deviation (with N-1 weighting)

(1) NOTE: Use for comparative purposes only, not design criteria.

TABLE 9. THREE POINT INTERLAMINAR SHEAR TEST
SPECIMEN BREAKDOWN (Continued)

Specimen Group — NO. 5

650^{o}F, Vacuum Pressure Only

Tested Per ASTM D2344-76:
Recommended Support Span = 5t
Recommended Specimen Length = 7t
Recommended Rate of Cross Head
Motion = 0.05 in./min

Specimen No.	t (in.)	w (in.)	Load (lbf)	Shear Strength (psi) (1)
5–1	0.164	0.257	104	1851
5–2	0.164	0.257	98	1744
5–3	0.165	0.254	118	2112
5–4	0.163	0.256	121	2175
5–5	0.163	0.257	95	1701
			Avg	1917
			σ*	215.37

*σ = Standard Deviation (with N-1 weighting)

(1) NOTE: Use for comparative purposes only, not design criteria.

TABLE 9. THREE POINT INTERLAMINAR SHEAR TEST SPECIMEN BREAKDOWN (Continued)

Specimen Group — NO. 5A

650°F, Vacuum Pressure Only

Tested Per ASTM D2344-76:
Recommended Support Span = 5t
Recommended Specimen Length = 7t
Recommended Rate of Cross Head Motion = 0.05 in./min

Specimen No.	t (in.)	w (in.)	Load (lbf)	Shear Strength (psi) (1)
5A–1	0.156	0.260	93	1720
5A–2	0.156	0.259	98	1819
5A–3	0.156	0.259	95	1763
5A–4	0.155	0.255	V O	I D
5A–5	0.156	0.258	97	1808
5A–6	0.157	0.256	101	1885
			Avg	1799
			σ*	62.0

*σ = Standard Deviation (with N-1 weighting)

(1) NOTE: Use for comparative purposes only, not design criteria.

TABLE 9. THREE POINT INTERLAMINAR SHEAR TEST SPECIMEN BREAKDOWN (Continued)

Specimen Group — NO. 6

450°F, Vacuum Plus Light Die Pressure

Tested Per ASTM D2344-76:
Recommended Support Span = 5t
Recommended Specimen Length = 7t
Recommended Rate of Cross Head Motion = 0.05 in./min

Specimen No.	t (in.)	w (in.)	Load (lbf)	Shear Strength (psi) (1)
6–1	0.154	0.259	87	1636
6–2	0.155	0.253	88	1683
6–3	0.155	0.257	95	1789
6–4	0.156	0.257	92	1721
6–5	0.156	0.257	96	1796
			Avg	1725
			σ*	68.63

*σ = Standard Deviation (with N-1 weighting)

(1) NOTE: Use for comparative purposes only, not design criteria.

TABLE 9. THREE POINT INTERLAMINAR SHEAR TEST
SPECIMEN BREAKDOWN (Continued)

Specimen Group — NO. 6A
450^{o}F, Vacuum Plus Light Die Pressure

Tested Per ASTM D2344-76:
Recommended Support Span = 5t
Recommended Specimen Length = 7t
Recommended Rate of Cross Head Motion = 0.05 in./min

Specimen No.	t (in.)	w (in.)	Load (lbf)	Shear Strength (psi) (1)
6A–1	0.157	0.255	96	1798
6A–2	0.157	0.257	98	1822
6A–3	0.156	0.259	93	1726
6A–4	0.153	0.258	101	1919
6A–5	0.157	0.259	94	1734
6A–6	0.155	0.260	108	2010
			Avg	1835
			σ*	110.66

*σ = Standard Deviation (with N-1 weighting)

(1) NOTE: Use for comparative purposes only, not design criteria.

TABLE 9. THREE POINT INTERLAMINAR SHEAR TEST SPECIMEN BREAKDOWN (Continued)

Specimen Group — NO. 7

500°F, Vacuum Plus Light Die Pressure

Tested Per ASTM D2344-76:
Recommended Support Span = 5t
Recommended Specimen Length = 7t
Recommended Rate of Cross Head Motion = 0.05 in./min

Specimen No.	t (in.)	w (in.)	Load (lbf)	Shear Strength (psi) (1)
7–1	0.132	0.257	84	1857
7–2	0.134	0.257	85	1851
7–3	0.134	0.259	88	1902
7–4	0.134	0.260	82	1765
7–5	0.135	0.260	88	1880
			Avg	1851
			σ*	52.14

*σ = Standard Deviation (with N-1 weighting)

(1) NOTE: Use for comparative purposes only, not design criteria.

TABLE 9. THREE POINT INTERLAMINAR SHEAR TEST SPECIMEN BREAKDOWN (Continued)

Specimen Group – NO. 8

550°F, Vacuum Plus Light Die Pressure

Tested Per ASTM D2344-76:
Recommended Support Span = 5t
Recommended Specimen Length = 7t
Recommended Rate of Cross Head Motion = 0.05 in./min

Specimen No.	t (in.)	w (in.)	Load (lbf)	Shear Strength (psi) (1)
8–1	0.132	0.255	66	1471
8–2	0.132	0.260	71	1552
8–3	0.132	0.259	70	1536
8–4	0.132	0.259	73	1601
8–5	0.134	0.256	72	1574
			Avg	1547
			σ*	48.90

*σ = Standard Deviation (with N-1 weighting)

(1) NOTE: Use for comparative purposes only, not design criteria.

TABLE 9. THREE POINT INTERLAMINAR SHEAR TEST SPECIMEN BREAKDOWN (Continued)

Specimen Group – NO. 9

600°F, Vacuum Plus Light Die Pressure

Tested Per ASTM D2344-76:
Recommended Support Span = 5t
Recommended Specimen Length = 7t
Recommended Rate of Cross Head Motion = 0.05 in./min

Specimen No.	t (in.)	w (in.)	Load (lbf)	Shear Strength (psi) (1)
9–1	0.136	0.256	65	1400
9–2	0.136	0.254	70	1520
9–3	0.137	0.255	66	1417
9–4	0.137	0.255	67	1438
9–5	0.138	0.255	67	1428
			Avg	1441
			σ*	46.57

*σ = Standard Deviation (with N-1 weighting)

(1) NOTE: Use for comparative purposes only, not design criteria.

TABLE 9. THREE POINT INTERLAMINAR SHEAR TEST SPECIMEN BREAKDOWN (Continued)

Specimen Group — NO. 10
650°F, Vacuum Plus Light Die Pressure

Tested Per ASTM D2344-76:
Recommended Support Span = 5t
Recommended Specimen Length = 7t
Recommended Rate of Cross Head Motion = 0.05 in./min

Specimen No.	t (in.)	w (in.)	Load (lbf)	Shear Strength (psi) (1)
10–1	0.134	0.253	62	1438
10–2	0.134	0.254	65	1432
10–3	0.134	0.256	64	1399
10–4	0.134	0.256	66	1443
10–5	0.135	0.256	68	1476
			Avg	1438
			σ*	27.50

*σ = Standard Deviation (with N-1 weighting)

(1) NOTE: Use for comparative purposes only, not design criteria.

TASK III
DETERMINATION OF SIMULATED R&M SOLVENT ATTACK EFFECTS ON PROTECTED AND UNPROTECTED LAMINATES

One of the unanswered questions with regard to polysulfone practicality in U.S. Army field operations is its susceptibility to attack by certain solvents. Methyl-ethyl-ketone and acetone are available to maintenance personnel and might be improperly used during repair operations, such as paint stripping or adhesive bonding preparation. Data are available on property reduction of reinforced polysulfone after twenty-four-hour immersion in solvent, but this is obviously an extreme and unrealistic criterion. Therefore, it was proposed that the degree of damage be assessed in the possible circumstance wherein a solvent soaked rag is rested upon a reinforced polysulfone laminate and remains for two-hours or until dry.

The effect of both MEK and acetone was examined on thin-skin two-ply laminates in both the painted and unpainted conditions. The Kevlar 49 style 285 fabric/polysulfone or polyphenylsulfone laminates prepared for this investigatory task were consolidated at 600°F and 100 psi for 30 minutes. To permit testing thin laminates, honeycomb sandwich panels were prepared by bonding the two-ply laminate skins to HRP-10 4.0 PCF honeycomb core with AF126 Grade 10 film adhesive and hot press curing at 30-50 psi at 250°F for 90 minutes.

For reasons of material availability and high material cost, we elected to use the two-ply (285 style Kevlar 49 fabric/polysulfone or polyphenylsulfone) laminate on only the compression face of the sandwich panel. Five available substitutes for use on the tension face of the sandwich panel were analyzed. One, two and three-ply laminates of readily available, in-house, material were checked in order to provide a minimum tensile strength of two times the Kevlar compression face strength and thus ensure a failure in the Kevlar 49/thermoplastic material. The chosen substitute was a precured three-ply fiberglass (1002 scotchply/epoxy) laminate, oriented at 0°/90°/0°.

Flexural testing was performed in accordance (per contractual requirement) with MIL-A-25463 – Military Specification – Adhesive, Metallic Structural Sandwich Construction; Section 4.6.7 – Normal Temperature Sandwich Flexure Test. Three exceptions to this test method were taken; three to five specimens per group were tested instead of six as recommended by MIL-A-25463, test set up and specimen size also differed from those prescribed in the military specification. Number of specimens and maximum size was dictated by the amount of the available material. Test set up and specimen size may be noted in Figure 10.

Utilizing the loading diagram and description of sectional areas shown in Figure 11, the maximum beam flexural strength was determined from the face sheet bending stress equation for the Kevlar 49/thermoplastic laminate as follows:

$$f_{b_1} = \frac{M}{hwt_1}$$

where:

M = maximum bending moment = $\frac{Pa}{2}$

h = distance between the upper and lower laminate centroidal axes = $0.475 + \frac{(0.018)}{2} + \frac{(0.03)}{2} = 0.499$

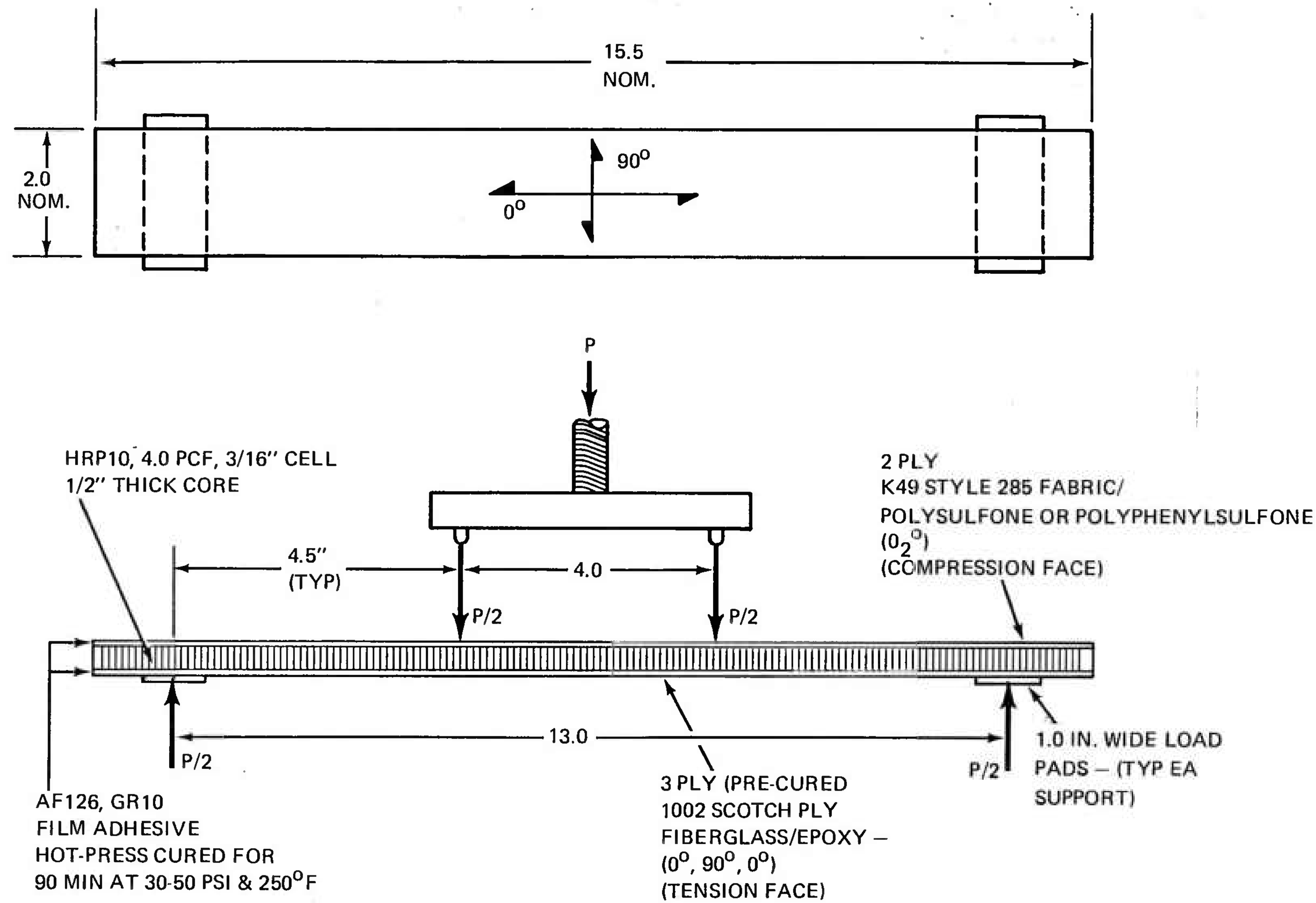

Figure 10. Typical Test Set-Up and Specimen Size for 4 Point Sandwich Flex Test

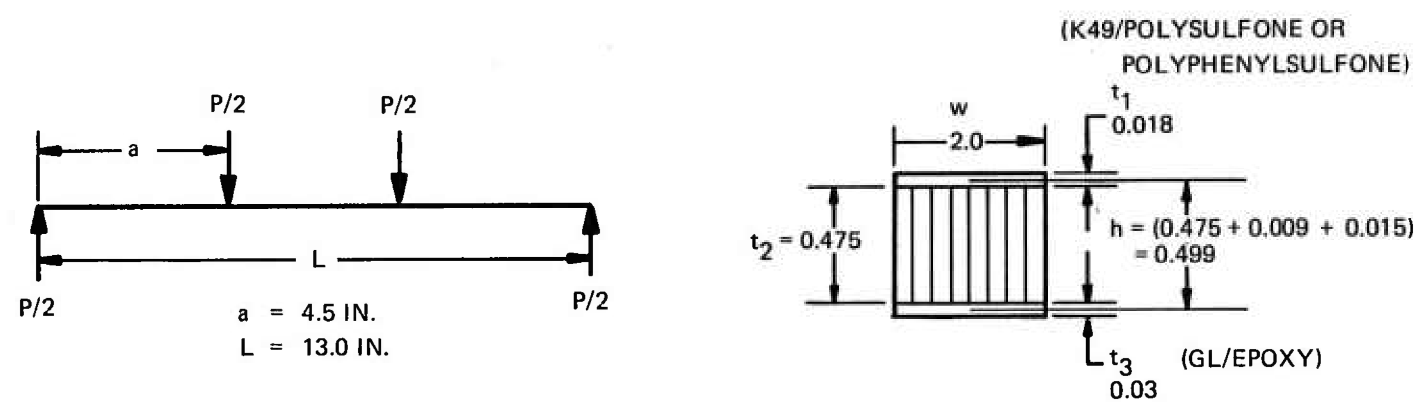

Figure 11. Sandwich Beam Sectional Area and Loading Diagram

w = specimen width

t = thickness of K49/polyphenylsulfone or polysulfone laminate = 0.018

Introducing these values into the bending stress equation a simplified equation now develops for the sandwich beam bending stress:

$$f_{b_1} = \frac{Pa}{2hwt_1} = \frac{P\ (4.5)}{2\ (0.499)\ W\ (0.018)}$$

$$f_{b_1} = 250.5\,\frac{P}{W}$$

Relative stiffness of the (nonhomogeneous material) sandwich beams may be obtained by the formula:

$$EI = \frac{P/2a}{24\ y}\ (3L^2 - 4a^2)$$

$$EI = (P/y)\left(\frac{a}{48}\right)\ (3L^2 - 4a^2)$$

where:

P/y = slope of the tangent to the initial straight line portion of the load-deflection curve (lbs per inch of deflection)

a = 4.5 In. (See Figure 11)

L = 13.0 In. (See Figure 11)

Substituting these values into the above equation, a reduced equation is now obtained for the relative stiffness of the honeycomb sandwich beams:

$$EI = (P/y)\left(\frac{4.5}{48}\right)[3\ (13^2) - 4\ (4.5^2)\ ]$$

$$EI = 39.9375\ (P/y)$$

Results of four point flex testing on honeycomb sandwich beams painted and unpainted, with and without exposure to solvent soaked rags, are summarized in Table 10. Individual specimen dimensions and test results are given in Table 11.

Specimens were painted in accordance with MIL-F-18264D – "Finishes: Organic, Weapons System, Application and Control of" – 23 April 1971.

Two primer coats were applied in accordance with MIL-F-23377 – "Primer Coating, Epoxy – Polyamide, Chemical and Solvent Resistant, for Weapons Systems" – 7 August 1962.

Two top coats were applied per MIL-L-46159 – "Lacquer, Acrylic, Low Reflective, Olive Drab" – 15 January 1973.

TABLE 10. SANDWICH BEAM FOUR POINT FLEX TEST SUMMARY

Specimen Material and Treatment							Number of Specimens in Group	Strength (ksi)		Stiffness (EI) psi-in.^{4} (x 10^4)	
Polysulfone (Udel)	Polyphenylsulfone (Radel)	Control No Solvent	Acetone	MEK	Painted	Unpainted		Avg	σ*	Avg	σ*
X		X			X		3	14.536	0.239	2.872	0.257
X		X				X	3	12.783	0.399	2.493	0.168
X			X		X		3	16.028	0.576	2.546	0.144
X			X			X	3	15.154	0.313	2.556	0.277
X				X	X		3	13.870	0.237	2.547	0.101
X				X		X	3	14.317	0.119	2.641	0.081
	X	X			X		4	16.271	1.896	1.916	0.108
	X	X				X	4	16.616	1.718	1.825	0.192
	X		X		X		5	18.420	1.451	2.084	0.153
	X		X			X	5	15.351	0.917	1.943	0.137
	X			X	X		3	16.717	0.870	2.480	0.272
	X			X		X	3	16.526	0.667	2.269	0.204

*σ = Standard Deviation (with N-1 weighting)

4-PT FLEX TEST 2-PLY KEVLAR 49 STYLE 285 FABRIC THERMOPLASTIC MATRICES
SANDWICH BEAMS

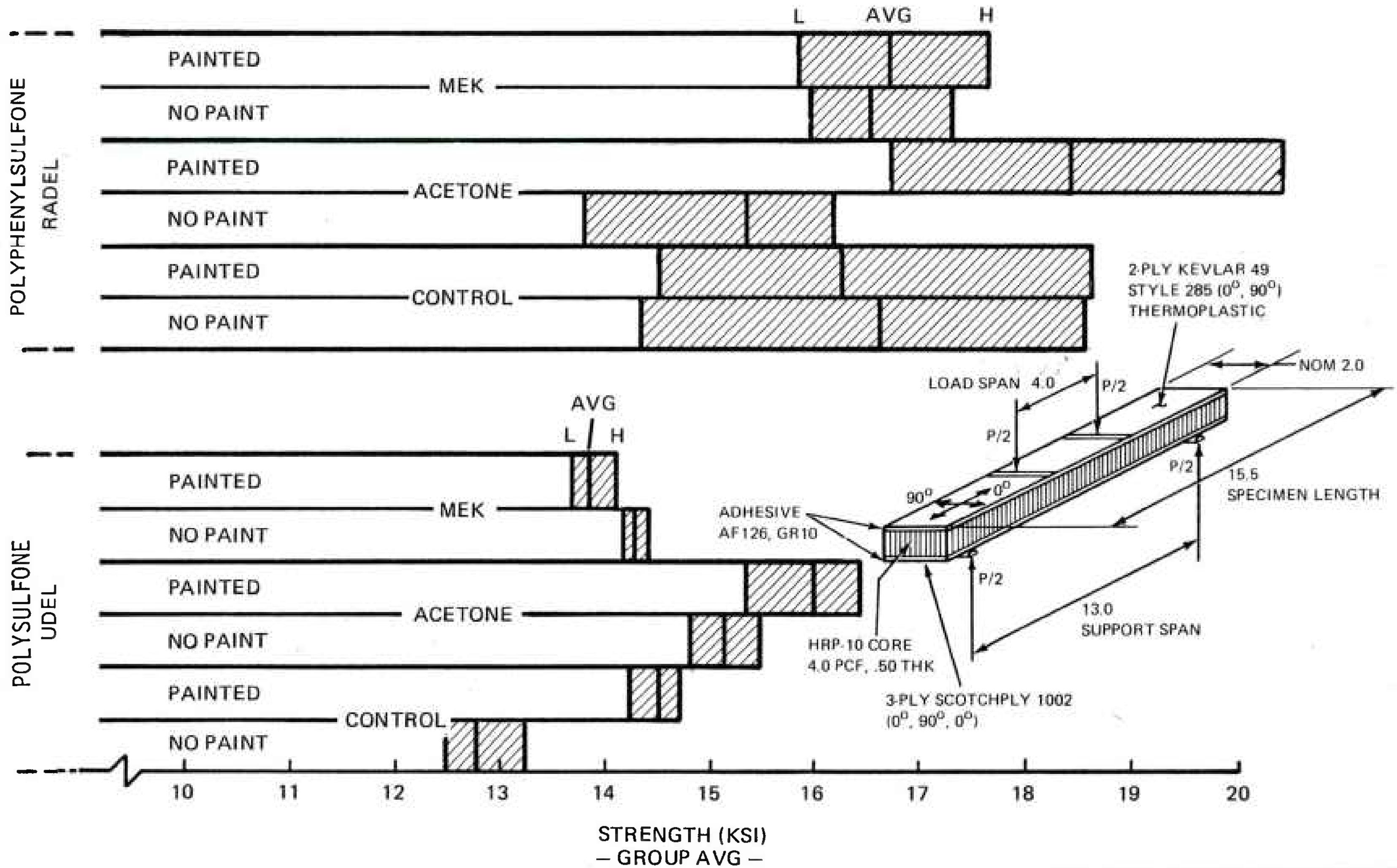

Figure 12. Flexural Strength vs Solvent Exposure

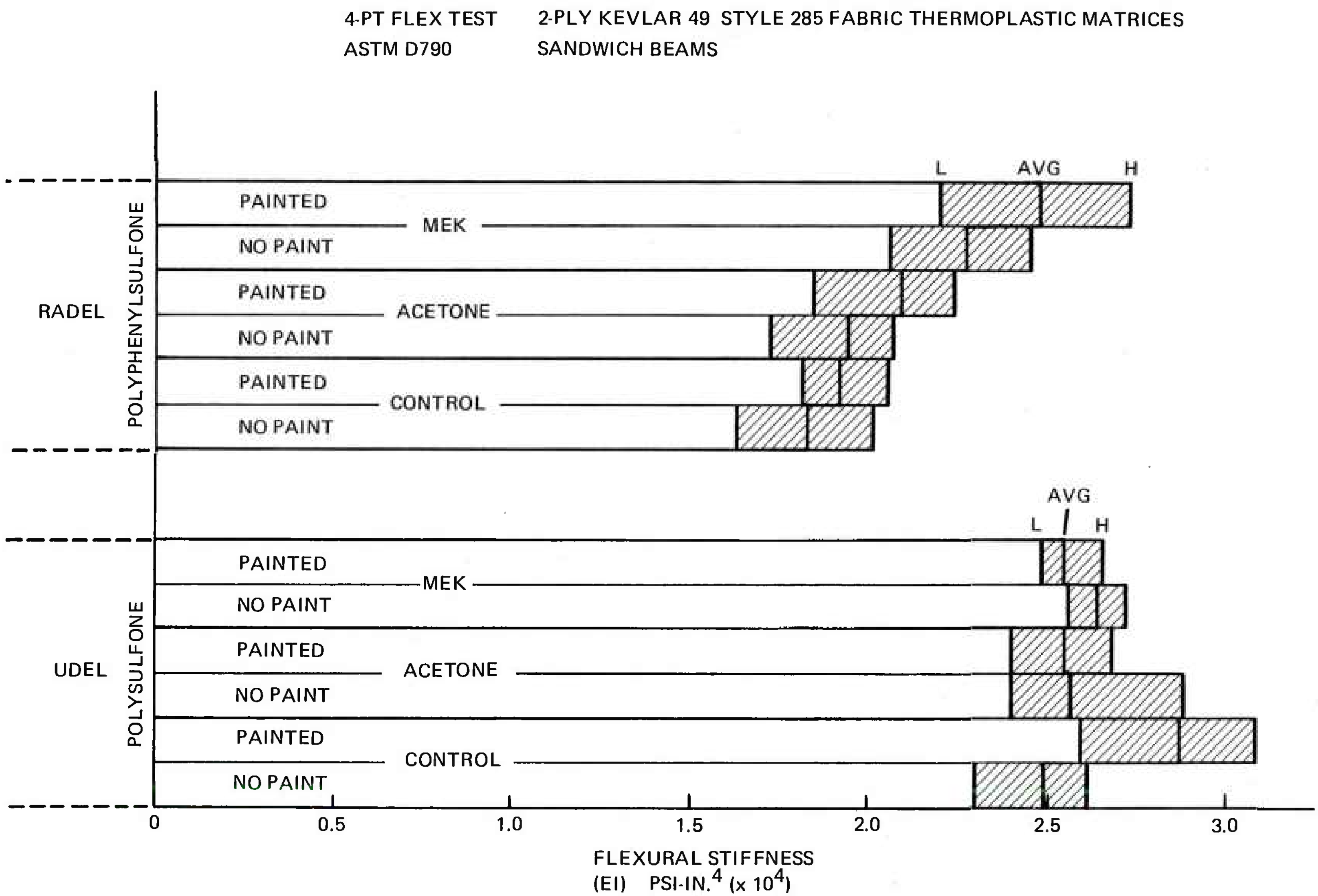

Figure 13. Flexural Stiffness vs Solvent Exposure

TABLE 11. SANDWICH BEAM SPECIMEN GROUP BREAKDOWN
FOUR POINT FLEX TEST RESULTS

SPECIMEN MATERIAL

Thermoplastic Compression Laminate	–	2 Ply Kevlar 49/Polysulfone Style 285 Fabric – (0^o_2 – orientation)
Tension Laminate	–	3 Ply 1002 Scotchply Fiberglass/Epoxy ($0^o/90^o$ orientation)
Core	–	HRP-10, 4.0 PCF, 3/16 in. Cell, Nom. 1/2 in. THK
Adhesive (Core to Skin)	–	AF-126, GR-10 Film Adhesive Hot Press Cured for 90 Minutes @ 250^oF and 30-50 psi

SOLVENT EXPOSURE – NONE – CONTROL GROUP

TEST SPEED/TEST TEMPERATURE – Rate of Crosshead Motion = 0.02 in. per min/Room Temperature

Specimen No.	w (in.)	t (in.)	Painted	Max Load (lbs)	Flex Strength (ksi)	Deflection at Max Load (in.)	P/Y	Stiffness EI psi – $in.^4(x10^4)$
B4	2.178	0.539	Yes	124	14.262	0.250	162/0.25	2.588
B5	2.138	0.539	Yes	125	14.646	0.30	184/0.25	2.939
B6	2.130	0.538	Yes	125	14.701	0.30	174/0.225	3.088
				Avg	14.536			2.872
				σ^*	0.239			0.257

σ^* = Standard Deviation (with N-1 Weighting)

TABLE 11. SANDWICH BEAM SPECIMEN GROUP BREAKDOWN
FOUR POINT FLEX TEST RESULTS (Continued)

SPECIMEN MATERIAL

Thermoplastic Compression Laminate	–	2 Ply Kevlar 49/Polysulfone Style 285 Fabric – (0^o_2 – orientation)
Tension Laminate	–	3 Ply 1002 Scotchply Fiberglass/Epoxy ($0^o/90^o$ orientation)
Core	–	HRP-10, 4.0 PCF, 3/16 in. Cell, Nom. 1/2 in. THK
Adhesive (Core to Skin)	–	AF-126, GR-10 Film Adhesive Hot Press Cured for 90 Minutes @ 250^oF and 30-50 psi
SOLVENT EXPOSURE	–	NONE – CONTROL GROUP
TEST SPEED/TEST TEMPERATURE	–	Rate of Crosshead Motion = 0.02 in. per min/Room Temperature

Specimen No.	w (in.)	t (in.)	Painted	Max Load (lbs)	Flex Strength (ksi)	Deflection at Max Load (in.)	P/Y	Stiffness EI psi – in.^{4}(x10^4)
B1	2.062	0.535	No	103	12.513	0.225	245/0.425	2.302
B2	2.148	0.535	No	108	12.595	0.275	160/0.25	2.556
B2	2.100	0.536	No	111	13.241	0.2675	164/0.25	2.620
				Avg	12.783			2.493
				σ^*	0.399			0.168

σ^* = Standard Deviation (with N-1 Weighting)

TABLE 11. SANDWICH BEAM SPECIMEN GROUP BREAKDOWN
FOUR POINT FLEX TEST RESULTS (Continued)

SPECIMEN MATERIAL

Thermoplastic Compression Laminate — 2 Ply Kevlar 49/ Polysulfone Style 285 Fabric — (0^{0}_{2} – orientation)

Tension Laminate — 3 Ply 1002 Scotchply Fiberglass/Epoxy ($0^{o}/90^{o}$ orientation)

Core — HRP-10, 4.0 PCF, 3/16 in. Cell, Nom. 1/2 in. THK

Adhesive (Core to Skin) — AF-126, GR-10 Film Adhesive Hot Press Cured for 90 Minutes @ 250^{o}F and 30-50 psi

SOLVENT EXPOSURE — MEK

TEST SPEED/TEST TEMPERATURE — Rate of Crosshead Motion = 0.02 in. per min/Room Temperature

Specimen No.	w (in.)	t (in.)	Painted	Max Load (lbs)	Flex Strength (ksi)	Deflection at Max Load (in.)	P/Y	Stiffness EI psi – in.^{4}(x10^{4})
A1	2.090	0.539	Yes	118	14.143	0.225	150/0.225	2.663
A2	2.100	0.540	Yes	115	13.718	0.225	140/0.225	2.485
A3	2.150	0.540	Yes	118	13.748	0.35	156/0.25	2.492
				Avg	13.870			2.547
				σ*	0.237			0.101

σ* = Standard Deviation (with N-1 Weighting)

TABLE 11. SANDWICH BEAM SPECIMEN GROUP BREAKDOWN
FOUR POINT FLEX TEST RESULTS (Continued)

SPECIMEN MATERIAL

Thermoplastic Compression Laminate — 2 Ply Kevlar 49/Polysulfone Style 285 Fabric — (0^{o}_{2} – orientation)

Tension Laminate — 3 Ply 1002 Scotchply Fiberglass/Epoxy ($0^{o}/90^{o}$ orientation)

Core — HRP-10, 4.0 PCF, 3/16 in. Cell, Nom. 1/2 in. THK

Adhesive (Core to Skin) — AF-126, GR-10 Film Adhesive Hot Press Cured for 90 Minutes @ 250^{o}F and 30-50 psi

SOLVENT EXPOSURE — MEK

TEST SPEED/TEST TEMPERATURE — Rate of Crosshead Motion = 0.02 in. per min/Room Temperature

Specimen No.	w (in.)	t (in.)	Painted	Max Load (lbs)	Flex Strength (ksi)	Deflection at Max Load (in.)	P/Y	Stiffness EI psi – in.^{4}($\times 10^{4}$)
A7	2.142	0.535	No	122	14.268	0.40	166/0.25	2.652
A8	2.132	0.535	No	123	14.452	0.3875	160/0.25	2.556
A9	2.130	0.539	No	121	14.230	0.35	170/0.25	2.716
				Avg	14.317			2.641
				σ^*	0.119			0.081

σ^* = Standard Deviation (with N-1 Weighting)

TABLE 11. SANDWICH BEAM SPECIMEN GROUP BREAKDOWN
FOUR POINT FLEX TEST RESULTS (Continued)

SPECIMEN MATERIAL

Thermoplastic Compression Laminate	—	2 Ply Kevlar 49/Polysulfone Style 285 Fabric — (0^o_2 — orientation)
Tension Laminate	—	3 Ply 1002 Scotchply Fiberglass/Epoxy ($0^o/90^o$ orientation)
Core	—	HRP-10, 4.0 PCF, 3/16 in. Cell, Nom. 1/2 in. THK
Adhesive (Core to Skin)	—	AF-126, GR-10 Film Adhesive Hot Press Cured for 90 Minutes @ 250^oF and 30-50 psi

SOLVENT EXPOSURE — ACETONE

TEST SPEED/TEST TEMPERATURE — Rate of Crosshead Motion = 0.02 in. per min/Room Temperature

Specimen No.	w (in.)	t (in.)	Painted	Max Load (lbs)	Flex Strength (ksi)	Deflection at Max Load (in.)	P/Y	Stiffness EI psi – in.^{4}(x10^4)
A4	2.112	0.541	Yes	137	16.249	0.35	160/0.25	2.556
A5	2.118	0.540	Yes	130	15.375	0.30	168/0.25	2.684
A6	2.100	0.539	Yes	138	16.461	0.40	150/0.25	2.396
				Avg	16.028			2.546
				σ*	0.576			0.144

σ* = Standard Deviation (with N-1 Weighting)

TABLE 11. SANDWICH BEAM SPECIMEN GROUP BREAKDOWN
FOUR POINT FLEX TEST RESULTS (Continued)

SPECIMEN MATERIAL

Thermoplastic Compression Laminate — 2 Ply Kevlar 49/ Polysulfone
Style 285 Fabric — (0°_{2} – orientation)

Tension Laminate — 3 Ply 1002 Scotchply Fiberglass/Epoxy ($0^{\circ}/90^{\circ}$ orientation)

Core — HRP-10, 4.0 PCF, 3/16 in. Cell, Nom. 1/2 in. THK

Adhesive (Core to Skin) — AF-126, GR-10 Film Adhesive Hot Press Cured for 90 Minutes @ 250°F and 30-50 psi

SOLVENT EXPOSURE — ACETONE

TEST SPEED/TEST TEMPERATURE — Rate of Crosshead Motion = 0.02 in. per min/Room Temperature

Specimen No.	w (in.)	t (in.)	Painted	Max Load (lbs)	Flex Strength (ksi)	Deflection at Max Load (in.)	P/Y	Stiffness EI psi – in.^{4}($\times 10^4$)
A10	2.160	0.537	No	128	14.844	0.375	90/0.125	2.876
A11	2.100	0.539	No	127	15.149	0.425	120/0.2	2.396
A12	2.170	0.540	No	134	15.469	0.475	150/0.25	2.396
				Avg	15.154			2.556
				σ*	0.313			0.277

σ* = Standard Deviation (with N-1 Weighting)

TABLE 11. SANDWICH BEAM SPECIMEN GROUP BREAKDOWN
FOUR POINT FLEX TEST RESULTS (Continued)

SPECIMEN MATERIAL

Thermoplastic Compression Laminate	—	2 Ply Kevlar 49/Polyphenylsulfone Style 285 Fabric — (0^o_2 — orientation)
Tension Laminate	—	3 Ply 1002 Scotchply Fiberglass/Epoxy ($0^o/90^o$ orientation)
Core	—	HRP-10, 4.0 PCF, 3/16 in. Cell, Nom. 1/2 in. THK
Adhesive (Core to Skin)	—	AF-126, GR-10 Film Adhesive Hot Press Cured for 90 Minutes @ 250^oF and 30-50 psi
SOLVENT EXPOSURE	—	NONE — CONTROL GROUP
TEST SPEED/TEST TEMPERATURE	—	Rate of Crosshead Motion = 0.02 in. per min/Room Temperature

Specimen No.	w (in.)	t (in.)	Painted	Max Load (lbs)	Flex Strength (ksi)	Deflection at Max Load (in.)	P/Y	Stiffness EI psi — in.^{4}(x10^4)
3–4	2.080	0.535	Yes	142	17.101	0.60	230/0.475	1.934
3–5	2.068	0.536	Yes	120	14.536	0.4625	260/0.575	1.806
3–6	2.018	0.537	Yes	120	14.896	0.450	175/0.375	1.864
1–2	2.012	0.538	Yes	149	18.551	0.625	335/0.65	2.058
				Avg	16.271			1.916
				σ^*	1.896			0.108

σ^* = Standard Deviation (with N-1 Weighting)

TABLE 11. SANDWICH BEAM SPECIMEN GROUP BREAKDOWN
FOUR POINT FLEX TEST RESULTS (Continued)

SPECIMEN MATERIAL

Thermoplastic Compression Laminate — 2 Ply Kevlar 49/Polyphenylsulfone Style 285 Fabric – (0^{o}_{2} – orientation)
Tension Laminate — 3 Ply 1002 Scotchply Fiberglass/Epoxy ($0^{o}/90^{o}$ orientation)
Core — HRP-10, 4.0 PCF, 3/16 in. Cell, Nom. 1/2 in. THK
Adhesive (Core to Skin) — AF-126, GR-10 Film Adhesive Hot Press Cured for 90 Minutes @ 250^{o}F and 30-50 psi

SOLVENT EXPOSURE — NONE – CONTROL GROUP

TEST SPEED/TEST TEMPERATURE — Rate of Crosshead Motion = 0.02 in. per min/Room Temperature

Specimen No.	w (in.)	t (in.)	Painted	Max Load (lbs)	Flex Strength (ksi)	Deflection at Max Load (in.)	P/Y	Stiffness EI psi – in.^{4}(x10^4)
3–1	1.830	0.535	No	135	18.480	0.65	315/0.775	1.623
3–2	1.982	0.536	No	133	16.809	0.675	245/0.575	1.702
3–3	2.152	0.537	No	123	14.318	0.50	245/0.5	1.951
1–5	2.006	0.541	No	135	16.858	0.575	240/0.475	2.018
				Avg	16.616			1.825
				σ*	1.718			0.192

σ* = Standard Deviation (with N-1 Weighting)

TABLE 11. SANDWICH BEAM SPECIMEN GROUP BREAKDOWN
FOUR POINT FLEX TEST RESULTS (Continued)

SPECIMEN MATERIAL

Thermoplastic Compression Laminate	—	2 Ply Kevlar 49/Polyphenylsulfone Style 285 Fabric – (0^o_2 – orientation)
Tension Laminate	—	3 Ply 1002 Scotchply Fiberglass/Epoxy ($0^o/90^o$ orientation)
Core	—	HRP-10, 4.0 PCF, 3/16 in. Cell, Nom. 1/2 in. THK
Adhesive (Core to Skin)	—	AF-126, GR-10 Film Adhesive Hot Press Cured for 90 Minutes @ 250^oF and 30-50 psi
SOLVENT EXPOSURE	—	MEK
TEST SPEED/TEST TEMPERATURE	—	Rate of Crosshead Motion = 0.02 in. per min/Room Temperature

Specimen No.	w (in.)	t (in.)	Painted	Max Load (lbs)	Flex Strength (ksi)	Deflection at Max Load (in.)	P/Y	Stiffness EI psi – in.^{4}(x10^4)
11–4	2.030	0.535	Yes	135	16.659	0.50	235/0.375	2.503
11–5	2.130	0.535	Yes	135	15.877	0.525	240/0.35	2.739
11–6	2.062	0.535	Yes	145	17.615	0.55	275/0.5	2.197
				Avg	16.717			2.480
				σ^*	0.870			0.272

σ^* =Standard Deviation (with N-1 Weighting)

TABLE 11. SANDWICH BEAM SPECIMEN GROUP BREAKDOWN
FOUR POINT FLEX TEST RESULTS (Continued)

SPECIMEN MATERIAL

Thermoplastic Compression Laminate	—	2 Ply Kevlar 49/Polyphenylsulfone Style 285 Fabric — (0^o_2 — orientation)
Tension Laminate	—	3 Ply 1002 Scotchply Fiberglass/Epoxy ($0^o/90^o$ orientation)
Core	—	HRP-10, 4.0 PCF, 3/16 in. Cell, Nom. 1/2 in. THK
Adhesive (Core to Skin)	—	AF-126, GR-10 Film Adhesive Hot Press Cured for 90 Minutes @ 250^oF and 30-50 psi
SOLVENT EXPOSURE	—	MEK
TEST SPEED/TEST TEMPERATURE	—	Rate of Crosshead Motion = 0.02 in. per min/Room Temperature

Specimen No.	w (in.)	t (in.)	Painted	Max Load (lbs)	Flex Strength (ksi)	Deflection at Max Load (in.)	P/Y	Stiffness EI psi — $in.^4 (x10^4)$
11–1	2.070	0.532	No	132	15.974	0.525	230/0.375	2.449
11–2	2.070	0.532	No	135	16.337	0.625	275/0.475	2.312
11–3	2.060	0.533	No	142	17.267	0.625	205/0.4	2.047
				Avg	16.526			2.269
				σ^*	0.667			0.204

σ^* = Standard Deviation (with N-1 Weighting)

TABLE 11. SANDWICH BEAM SPECIMEN GROUP BREAKDOWN FOUR POINT FLEX TEST RESULTS (Continued)

SPECIMEN MATERIAL

Thermoplastic Compression Laminate	—	2 Ply Kevlar 49/ Polyphenylsulfone Style 285 Fabric — (0^o_2 – orientation)
Tension Laminate	—	3 Ply 1002 Scotchply Fiberglass/Epoxy ($0^o/90^o$ orientation)
Core	—	HRP-10, 4.0 PCF, 3/16 in. Cell, Nom. 1/2 in. THK
Adhesive (Core to Skin)	—	AF-126, GR-10 Film Adhesive Hot Press Cured for 90 Minutes @ 250°F and 30-50 psi
SOLVENT EXPOSURE	—	ACETONE
TEST SPEED/TEST TEMPERATURE	—	Rate of Crosshead Motion = 0.02 in. per min/Room Temperature

Specimen No.	w (in.)	t (in.)	Painted	Max Load (lbs)	Flex Strength (ksi)	Deflection at Max Load (in.)	P/Y	Stiffness EI psi – in.^{4}(x10^4)
4–4	2.050	0.540	Yes	158	19.307	0.65	287/0.625	1.834
4–5	2.078	0.540	Yes	145	17.480	0.70	225/0.425	2.114
4–6	1.930	0.541	Yes	157	20.377	0.5625	280/0.5	2.237
1–1	2.022	0.539	Yes	147	18.211	0.625	400/0.7375	2.166
1–3	2.022	0.541	Yes	135	16.725	0.55	285/0.55	2.069
				Avg	18.420			2.084
				σ*	1.451			0.153

σ* = Standard Deviation (with N-1 Weighting)

TABLE 11. SANDWICH BEAM SPECIMEN GROUP BREAKDOWN
FOUR POINT FLEX TEST RESULTS (Continued)

SPECIMEN MATERIAL

Thermoplastic Compression Laminate	—	2 Ply Kevlar 49/ Polyphenylsulfone Style 285 Fabric – (0^o_2 – orientation)
Tension Laminate	—	3 Ply 1002 Scotchply Fiberglass/Epoxy ($0^o/90^o$ orientation)
Core	—	HRP-10, 4.0 PCF, 3/16 in. Cell, Nom. 1/2 in. THK
Adhesive (Core to Skin)	—	AF-126, GR-10 Film Adhesive Hot Press Cured for 90 Minutes @ 250°F and 30-50 psi

SOLVENT EXPOSURE — ACETONE

TEST SPEED/TEST TEMPERATURE — Rate of Crosshead Motion = 0.02 in. per min/Room Temperature

Specimen No.	w (in.)	t (in.)	Painted	Max Load (lbs)	Flex Strength (ksi)	Deflection at Max Load (in.)	P/Y	Stiffness EI psi – in.^{4}(x10^4)
4–1	1.810	0.538	No	100	13.840	0.50	140/0.325	1.720
4–2	1.978	0.537	No	120	15.197	0.525	245/0.5	1.957
4–3	2.000	0.538	No	125	15.656	0.675	290/0.6	1.930
1–4	2.003	0.538	No	127	15.883	0.55	285/0.55	2.069
1–6	2.013	0.538	No	130	16.177	0.40	255/0.50	2.037
				Avg	15.351			1.943
				σ^*	0.917			0.137

σ^* = Standard Deviation (with N-1 Weighting)

TASK IV
PANEL FABRICATION

Six (6) panels of 5-ply Kevlar 49/polysulfone were fabricated for AMMRC testing All panels were 17.75" x 18.0" x 0.040" in size. Five ply laminates of Kevlar 49 style 285 fabric, pre-impregnated with P1700 polysulfone using methylene chloride solvent dispersal, were consolidated at 600^{o}F and 100 psig for 30 minutes. Postforming parameters for each specimen are contained in Table 12. Figure 4 shows the metal tools utilized in thermoform ng the consolidated blanks for Task II, Task III, and Task IV.

TABLE 12. POST FORMING PARAMETERS FOR AMMRC PANELS

Specimen No.	Max Part Temp During Postforming Operation	Postforming Pressure	Bottom Die Trave Into Part
1	450	Vacuum Plus Light Die Pressure	3/4 In.
2	500	Vacuum Plus Light Die Pressure	3/4 In.
3	550	Vacuum Plus Light Die Pressure	3/4 In.
4	600	Vacuum Plus Light Die Pressure	3/4 In.
5	650	Vacuum Plus Light Die Pressure	3/4 In.
Control	— No Postforming Process —		

6 Panels Total

Polybutylene Terapthalate	Products	Characteristics
	Tenite 6 PRO Deroton Tap 10 Hostadur BVP 860 Celanex 2001 Valox 310	Principally a molding compound available in unreinforced grades • Low deflection temperature under-load • Tensile strength < Nylon 6.6 (8000 psi) • Notch sensitive under impact – low temperature • Affected by chlorinated hydro-carbon solvents (Methylene Chloride) • Low water absorption • Melts at 435^{o}F • Processes at 482^{o}F • Creeps at elevated temperature (120^{o}F)

Conclusions

While this polymer processes in desirable temperature range and exhibits generally good chemical resistance, it is attacked by chlorinated hydrocarbon solvents, such as methylene chloride, and has poor elevated temperature creep properties, within service temperature range of –65^{o} to +165^{o}F.

Recommendation

Does not appear to warrant development for continuous fiber reinforced composites for aircraft.

Nylon 6.6

Basic drawback is water absorption and creep, making long term environmental degradation likely.

Not recommended as the matrix in fiber reinforced composites for aircraft.

Polysulfone (Udel) P-1700

Recommended for continued use in manufacturing technology development because of large data base. Should be replaced with systems impervious to aromatic and chlorinated hydrocarbons, when available.

Polyphenysulfone 5010 (Radel)

Processes similar to polysulfone — Superior in resistance to methylene chloride. Attacked by MIL-H-83306 Phosphate Ester type hydraulic fluid.

Should be considered for P-1700 replacement on military helicopters.

PKXA .41, .517 Silane End-Capped Polysulfone

Lower mechanical properties than P-1700. Cross-linking stability suspect at RT, degrading formability and properties. Not reprocessable. Resistant to methylene chloride.

Solvent resistance achieved through cross-linking which occurs at room temperature aging environment. Material not believed to be reformable as result of cross-linking. Not recommended for further development.

Polyether Sulfone 300P

Superior solvent resistance to methylene chloride over P-1700. Processes at 50°-100°F higher temperature than P-1700. Good properties through 350°F, fluid immersion in common aircraft fluids in stressed condition caused delamination.

Not recommended for further development.

KM-1 (600P)

Limited tests encouraging — continue evaluation.

Polyarylsulfone CM-1

Limited tests encouraging — continue evaluation.

General

Development of hot melt preimpregnation has shown encouraging results with Udel P-1700 and CM-1 polyarylsulfone.

Emergence of hot roll continuous impregnation from film and continuous fibers may make highly solvent resistant polymers candidates for further development.

Further hot melt development recommended with candidates offered by suppliers in film form.

TASK II & III – CONCLUSIONS AND RECOMMENDATIONS

The experimental portion of this program has been performed to examine the effects of post-forming conditions on the mechanical properties of a polysulfone composite laminate and to determine the effects of solvent exposure on the strength of thin thermoplastic laminates.

The flexural mechanical properties of a laminate comprising woven Kevlar 49 fabric/P1700 polysulfone decrease with increasing thermoforming temperature. Postforming at 450°F shows no difference in flexural strength with respect to the non-postformed control laminate. The strength decreases with increasing postforming temperature (to 650°F) to a minimum of about 62% of the control. Visual examination of the specimens show no discernable difference in any of the specimens except that there is an increase in the specimen thickness with increasing post-forming temperature. This swelling affects the calculated stresses but does not alter the general trend of decreasing strength with increasing temperature. The flexural modulus also shows the same trend but to a lesser degree.

The interlaminar, short beam shear specimens also showed a reduction in shear strength with increasing postforming temperature.

There appears to be no difference in either the flexural or short beam shear test results with respect to the postforming pressures; vacuum only or vacuum with light die pressure.

The reference (1) investigation originally identified the non-reversible swelling which occurs in a thermoforming cycle, in which a pre-consolidated flat laminate is heated to post-forming temperatures (450°–500°F) under ambient pressure. The effort in the current study was directed at determining the effect of this swelling on the matrix dominated post formed material properties.

Determination of the physical or chemical principles causing the swelling was not addressed within the scope of the contract. It is speculated however, that the unrestrained expansion of the polysulfone at temperatures above glass transition results in deconsolidation of the laminate; i.e., the polymer, which is not bound homogenously by elastic cross-linking expands from the mechanical molecular arrangement created in the 100 psi, 600°F consolidation cycle and the thermal contraction during cool-down produces insufficient force to regain the original thickness. This loss of densification must inevitably have an effect on shear strength and fiber stabilization in compression/flexure. Further investigation might be directed toward non-destructive test of the laminate, GPC or HPLC characterization, TGA or TMA analysis. Isothermal decomposition is not indicated at 250°F for up to 1000 hours exposure with P1700 and Kevlar 49, Reference 14, hence it is not immediately suspect at 450° to 600° for 1 minute aging.

The matrix degradation appears also to be time related (see Reference 1), the longer at elevated temperature, the greater the strength loss. Therefore, in the design and manufacturing of structural elements using thermoplastics, it should be planned to postform at the lowest possible temperature and shortest time consistent with forming requirements and to use design mechanical properties consistent with the material strength and stiffness after such a temperature-time exposure.

It has been determined from the Task III test results that when realistically exposed to acetone or MEK the two thermoplastic resins tested (polyphenylsulfone-polysulfone) evidenced no strength or stiffness loss. In fact, the test results indicate an improvement in strength for the (P1700) polysulfone whn painted and/or exposed to acetone. Although there were only 3 replicates per condition, and all the data may be considered to be within normal test scatter, the trend of strength improvement appears correct. Some loss in strength is indicated when unpainted polyphenylsulfone is exposed to acetone. The painting appears to protect the Polyphenylsulfone from the acetone for the kind of exposure used in this experiment. The polyphenylsulfone exposed to MEK, painted or unpainted, shows no strength difference with respect to the control specimens.

These results indicate that the two thermoplastic resins tested could be put into normal U.S. Army field operations without undue concern for exposure to available solvents. Normal cleaning and wiping operations would not degrade strength or stiffness. Immersion is detrimental and normal wiping is not. The question that arises is "what length of the time and severity of exposure is detrimental and what visual signs of degradation exist?" If an unnatural exposure went undetected during the event, "what visual signs would exist that would indicate that corrective action would be necessary?" Information from actual field service exposure is the subject of further U.S. Army investigation under separate contract.

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3. The American Society for Testing Materials Document D2344-76, "Standard Test Method for Apparent Interlaminar Shear Strength of Parallel Fiber Composites by Short-Beam Method".

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5. Reinforced Thermoplastics, Titow and Lanham, 1975, Halsted Press, John Wiley and Sons, Inc., N.Y.C.

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9. Advanced Thermoplastic Composite Development, Hill, House, Hoggatt, Boeing Aerospace, NASC Contract N00019-77-C-0561, dated May, 1979.

10. Development of a Low Cost Graphite Reinforced Composite Secondary Structural Component, Goad, Wennhold, G.D. Convair Report NADC-77187-30, Contract N62269-74-C-0369, dated 10/77.

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12. Development of Hybrid Thermoplastic Composites, Hill, Hoggatt, Boeing Aerospace, Report No. D180-18752-3, NASC Contract N00019-76-C-0170, dated March 1977.

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17. Development and Applications of Continuous Graphite Reinforced Thermoplastic Advanced Composites, Maximovitch, G.D. Convair, SAMPE Paper, dated 1974.

18. Boeing Vertol/DuPont IR&D Thermoplastic Matrix Screening Discussions and Interlaminar Shear Tests, Hoffstedt, Dr. Funer, Dr. Juan.

19. Boeing Vertol Fabrication Investigation, IR&D Compound Curvature Fairings with E-Glass/Phenoxy, E-Glass Polysulfone, Hoffstedt, Pinckney, 1976.

20. Investigation of Reinforced Thermoplastics for Naval Aircraft Structural Applications, Hoggatt, BAC, Boeing Report No. D180-17531-1, Contract N00019-72-C-0526, dated 5/73.

21. Interim Technical Report Reinforced Thermoplastic Application to Helicopter Secondary Structures, Hoffstedt, Ritter, Swatton, Boeing Vertol Report No. D210-11550-1, Contract DAAK51-79-C-0019, dated 9/79.

APPENDIX A

INTRODUCTION

During the final in-house review of this report it was decided to research the limited published data available to date, and to wait for some current representative unpublished data from Seattle (BAC) obtained through the effort of an ongoing program. The comparison of data obtained under this contract with the published data[1] was favorable (e.g., interlaminar shear value of 3,050 psi with 61% fiber volume). However, the data later obtained from Seattle (BAC) exhibited much higher interlaminar shear values. It was then decided, at no direct cost to the Government, to verify the Seattle (BAC) findings using their specimen configuration of 7-ply Kevlar 49 style 285/P1700 polysulfone. Results provided confirmation of Seattle's (BAC) latest unpublished data. It remained incumbent upon Boeing Vertol to verify the interlaminar shear data (obtained under this contract), at no direct cost to the Government, using an in-house consolidated laminate (homogeneous 15-ply Kevlar 49 style 285/P1700 polysulfone). These results were of similar magnitude to the unpublished Seattle (BAC) data, one order of magnitude greater than data obtained under this contract and earlier published data. It then remained to validate or invalidate the configuration of a bonded "stack-up" specimen used under this contract (3 laminates comprised of 5-plys of Kevlar 49 style 285/P1700 polysulfone each, bonded together at 250°F and 50 psi for 60 minutes utilizing AF 163 Grade 10 film adhesive). Laminates were consolidated in-house but otherwise constructed in an identical manner. Test data showed lower values than a 15-ply homogeneous laminate, but, 64% higher values than the subcontracted consolidated material used under this contract.

OBJECTIVES

In order to understand why portions of the test data, obtained under this contract, were directly comparable with existing data[1] but relatively poor when compared to new data, it remained to logically and methodically retrace each step (including fabrication, testing, and final comparison) utilized to obtain the data in question and:

1) To validate BAC data (new, unpublished)

2) To evaluate the effect of secondary bonding upon interlaminar shear testing

3) To evaluate consolidation process

4) To study the effect of specimen geometry upon interlaminar shear testing

SPECIMEN FABRICATION

In an effort to verify the BAC (Seattle) unpublished interlaminar shear data, specimens were fabricated to the configuration used by BAC for their testing (see Figure A-1).

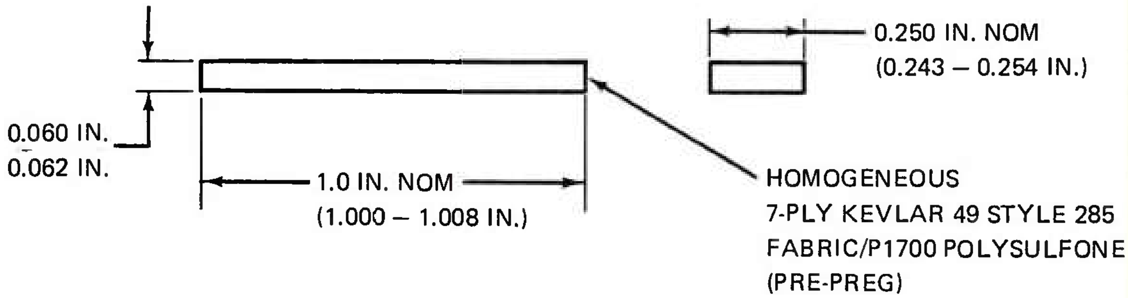

Figure A–1. 7-Ply Homogeneous Specimen

The 7-ply laminate was hot-press consolidated at 600°F with 100 PSIG for 30 minutes. After consolidation and cutting to size, ten of the twenty specimens were put into an oven for one minute at 550°F under no added pressure to simulate typical conditions of the thermoforming operation; the remaining ten specimens were to be control articles and therefore were not exposed to the aforementioned post-heating cycle. Subsequent interlaminar shear testing revealed values of the same order of magnitude as recorded in the BAC unpublished data.

Due to the above result, the interlaminar shear test specimens fabricated under this contract had then to be verified. Specimens were cut to the same dimensions as described in Task II of the report. The laminate fabricated for this auxiliary test was a 15-ply solid homogeneous Kevlar 49 style 285 fabric/P1700 polysulfone pre-preg (see Figure A-2), consolidated in-house (at 600°F with 100 PSIG for 30 minutes), as opposed to a 3 laminate "stack-up" of 5-ply each laminate, consolidated at a subcontractor. After the consolidation and cutting processes, ten of the twenty specimens were again put into an oven at 550°F with no added pressure for one minute to simulate typical conditions of the thermoforming operation. The remaining ten specimens became the control set. Interlaminar shear test results demonstrated values commensurate with the BAC unpublished data, but, one order of magnitude greater than the values obtained under this contract.

The bonded "stack-up" interlaminar shear specimen remained as the final configuration to undergo verification. Every procedure that was included in the initial fabrication process (for interlaminar shear test specimens reported on in Task II of the report) was repeated during this re-test activity with only one exception – the laminates were consolidated in-house as opposed to subcontractor consolidated. Three 5-ply Kevlar 49 style 285 fabric/P1700 polysulfone laminates were hot press consolidated at 600°F with 100 PSIG for 30 minutes. After laminate consolidation, these three laminates were bonded together utilizing AF163 Grade 10 film adhesive at 250°F with 50 PSIG for 60 minutes, resulting in a non-homogeneous 15-ply laminate (see Figure A-3). For the effect of bonding on laminate ILS see Test Results Section.

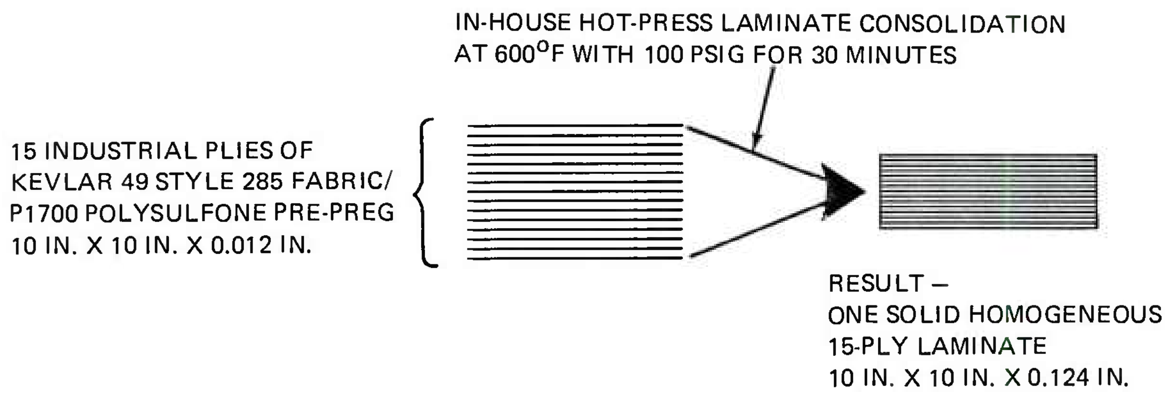

Figure A-2. 15-Ply Homogeneous Specimen

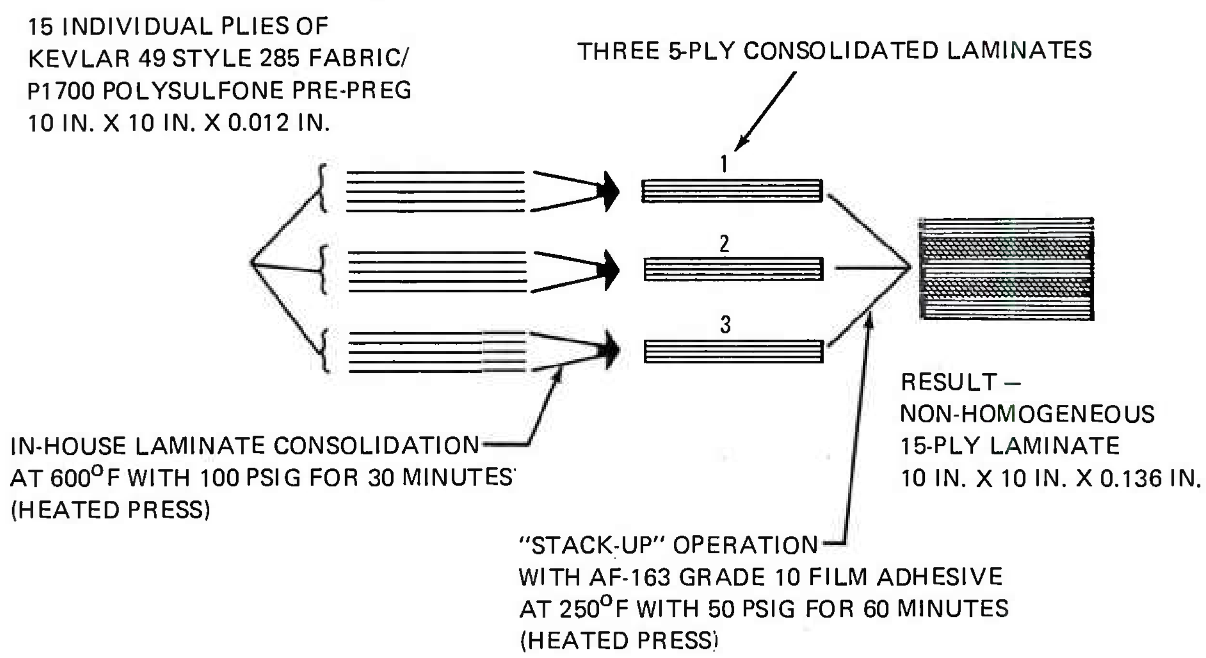

Figure A-3. Bonded "Stack-Up" Specimen

TEST PROCEDURE

For these verification tests, the same methods for horizontal shear tests (described in Task II of the report) were utilized, with one exception: The procedure for interlaminar shear testing used by BAC (Seattle) recommended the use of a 1-inch long specimen on a four times the thickness support span. Only during the verification of the BAC data was their method of testing attempted.

TEST RESULTS

The BAC unpublished data was the first to undergo verification testing at Boeing Vertol. A close examination of the test procedure utilized by BAC revealed a 1-inch long specimen supported on a span length equal to 4.0 times the specimen thickness. During the test set-up operation at Boeing Vertol it was discovered that the test fixtures could not accept such a small support span as was represented by the 4.0 times the specimen thickness dimension. It was decided to test the material at support spans equal to 4.5, 5.0, 5.5 and 6.0 times the specimen thickness and through the use of linear regression methods, obtain the resultant value representative of a test performed at a support span of 4.0 times the specimen thickness. The results of this initial exercise demonstrated values of the same order of magnitude obtained by the BAC interlaminar shear tests (see Table A-1 and Figure A-4).

TABLE A-1. THREE POINT INTERLAMINAR SHEAR TEST SPECIMEN BREAKDOWN

Specimen Group — 7 Ply
Homogeneous Laminate
Control — No Post-Form (Heat)

Tested Per BAC (Seattle) Procedure
Recommended Support Span = (A)
Recommended Specimen Length = 1.0 in
Recommended Rate of Cross Head Motion = 0.05 in./min

Specimen No.	t (in.)	w (in.)	Load (lbf)	Shear Strength (psi)	Avg	Support Span (A)
C-1	0.062	0.262	107.0	4940	4890	4.5t
C-2	0.062	0.260	104.0	4839		
C-3	0.063	0.258	103.0	4753	4774	5.0t
C-4	0.062	0.248	98.3	4795		
C-5	0.062	0.257	100.0	4707	4695	5.5t
C-6	0.062	0.248	96.0	4683		
C-7	0.062	0.253	94.2	4504	4411	6.0t
C-8	0.061	0.250	87.8	4318		
			Avg	4692		
			σ*	197		

*σ = Standard Deviation (with N-1 weighting)

TABLE A–1. THREE POINT INTERLAMINAR SHEAR TEST SPECIMEN BREAKDOWN (Continued)

Specimen Group — 7 Ply
Homogeneous Laminate
Post-Heated 1 minute at 550°F

Tested Per BAC (Seattle) Procedure
Recommended Support Span = (A)
Recommended Specimen Length = 1.0 in.
Recommended Rate of Cross Head Motion = 0.05 in./min

Specimen No.	t (in.)	w (in.)	Load (lbf)	Shear Strength (psi)	Avg	Support Span (A)
P-1	0.060	0.248	95.0	4788	4730	4.5t
P-2	0.061	0.254	96.5	4671		
P-3	0.061	0.246	87.4	4368	4580	5.0t
P-4	0.062	0.245	97.0	4789		
P-5	0.062	0.252	95.5	4584	4621	5.5t
P-6	0.062	0.248	95.5	4658		
P-7	0.061	0.243	80.0	4048	4270	6.0t
P-8	0.062	0.254	94.3	4491		
				Avg	4550	
				σ*	248	

*σ = Standard Deviation (with N-1 weighting)

Having verified the unpublished data from BAC, logic demanded a recheck of the data obtained under this contract. For this, it was decided to:

(a) Evaluate the effect of a bonded "stack-up" specimen on interlaminar shear strength. This was accomplished by fabricating specimens having the same number of fabric plys, but, consolidating them as a single, homogeneous, 15-ply laminate.

(b) Evaluate the consolidation process as performed by the subcontractor. This was accomplished by fabricating specimens of the bonded "stack-up" configuration. With the exception of the consolidation process, the specimens were identical in all respects to those fabricated under this contract. Consolidation was accomplished by Boeing Vertol (using in-house heated presses) instead of by a subcontractor.

The results of interlaminar shear testing on the homogeneous 15-ply laminate again demonstrated values along the same order of magnitude as obtained under the representative BAC testing, one order of magnitude greater than data obtained under this contract. See Table A-2 for individual specimen dimensions and test results.

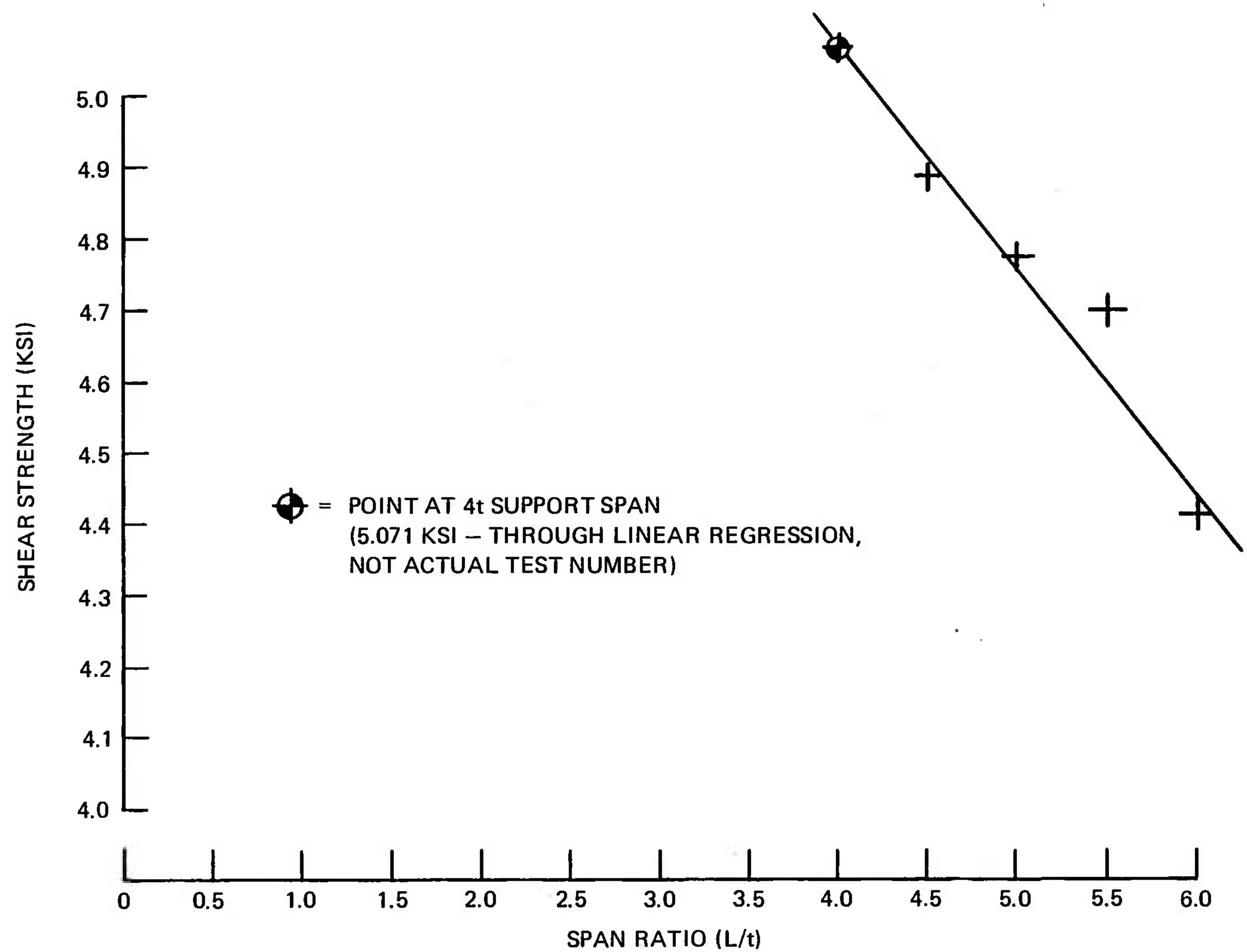

Figure A-4. 7-Ply Kevlar 49/285 Style/P1700 Polysulfone Homogeneous Laminate Control – No Postform (Sheet 1 of 2)

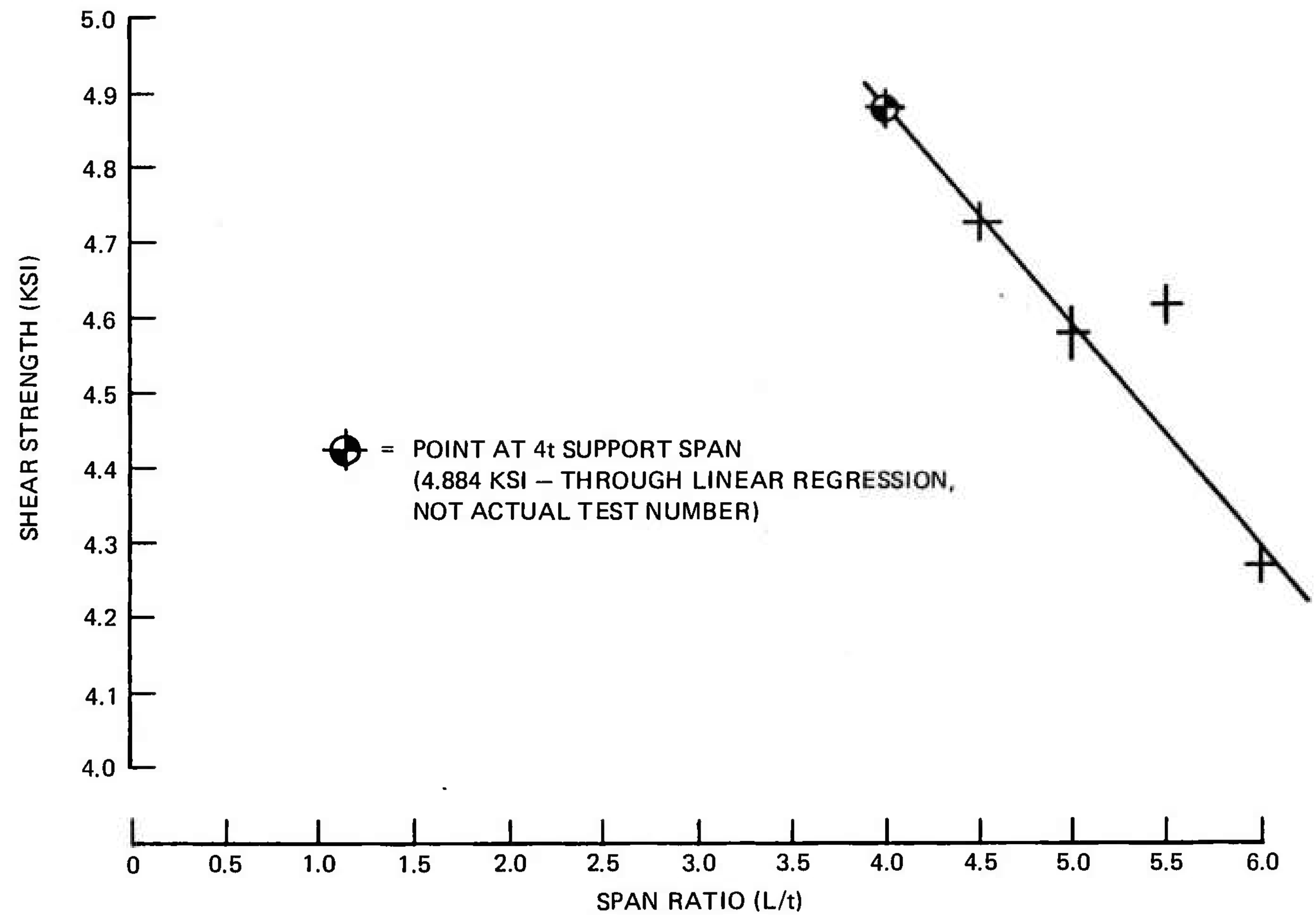

Figure A–4. 7-Ply Kevlar 49/285 Style/P1700 Polysulfone Homogeneous Laminate Postformed 1 Minute at 550° F/No Added Pressure (Sheet 2 of 2)

TABLE A–2. THREE POINT INTERLAMINAR SHEAR TEST SPECIMEN BREAKDOWN

Specimen Group — 15-Ply
Homogeneous Laminate
Control — No Post-Heat

Tested Per ASTM D2344-76:
Recommended Support Span = 5t
Recommended Specimen Length = 7t
Recommended Rate of Cross Head Motion = 0.05 in./min

Specimen No.	t (in.)	w (in.)	Load (lbf)	Shear Strength (psi)
A-1	0.123	0.249	193	4726
A-2	0.123	0.269	206	4670
A-3	0.123	0.256	182	4335
A-4	0.123	0.266	225	5158
A-5	0.123	0.273	225	5025
A-6	0.123	0.259	217	5109
A-7	0.123	0.245	197	4903
A-8	0.123	0.252	202	4888
A-9	0.123	0.271	237	5333
A-10	0.123	0.251	212	5150
			Avg	4930
			σ*	292

*σ = Standard Deviation (with N-1 weighting)

TABLE A–2. THREE POINT INTERLAMINAR SHEAR TEST SPECIMEN BREAKDOWN (Continued)

Specimen Group – 15-Ply
Homogeneous Laminate
Post-Heated at 550°F for 1 Minute

Tested Per ASTM D2344-76:
Recommended Support Span = 5t
Recommended Specimen Length = 7t
Recommended Rate of Cross Head Motion = 0.05 in./min

Specimen No.	t (in.)	w (in.)	Load (lbf)	Shear Strength (psi)
SP-1	0.123	0.258	195	4609
SP-2	0.123	0.264	208	4804
SP-3	0.124	0.250	200	4839
SP-4	0.123	0.250	186	4537
SP-5	0.123	0.268	216	4914
SP-6	0.123	0.256	198	4716
SP-7	0.124	0.261	212	4913
SP-8	0.124	0.242	180	4499
SP-9	0.123	0.268	215	4892
SP-10	0.123	0.250	171	4171
			Avg	4689.4
			σ*	238.6

*σ = Standard Deviation (with N-1 weighting)

The results of interlaminar shear testing on the bonded "stack-up" specimens demonstrated values lower than a 15-ply homogeneous laminate, but, 64% higher values than the subcontracted consolidated material used under this contract. See Table A-3 for individual specimen dimensions and test results.

TABLE A–3. THREE POINT INTERLAMINAR SHEAR TEST SPECIMEN BREAKDOWN

Specimen Group — Bonded
"Stack-Up" Specimens (15 Ply Total)
Control — No Post-Heat

Tested Per ASTM D2344-76:
Recommended Support Span = 5t
Recommended Specimen Length = 7t
Recommended Rate of Cross Head Motion = 0.05 in./min

Specimen No.	t (in.)	w (in.)	Load (lbf)	Shear Strength (psi)
F-1	0.136	0.252	163	3567
F-2	0.136	0.270	178	3636
F-3	0.136	0.264	164	3426
F-4	0.136	0.264	167	3488
F-5	0.136	0.266	169	3504
F-6	0.136	0.256	156	3361
F-7	0.136	0.259	163	3471
F-8	0.136	0.240	156	3585
F-9	0.135	0.263	172	3633
F-10	0.136	0.265	173	3600
			Avg	3527
			σ*	92.1

*σ = Standard Deviation (with N-1 weighting)

TABLE A–3. THREE POINT INTERLAMINAR SHEAR TEST SPECIMEN BREAKDOWN (Continued)

Specimen Group — Bonded
"Stack-Up" Specimens (15 Ply Total)
Post-Formed 1 Minute @ 550^{o}F
(with no added pressure)

Tested Per ASTM D2344-76:
Recommended Support Span = 5t
Recommended Specimen Length = 7t
Recommended Rate of Cross Head Motion = 0.05 in./min

Specimen No.	t (in.)	w (in.)	Load (lbf)	Shear Strength (psi)
PP-1	0.137	0.250	147	3219
PP-2	0.137	0.251	152	3315
PP-3	0.137	0.264	170	3525
PP-4	0.137	0.268	160	3268
PP-5	0.136	0.258	147	3142
PP-6	0.137	0.259	151	3192
PP-7	0.137	0.261	154	3230
PP-8	0.137	0.244	136	3051
PP-9	0.136	0.262	149	3136
PP-10	0.136	0.254	137	2974
			Avg	3205
			σ*	151.0

*σ = Standard Deviation (with N-1 weighting)

CONCLUSIONS

It may be concluded that the subcontracted consolidation process of Boeing Vertol specimen material (utilized under this contract) had not achieved the optimum material strength characteristics. However, interlaminar shear and flexural strength test data should always be used for comparative purposes only, and not design criteria. Thus, the comparative nature of this program has not been degraded.

It is probable that the difference in coefficient of thermal expansion between polysulfone and epoxy (14×10^{-6} vs 42×10^{-6} in./in./$^{\circ}$F) causes residual strains normal to and within the plane of the laminate, contributing to reduced interlaminar shear strength. This is further affected by the reinforcement of the polysulfone with Kevlar 49, decreasing its apparent thermal expansion and increasing its apparent modulus significantly relative to the low modulus high expansion epoxy, thus forcing the epoxy to make the strain accommodation. The lower thermal coefficient of polysulfone with respect to epoxy may account for some of the improvement in impact damage reported with glass, graphite and Kevlar 49 laminates in this case due to reduced residual strain in the resin after processing.

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