COMPOSITE SYSTEMS FOR AIRCRAFT CONSTRUCTION

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INTRODUCTION

The consideration of FRP aircraft structures requires an understanding of the properties resulting from composite structures. Properties of composite materials are a function of three major factors: (1) resin; (2) reinforcement; and (3) fabrication technique. This paper reviews recent progress in the areas of resin, reinforcement, and fabrication. Several new developments may provide improved composite structure for aircraft applications.

RESINS

The two major resins used for FRP structures are polyester and epoxy. These resins are similar in many ways. Both are available at low molecular weight and in liquid solutions that are easy and convenient to process for a short period of time, after which the resins begin to harden into a rigid, solid condition. Resins such as polyesters and epoxies, which chemically crosslink under specific conditions to form irreversibly solid material, are called thermosets. The pot life, or working time, for a thermoset resin is a function of the type and concentration of the catalyst or hardener. Pot life can vary from several minutes to several weeks.

Important considerations in resin selection are cost, physical properties, safety (contain flammable solvents, cause dermatitis), ease of fabrication and convenience.

Polyesters

Polyester-laminating resins are solutions of alkyd polymers in reactive monomers. Typical alkyds are solid polymers with molecular weight 2000 to 3500. When dissolved in a low-viscosity, low molecular weight reactive monomer, a syrupy solution results. Commonly used monomers are styrene and vinyl toluene. Monomer concentration may vary from 25 percent to 50 percent (wt.), with higher monomer levels contributing to lower viscosity in the resultant solution. The addition of a peroxide catalyst to a liquid polyester chemically activates the resin to molecularly crosslink the system into a hard, solid product.

The time between catalyst addition and resin hardening is called pot life or working time. Final cured resin properties are determined by the composition and molecular weight of the original alkyd, the concentration and type of monomer, and to a lesser extent by the peroxide catalyst.

The advantages of polyster laminating resins are low cost, low viscosity, good strength, and rapid cure at low temperatures. The primary disadvantages are high shrinkage during cure, monomer loss during cure (which can result in property variation), fire hazard, and stickiness or mess (worse than epoxy) in hand lay-up operations.

Epoxy

Epoxy resins are presently used for all FRP sailplane construction. Epoxies can react through a variety of chemical mechanisms. The type of hardener or coreactant used with the epoxy resin has a definite effect on the properties of the cured system. A given epoxy resin can be cured by many different curing agents, therefore, the specification of an epoxy resin normally includes the specification of the type and the concentration of hardener. Figure 1 illustrates the effect of different curing agents on the mechanical properties of a general purpose bisphenol-A epoxy resin.

The economic requirements of sailplane manufacture exclude the use of the higher performance (higher mechanical properties) epoxy systems. The economics of reference are the costs of heated, matched metal dies versus hand lay-up on a master mold. Limited production of a single sailplane design has restricted, and probably always will limit, the method of fabrication to room-temperature cured, hand lay-up techniques.

The most widely used epoxy systems for hand lay-up are based on diglycidol ether of bisphenol. The term epoxy is often used indiscriminately for DGEBA based epoxies, although the term epoxy applies equally well to other epoxies that are not derived from bisphenol-A. In sailplane construction, DGEBA epoxy resins have been used on most European and several United States produced FRP sailplanes.

In addition to the selection of epoxy resin and hardener, the system is often further modified by the addition of diluents. The addition of a diluent may result in a specific change in viscosity to improve processing or fabrication. Catalysts can also be added to accelerate curing at low temperature. The addition of silanes may improve the bond to fibrous reinforcements.

Polyesters and epoxies meet the basic requirements for a matrix for structural composites. They are economical; available as liquids; cure to a rigid solid condition; harden at room temperature; exhibit good aging characteristics; and they are ideal for hand lay-up fabrication of FRP structures. However, neither polyester nor epoxy resins are very useful in the cured state unless they are

DGBEBA with Various Hardeners

Hardener Type General Specific	Amine TETA	Modified Polyamine Araldite 956	Amido Amine Araldite 955
Typical Usage, phr	10-12	20-25	35
Pot Life, min.	20-25	35	35
Viscosity, cps. 77F	2500	2500	6400
Properties			
Tensile Str. psi	9000	10,500	8500
Flexural Str. psi	18000	17,500	16000
Tensile Elongation,%	3.8		2.5
Heat Distortion, C	66	100	59
Cure Schedule	7 days R. T.	R.T. gel +2 hrs.@ 100C	14 days R.T.

ARALDITE ^{TM} manufactured by CIBA PRODUCTS COMPANY

FIGURE 1

filled or reinforced. Reinforcement of these resins provides the strength required for load bearing, structural applications.

REINFORCEMENTS

Glass fiber is the most common reinforcement for FRP structures. Fibers such as graphite, boron, aromatic polyamide, polyamide, beryllium, and micro fibers (wiskers) may also be useful. The properties of these reinforcements are listed in Fig. 2. The dominant factor in fiber selection is cost. Glass fibers cost approximately $0.33/lb; the cost of graphite varies from $40 to $180/lb; while most other high modulus reinforcements cost over $100/lb.

The economics of glass fiber production and the excellent properties of glass fiber at ambient and elevated temperature make it an ideal reinforcing material for composites. Furthermore, glass fiber is available in many forms: roving, chopped strand, woven fabric, woven roving, and chopped strand mat. The selection of the proper glass fiber for a specific application should include consideration of the fiber bundle size, the filament size (diameter), and the type of binder and silane on the glass fiber. The specific aspects of glass fiber selection are thoroughly discussed in "Fiberglas Reinforcement for Sailplanes," by Barry R. Elson, presented at this conference.

Boron and Graphite

Boron and graphite fibers were acclaimed in the 1960s as the fibers of the future. Enormous military expenditures, stimulated by the needs of the U.S. space program, resulted in the developmnnt of laboratory production of boron and graphite filaments. The initial research data indicated that both graphite and boron could be performance/cost competitive with glass fiber. Costs for these high-modulus fibers were projected to be $10 to $15 when full commercialization was achieved. In the mid-1960s the need for a commercial high-modulus fiber was increasing and the research funding was not. The decision was made to stop funding both boron and graphite development programs on an equal basis; and, alternatively, fund the project with the greatest chance for the quickest commercialization, while the other fiber program would be funded at a lower level as a back-up project. The choice at that time was to push boron into commercialization as rapidly as possible and to carry on the graphite fiber work at a lower priority.

The production of boron fiber is based on a technique of electro-deposition of boron on a tungsten filament. The high cost of the tungsten filament excludes low-cost boron filament production using this technique. Although methods of manufacturing substrateless boron filament have been proposed, none are known to be commercial. The speculation that an economical manufacturing technique for boron filament would be developed has proven erroneous to date. In the meantime, great strides have been made in the commercialization of a variety of graphite fibers.

Graphite fibers are produced by the pyrolysis of rayon fiber or poly-

Properties - Fiberous Reinforcement

FIBER	MODULUS of ELASTICITY		Sp. Gr.	Tensile Str. psi x 10^3
	psi x 10^6	Spec. Mod.		
Nylon	0.4	1	1.1	100
Carbon	6	11	1.5	120
Glass "E"	10.5	11	2.5	450
Aluminum	10.6	11	2.7	90
Glass "S"	12.5	14	2.5	700
Aromatic Polyimide	18.0	35	1.5	350
Steel	30	11	7.8	600
Graphite HS	40	60	1.8	400
Boron	60	65	2.6	450
Graphite HM	70	97	2.0	325

FIGURE 2

acrylonitrile. Other techniques claim the direct conversion of coal tar pitch to graphite fiber under high-temperature conditions. Graphite fibers are available from several major suppliers in the United States, England, and Japan. Initial work to develop high modulus (760×10^6 psi), graphite fibers has succeeded, but such high-modulus fibers tend to have lower tensile strength and poorer handling properties than medium modulus fiber ($30-50 \times 10^6$ psi). The present emphasis is to produce a medium modulus with high tensile strength. The medium modulus fibers are also more economical to produce, requiring less heating at elevated temperature. Graphite fibers of $40-50 \times 10^6$ psi modulus are presently available in continuous strand and tow for $40 to $50/lb.

The handling properties of boron and graphite yarns differ considerably. Boron filament is very stiff and sharp; the filament diameter is approximately 4 mm. The graphite fiber is only 8 microns in diameter. This small fiber is much too delicate to handle alone; graphite filaments are therefore grouped into bundles to form a roving or yarn. The yarn is handled in much the same manner as glass roving. Boron filaments do not ordinarily have a surface treatment or coating. Graphite yarns often have a PVA coating to help retain yarn integrity during handling. When a PVA coating is present on the graphite, it should be removed prior to impregnation.

Polyamide

Although many millions of dollars have been spent by industry and government on high-temperature organic fibers, very few have reached commercialization. DuPont's Nomex fiber has been commercial for nearly a decade, but it is not widely used as a fibrous reinforcement for composites. A newer DuPont fiber PRD-49, an aromatic polyamide, is finding good acceptance as a reinforcing fiber. Many other high-temperature resistant, high-modulus fibers that have been developed, or proposed, are simply too costly in small volumes to produce.

Wiskers

The concept of fibrous reinforcement on the molecular scale is theoretically sound but has yet to be reduced to practice. Small single-crystal fibers have been grown with aspect ratios as high as 10,000 to 1. The efficiency of such reinforcements in composite structures should far exceed that of macro fibers such as glass and graphite. In practice, however, such wiskers are extremely difficult to wet-out and bond with resin. The resultant efficiency of wisker reinforced composites is consequently very low. Wiskers may eventually be the ultimate reinforcement, but many problems remain to be solved. Wiskers physical properties are shown in Fig. 3.

For the present and the near future, the dominant fibrous reinforce-

Physical Properties of Wiskers*

TYPE	DENSITY gm/cm^3	TENSILE STR. psi x 10^6	MODULUS psi x 10^6	SP. STR. in.x 10^6
Aluminum Oxide	3.9	2-4	100-350	14-28
Aluminum Nitride	3.3	2-3	50	13-21
Beryllium Oxide	1.8	2-2.5	100	31-43
Boron Carbide	2.5	1	65	11
Graphite	2.0	3	142	37
Magnesium Oxide	3.6	3.5	45	27
Silicon Carbide	3.2	1-5	70	26-44
Silicon Nitride	3.2	1	55	4-13

*Data Published by THERMOKENETIC FIBERS, INC. NUTLEY, NEW JERSEY

FIGURE 3

ment for structural composites will continue to be glass. Continued improvements in silane technology, glass manufacture, and resin formulation will improve the efficiency of glass/epoxy systems. The more general use of S-glass would permit more immediate improvement of existing systems. The decrease in the price of graphite fiber has been dramatic in recent years, and continued cost reduction will allow the applications for graphite reinforced composites to expand.

On a cost/performance basis, graphite may close in on glass rapidly as:

1. the cost of graphite fiber is further reduced;
2. the technology of sizings (coupling agents) for graphite fiber is developed; and
3. higher strength yarns are produced.

One should recall that the technology of glass reinforced composites has evolved over the last thirty years. Bare glass fiber is not a very good reinforcement and it is extremely difficult to work with. The coupling agents, lubricants, and binders of glass fiber allow it to be a functional reinforcement; this technology has yet to be perfected for the new high-modulus fibers.

COMPOSITE STRUCTURES

A composite structure offers a means to utilize the combined properties of materials in applications where the properties of the same materials used individually would be insufficient. The combination of fiber reinforcement and resin matrix allows the designer to utilize the best characteristics of each component. The fibers are usually oriented to carry the applied load in tensile and/or compression, while the resin matrix transfers the applied stress between fiber, maintains fiber orientation, and protects the fibers from mechanical and environmental damage. Figure 4 gives the property data of representative reinforced epoxy composites.

In unidirectional structures, such as spars, it is worthwhile to consider improving the elastic modulus by using fibers with a higher modulus than glass fiber. Figure 5 shows property data for unidirectional laminates with incremental substitution of boron fiber for glass fiber. The modulus data in Fig. 5 was previously published by T. W. Langley of Texaco Experiment, Inc. From his data the weight percentage of boron, glass, and resin have been calculated and the composite materials cost have been determined. The data shows that to triple the composite modulus the composite cost must be increased seventeenfold; or, stated another way, the modulus-to-cost ratio would be approximately 1 to 6. In Fig. 6, I have prepared similar data based on the incremental substitution of high-modulus (60 x 10^6 psi) graphite fiber for glass. Figure 6 shows a modulus-to-cost ratio of approximately 1 to 5 for graphite when it is substituted for glass. It is interesting to note the difference between the specific gravity of boron and graphite composites. The high specific gravity of boron is largely a result of the tungsten substrate in the boron fiber. Figures 5 and 6 represent data derived from unidirectional composites.

The data presented thus far indicates that most high-modulus fiber composites are too expensive to be incorporated into sailplane structures without dramatically increasing the cost of ship. A future extrapolation of the data suggests a more practical conclusion.

Assume, for example, that 100 lb of unidirectional composite are incorporated into a sailplane structure. Using E-glass/epoxy composites, the cost of the unidirectional materials is approximately \$40 (\$0.39 x 100 lb). The typical elastic modulus of such composites is 4 - 5 x 10^6 psi. Now, using S-2 glass and 2 to 3 percent graphite fiber (60 x 10^6 psi modulus) in place of E-glass, the modulus will be approximately doubled (10 x 10^6 psi) and the cost will be approximately \$3/lb (\$300 for 100 lb). The added cost per sailplane would be \$260. Although this would not improve the problem of torsional binding in the

UNIDIRECTIONAL EPOXY/FIBER COMPOSITE PROPERTIES*

FIBER TYPE	TENSILE STR. psi x 10^3	TENSILE MOD. psi x 10^6	COMP. STR. psi x 10^3	DENSITY
S Glass	180	7.0	130	0.072
E Glass	60-120	3.8-5.0	90	0.070
HS Graphite	190	20	150	0.057
HM Graphite	110	30	110	0.057
Boron	320	36		0.074
PRD-49**	170	12	50	0.050
Beryllium	97	28		0.058

FIGURE 4

BORON/GLASS/EPOXY COMPOSITES

Vol.% Boron	0	10	20	30	40	50	60	70
Vol.% Glass	65	56	47	38	29	20	11	2
Vol.% Resin	35	34	33	32	31	30	29	28
Flexural Modulus* psi x 10^6	5	16	23	28	33	36	38	40
Wt.% Boron	0	13	25	37	49	61	72	84
Wt.% Glass	81	69	57	46	35	24	13	2
Wt.% Resin	19	18	18	17	16	15	15	14
\$ Boron @ \$50/lb	0	6.50	12.50	18.50	24.50	30.50	36.00	42.00
\$ Glass @ 35¢/lb	.28	.24	.20	.16	.12	.08	.05	.01
\$ Resin @ 65¢/lb	.11	.11	.11	.10	.09	.09	.09	.08
Materials Cost \$/lb	.39	6.85	12.81	18.76	24.71	30.67	36.14	42.09
Specific Gravity	2.04	2.05	2.07	2.10	2.12	2.14	2.16	2.19

* T.W. Langley, Texeco Experiment, Inc., Richmond, Virginia

FIGURE 5

GRAPHITE/GLASS/EPOXY COMPOSITES

Vol.% Graphite	0	10	20	30	40	50	60	70
Vol.% Glass	65	56	47	38	29	20	11	2
Vol.% Resin	35	34	33	32	31	30	29	28
Flexural Modulus* psi x 10^6	5	16	23	28	33	36	38	40
Wt.% Graphite	0	10	21	31	43	54	67	80
Wt.% Glass	81	71	61	51	39	28	16	3
Wt.% Resin	19	19	18	18	18	18	17	17
\$ Graphite @ \$50/lb	0	5.00	10.50	15.50	21.50	27.00	33.50	38.00
\$ Glass @ 35¢/lb	.28	.25	.21	.18	.14	.10	.06	.02
\$ Resin @ 60¢/lb	.11	.11	.11	.11	.11	.11	.11	.11
Materials Cost \$/lb	.39	5.36	10.82	15.79	21.75	27.21	33.67	38.13
Specific Gravity	2.04	1.99	1.95	1.91	1.88	1.84	1.80	1.76

*Theoretical calculations based on graphite fiber modulus of 60 x 10^6

FIGURE 6

wing, it would substantially improve the wing flutter characteristics induced in high-speed flight. It also presents a solution to the problem of flex in very high aspect ratio, long-span wings. Figure 7 shows the calculations for determining the above referenced cost of $300/lb for a S-2 glass/graphite/epoxy unidirectional laminate. Figure 8 plots modulus for S-2 and E-glass unidirectional laminates when graphite fiber is incrementally substituted for glass fiber.

The high cost of many "advanced" composite systems may make them impractical for use in sailplane construction at this time and possibly in the near future. In specific cases, however, higher strength composites can also result from the more selective use of existing low-cost resins and fibers. In a wing spar, for example, the tensile modulus and compressive properties of the unidirectional laminate may be optimized by proper resin and glass selection. Several combinations of glass roving have been tested and found to exhibit the properties shown in Fig. 9. Several 181 style glass fabric/epoxy laminates have been tested and this data is presented in Fig. 10.

In the design of torsionally stressed skins, impact stress, shear strength, and flexural strength may be more important than tensile or compressive strength. Thus, we should not confine ourselves to one resin system in building a sailplane, but instead we should selectively utilize different resin/glass systems where they are most ideal.

FATIGUE

A difficult, yet essential consideration in the design of composite systems is structural fatigue. Fatigue strength of FRP structures is probably the least understood characteristic of fiber reinforced composites. Many different theories on fatigue in reinforced plastics have been proposed, but few are acknowledged to be widely accepted.

Fiber reinforced epoxy systems do exhibit fatigue under stress. Structural damage and strength reduction can occur during the initial application of stress. The most common type of failure is delamination of the composite at the resin/fiber interface. If stress is applied to initiate an interfacial crack, the crack will continue to propagate until a cross-ply fiber or resin inclusion is reached, at which point the crack may terminate.

The frequency of interfacial bond failure can be reduced by:

1. increasing the matrix-fiber bond efficiency;
2. using more ductile resin matrices;
3. introducing crack terminating additives into the resin; and
4. reducing the applied stress or increasing the design load of the composite.

A commonly employed technique for improving the resin/fiber bond is to coat the fiber with a silane coupling agent. In theory, the silane molecule should be applied in a continuous monomolecular layer to the fiber. The silane molecules are bifunctional and polar. They orient themselves along the fiber in such a manner that one end of the silane molecule is bonded to the fiber and the other end is chemically reacted with the resin. Silane molecules are made with specific reactive functional groups for use with different types of resins. The effect of the silane additive is shown in the data in Fig. 11. Glass fabrics and fibers are commercially available with specific silane agents on them. Further developments in silane technology will undoubtedly increase the strength of FRP composites. Silanes may promote a more continuous interfacial bond, improving the fatigue life of FRP composites because a continuous bond may allow an applied stress to be evenly distributed to a reinforcing fiber. Discontinuous bonds promote high local stresses at resin/fiber/void interfaces, and delaminations are easily initiated best under such conditions.

GRAPHITE/S-GLASS/EPOXY COMPOSITES

Vol.% Graphite	0	10	20	30	40	50	60	70
Vol.% Glass	65	56	47	38	29	20	11	2
Vol.% Resin	35	34	33	32	31	30	29	20
Flexural Modulus* psi x 10^6	7.5	18	24	29	34	36	38	40
Wt.% Graphite	0	10	21	31	43	54	67	80
Wt.% Glass	81	71	61	51	39	28	16	3
Wt.% Resin	19	19	18	18	18	18	17	17
$ Graphite @ $50/lb		5.00	10.50	15.50	21.50	27.00	33.50	38.00
$ Glass @ $2/lb	1.62	1.42	1.22	1.02	.78	.56	.32	.06
$ Resin @ 60¢/lb		.11	..11	.11	.11	.11	.11	.11
Materials Cost $/lb.	1.73	6.53	11.83	16.63	22.39	27.67	33.93	38.17
Specific Gravity	2.04	1.99	1.95	1.91	1.88	1.84	1.80	1.76

* Theoretical calculations based on a graphite fiber modulus of $60x10^6$

FIGURE 7

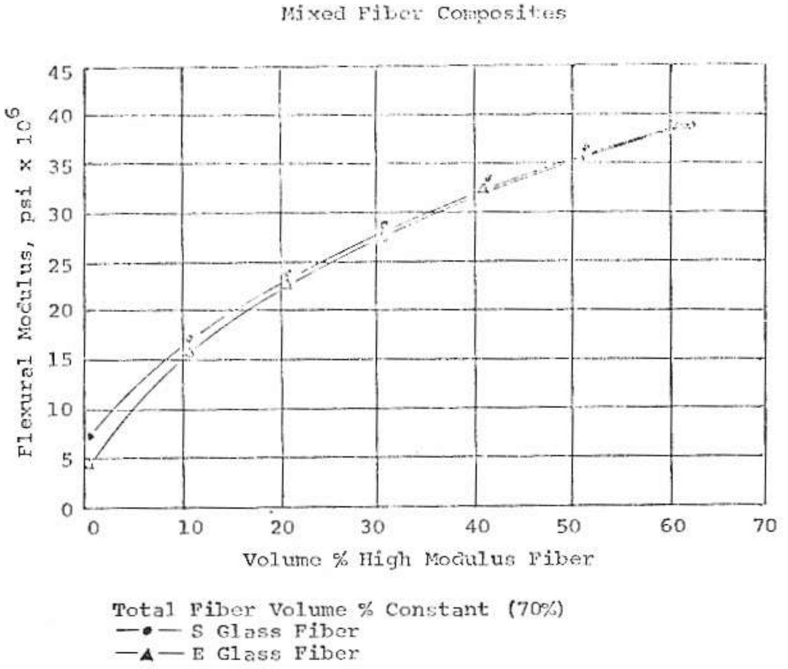


FIGURE 8

UNIDIRECTIONAL GLASS/EPOXY COMPOSITES - TYPICAL PROPERTIES

RESIN	Laromin 260 (38) Epikote 162 (100)	Epon 826 (90) BGE (9) A-186 (1) TETA (12.5)	Epon 826 (90) BGE (9) A-186 (1) TETA (12.5)	Epon 826 (90) BGE (9) A-186 (1) TETA (12.5)	Epon 826 (90) BGE (9) A-186 (1) TETA (12.5)
GLASS	OCF 836	OCF 836	OCF 830	OCF 830	OCF 830
% GLASS (wt)	70	70	73	80	91
MECHANICAL PROPERTIES TENSILE STRENGTH psi	93,000	103,229	99,000	110,722	98,200
FLEXURAL STRENGTH psi	89,933	124,000	106,333	115,000	112,900
MODULUS OF ELASTICITY psi x 10^6	3.48	4.76	3.9	4.75	5.3

Cure: 7 days at room temperature, (23°C), hand lay-up, no pressure

FIGURE 9

PROPERTIES - EPOXY/181 STYLE FABRIC LAMINATES

LAMINATE NO.	GLASS wt%	TENSILE psi	FLEX STR psi	FLEX MOD	IMP STR ft-lb/in	HDT @264 psi	POT LIFE min.
L101	57	36,264	46,500	2.55×10^6	12.1	470	30-40
L102	55	35,309	48,000	2.46×10^6	12.4	490	30-40
L103	55	34,650	34,000	1.6×10^6	16.3	510	180-240
L104	51	32,609	43,000	2.05×10^6	11.2	490	30-40
L105	57	35,139	54,000	2.15×10^6	10.1	400	30
L106	60	35,600	38,000	1.9×10^6	11.1	400	180

RESIN COMPOSITION

L101	EPON 826(74) Genamide 2000(26)
L102	EPON 826(75) Genamide 2000(25)
L103	EPON 826(69) VERSAMIDE 140(25) BGE(6)
L104	EPON 826(64) GENAMIDE 2000(30) BGE(6)
L105	EPON 826(100) TETA(13)
L106	EPON 826(100) LANCAST A (30)

FIGURE 10

EFFECTS OF COUPLING AGENTS ON LAMINATE STRENGTH

Silane	None	Volan A	Z-6020	Z-6040	Z-8-009
Flexural Strength, psi					
As molded	78,400	85,000	81,000	85,900	98,700
After 2 hour boil	59,000	62,200	64,000	79,500	94,500
Compressive Strength, psi					
As molded	52,600	52,000	46,000	53,200	53,200
After 2 hour boil	26,400	42,000	46,000	49,300	43,300

181 style glass fabric
DGEBA cured with m-PDA

FIGURE 11

The use of matrices of high ductility inhibits the propagation of cracks. Resins that can elongate and deform under load are less susceptible to fatigue than resins that are brittle with low elongation. Resin ductility allows high specific strains in the matrix to be dissipated and reduced through matrix deformation. High ductility is not desirable in structural aircraft composites because high modulus of elasticity is often the primary design factor.

The use of highly ductile resins is not a satisfactory solution for structural fatigue problems. Ideally, in FRP composites resin elongation should exceed the elongation of the fiber, but once this is achieved, increasing the resin elongation still further will continue to reduce the modulus of the composite.

The incorporation of fine rubber particles into the resin matrix has been demonstrated to effectively improve the impact strength and the fatigue life of thermoset FRP composites. Such an approach is especially effective in polyester resin systems, but good results have also been attained in epoxies.

McGarry has reported substantial improvement in fracture resistance of DGEBA resins cured with DMP-30 (Shell Chemical) 2,4,6,-tri(dimethylaminoethyl) phenol, or the tri(2-ethylhexonic acid) salt of DMP-30; when CTBN rubber is added to the resin. CTBN is a carboxyl terminated butadiene/acrylonitrile copolymer, which is liquid at room temperature. Figure 12 shows the effect of CTBN concentration on resin toughness. The effect of CTBN addition to epoxies is further demonstrated in Fig. 13 where the crack density is plotted against flexural cycles in a 50 vol. percent, 181 style fabric/epoxy laminate.

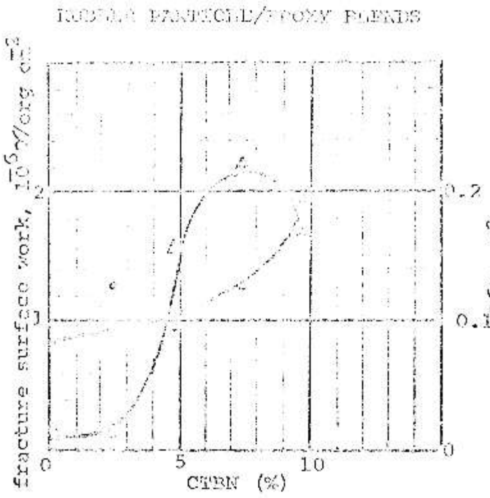
Fatigue life for FRP composites under uniform cyclical stress demonstrate predictable fatigue strength loss. Figure 14 illustrates fatigue strength properties of epoxy/glass laminates. The data in Fig. 14 was generated from constant amplitude stress cycling. It is much more difficult to predict fatigue strength or fatigue life from non-uniform, random application of stress.

Broutman and Sahu have presented a new theory to predict cumulative fatigue damage in fiber reinforced plastics. Their theory predicts the fatigue life of FRP from measuring the residual strength of a composite after a fractional life at a given stress level. Broutman and Sahu propose a modified Miner's Law to account for residual strength after the application of a two-stress level, fatigue test. The results of this study show the cumulative effect of high/low stressing and low/high stressing are not predictable by linear damage theory.

Davis has generated fatigue property data on unidirectional, non-woven epoxy/glass composites; on bidirectional woven composites. Figures 15 and 16 present the results of their study. The flexural fatigue data shows that non-woven fiber reinforcement is superior to woven reinforcement when tested for resistance to fatigue. Woven materials are lower in fatigue resistance because the reinforcing fibers are bent in the cured composite and also because the fibers abrade themselves under cyclic loading. Non-woven composites offer fatigue resistance because the fibers are very straight in the cured laminate and because the fibers are surrounded by resin which helps to protect and insulate them from other fibers. The flexural fatigue data was generated by cycling specimens under three-point loading. The axial fatigue data was derived from alternating cyclic loading in tensile and compression.

SUMMARY

The potential applications for FRP composites in aircraft structures will expand as higher modulus reinforcing materials are available at lower cost. Improved composites can be fabricated from blends of glass and higher modulus fibers to yield greater performance at moderate cost. The fatigue properties of FRP, especially with non-woven reinforcement, are superior to most other engineering materials.



Epon 828 epoxy resin cured with
5% curing agent D*
DMP-30

* Shell Chemical Company, New York

FIGURE 12

FATIGUE PROPERTIES:

RUBBER MODIFIED EPOXY/GLASS COMPOSITE

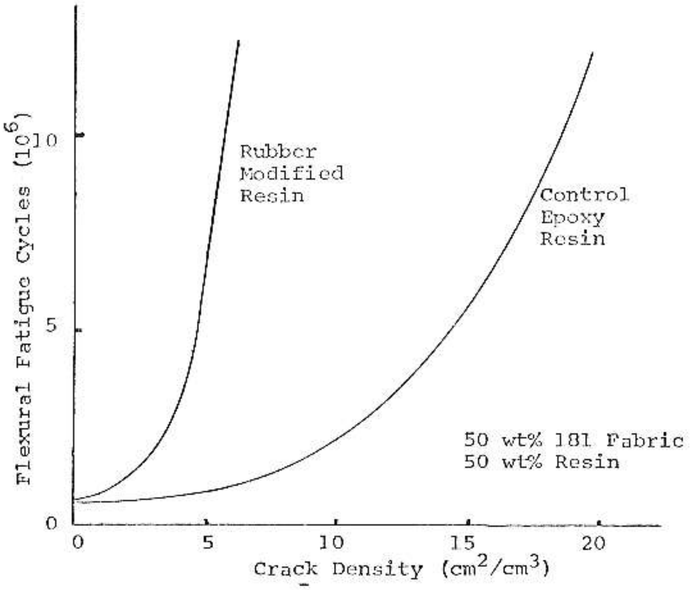


FIGURE 13

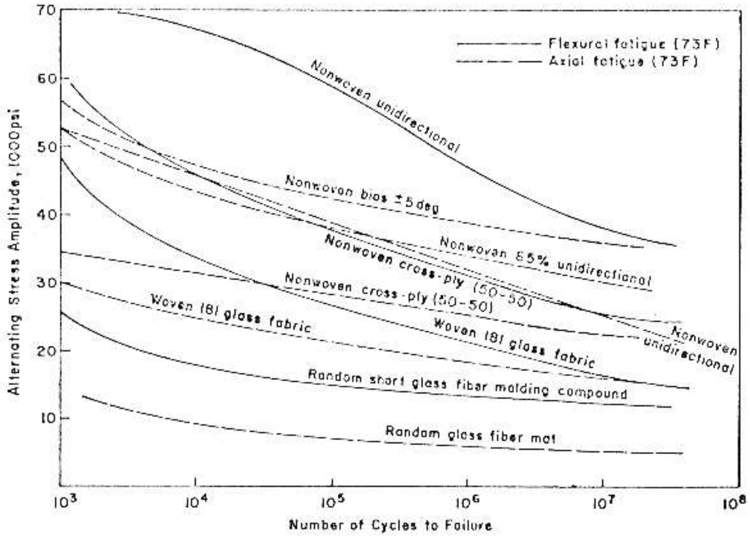


FIGURE 14

AXIAL FATIGUE PROPERTIES

MATERIAL	DENSITY	ULT TENSILE STR. psi	FLEXURAL MODULUS psix 10^6	FATIGUE STRENGTH psi	SPECIFIC FATIGUE STRENGTH
Epoxy/Glass					
Unidirectional ±5°	0.065	139,000	5.3	36,000	554,000
Unidirectional	0.065	158,000	5.6	25,000	385,000
Cross-ply (50-50)	0.065	75,000	3.7	22,000	338,000
Woven 181 Fabric	0.065	50,000	3.3	15,500	238,000
Aluminum, 2024-T4	0.100	68,000	10.6	26,000	260,000

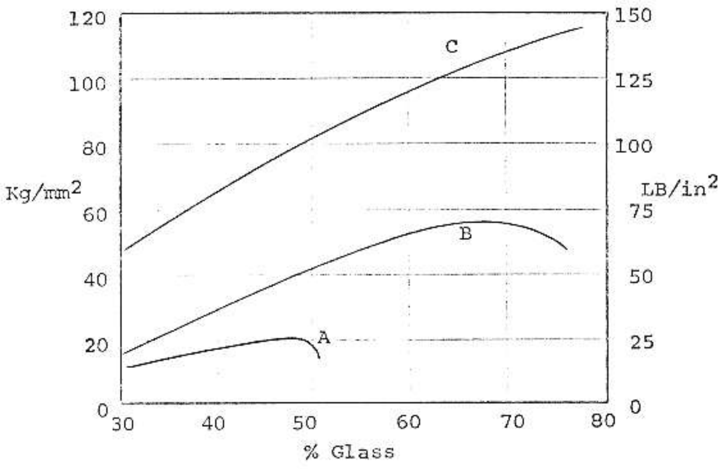
FIGURE 15

FLEXURAL FATIGUE PROPERTIES

MATERIAL	DENSITY lb/cu in	ULT.FLEX. STR psi	FLEXURAL MODULUS 10^6 psi	FATIGUE STRENGTH	SPECIFIC FATIGUE STRENGTH
Epoxy/Glass					
Unidirectional	0.065	165,000	5.3	36,000	554,000
Cross-ply (80-20)	0.065	150,000	5.0	33,000	508,000
Cross-ply (50-50)	0.065	120,000	3.5	25,000	385,000
Woven 181 Fabric	0.065	80,000	3.4	16,500	254,000
Sitka Spruce	0.016	9,000	1.2	2,700	169,000

FIGURE 16

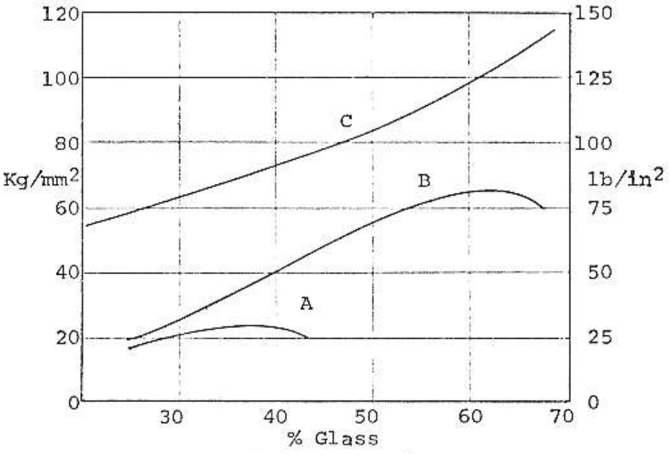
TENSILE STRENGTH
vs.GLASS CONTENT



A mat, B cloth, C roving

FIGURE 17

FLEXURAL STRENGTH
vs. GLASS CONTENT



A- mat, B- cloth, C- roving

FIGURE 18

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