Mechanical Properties of a Fiberglass Prepreg System at Cryogenic and Other Temperatures

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The test results given in this paper provide mechanical and physical properties of an epoxy E-glass system at cryogenic and elevated temperatures. E-glass cloth pre-impregnated with an epoxy resin was selected as the material for the fan blades in NASA's new cryogenic wind tunnel, the National Transonic Facility (NTF). Because of the limited data available on E-glass at cryogenic temperatures, a comprehensive testing program was undertaken at the Langley Research Center to develop a data base to support the design of the NTF fan blades. The fan blades were constructed of 7781 and 7576 style E-glass cloths with EF-2 resin. Tests were conducted that completely characterized the strength and elastic properties of laminates made of each of the cloths, as well as of a laminate representative of the fan blade construction, at cryogenic, room, and elevated temperatures. In addition to these tests, creep, fatigue, and thermal expansion tests were conducted.

Nomenclature

E = Young's modulus, GPa (psi)
G = shear modulus, GPa (psi)
α = thermal coefficient of expansion, m/m/K (in./in./°F)
ν = Poisson's ratio
σ = tensile strength, MPa (psi)
$\bar{\sigma}$ = tensile fatigue strength limit, MPa (psi)
τ = inplane shear strength, MPa (psi)

Subscripts

c = compression
T = tension
x,y = structural axes
$1,2$ = material axes (1 direction aligned with cloth's warp direction)

Introduction

VARIOUS composite materials were screened for application in the design of the National Transonic Facility (NTF) fan blades. An E-glass pre-impregnated with epoxy resin (prepreg) was selected as the most promising material for the fan blades because of its low cost, repairability, high damping, and fatigue resistance. However, the use of fiberglass systems for cryogenic applications is not widespread and the data base is very small. Therefore, a testing program was undertaken at Langley Research Center (LaRC) to determine the physical and mechanical properties of the selected material at elevated and cryogenic temperatures.

The NTF wind tunnel will operate at pressures from 57.2×10^3 to 896.7×10^3 Pa (8.3-130 psia), flow stream temperatures of 353-89 K (175 to −300°F), at Reynolds numbers up to 120 million, and is powered by a 93.2×10^6 W (125,000 hp) fan. The fan system consists of 25 blades attached to the outer rim of a 3.96 m (13 ft) diam disk that rotates at speeds up to 600 rpm.

Two basic fiberglass cloths (7781 E-glass and 7576 E-glass) were used in fabricating the NTF fan blades (Fig. 1). The material specifications, specimen, preparation, and the tests that were used to characterize the E-glass prepregs (the two basic cloth laminates and a laminate representative of the fan blade structure) are described herein, as well as in Ref. 1. Test results for the 7781-E-glass, the 7576 E-glass, and the representative laminates at temperatures of 89 K (−300°F), room temperature, and 367 K (200°F) are presented.

Material Description

Two styles of fiberglass cloth pre-impregnated with an epoxy resin were considered for use in the fan blade (Table 1). The first was 7781 style E-glass with a Volan "A" finish. This cloth has a ratio of 60 fibers in the warp direction to 54 in the fill direction and is 0.22 mm (0.0085 in.) thick. The second material is 7576 style E-glass with a VM 665 finish. This cloth has a ratio of 120 fibers in the warp direction to 24 in the fill direction and is 0.28 mm (0.011 in.) thick. The epoxy resin system is commerically known as EF-2 or the Polaris formulation. It consists of a 1:1 mixture of Epon 828 and Epon 1031 with 90 parts by weight (pbw) of MNA (methyl natic anhydride) and 0.5 pbw of BDMA (benzyl demethyl amike). Test specimens were machined from laminates made of each of the individual prepreg cloths as shown in Fig. 2. In addition, specimens were also cut from laminates utilizing both

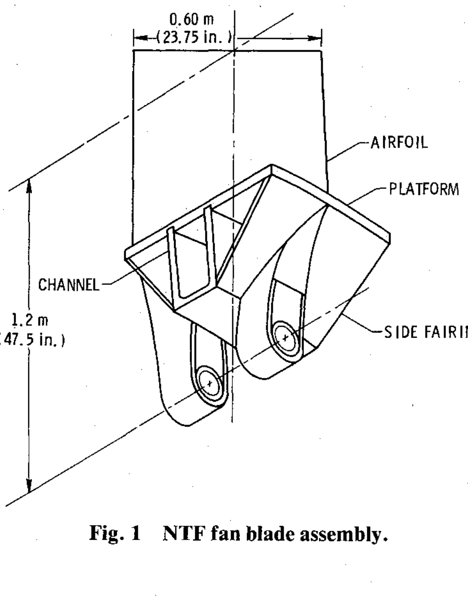

Fig. 1 NTF fan blade assembly.

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Table 1 Material and laminate description

Material	Fibers Warp direction	Fibers Fill direction	Material plies per laminate
7781 E-glass cloth	60	54	14
7576 E-glass cloth	120	24	11
Representative laminate	Combination of 7781 and 7576 glass		19

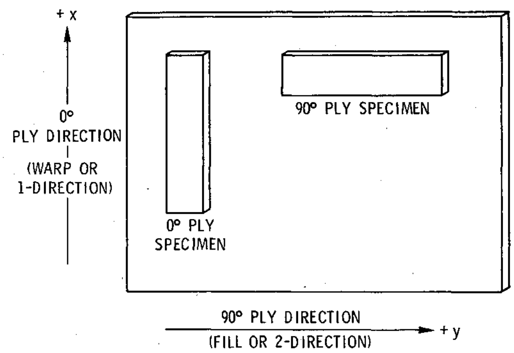

Fig. 2 Test specimen ply orientation.

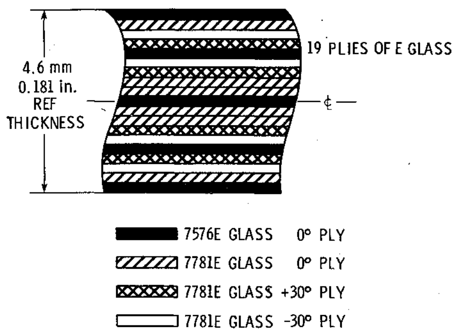

Fig. 3 Stacking sequence of representative laminate.

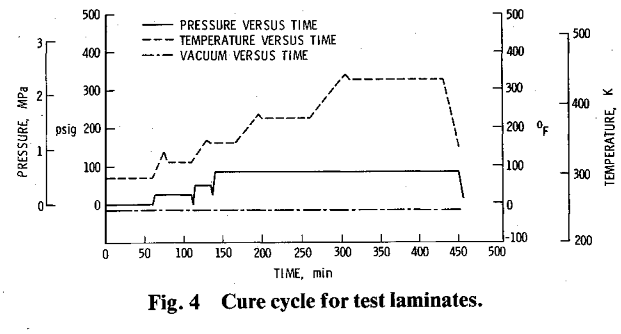

Fig. 4 Cure cycle for test laminates.

prepreg cloths in a stacking sequence that closely resembles the lay-up of the fan blade. This laminate is shown in Fig. 3 and is hereafter referred to as the "representative" laminate. For all specimens, the "as-molded" resin content was in the range of 27-33%.

Preparation and Cure Process

In preparation for the cure process, the laminates were first laid up on a flat plate and then vacuum bagged. The entire assembly was then placed in an autoclave at ambient temperature with a vacuum. The basic cure cycle is shown in Fig. 4. Primary methods used to verify laminate quality included visual inspection with a high-intensity light and resin burn-out tests on selected specimens.

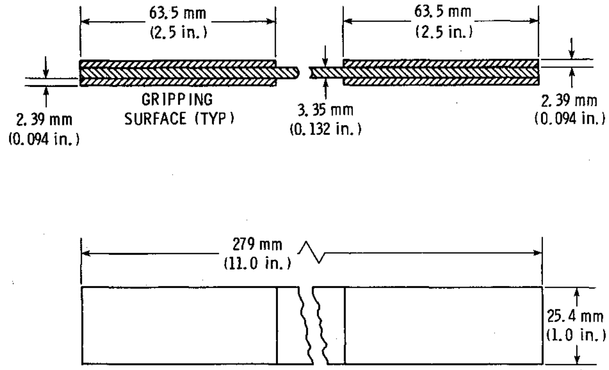

Fig. 5 Typical tensile test specimen.

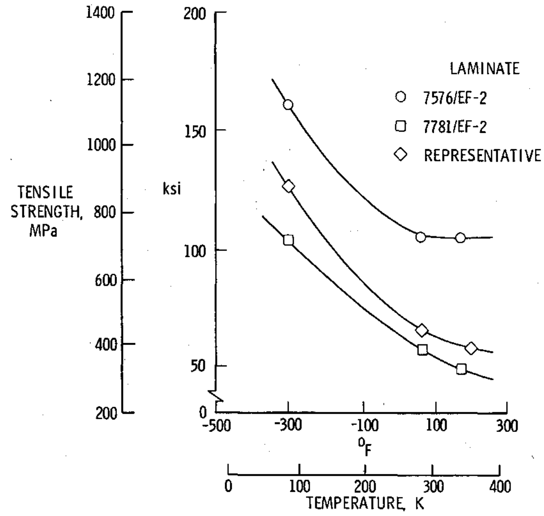

Fig. 6 Tensile strength vs temperature for 0 deg direction.

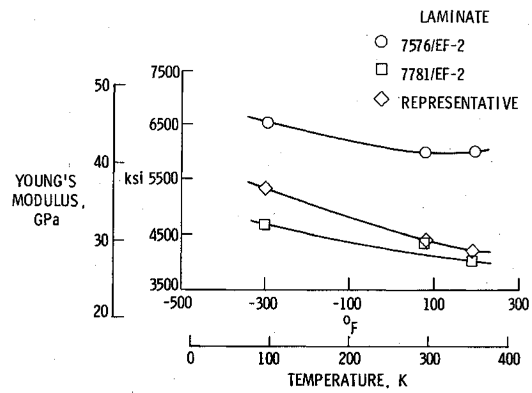

Fig. 7 Young's modulus of elasticity vs temperature for 0 deg direction.

Tensile Tests

The American Society for Testing and Materials (ASTM) D3039-76 method was used to test the tensile specimens.[2] The equipment used was a 89.0 kN (20,000 lb) tensile test machine. The tensile specimens (Fig. 5) are 0.0254 m (1 in.) wide by 0.279 m (11 in.) long with a thickness determined by the number of plies in each laminate. The test specimen and grips were enclosed by a chamber capable of maintaining either the elevated temperature or the cryogenic environment. Liquid nitrogen (LN_2) was vaporized to cool the chamber. Five specimens of each of the three laminates (7781/EF-2, 7576/EF-2, and representative) were tested in the 0 and 90 deg directions at temperatures of 367 K (200°F), room tem-

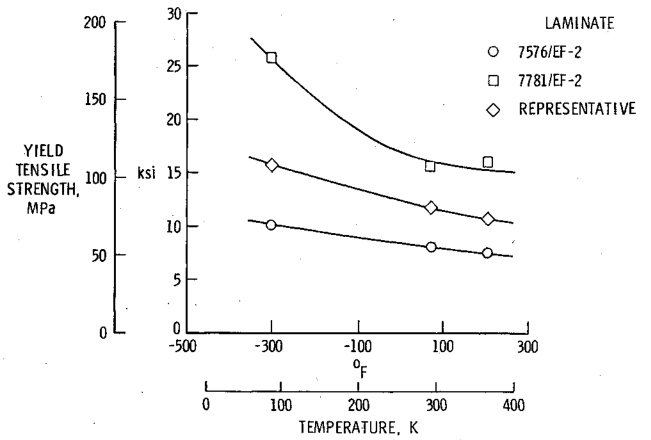

Fig. 8 Yield tensile strength vs temperature for 90 deg direction.

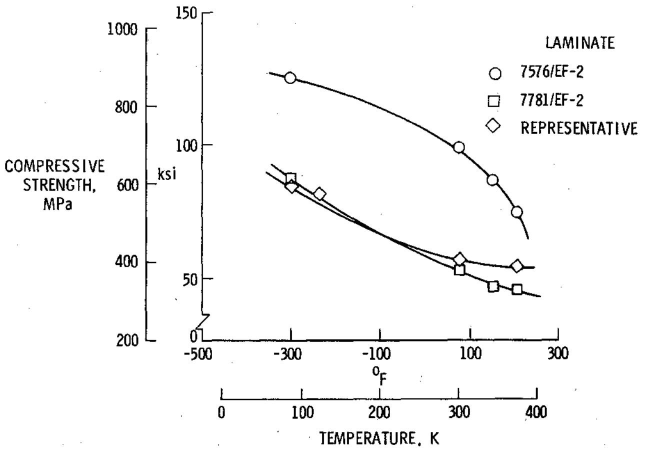

Fig. 10 Compressive strength vs temperature for 0 deg direction.

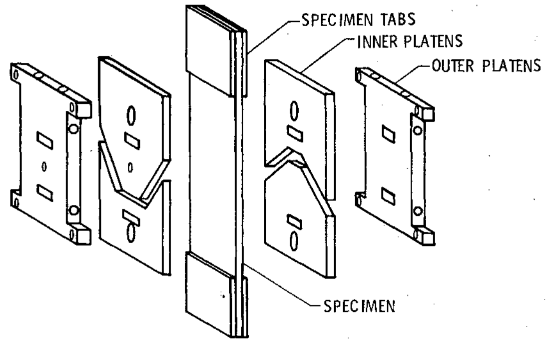

Fig. 9 Compression test specimen and test fixture.

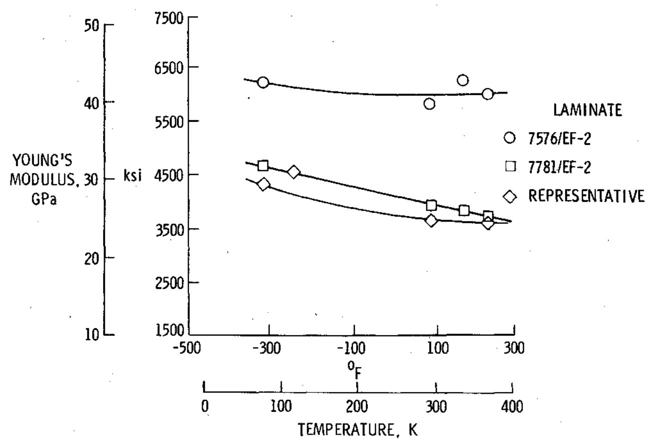

Fig. 11 Compressive modulus of elasticity vs temperature for 0 deg direction.

perature (RT), and 89 K (−300°F). A uniform head speed of 1.27 mm (0.05 in.)/min was used for all testing.

The material strain was measured with a 0.0508 m (2 in.) extensometer mounted on the test beam for the RT and 367 K (200°F) tests. Strain gages were used for these measurements at 89 K (−300°F). The yield strength was determined by the 0.2% offset method. Strain was measured in the lateral and parallel fiber directions to obtain Poisson's ratios. The tensile strength and Young's modulus as a function of temperature for the 0 deg fiber direction are shown in Figs. 6 and 7, respectively. The yield strength for the 90 deg fiber orientation as a function of temperature is shown in Fig. 8. The test data show that the material becomes increasingly stronger at colder temperatures. The tensile strength of the representative laminate falls between the strengths of the 7781/EF-2 and 7576/EF-2 laminates. This is to be expected since the 7781/EF-2 laminate is nearly balanced and the 7576/EF-2 laminate is highly unbalanced. The average ultimate strength of the representative laminate at 367 K (200°F) in the 0 deg direction is 394 MPa (57,086 psi) and is 235 MPa (34,128 psi) in the 90 deg direction.

Compression Tests

The ASTM D3410-75 test method was used as a guideline for compressive testing of the fan blade material.[3] However, because of the complexity of the compressive fixture required by the reference test standard, a face-supported compression fixture was used as discussed in Ref. 4. This face-supported compression fixture (Fig. 9) was used to provide constraint and also allowed for environmental conditioning. The temperature changes were accomplished by using cartridge heaters or liquid nitrogen manifolding. The inner platens were split to allow for axial compression, while the outer platens provided primary constraint. Cutouts were made through both platens on each side to allow for the attachment of the mechanical extensometers used to monitor axial strain. Hydraulic grips were used to transfer the load to the specimen by frictional forces between the grips and the tabs.

Five specimens were tested at each of the three test temperatures: 367 K (200°F), RT, and 89 K (−300°F). Measurements were taken to insure alignment of the specimen and testing machine axes. Load and strain data were obtained for each specimen throughout the test by monitoring the output of a load cell.

Ultimate compressive strength and modulus data were obtained from these tests. These data (shown in Figs. 10 and 11) for the 0 deg ply fiber direction show the compressive strength to be significantly higher at colder temperatures.

Fatigue Tests

The ASTM D3479-76 test method was used for determination of the constant-amplitude tension-tension fatigue properties.[5] The load-control fatigue tests were conducted at a frequency of 15 Hz and at a stress ratio of 0.01. The fatigue test specimens were 0.038 m (1.5 in.) wide and 0.0279 m (11 in.) long with the thickness depending upon the laminate. The distance between the grips was 0.20 m (8 in.).

For the elevated temperature tests, electric heaters were mounted on a special fixture to heat the specimen to 367 K (200°F). For the cryogenic fatigue tests, LN_2 was vaporized through the test fixture cooling the specimen to 83 K (−310°F). Thermocouples were mounted on the test fixture and a probe was used to monitor the temperature of the test specimen.

The fatigue strength limit is defined for the fan blade materials to be the maximum stress that can be applied for

Table 2 Tension-tension fatigue test results

Laminate (0 deg direction)	Temp., K	Applied load, MPa (psi)	No. of specimens	No. of cycles	Average residual strength, MPa (psi)
7576/EF-2	83	146 (21,180)	3	1×10^6	503 (72,919)
	RT	146 (21,180)	5	1	---
	367	145 (21,105)	2	1	542 (78,648)
7781/EF-2	83	98 (14,256)	7	1×10^6	349 (50,651)
	RT	98 (14,256)	6	1	306 (44,382)
	367	84 (12,131)	4	1	310 (44,939)
Representative	83	135 (19,584)	4	1×10^6	347 (50,371)
	RT	135 (19,584)	4	1	333 (48,328)
	RT	135 (19,584)	1	5	---
	367	118 (17,129)	4	1	---
	367	118 (17,126)	1	5	---

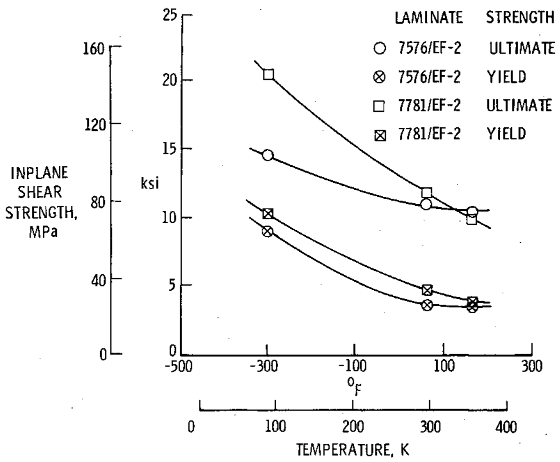

Fig. 12 Inplane shear strength vs temperature.

1×10^6 cycles without failure. This stress level was used as the allowable stress during the design of the fan blades. The fatigue limits were established by varying the fatigue test loads in increments of 5% of the ultimate tensile strength. At room temperature and at 367 K (200°F) the fatigue limits of the 7576/EF-2, 7781/EF-2, and representative laminates were found to be 20, 25, and 30% of the laminates' ultimate tensile strengths, respectively.

The environmental chamber used for the fatigue tests did not fully enclose the test specimens (the ends of the specimens were exposed to room temperature). Attempts to increase the applied cyclic load beyond the room temperature fatigue limit resulted in failures in portions of the specimens extending outside of the cryogenic environment. However, a number of fatigue tests were conducted at cryogenic temperatures for each of the three laminates to demonstrate that the cryogenic fatigue limits are at least as great as the room temperature fatigue limits.

Table 2 gives the test loads, test temperatures, number of specimens for each test condition, and residual strengths of many of the specimens. Two representative laminate specimens were tested for 5×10^6 cycles without failure. For the residual strength tests, the environmental chamber fully enclosed the specimens. It is noted that after 1×10^6 cycles, the residual strength at cryogenic temperature is about the same as that measured at the other temperatures. For the representative laminate, the cryogenic residual strength after 1×10^6 cycles was approximately 40% of the cryogenic ultimate strength, whereas for the room temperature fatigue tests, the residual strength was about 75% of the room temperature ultimate strength.

A limited amount of compression-compression fatigue testing of the 7781/EF-2 and representative laminates in the 90 deg direction was conducted. Stabilizing face plates were applied to the specimens. The specimens were tested for 1×10^6 cycles at the same load levels given in Table 2 without failure.

Inplane Shear Tests

The ASTM D3518-76 test method was used for the determination of the inplane shear stress-strain response.[6] The method is based on the uniaxial tensile stress-strain response of a ±45 deg laminate that is symmetrical about the midplane. The in-plane shear test is essentially a tension test of a ±45 deg symmetric laminate in accordance with the tensile test procedure described in ASTM D3039-76.

Five specimens were tested at each of the three test temperatures. The environmental chamber was used to control the temperature at 367 and 89 K (200 and −300°F). The yield strength was determined by the 0.2% offset method.

Inplane shear tests were completed for both the 7781/EF-2 and the 7576/EF-2 laminates. The results from these tests are presented in Fig. 12. These data show that for the 7781/EF-2 laminate, the ultimate strength is more than twice the yield strength. For the 7576/EF-2 laminate, the ultimate strength at RT and 367 K is approximately three times the yield strength and at 89 K the ultimate strength is about 1.6 times the yield strength. For the representative laminate, the in-plane shear test was not considered a viable test because the laminate does not make up a ±45 deg symmetric laminate.

Interlaminar Shear Tests

ASTM D2733-70 was one of two test methods used to determine the interlaminar shear strength.[7] Concern about "low" shear strengths obtained when using the fixture specified by the ASTM test method led to use of a second interlaminar shear test fixture after consultation with personnel from the National Bureau of Standards (NBS). The ASTM fixture is hereafter referred to as the "standard" fixture, while the second fixture is referred to as the "guillotine" fixture. The two test fixtures differed only in the method of retaining the side-supporting steel plates to the specimens. The ASTM method specified that these side plates be held against the specimen with two small "C" clamps located 0.0635 m (2.5 in.) apart. These clamps were to be tightened evenly and firmly to prevent peeling of the specimen during the test, but not to the point where the specimen was crushed. The guillotine method specified that the side plates be held together by eight screws (8-32 NC) evenly spaced in the 0.0762 m (3.0 in.) long side plates. These screws were torqued to 9.038×10^6 dyne-cm (8 in.-lb) each. This fixture provided a more uniform pressure on the specimen to prevent peeling.

Two different methods were also used to fabricate test specimens for these interlaminar shear tests. Specimens fabricated by the first method, hereafter referred to as

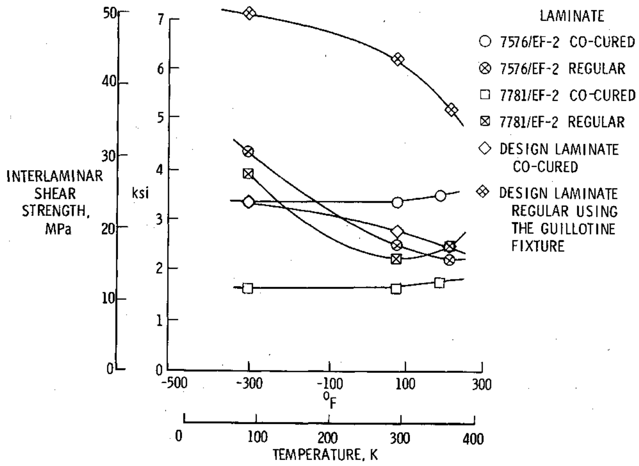

Fig. 13 Interlaminar ultimate shear strength vs temperature.

"regular" specimens, were machined from a laminate with two saw cuts through the center ply. These two cuts were made from opposite sides of the test specimens 12.7 mm (0.5 in.) apart. The other specimens, hereafter referred to as "co-cured," were fabricated in two steps. After the first half (layers on one side of the center plane) of the specimen was partially cured, the remainder of the laminate was applied to it and the entire assembled laminate was co-cured to the final state. The grooves (previously referred to as saw cuts) through the center ply were molded as an integral part of the specimens. Interlaminar shear tests, utilizing the standard fixture, were conducted on the 7781/EF-2 and 7576/EF-2 laminates made from both the regular and co-cured methods.

For the representative laminate, the co-cured specimens were tested using the standard fixture and the regular specimens were tested using the guillotine fixture. All tests were completed at temperatures of 367 K (200°F), RT, and 89 K (−300°F). The results of these tests are shown in Fig. 13. In general, these results indicate that the matrix strength of the laminates increases as the temperature decreases to 89 K (−300°F).

Thermal Expansion Tests

Coefficient of thermal expansion tests were performed in the 0 and 90 deg directions in accordance with the ASTM D696-70 test method.[8] Five specimens of each laminate for each direction were fabricated. The test specimens were 12.7 mm thick by 2.54 cm wide by 15.24 cm long (0.50 × 1.0 × 6.0 in.).

Reference readings were tabulated at room temperature. The thermal canister containing the specimen and specimen holder was filled with liquid nitrogen, and the specimen was allowed to soak. Periodic micrometer readings were taken until equilibrium temperature was reached. The specimen and holder were removed from the liquid nitrogen and allowed to set at room temperature for approximately 15 min. The specimen and holder were placed in a canister of room temperature water and allowed to soak until the readings coincided with the original reference measurements. Then the specimen and holder were removed and placed in another canister of water at a temperature of 373 K (212°F). After reaching thermal equilibrium and tabulating measurements, the specimen and holder were returned to the cannister of room temperature water. This test was performed three times per specimen. Table 3 gives the coefficients of thermal expansion for 293-78 K (68 to −320°F) and 293-373 K (68 to −212°F) for each of the laminates.

The accuracy of the test setup and procedure was verified by performing a test using a copper specimen whose coefficient of linear thermal expansion was known.

Table 3 Linear thermal expansion test results

Laminate	Ply orientation, deg	Coefficient of linear thermal expansion, m/m/K × 10^{-6} (in./in./°F × 10^{-6}) 293-78 K	293-373 K
7576/EF-2	0	6.59 (3.66)	8.07 (4.48)
	90	15.51 (8.62)	16.32 (9.07)
7781/EF-2	0	10.82 (6.01)	12.70 (7.06)
	90	10.87 (6.04)	14.37 (7.98)
Representative	0	8.58 (4.77)	10.66 (5.92)
	90	12.78 (7.10)	16.02 (8.90)

Table 4a Creep test results for representative laminate

Load, MPa (psi)	Time, h	Strain	Temperature
0.00	0.00	0.00	RT
89.6 (12,938)	0.00	.0352	367 K (200°F)
	0.50	.0357	
	1.0	.0357	
	10.0	.0359	
	50.0	.0363	
	100.0	.0364	
	200.0	.0367	
	300.0	.0369	
89.6 (12,938)	500.0	.0370	367 K (200°F)
0.00	507.0	.0021	RT

Table 4b Creep test results for representative laminate

Load, MPa (psi)	Time, h	Average strain	Temperature
0.00	0.00	0.00	RT
89.6 (12,938)	0.00	0.0353	367 K (200°F)
	0.05	0.0356	
	0.10	0.0357	
	0.15	0.0358	
89.6 (12,938)	0.50	0.0361	367 K (200°F)
0.00	0.00	0.00	RT

Creep Tests

The ASTM D2990-77 test method for the determination of tensile creep under specified environmental conditions was used.[9] The specimen was mounted in the grips of the testing machine with the lower grip attached to a load cell that measures the applied load. The thermocouples on the test specimen were monitored by a digital temperature recorder. The strain and time were monitored for the duration of the test.

A representative laminate creep specimen was loaded to 89.6 MPa (12, 983 psi), 35% of the ultimate tensile strength and tested for 500 h at 367 K (200°F). The load was then released and the specimen returned to RT. Upon releasing the load, the specimen was allowed to relax at RT for 7 h to check for any permanent set. The maximum strain was 0.0370. A small permanent strain in the laminate of 0.0021 was recorded (Table 4a).

Also, to simulate the fan blade operations in the NTF, three short-duration (½ h) tests were completed with a representative specimen. The accumulating strain from the beginning until the end of the short-duration tests was measured. These tests were completed by heating the chamber to 367 K (200°F), applying a 89.6 MPa load for ½ h, releasing the load, and allowing the specimen to return to RT. The maximum strain under load was approximately 0.0361 and returned to zero when the load was released (Table 4b). The test data showed no sign of a permanent set in the material.

Table 5 Resideual strength for thermally cycled laminates

Test	Laminate	Before cycling, MPa (psi)	After cycling, MPa (psi)	Decrease in strength, %	Test temp, K
Tensile	7576/EF-2	728 (105,524)	674 (97,889)	7.4	353
Tensile	7781/EF-2	335 (48,523)	293 (42,518)	12.5	353
Interlaminar shear	7781/EF-2 co-cured	11 (1,573)	9 (1,263)	18.2	RT

Table 6 Properties of 7781/EF-2 laminate

Property	$T=367$ K (200°F)	RT	$T=89$ K (−300°F)
$(\sigma_1)_T$ ult, MPa (psi)	334 (48,523)	393 (57,024)	720 (104,390)
$(\sigma_2)_T$ ult, MPa (psi)	295 (42,652)	301 (43,582)	617 (89,450)
$(\sigma_2)_T$ yield, MPa (psi)	111 (16,077)	106 (15,327)	178 (25,754)
$(\sigma_1)_C$ ult, MPa (psi)	327 (47,473)	379 (54,992)	619 (89,758)
(τ_{12}) ult, MPa (psi)	68.9 (9988)	82.1 (11,911)	144 (20,889)
(τ_{12}) yield, MPa (psi)	26.2 (3803)	32.5 (4712)	71.9 (10,421)
$(E_1)_T$, GPa (psi)	27.4 (3.97×10^6)	30.1 (4.37×10^6)	31.7 (4.60×10^6)
$(E_2)_T$, GPa (psi)	24.2 (3.51×10^6)	26.5 (3.84×10^6)	28.6 (4.15×10^6)
$(E_1)_C$, GPa (psi)	24.8 (3.60×10^6)	26.2 (3.80×10^6)	31.9 (4.62×10^6)
G_{12}, GPa (psi)	4.28 (0.62×10^6)	5.18 (0.75×10^6)	9.87 (1.43×10^6)
ν_{12}	0.108	0.144	0.281
ν_{21}	0.119	0.129	0.231
$\bar{\sigma}_1$, MPa (psi)	83.6 (12,131)	98.3 (14,256)	≥98.3 (14,256)
	RT to 373 K		RT to 78 K
α_1, m/m/K (in./in./°F)	12.70×10^{-6} (7.06×10^{-6})		10.82×10^{-6} (6.01×10^{-6})
α_2, m/m/K (in./in./°F)	14.37×10^{-6} (7.98×10^{-6})		10.87×10^{-6} (6.04×10^{-6})

Table 7 Properties of 7576/EF-2 laminate

Property	$T=367$ K (200°F)	RT	$T=89$ K (−300°F)
$(\sigma_1)_T$ ult, MPa (psi)	728 (10,524)	730 (105,900)	1122 (162,735)
$(\sigma_2)_T$ ult, MPa (psi)	68.7 (9,966)	69.3 (10,053)	129 (18,729)
$(\sigma_2)_T$ yield, MPa (psi)	52.8 (7,662)	55.8 (8,087)	69.5 (10,087)
$(\sigma_1)_C$ ult, MPa (psi)	528 (76,651)	692 (100,337)	875 (126,959)
(τ_{12}) ult, MPa (psi)	73.3 (10,637)	76.3 (11,062)	102 (14,775)
(τ_{12}) yield, MPa (psi)	24.3 (3,530)	23.7 (3,442)	63.4 (9,202)
$(E_1)_T$, GPa (psi)	41.7 (6.05×10^6)	41.5 (6.02×10^6)	45.1 (6.54×10^6)
$(E_2)_T$, GPa (psi)	17.2 (2.49×10^6)	18.2 (2.64×10^6)	26.3 (3.82×10^6)
$(E_1)_C$, GPa (psi)	40.7 (5.91×10^6)	39.6 (5.75×10^6)	42.5 (6.17×10^6)
G_{12}, GPa (psi)	5.52 (0.80×10^6)	6.83 (0.99×10^6)	10.35 (1.50×10^6)
ν_{12}	0.245	0.257	0.290
ν_{21}	0.085	0.098	0.182
$\bar{\sigma}_1$, MPa (psi)	146 (21,105)	164 (21,180)	≥164 (21,180)
	RT to 373 K		RT to 78 K
α_1, m/m/K (in./in./°F)	8.07×10^{-6} (4.48×10^{-6})		6.59×10^{-6} (3.66×10^{-6})
α_2, m/m/K (in./in./°F)	16.32×10^{-6} (9.07×10^{-6})		15.51×10^{-6} (8.62×10^{-6})

Table 8 Properties of representative laminate

Property	$T=367$ K (200°F)	RT	$T=89$ K (−300°F)
$(\sigma_X)_T$ ult, MPa (psi)	394 (57,086)	450 (65,282)	882 (128,000)
$(\sigma_Y)_T$ ult, MPa (psi)	235 (34,128)	263 (38,138)	407 (59,055)
$(\sigma_Y)_T$ yield, MPa (psi)	74 (10,716)	82 (11,842)	108 (15,672)
$(\sigma_X)_C$ ult, MPa (psi)	387 (56,112)	401 (58,222)	593 (86,016)
$(\sigma_Y)_C$ ult, MPa (psi)	329 (47,700)	370 (53,700)	---
$(E_X)_T$, GPa (psi)	28.6 (4.15×10^6)	30.2 (4.37×10^6)	36.7 (5.32×10^6)
$(E_Y)_T$, GPa (psi)	20.1 (2.97×10^6)	22.3 (3.24×10^6)	31.7 (4.60×10^6)
$(E_X)_C$, GPa (psi)	24.1 (3.50×10^6)	24.8 (3.60×10^6)	29.0 (4.20×10^6)
$(E_Y)_C$, GPa (psi)	26.1 (3.79×10^6)	26.6 (3.86×10^6)	---
ν_{XY}	0.299	0.299	0.359
ν_{YX}	0.199	0.208	0.224
$\bar{\sigma}_X$, MPa (psi)	118 (17,129)	135 (19,585)	≥135 (19,585)
	RT to 373 K		RT to 78 K
α_x, m/m/K (in./in./°F)	10.66×10^{-6} (5.92×10^{-6})		8.58×10^{-6} (4.77×10^{-6})
α_y, m/m/K (in./in./°F)	16.02×10^{-6} (8.90×10^{-6})		12.78×10^{-6} (7.10×10^{-6})

The test data showed a strain immediately reaching approximately 96% of its total upon applying the load.

Thermal Cycle Tests

The 7781/EF-2 and 7576/EF-2 laminates were thermally cycled from 89 to 367 K (−300 to 200°F) to determine what effects thermal cycling would have on these materials. Test specimens used for the thermal cycle tests consisted of 14 tensile specimens, 5 interlaminar shear specimens, and 4 thermal expansion specimens. The specimens were placed in a tray and were lowered to 6.4 mm (0.25 in.) above the liquid nitrogen level in a cryogenic container until thermal eqilibrium was reached. The tray was then raised through an RT region and into an enclosure maintained at 367 K (200°F). Four thermostatic controlled quartz lamps were used to maintain this temperature. The specimens were in each environment approximately 20 min. To complete the thermal cycle, the specimens were brought to room temperature before returning to the cryogenic environment. These temperatures were monitored by thermocouples.

The tensile specimens were thermally cycled 256 cycles. Tensile tests after thermal cycling showed an approximate decrease in strength of 12.5% for the 7781/EF-2 laminate and 7% for the 7576/EF-2 laminate at 353 K (Table 5). The interlaminar shear specimens were thermal cycled 251 cycles. Interlaminar shear tests after thermal cycling of the 7781/EF-2 laminate showed an approximate decrease in strength of about 18% at RT.

The previously described thermal expansion specimens were thermally cycled to observe the effects of thermal cycling on thick laminates. None of the specimens, which were periodically checked visually with a magnifying glass, showed any signs of damage due to thermal cycling.

Summary of Results

The results of the material properties tests of the 7781/EF-2, 7576/EF-2, and representative laminates are summarized in Tables 6-8, respectively, for each of the three test temperatures. In addition to the data previously presented and discussed, the tables give the ultimate tensile strength and tensile modulus in the 90 deg direction for each of the three laminates, the ultimate compressive strength and compressive modulus of the representative laminate in the 90 deg direction, the inplane shear modulus of the two basic cloth laminates, and the two Poisson ratios for each of the three laminates.

Conclusions

The test results given in this paper provide mechanical and physical properties of the epoxy/E-glass system at cryogenic and elevated temperatures. The characterization test results indicate that the material follows the general trends of metals and other glass reinforced plastics at cryogenic temperatures. That is, the material strengths and moduli increases with decrease in temperature. A slight degradation in strength was observed at the elevated temperature. The test results provided an adequate data base to support the design of the NTF fan blades.

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