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KEVLAR® 49 Aramid Fibers for High Performance Composites

Louis H. Miner
Textile Fibers Dept.,
E. I. du Pont de Nemours & Co., Inc.

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FIBER PROPERTIES

PHYSICAL PROPERTIES - The physical properties of KEVLAR® 49 aramid fiber compared with other organic fibers, stainless steel, and fiberglass are shown in Table I. The tensile strength of KEVLAR® 49 is more than twice that of nylon or Dacron® polyester, and 15% better than E-glass. Modulus, or stiffness, is more than 20 times that of nylon, almost 10 times that of Dacron®, and twice that of E-glass. The fiber elongation to break is quite low and the density, while slightly higher than nylon or Dacron®, is over 40% lower than glass. Compared to steel, it is as strong at one-fifth the weight.

The linear stress/strain curve to failure of

KEVLAR® 49 is similar to glass and other inorganic reinforcing fibers but quite unlike other organic fibers (Figure 1). KEVLAR® 49, available in yarns of up to 1420 denier* (1580 decitex)**, and rovings (i.e., multiple plies of yarn) of up to 7100 denier (7890 dtex) is comprised of multiple continuous, round cross-section filaments having a denier per filament (dpf) of almost 1.5 (1.67 decitex). This is equivalent to a diameter of 0.5 mil (0.0005 in., 0.013 mm). Because it is relatively insensitive to fiber surface defects, the tensile strength of KEVLAR® 49 along the length of the

*denier is weight in grams of 9,000 meters.

**decitex is weight in grams of 10,000 meters.

ABSTRACT

KEVLAR® IS THE REGISTERED TRADEMARK for one member of Du Pont's family of aromatic polyamide fibers which have been granted the generic name "aramid" by the Federal Trade Commission. It is available in three different types: KEVLAR® 49, with its high tensile strength (400,000 psi; 2760 MN/m²) and high modulus (18 million psi; 124,000 MN/m²) is designed for the reinforcement of plastics and offers industry a new level of composite performance. KEVLAR® 49 is also used in coated fabrics, ropes and cables. KEVLAR® 29, with the same high tensile strength and a modulus of 9 million psi (62,000 MN/m²), is especially well suited for a number of industrial applications including ropes, cables, coated fabrics,

and protective clothing. KEVLAR® has properties similar to those of KEVLAR® 29 and is designed for the reinforcement of rubber, specifically tires, belts, and hose. This presentation, however, will concentrate on KEVLAR® 49 because of its unique combination of high strength, high modulus, and light weight, and because of its many demonstrated properties in reinforced plastics as a replacement for fiber glass.

The short time since its commercial introduction in 1972 has not allowed extensive evaluation of KEVLAR® 49 and its composites for specific automotive applications. However, we believe that work in other end-uses reported here will provide valuable background information for future evaluations in the automobile industry.

TABLE I

COMPARATIVE YARN PROPERTIES

	<u>Kevlar® 49</u>	<u>Type 728 Nylon</u>	<u>Type 68 Dacron®</u>	<u>E-HTS Glass</u>	<u>Stainless Steel</u>
Tensile Strength, psi (MN/m ²)	400,000* (2756)	143,000* (985)	162,500* (1120)	350,000** (2412)	250,000 (1722)
Modulus, psi (MN/m ²)	18,000,000 (124,000)	800,000 (5512)	2,000,000 (13,780)	10,000,000 (68,900)	29,000,000 (199,800)
Elongation to Break, %	2.5	18.3	14.5	3.5	2.0
Density, lb/in ³ (g/cm ³)	0.052 (1.44)	0.041 (1.14)	0.050 (1.38)	0.092 (2.55)	0.284 (7.83)

*Unimpregnated twisted yarn test - ASTM D2256.

**Impregnated strand test - ASTM D2343.

fiber is uniform compared with other reinforcing fibers like glass (Ref. 1)*. The tensile strength of 400,000 psi (2760 MN/m²) is measured per ASTM D2256 using a conventional twisted yarn test employed by the textile industry. If, however, KEVLAR® 49 is tested by the ASTM D2343 resin impregnated strand test commonly used by fiberglass manufacturers, the ultimate useful tensile strength is in excess of 500,000 psi or 3445 MN/m² (Figure 1). The combination of high tensile strength and modulus with the 0.052 pounds per cubic inch (1.44 g/cc) density gives KEVLAR® 49 a higher specific*** tensile strength than currently available from any other commercially available material and a respectable specific*** modulus even when compared with such high modulus materials as boron and graphite. These relative data (Figure 2) form the key to market opportunities in plastic composites and other uses where the ratio of strength or stiffness to weight is important.

KEVLAR® 49 fibers also have excellent toughness which gives good textile processibility and high impact strength.

THERMAL PROPERTIES - KEVLAR® 49 has good thermal stability. It retains a high percentage of room temperature properties when tested at temperatures up to 355°F (180°C) (Figure 3). The fiber does not melt or support combustion but will carbonize at about 800°F (427°C). At

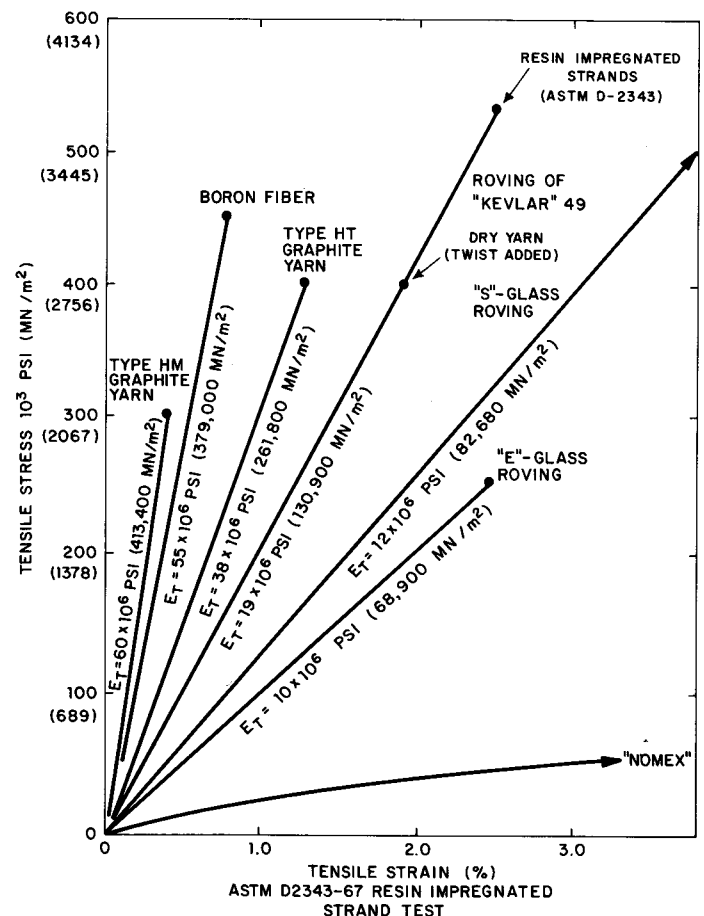


Fig. 1 - Stress-strain behavior of reinforcing fibers

*Numbers in parentheses designate references at end of paper.

***tensile strength or modulus divided by density.

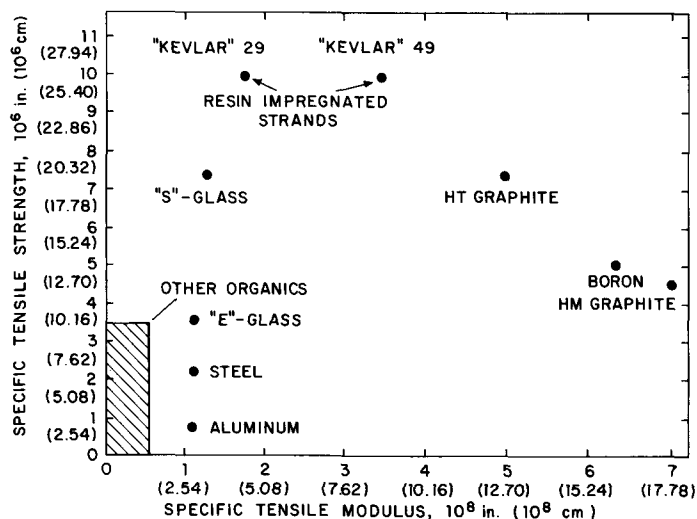


Fig. 2 - Specific tensile strength and specific modulus of reinforcing fibers

cryogenic temperatures as low as -320°F (-196°C), its performance is excellent with essentially no embrittlement or degradation of fiber properties. It has excellent thermal dimensional stability with a slightly negative coefficient of thermal expansion (-2×10^{-6} in./in. $^{\circ}\text{C}$; $-1.1 \times 10^{-6}/^{\circ}\text{F}$).

CHEMICAL AND ULTRAVIOLET RESISTANCE - The chemical resistance of KEVLAR® 49 yarn is excellent except in a few strong acids and strong bases (Table II). Since it is self-screening, the effect of ultraviolet light will vary with the thickness of the item exposed. However, no strength loss has been observed in exposures of plastic composites reinforced with KEVLAR® 49, since the resin matrix shields the fibers from UV degradation.

KEVLAR® 49 yarn is not dyeable and has an equilibrium moisture level of 3.5-4.5% (72°F , 22°C ; 55% RH).

COMPOSITE PROPERTIES

The excellent fiber properties are reflected in plastic composites reinforced with KEVLAR® 49. The fiber is supplied without finish or size and, because of its organic nature, can be combined with most commercially available resins. Experience has shown, though, that the presence of moisture on the surface of the yarn can adversely affect interlaminar shear properties with some resin systems. Specifically, KEVLAR® 49 yarn and roving should be predried to less than 1% moisture when anhydride-cured epoxy resins are being used.

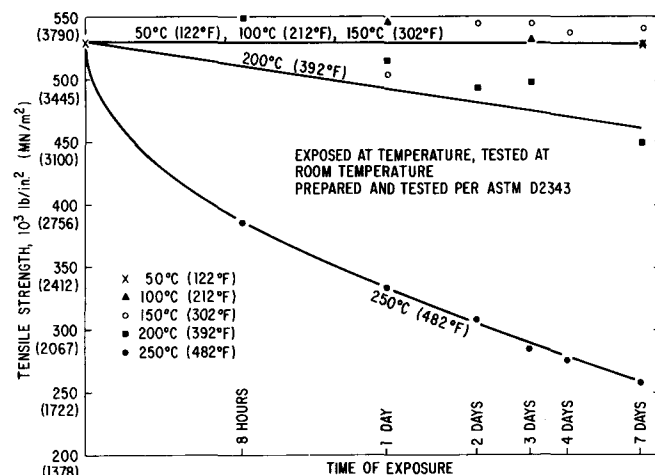


Fig. 3 - The effect of elevated temperature exposure on the tensile strength of Kevlar® 49/epoxy roving strands

Most of the processes used for combining resins with glass fibers are adaptable to KEVLAR® 49 with little or no modification. These include wet lay-up, prepregging of fabrics and tapes, filament winding, pultrusion, and the preparation of chopped fiber molding compounds. However, to date a chopped strand mat (CSM) or a method for chopper gun lay-up with KEVLAR® have not been developed.

Table III outlines the mechanical properties of unidirectional laminates made with KEVLAR® 49, graphite, and E-glass. Significant advantages are seen for KEVLAR® 49 in density, tensile strength and stiffness over glass. Other laminate properties, with the exception of compressive strength, are in good balance. While unidirectional composites of KEVLAR® 49 tested in tension have a linear stress-strain curve to failure, when tested in compression, their behavior is elastic at a low strain and plastic at high strains. This unique compressive behavior of KEVLAR® 49 aramid compared with other inorganic reinforcing fibers is fundamental to its metal-like ductility which is illustrated in a 3-point bending test (Figure 4) (Ref. 2).

A composite having higher compressive strength for demanding structural applications can be achieved by combining KEVLAR® 49 with higher modulus fibers such as graphite or boron. This "hybrid" composite has a balance of properties unavailable with any reinforcing fiber used alone. For example, a hybrid consisting of 50% KEVLAR® 49 and 50% "Thornel" 300 graphite fiber*

*Product of Union Carbide Corp.

in an epoxy resin demonstrates a flexural yield strength of over 90,000 psi (620 MN/m²) compared to 45,000 psi (310 MN/m²) for a similar composite prepared with all-KEVLAR® 49. Moreover, the impact strength of the hybrid is twice that of the composite reinforced with "Thornel" 300 alone. Combinations with lower elongation graphite fiber such as the HMS** show even greater improvements in impact strength (Figure 5). KEVLAR® 49 may also be hybridized with fiberglass for economic considerations without sacrificing the desirable properties of either reinforcement. Generally, glass/KEVLAR® 49 hybrid weighs less than an all-glass composite, while having better compressive strength than an all-KEVLAR® 49 laminate.

Other significant and useful mechanical properties of composites of KEVLAR® 49 are high stress-rupture life (Figure 6), good cyclic tension-tension fatigue resistance (Figure 7), and noteworthy vibration damping characteristics (Figure 8). The ball-drop impact strength of composites of KEVLAR® 49 aramid is superior to glass reinforced composites and much higher than graphite laminates (Ref. 3). KEVLAR® 49 also has high fracture toughness, or the ability to arrest crack propagation (Ref. 4).

The environmental stability of composites of KEVLAR® 49 aramid is generally good except in extremely hostile environments. This is illustrated by the relatively small loss of interlaminar shear strength after exposure to several typical environments for extended periods (Table IV). These results indicate that the resin-to-fiber bond has been maintained and good composite durability can be expected. Table IV, however, emphasizes that the particular resin matrix employed can have a significant effect on composite environmental stability.

The machinability of composites of KEVLAR® 49 is somewhat different than that of the more brittle inorganic fiber reinforced composites. The toughness of KEVLAR® 49 requires that a shearing rather than a shattering action be used in cutting the fibers. In thin laminates (10-20 mils; 0.25-0.51 mm) differences are not great enough to require changes in procedure from glass composites, but in thicker laminates some tool redesign is desirable. In general, machining of composites of KEVLAR® 49 is more analogous to wood finishing than to metal finishing. Tooling and procedures have been developed which overcome most machining problems and detailed information is available upon request.

**Product of Hercules Corp.

TABLE II
CHEMICAL RESISTANCE OF KEVLAR® 49 YARN

Environment (24 hrs. exposure at room temp.)	Tensile Strength Loss (%)
ACIDS	
Acetic (99.7%)	None
Hydrochloric (37%)	None
Hydrofluoric (48%)	10%
Nitric (70%)	60%
Sulfuric (96%)	100%
BASES	
Ammonium Hydroxide	None
Sodium Hydroxide	10%
SOLVENTS	
Acetone	None
Benzene	None
Methyl Ethyl Ketone	None
Toluene	None
OTHER CHEMICALS	
Gasoline	None
Salt Water	<0.5%
Water, Boiling (100 hrs)	2%

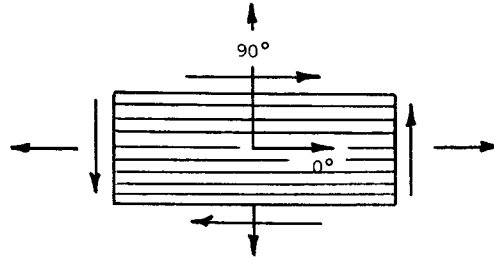
APPLICATIONS

AEROSPACE - Commercial aircraft use a substantial amount of reinforced plastics in interior finishing and trim and in exterior fairings. KEVLAR® 49 has been adopted in a number of these parts on the Lockheed L-1011, Concorde SST, and Dehavilland DHC-7 because of weight savings up to 30% compared to similar parts made with glass. Other major aircraft and helicopter manufacturers are adopting KEVLAR® 49 for semi-structural and structural applications such as flooring, doors, fairings, seats, fuselage skins and radomes (Ref. 5).

Figure 9 shows schematically areas of a commercial helicopter where KEVLAR® 49 has been evaluated as a replacement for glass reinforced or metal parts. A significant reduction in overall airframe weight of 11% is achievable by such replacement. Analogously, overall automobile weight could be reduced by the use of KEVLAR® 49 reinforcement.

INDUSTRIAL AND CONSUMER - A number of uses for KEVLAR® 49 have developed in markets outside aerospace. Some of the most promising near-term applications are in boat hulls, sporting goods, pultruded products, electrical and electronic applications, ballistic protection materials, coated fabrics, and cables and tension members.

TABLE III
UNIDIRECTIONAL COMPOSITE LAMINA PROPERTIES



	<u>Kevlar® 49</u>	<u>E-Glass</u>	<u>Graphite</u>
Density, lbs/in ³ (g/cm ³)	0.050 (1.38)	0.075 (2.08)	0.055 (1.52)
Tensile Strength 0°, 10 ³ psi (MN/m ²)	200 (1378)	160 (1102)	180 (1240)
Compressive Strength 0°, 10 ³ psi (MN/m ²)	40 (276)	85 (586)	160 (1102)
Tensile Strength 90°, 10 ³ psi (MN/m ²)	4.0 (27.6)	5.0 (34.4)	6.0 (41.3)
Compressive Strength 90°, 10 ³ psi (MN/m ²)	20 (138)	20 (138)	20 (138)
In-Plane Shear Strength 10 ³ psi (MN/m ²)	6.4 (44.1)	9.0 (62.0)	9.0 (62.0)
Interlaminar Shear Strength 10 ³ psi (MN/m ²)	7-10 (48.2-68.9)	12 (82.7)	14 (96.5)
Poisson's Ratio	0.34	0.30	0.25
Tens. & Comp. Modulus 0°, 10 ⁶ psi (MN/m ²)	11 (75,790)	5.7 (39,270)	19 (130,900)
Tens. & Comp. Modulus 90°, 10 ⁶ psi (MN/m ²)	0.8 (5512)	1.3 (8960)	0.9 (6200)
In-Plane Shear Modulus 10 ⁶ psi (MN/m ²)	0.3 (2070)	0.5 (3445)	0.7 (4820)

MARINE - In boat hulls and many sporting goods applications, KEVLAR® 49 can offer both a significant weight savings and improved stiffness versus glass (Ref. 6). Superior vibration damping and good impact resistance are also obtained. A kayak made with fabrics of KEVLAR® 49, for example, weighs about 18 pounds (8.2 kg) while a comparable boat made with glass would be over 30 pounds (13.6 kg).

KEVLAR® 49 is also being used in powerboat (Figure 10) and sailboat construction. The advantages over glass are the same as those observed in canoes and kayaks - weight savings with improved impact resistance and stiffness. Light weight results in a faster, more responsive boat. Better fuel economy is achieved in power-

boats by weight reduction through the use of reinforcement with KEVLAR®.

SPORTING GOODS - KEVLAR® 49 is also used in sporting goods uses. In golf shafts, javelins, archery bows, fishing rods, tennis rackets, skis, and other items, KEVLAR® 49 can be used in combination with graphite. In this hybrid construction, KEVLAR® 49 offers high tensile strength, good impact resistance, and more favorable economics, while graphite adds stiffness and required compressive strength. In these and many other reinforced plastic applications, this hybrid approach can provide a better product than possible with any one reinforcing fiber alone.

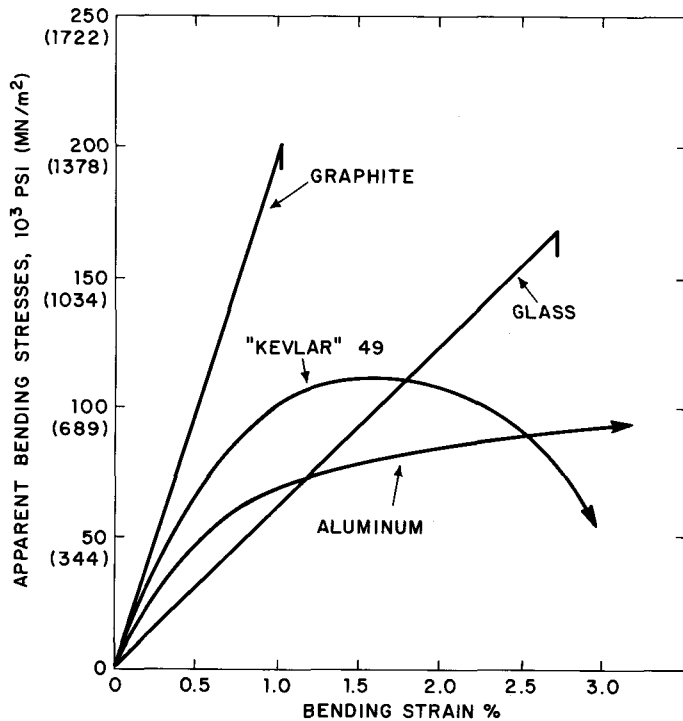
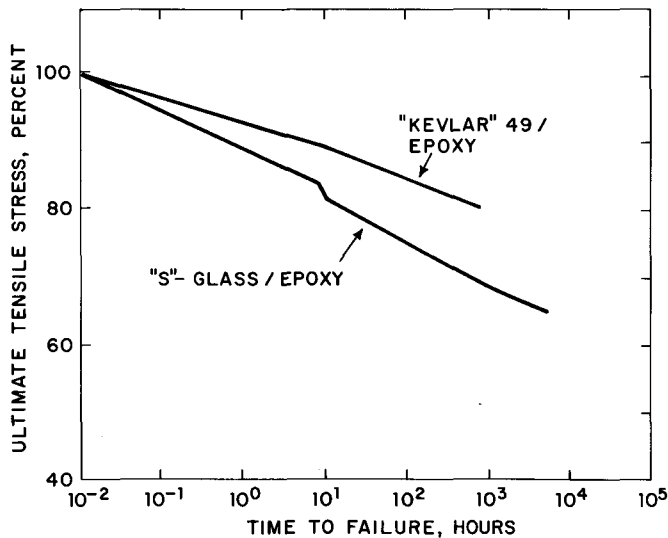


Fig. 4 - Unidirectional composite bending stress/strain curves (in epoxy resin)



DATA COURTESY OF T.T. CHIAO
LAWRENCE LIVERMORE LABORATORY
REF. 7

Fig. 6 - Stress-rupture behavior of Kevlar® 49 and "S"- glass unidirectional composites

PULTRUSION - A number of pultruded shapes have been successfully prepared using KEVLAR® 49. The properties of pultruded rods outlined in Table V show the expected advantages for KEVLAR® 49 aramid over glass in modulus and weight reduction. Similar advantages versus glass are

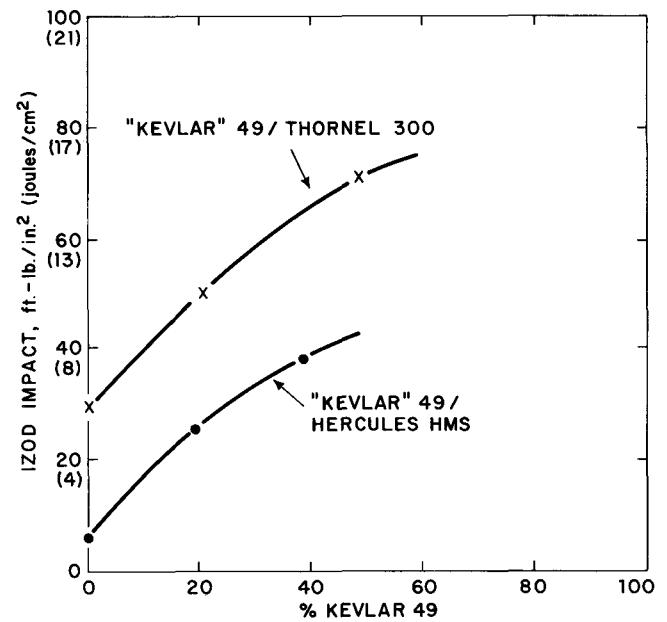


Fig. 5 - Impact strength of unidirectional hybrid composites (v/o = 60%)

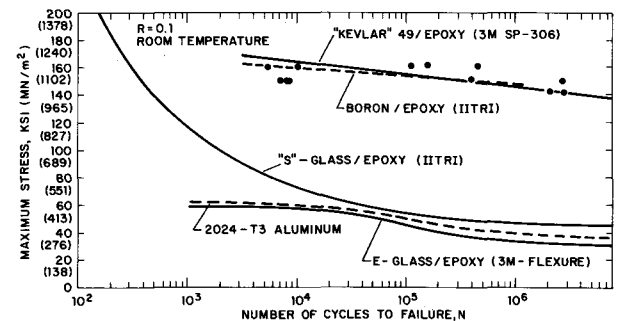


Fig. 7 - Tension - tension fatigue behavior of unidirectional composites and aluminum

seen when short length KEVLAR® fibers are used in the preparation of molding compounds (Table VI).

ROPES AND CABLES - KEVLAR® 49 is replacing steel in tension members and cables where its very high specific tensile strength, low stretch, good electrical properties, cyclic and creep fatigue resistance, and toughness are important. The outstanding strength-to-weight ratio is the primary reason for the use of KEVLAR® in very long cables such as those used in oceanographic and aerospace markets.

COATED FABRICS - Fabrics of KEVLAR® 49 aramid are uniquely qualified as load-bearing substrates in a variety of coated fabric applications. Coated fabrics based on KEVLAR® 49 for architecture (Teflon®, urethane, PVC) offer significant weight saving at a given tensile

	LOSS FACTOR $\times 10^{-4}$
1020 STEEL	< 20
DUCTILE CAST IRON	30
GRAPHITE/EPOXY	30
FIBERGLASS/EPOXY	47
"KEVLAR" 49/EPOXY	160
CURED POLYESTER RESIN	400

strength and modulus compared with glass or Dacron® polyester, along with superior tear strength.

PRODUCT FORMS

KEVLAR® 49 is supplied by Du Pont in yarns and rovings (Table VII), while a variety of balanced and unidirectional fabrics are available from commercial weavers. Other products such as nonwoven fabrics and felts, heavy denier pultrusion rovings, and staple fibers are under development. Specific product descriptions are available upon request. In addition, detailed information is available on the use of KEVLAR® 49 aramid in specific applications.

SUMMARY

KEVLAR® aramid has been accepted by the automotive industry to date as a reinforcement for rubber - tires, V-belts, and hose. On the other hand, it is a proven replacement for fiberglass reinforcement in many aerospace and commercial applications where weight savings, higher modulus, fracture toughness, vibration damp-

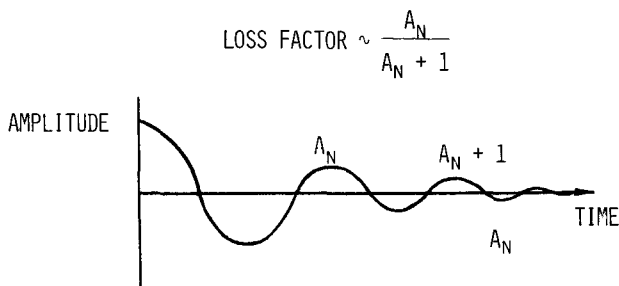


Fig. 8 - Decay of free vibrations

TABLE IV

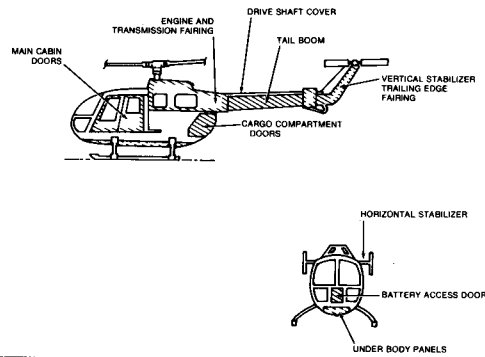
LONG-TERM ENVIRONMENTAL STABILITY OF COMPOSITES OF KEVLAR® 49 AND FIBERGLASS

Environmental Conditions	Interlaminar Shear Strength*, psi (MN/m ²)		
	Kevlar® 49/ 250°F Epoxy**	Kevlar® 49/ 350°F Epoxy***	"S"-Glass/ 350°F Epoxy***
None, Control	7180 (49.5)	5900 (40.6)	11,500 (79.2)
Boiling Water 3 1/2 Years	2300 (15.8)	3070 (21.2)	-0- (-0-)
Salt Water 3 1/2 Years	4670 (32.2)	5900 (40.6)	11,000 (75.8)
Jet Fuel (Texaco "Abjet" K-40) 3 1/2 Years	6605 (45.5)	5900 (40.6)	11,500 (79.2)
Lubricating Oil ("Skydrol") 3 1/2 Years	6750 (46.5)	5900 (40.6)	11,500 (79.2)

*ASTM D2344, Short Beam Shear

**Interior Grade, General Purpose

***Exterior Grade, High-Temperature



COMPONENTS CONSIDERED FOR FABRICATION IN "KEVLAR" 49	PERCENTAGE REDUCTION (%)
COMPONENTS CURRENTLY FABRICATED FROM S-GLASS COMPOSITE	
FUSELAGE UNDERBODY PANELS	20
REAR CARGO COMPARTMENT DOORS	40
ENGINE AND TRANSMISSION FAIRING	20
CABIN DOORS	20
BATTERY ACCESS DOOR	55
VERTICAL STABILIZER TRAILING EDGE FAIRING	20
COMPONENTS CURRENTLY FABRICATED FROM ALUMINUM ALLOY	
FLOOR PANELS (MAG. AND ALUMINUM)	42
TAIL ROTOR DRIVE SHAFT COVER	48
TAIL BOOM	22
HORIZONTAL STABILIZER AND END PLATES	20
CABIN ROOF AND SIDE STRUCTURE	47
EFFECT ON BO-105 STRUCTURE WEIGHT	11

Fig. 9 - Commercial helicopter components

ing, improved static or dynamic fatigue life, or its unique "fail-safe" impact behavior are required. As pending Government legislation dictate increased fuel economy, the demonstrated properties of this material should become attractive to the automotive industry. Possible applications for KEVLAR® 49 - or the sister aramid Special Product, KEVLAR® 29 - include:

- door anti-intrusion beams for weight savings and impact resistance
- various chassis components such as radiator or transmission supports
- caliper brake pistons for dimensional stability and lighter weight
- brake lining or clutch plate reinforcement replacing asbestos

- selective addition to increase the fracture toughness (crack inhibition) of existing fiberglass reinforced parts

KEVLAR® aramid can be used by itself or in combination with fiberglass or graphite in many of the same processes common to the plastics industries. Many detailed publications on the use of KEVLAR® Special Products are available from the manufacturer.

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2. D. L. G. Sturgeon, "PRD-49 High Modulus Organic Fibers for Aluminum Replacement", pre-



Fig. 10 - Powerboat with hull reinforced with Kevlar® 49

TABLE V

PROPERTIES OF PULTRUDED RODS

Property	Reinforcement	
	Kevlar® 49	Glass
Rod Diameter, in. (mm)	3/8 (9.5)	3/8 (9.5)
Fiber Volume, %	60	58
Flex Modulus, 10^6 psi (MN/m ²)	9.6 (66,150)	5.7 (39,270)
Weight, g/ft (g/cm)	29.3 (0.96)	45.5 (1.5)

TABLE VI

TYPICAL PROPERTIES OF EPOXY MOLDING COMPOUNDS

Property	Reinforcement*	
	Kevlar® 49	Glass
Fiber Volume, %	50	47
Fiber Length, in. (mm)	1/2 (12.7)	1/2 (12.7)
Specific Gravity	1.32	1.86
Tensile Strength, psi (MN/m ²)	28,500 (196)	14,400 (99)
Tensile Modulus, 10^6 psi (MN/m ²)	2.96 (20,390)	2.23 (15,360)

*Test specimen machined from molded plaques.

sented to an Aerospace Industry Seminar in London, Sept. 7, 1972.

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4. C. Zweben, "Fracture of KEVLAR® 49, E-Glass, and Graphite Composites", presented to the

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5. R. A. Wolffe, "PRD-49 Composites for Aerospace Applications", presented to an Aerospace Industry Seminar in London, Sept. 7, 1972.

6. D. L. G. Sturgeon, et al., "KEVLAR® 49 Composites for Sporting Goods and Recreational

TABLE VII

YARNS AND ROVINGS OF KEVLAR® 49

<u>Denier</u>	<u>Decitex</u>	<u>Yield (yd/lb)</u>	<u>Yield m/kg</u>	<u>Filaments</u>	<u>Twist</u>
195	217	22,924	46,155	134	0
380	422	11,763	23,684	267	0
1140	1267	3,921	7,895	768	0
1420	1578	3,148	6,338	1000	0
4560	5066	980	1,973	3072	0
7100	7888	630	1,268	5000	0

Equipment", presented to the 29th Annual SPI Meeting, Washington, D.C., February, 1974.

7. T. T. Chiao, et al., "Stress-Rupture Behavior of Strands of an Organic Fiber/Epoxy Matrix", presented to the American Society of Testing and Materials Third Symposium on Composite Materials, Williamsburg, Va., March, 1973.

We believe this information is the best currently available on the subject. It is subject to revision as additional knowledge and experience are gained. Du Pont makes no guarantee of results and assumes no obligation or liability whatsoever in connection with this information. This publication is not a license to operate under, or intended to suggest infringement of, any existing patents.



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