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MECHANICAL PROPERTIES OF THE FIBERGLASS PREPREG SYSTEM USED FOR THE NATIONAL TRANSONIC FACILITY REPLACEMENT BLADE SET

Clarence P. Young, Jr. and John W. Wallace

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NASA
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Space Administration

Langley Research Center
Hampton, Virginia 23665-5225

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Summary

This paper presents the results of mechanical and physical properties characterization testing for the fiberglass prepreg system used to fabricate 15 of the replacement set of 25 fan blades for the National Transonic Facility. The fan blades were fabricated to be identical to the original blade set with the exception that the 7576 style E-glass cloth used for the replacement set has a different surface finish than the original 7576 cloth. The 7781 E-glass cloth and resin system were unchanged. The data are presented for elevated, room and cryogenic temperatures. The results are compared with data from the original blade set and evaluated against selected structural design criteria. Test experience is described along with recommendations for future testing of these materials if required.

List of Symbols

C.T.E.	Coefficient of thermal expansion
E	Young's modulus
Hz	Hertz
ksi	Kips per square inch
R.T.	Room temperature
σ	Stress
τ	Interlaminar shear stress

Subscripts:

ult	Ultimate strength
T	Tension
c	Compression

Introduction

As a result of a mishap in the National Transonic Facility on January 18, 1989, all 25 fan blades were destroyed. The blades were destroyed due to the high energy release of metallic parts from the drive shaft external thermal barrier retainer band. These parts impacted metallic aerodynamic fairing plates releasing them into the air stream. Several metallic plates passed through the fan damaging all 25 blades beyond repair.

The fiberglass prepreg system used for the original blade set was tested extensively and reported in references 1 and 2. Two fiberglass cloths (7781 E-glass and 7576 E-glass) were used to fabricate the blades. Ten blades manufactured from this system were on hand at the time of the mishap. However, for the last 15 blades, the 7576 prepreg material was no longer available with the VM 665 finish. At the recommendation of the manufacturer, the CS-724 finish was selected. As a result of this difference, a comprehensive mechanical and physical properties characterization of the 7576 laminate and the design (representative) laminate was carried out in order to assure that the mechanical and physical properties of the modified system met the design requirements. The approach was to follow the same test procedures and use the same test specimen designs and test methods that were used in the original characterization program described in references 1 and 2.

The purpose of this paper is to document the results of the mechanical and physical properties tests of the fiberglass prepreg materials used for 15 of the replacement blades installed in the National Transonic Facility in 1989.

Material Layup Description

As previously mentioned, two styles of fiberglass cloth pre-impregnated with an epoxy resin system were used for the fan blades. The 7781 style E-glass cloth has a ratio of 60 fibers in the warp direction to 54 in the fill direction. The second material is the 7576 style cloth which has a ratio of 120 fibers in the warp direction to 24 in the fill direction (see table I). The stacking sequence for the design (representative) laminate is shown in figure 1 and a perspective of the blade illustrating the design layup is given in figure 2. Test specimens were cut from panels (ply layups) in the warp (0° direction) and fill (90° direction) direction as illustrated in figure 3. Panels were fabricated separately for the two cloths and for the actual design laminate layups. It should be noted that these panels are representative of the design laminate, and referred to in references 1 and 2 as the representative laminate. The panels were taken through the same cure cycles as the actual blades. Emphasis was placed on testing specimens taken in the warp direction which is the direction of principal loading in the fan blade. The reader is referred to references 1 and 2 for a more detailed description and discussion of the material system.

Mechanical Properties Tests

The intent of the test program was to use the same type specimens and test equipment as those used for the previous fan blade material characterization tests at the Langley Research Center (LaRC) (references 1 and 2). This approach would utilize previous test experience and provide a basis for direct comparison of the data to that for the original blade set. However, a number of mechanical/specimen problems were encountered in various tests and are discussed later in the paper.

Mechanical and physical properties characterization was carried out at elevated (200°F), room and cryogenic (−300°F) temperature in the 0° direction (principal loading direction). Also, a limited number of tests were conducted in the 90° direction, and, although not reported herein, these tests gave very good agreement with previously reported values. Reported values are the average for three specimens unless otherwise noted. The various tests and results are discussed in the following sections.

Tensile

The American Society for Testing and Materials (ASTM) D3039-6 method was used to test the tensile specimens. The tensile specimen geometry is shown in figure 4. Problems were encountered in testing this straight sided specimen, particularly at cryogenic temperatures.

Specimens with both tapered and square tabs were tested but little difference between performance was noted. The major problems were either (1) failure in the grip area, or (2) tab failure (shear surface between the tab and specimen). Very few specimens failed in the gage portion of the test specimen. Other related problems included (1) specimen size (too long for testing in the LaRC Structures and Materials Laboratory cryo chambers for the case where both the specimen and grips need to be cooled) and (2) lack of hydraulic grips on the Instron machine that was used to test specimens to failure at cryogenic temperatures.

A number of things were tried in an attempt to alleviate the aforementioned problems; these included, (1) different adhesive between specimen and grip tabs, (2) pin plus adhesive, (3) rivets in tabs plus adhesive, and (4) tapering (necking down) the specimen over the original straight-sided gage length. Finally, a tensile specimen made from the geometry illustrated in figure 5 worked to the extent the failure loads were near or equal to expected values before either the tabs failed, or the specimens failed across the net gage section. A typical instrumented test specimen mounting arrangement is illustrated in figure 6.

It is recommended that for any future testing the specimen geometry shown in figure 5 be used particularly for cryogenic temperatures. Straight-sided specimens (believed to reduce interaction effects in cross ply layups) should be avoided. Also consideration should be given to scaling down the specimen length to the extent that it can be tested in the machines already equipped with cryogenic chambers and hydraulic grips which are located in the LaRC Structures and Material Laboratories.

Because of the aforementioned problems, modulus values (based on extensiometer data) were obtained at cold temperatures in the LaRC materials laboratory where the gage portion of the specimen was cooled but not the grips.

The tensile strength results for the 7576 cloth with the 724 finish are given in table II and compared with values obtained for the original 665 finish. The tensile values for the 724 finish are slightly lower and follows the trend of data obtained from the manufacturer for the two finishes. The value given at −300°F does not represent a tensile failure in the specimen material but is based on failure loads resulting from tab failure (shear) which indicates that the material tensile strength should be as good or better than the average value given in the table. However, failure indications in the laminate were evident in all specimens and appeared to start at the slight radius transition between the taper and gage (straight sided) portion of the specimen shown in figure 5. The tensile strength and Young's modulus data are given in table III for the design laminate and are compared with the previously reported values given in reference 1. It is seen that the ultimate tensile strength for the design laminate is slightly lower at elevated and room temperature. The average value at −300°F (based on one tensile failure in the gaged section and one in which the tabs slipped on two other specimens) is also lower than the value reported for the original blade set material.

The Young's tensile modulus data given in table III for the design laminate were about 16 percent lower than the values reported in references 1 and 2. However, comparison with Young's modulus data obtained from fatigue specimens for the original blade set but not reported in the references gave excellent agreement. Although reasons for differences between the reported values of references 1 and 2 and the results from these tests are not understood they are still acceptable with regard to blade stiffness requirements. Also, it should be noted that the results of modal (vibration) testing did not show any significant differences in fundamental vibration frequencies for the last 15 blades manufactured when compared with the first 10 blades manufactured from the original material. In addition, the average value for the new blade set first mode frequency is 66.1 Hz compared to 57 Hz for the original blade set, which implies increased stiffness. This observation further supports the acceptability of the Young's modulus for the material.

Compression

The ASTM D3410-75 test method was used as a guideline for compressive testing (see fig. 7 for typical test setup) of the fan blade material. The reader is referred to references 1 and 2 for details on the procedure as it was basically unchanged and worked very well. The compression specimen geometry is shown in figure 4. The compression strength and modulus data are summarized for the 0° direction specimens in tables II and III. As indicated, the compression strength is greater than previously reported values for both the 7576 cloth and the design laminate, especially at −300°F. Also note from table III, the excellent agreement in compression modulus values.

Interlaminar Shear

The test method used to determine interlaminar shear strength was the "guillotine" method using the standard fixture and is described in detail in reference 1. The reader is referred to reference 1 for detailed information on curing of specimens, etc. These tests were performed only on the representative (design) laminate. The interlaminar shear strength values are given in table III. Note that the average values are lower when compared to the original blade data (approx. 5 to 17% reduction). However the trend of strength with temperature is the same and the blades are not highly loaded in shear.

Fatigue

The design laminate fatigue specimens were tested in the same manner as reported in references 1 and 2 using the ASTM D3479-76 test method. The load-control tests were conducted at a frequency of 10 Hz and at a stress ratio of .01. These tests were conducted at the stress level (30% of ultimate strength at room temperature) used as the allowable for fan blade design with a goal of 1 million cycles without failure.

The fatigue specimen is the same length and thickness as the tensile specimen but is 1½ inches in width. (See fig. 4.) The procedures described in references 1 and 2 were followed for fatigue testing at elevated and cryogenic temperatures. However, problems were encountered such as (1) failure at a lower number of cycles than expected and (2) failures in the grip area. It was found that premature fatigue specimen failures were associated with testing at a higher stress ratio (0.1 instead of .01), and with failure of the tabs in shear at the bond plane, or failure of the material in the grip area. After correcting for stress ratio, changing adhesives and varying grip pressures, tests were successfully completed for the design laminate in the 0° direction. The results are given in table IV and demonstrate that fatigue properties meet the design requirement of >30% of ultimate strength at elevated temperatures and 30% of the room temperature ultimate at ambient and cryogenic (−300°F) temperatures.

The fatigue specimens were tested for residual strength after cycling. The design laminate residual strength values for the fatigue specimens (obtained from tensile tests after 1 million cycles) were as good and in some cases higher than those obtained from the pure tensile tests. It is believed that the differences are attributed to specimen geometry differences (the fatigue specimen is wider than the tensile specimens and probably more stable) and also to failures in the tab regions for the smaller tensile specimens. (It should be noted that some of the fatigue tensile specimens also failed in the grip area.) The residual strength results are presented in table III.

Thermal Expansion

The linear coefficient of thermal expansion tests were performed in the 0° and 90° directions for the representative laminate using a DuPont 943 Thermomechanical Analyzer. The analyzer was calibrated using a known aluminum standard. This state-of-the-art instrument was used because the accuracy is better than the method used for the original blade set and the equipment used in the original tests was not available. Additionally, the analyzer gave continuous measurements as opposed to end points. The results are tabulated in table IV for the temperature ranges of room temperature (RT) to 200°F, and RT to −300°F. The results compare very well with design laminate (both the 0° and 90° direction) values obtained for the original blade set.

Creep

The test method for establishing tensile creep properties is ASTM D2990-77. The method and procedure is described in detail in reference 1. Three design laminate specimens (see fig. 4) were loaded to 18.8 ksi (approximately 30% ult. at 200°F) and elastically strained to 0.57 percent. The results are given in table IV and compared to values reported in the reference. As reported in reference 2, for the previous tests, the specimen(s) were loaded to a lower stress level (12.94 ksi) with a reported 500 hr strain average for three specimens of 0.37%. The permanent strain (avg. values) was .079%. Overall, the material exhibits excellent creep properties.

Thermal Cycling

For the thermal cycling tests, three tensile specimens each of the 7576 material and the design laminate were thermally cycled 256 times. The cycling consisted of taking the specimens from room temperature to 200°F, from 200°F to −300°F, and from −300°F back to room temperature. The specimens were held at each temperature for 20 minutes before being subjected to the next temperature. After the 256 cycles were completed the specimens were tested to failure at room temperature to determine their residual tensile strength. The results are given in table V. No previous data are available for the design laminate. The 7576 cloth lost 6.5% of its tensile strength while design laminate lost 5.0% of its tensile strength. In the original tests the 7576 cloth lost approximately 7.6% of its tensile strength due to the thermal cycling.

Additional Tests

Additional tests were performed on specimens containing the new 7576 E-glass cloth. These tests were 3-point flex, punch shear, and short beam shear. For the 3-point flex and short beam shear tests, the only design laminate data available from material tests for the original set of blades were for specimens tested at room temperature. For the punch shear tests the only data available were for design laminate specimens at room temperature. The data for these additional tests are shown in table VI.

It can be seen from table VI that in all cases ultimate stress levels increase with decreasing temperature. The data for the 3-point flex and short beam shear follow the general trend of the data for the other tests, that being the failure stress levels for the design laminate specimens are lower, at all temperatures, than the failure stress levels for the 7576 specimens.

Comparison of the 7576 E-glass data from unpublished data for the original blade set to the data from the new blades indicates the 3-point flex specimens at all temperatures and the room temperature design laminate punch shear specimens give lower failure (ultimate) stress levels in the new blade specimens. This same comparison of the 7576 short beam shear specimens gives mixed results. Room temperature data for the 7576 specimens indicate a slightly higher strength in the original blade material while the new material is higher at 200°F and much higher at −300°F. Room temperature data for the design laminate specimens indicate a higher strength for the new material.

Evaluation of Tensile and Fatigue Properties for Design Requirements

The NTF fan blades are designed for a minimum service life of 10 years with the likelihood of up to 50 years service in absence of a mishap. For comparison purposes, the measured stress at two critical points on the blade assembly (blade root and pin wrap see fig. 8) are compared with the fatigue and ultimate strength values in table VII. The minimum ultimate and fatigue strength values at 200°F are used as the basis for design, which is conservative since the strength and fatigue properties improve with decreasing temperatures. Note from table VI that the safety factors on ultimate and fatigue are reduced slightly for the replacement blade set at the selected points for comparison. This is due to the slightly reduced tensile strength of the design laminate. However, the safety factors are still quite acceptable. Another measure of blade structural integrity can be obtained from the data tabulated in table VIII. Using actual strain data obtained during tunnel operation and correcting for maximum pressure by analysis, safety factors on both strength and fatigue are shown for both the new and original blade set. It can be seen that the peak dynamic stresses for worst case loadings are still well below the endurance limit (fatigue strength at 10^6 cycles) for the material while a safety factor greater than 5 is calculated at the point of measurement (blade root).

Concluding Remarks

The mechanical and physical properties of the fiberglass prepreg system for the National Transonic Facility replacement blade set are presented. The 7576 cloth with the 724 surface finish gives acceptable properties. The representative (design) laminate properties for the new blade set compare well with those for the original blade set, and meet structural design requirements. Some differences between Young's tensile modulus and that reported from previous tests were observed, but are of no consequence insofar as structural design properties acceptability. Numerous problems were encountered in obtaining acceptable test results. Chief among these were specimen tab failures, grip region failures and equipment limitations, particularly for cryogenic testing.

Recommendations

It is recommended that tapered (instead of straight sided) specimens and different tab geometries be used for any future tensile testing and fatigue testing of the fan blade materials. Also the specimen(s) should be sized such that they can be tested in existing machines with required load and environmental capability for subjecting the entire specimen (including test machine grips) to the required test temperature.

References

1. Klich, P. J. and Cockrell, C. E.: Mechanical Properties of a Fiberglass Prepreg System at Cryogenic and Other Temperatures. AIAA Journal Volume 21, December 1983, Page 1772.
2. Klich, P. J., Richards, W. H. and Ahl, E. L., Jr.: National Transonic Facility Fan Blade Prepreg Material Characterization Tests. NASA TM 81800, July 1981.

TABLE I
MATERIAL AND LAMINATE DESCRIPTION

MATERIAL	FIBERS WARP DIRECTION	FIBERS FILL DIRECTION	PLIES PER LAMINATE	
			REPRESENTATIVE LAMINATE	7576 LAMINATE
7781 E-GLASS CLOTH	60	54	14	0
7576 E-GLASS CLOTH	120	24	5	11

TABLE II
TENSION AND COMPRESSION STRENGTH PROPERTIES OF STYLE 7576 LAMINATE WITH 724 FINISH COMPARED WITH ORIGINAL 665 FINISH

PROPERTY	200° F	R.T.	-300° F
$\sigma_{T,ult}$, ksi	87.7(105.5)	96.4(105.9)	>125*(162.7)
$\sigma_{C,ult}$, ksi	87.2(76.7)	112.7(100.3)	130.8(126.9)

( ) 665 Finish - data for original blades
*Average for two specimens - failed in grips (tabs sheared off)

TABLE III
MECHANICAL PROPERTIES OF DESIGN LAMINATE FOR NEW BLADES (LAST 15 MANUFACTURED) COMPARED WITH ORIGINAL BLADES

Property	200°F	R.T.	-300°F
$\sigma_{T,ult}$, ksi	54(57)	64(65)	113*(128)
$\sigma_{C,ult}$, ksi	61(56)	74(58)	122(86)
τ, ksi	4.8(5.3)	5.3(6.4)	6.9(7.2)
$E_T \times 10^{-6}$	3.5(4.2) (3.6)**	3.6(4.4) (3.7)**	4.5(5.3) (4.7)**
$E_C \times 10^{-6}$	3.9(3.5)	3.7(3.6)	4.5(4.2)

* For tapered tensile specimens
( ) Indicates average values for original blades
** Modulus for fatigue specimens from original blade set (not reported in references)

TABLE IV
FATIGUE STRENGTH, RESIDUAL STRENGTH FOR FATIGUE SPECIMENS, CREEP AND C.T.E. PROPERTIES FOR DESIGN LAMINATE

Property		200°F	R.T.	-300°F
Fatigue strength		>30% ult at temp.	>30% ult at R.T.	>30% ult at R.T.
Residual tensile strength @ R.T. for fatigue specimens, ksi		61.2	54.2(48.3)	54.1(50.4)
Creep Stress, ksi 500-hr strain, %		18.9(12.9) .58(.37)	——	——
Thermal expansion α, μin/in/°C	Direction	R.T. to 200°F		R.T. to -300°F
	0° 90°	11.0(10.7) 16.4(16.0)		8.8(8.6) 12.9(12.8)

( ) Denotes values for original blades (ref 2)

TABLE V
RESIDUAL TENSILE STRENGTH AFTER THERMAL CYCLING

7576 E-Glass	Design Laminate
90.1(97.9) ksi	60.6 ksi

( ) Indicates data from original blade set

TABLE VI
ADDITIONAL TEST DATA

a. 3-Point flex

Temperature	7576 E-Glass	Design Laminate
200°F	106.8(121.0)ksi	77.3 ksi
R.T.	122.6(140.9)ksi	88.9(101.6) ksi
-300°F	234.9(244.7)ksi	187.0 ksi

b. Short beam shear

Temperature	7576 E-Glass	Design Laminate
200°F	8.1(6.8) ksi	8.4 ksi
R.T.	11.0(11.4) ksi	10.9(8.6) ksi
-300°F	37.0(18.7) ksi	16.3 ksi

c. Punch shear

Temperature	7576 E-Glass	Design Laminate
200°F	15.5 ksi	18.8 ksi
R.T.	17.7 ksi	22.3(26.7) ksi
-300°F	30.7 ksi	>37.2 ksi*

*Shear load exceeded machine capacity of 20,000 lbf.
( ) Indicates data from original blade set

TABLE VII
COMPARISON OF MEASURED PEAK STRESSES WITH FATIGUE STRENGTH AND ULTIMATE STRENGTH

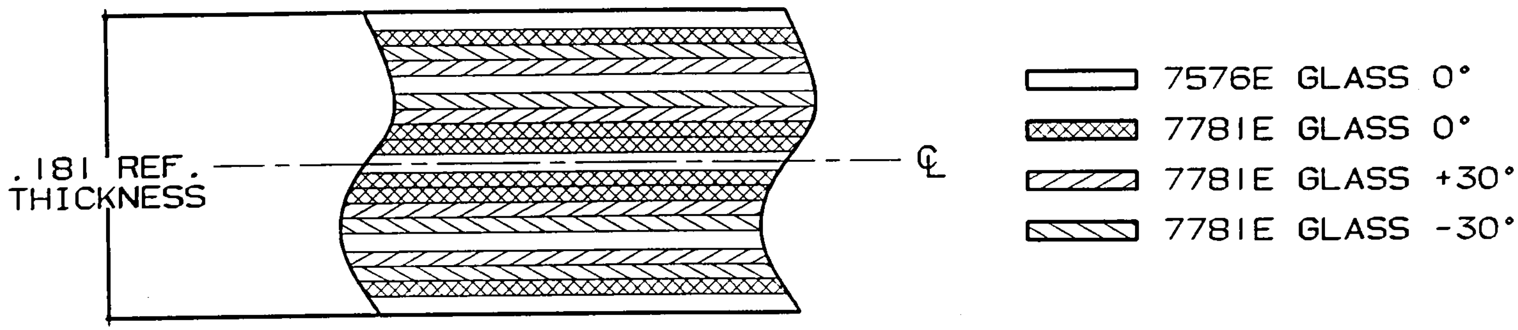
Test	Location	Measured stress ksi	Fatigue strength at 10^6 cycles ksi	Ultimate strength ksi	Safety factor on fatigue	Safety factor on ultimate
Fatigue	① Airfoil root	7.2	18.4(19.6)	54(57)	2.6(2.7)	7.5(7.9)
Centrifugal overspeed	② Pin wrap	14	18.4(19.6)	54(57)	1.3(1.4)	3.9(4.1)

( ) Averaged values for original blade set
① At surface of root of airfoil (figure 8)
② Pin wraparound laminate outer surface (figure 8)

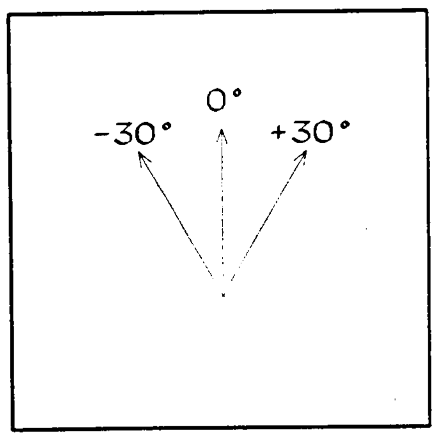
TABLE VIII
MEASURED PEAK STATIC AND DYNAMIC STRESSES AT AIRFOIL ROOT DURING TUNNEL OPERATION AT DESIGN LOAD CONDITIONS AND ASSOCIATED SAFETY FACTORS

Measured or test values	Stress, ksi	Safety factor
Measured peak stresses		
Static	8.6	—
Dynamic	1.9	—
Fatigue strength @ R.T. for 10^6 cycles	≥18.4(19.4)	1.74(1.84)
Ultimate strength @ 200°F	54(57)	5.12(5.40)

( ) Indicates values for original blade set



REPRESENTATIVE CROSS SECTION



- LAMINATE QUALITY EVALUATED BY
  - VISUAL INSPECTION
  - RESIN BURN-OUT TESTS

LAMINATE LAYUP ORIENTATION

Figure 1. Stacking sequence of representative laminate.

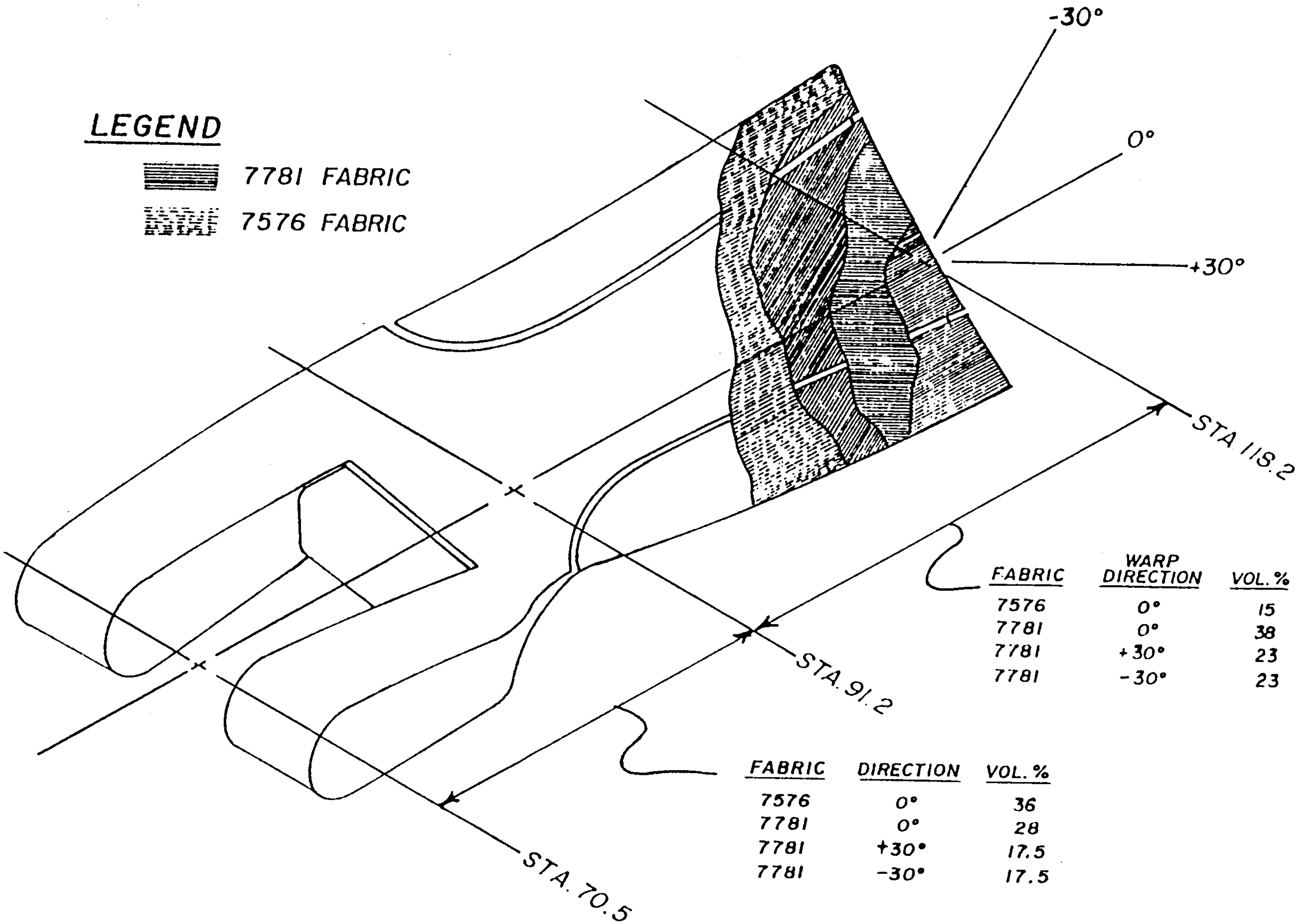


Figure 2. Perspective of fan blade illustrating ply orientation.

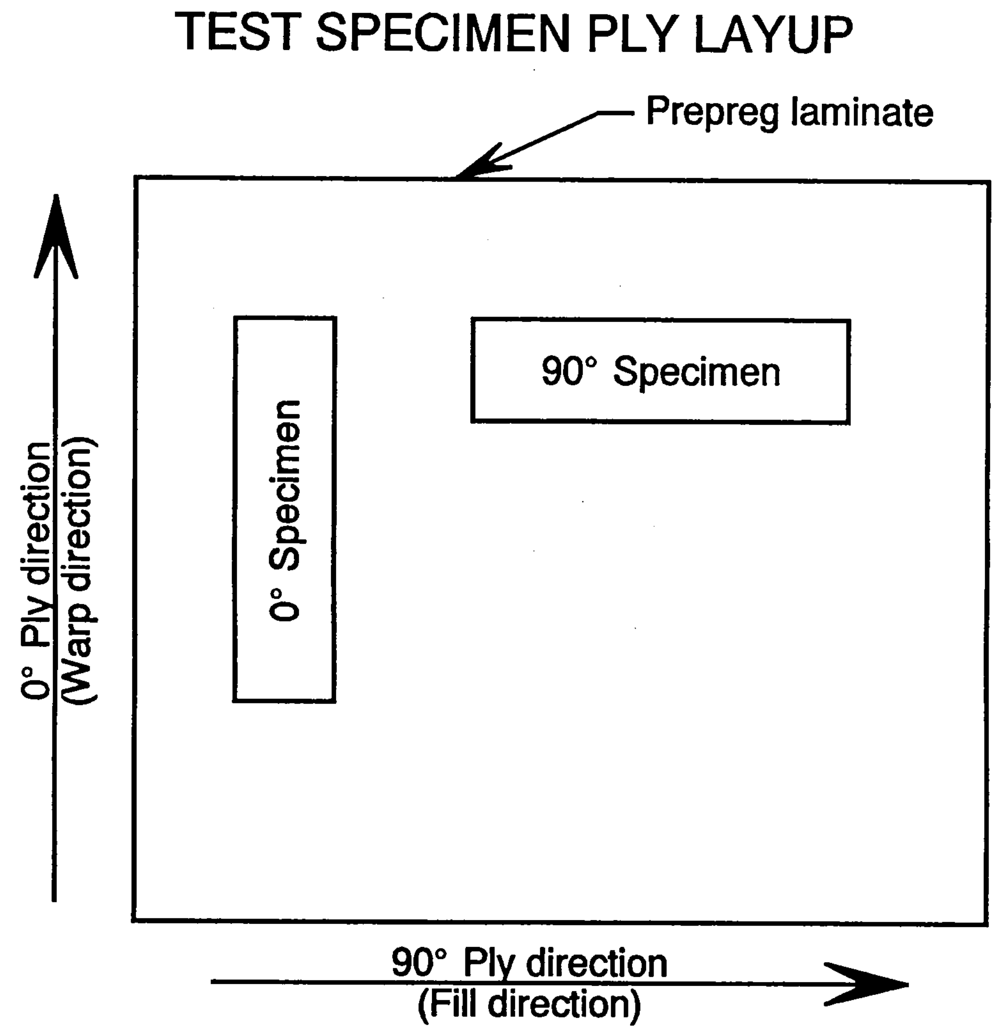


Figure 3. Test specimen ply layup illustrating orientation of test specimens.

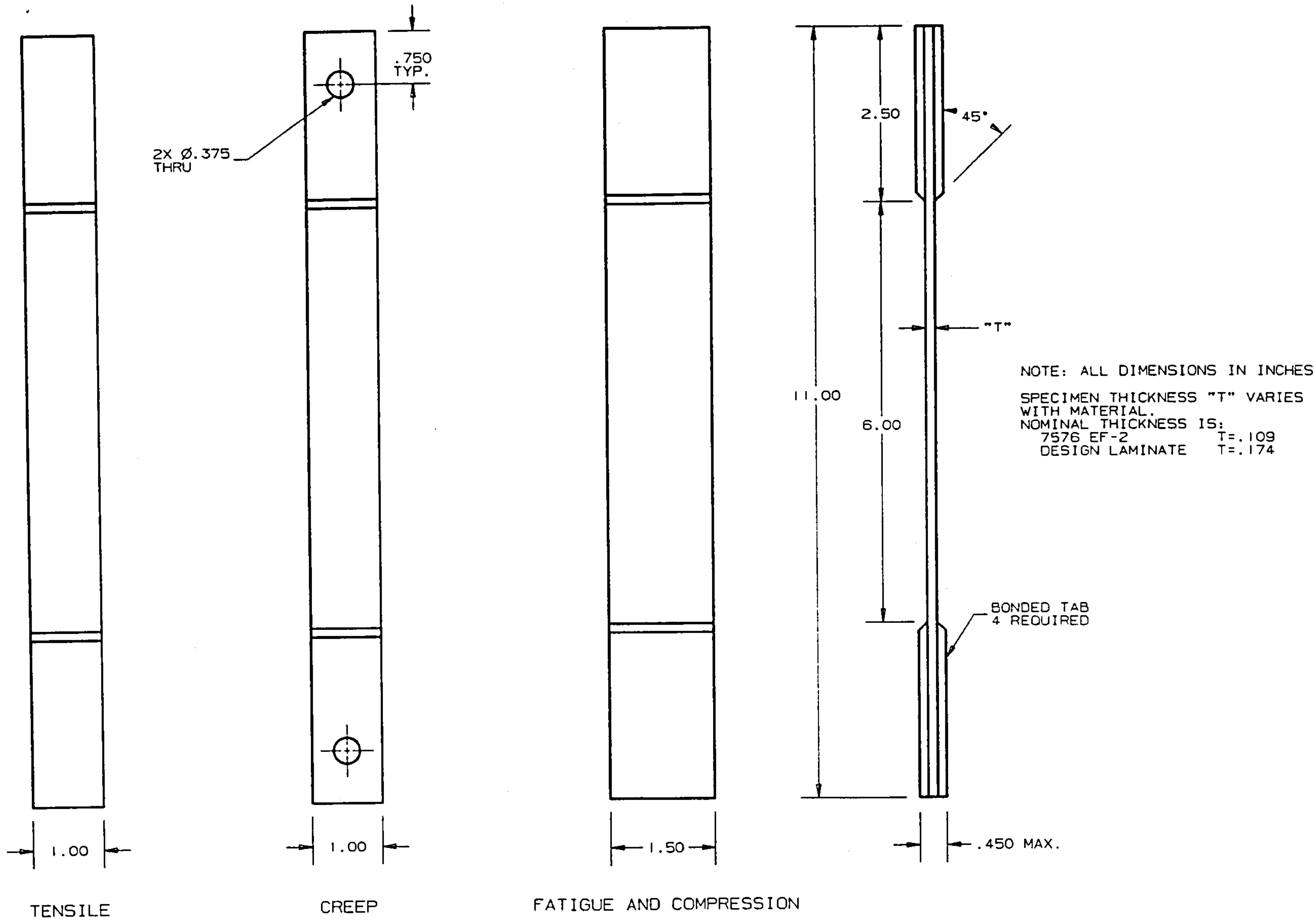


Figure 4. Typical test specimen geometries.

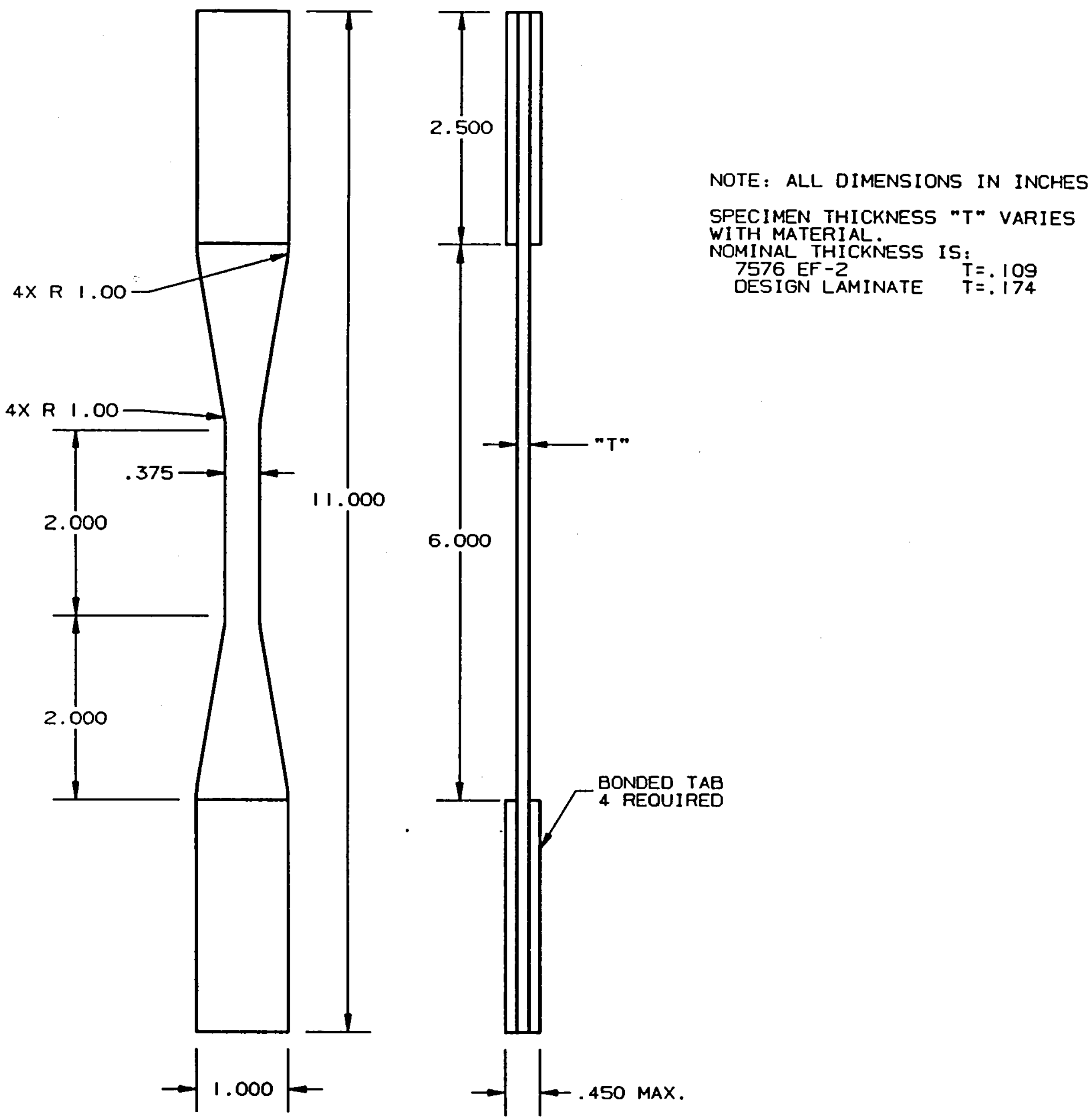


Figure 5. Tapered tensile specimen geometry.

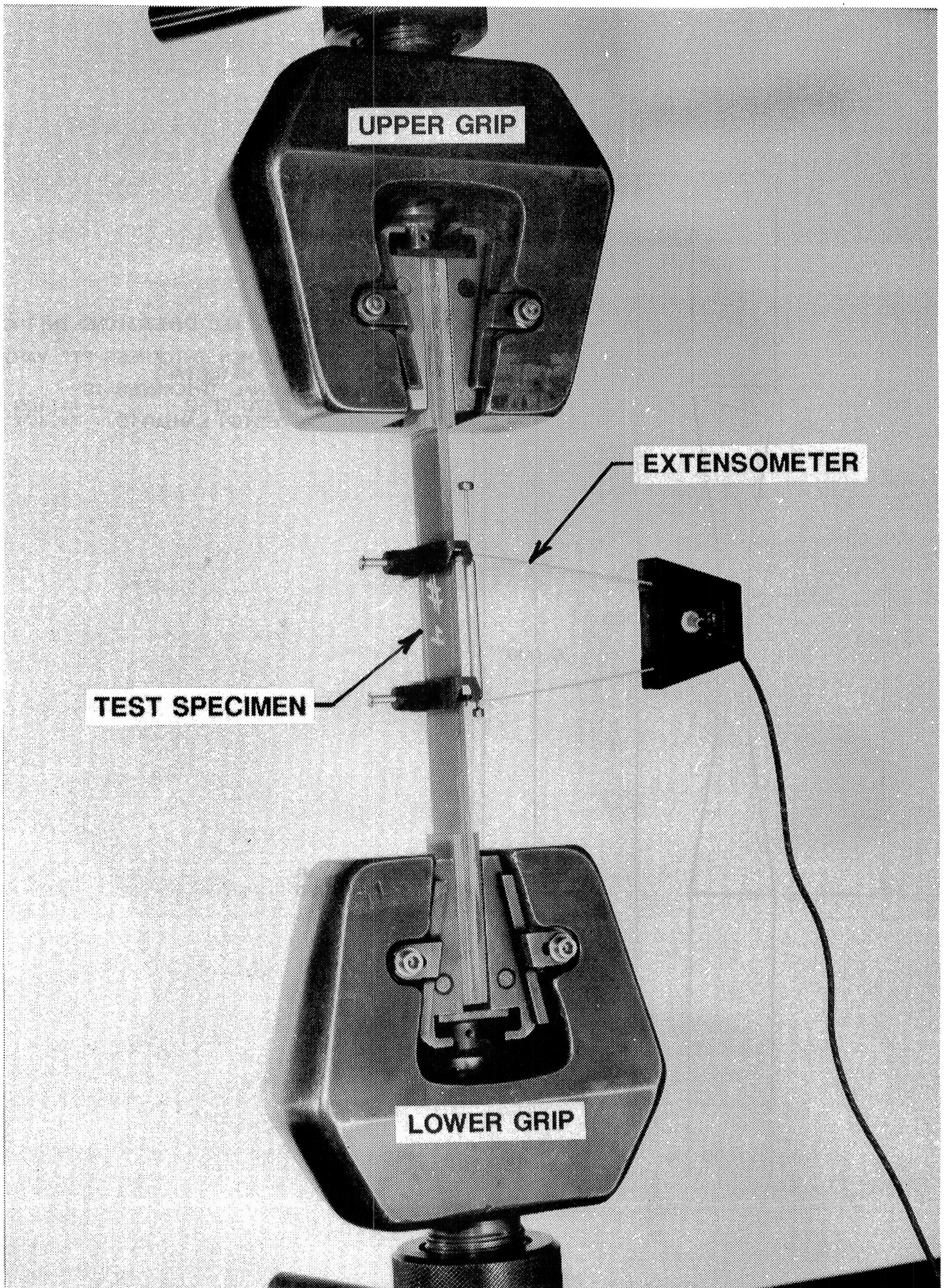


Figure 6. Typical tensile test specimen mounting.

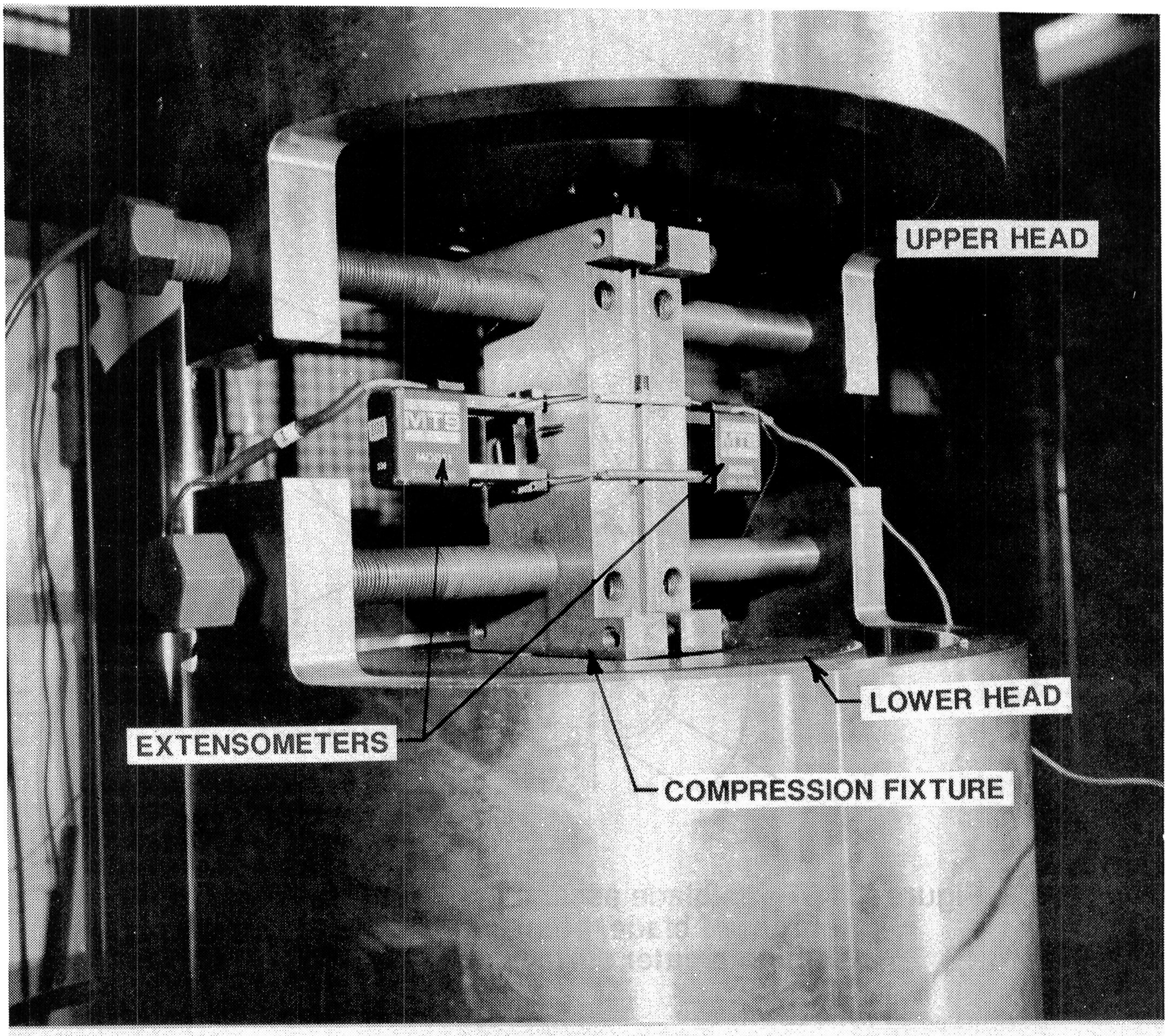


Figure 7. Compression test setup.

NTF Fan Blade Assembly

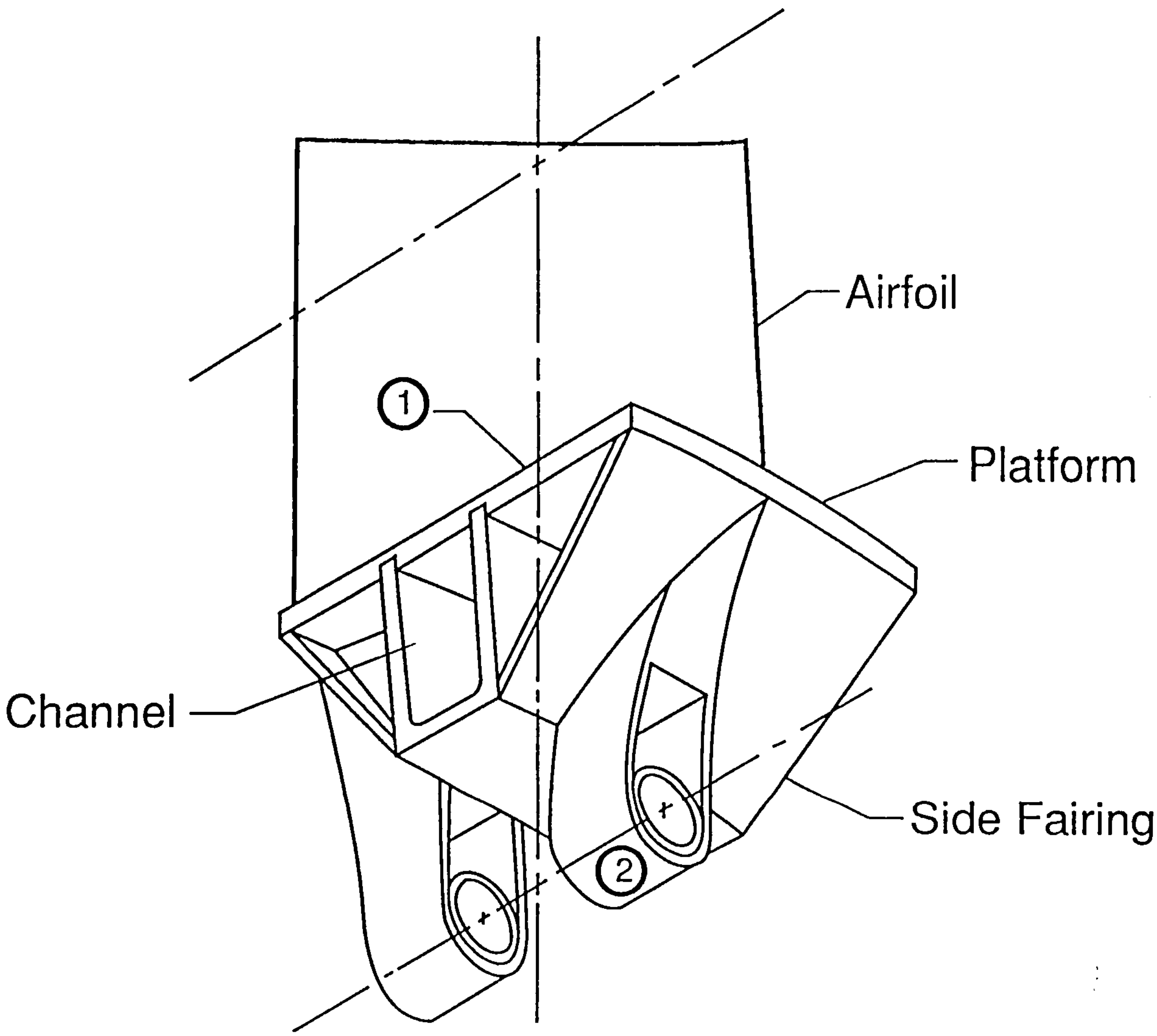


Figure 8. NTF fan blade assembly. Point 1 is at surface of root of blade, point 2 is pin wraparound laminate outer surface.

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15. Supplementary Notes

16. Abstract

This paper presents the results of mechanical and physical properties characterization testing for the fiberglass prepreg system used to fabricate 15 of the replacement set of 25 fan blades for the National Transonic Facility. The fan blades were fabricated to be identical to the original blade set with the exception that the 7576 style E-glass cloth used for the replacement set has a different surface finish than the original 7576 cloth. The 7781 E-glass cloth and resin system were unchanged. The data are presented for elevated, room and cryogenic temperatures. The results are compared with data from the original blade set and evaluated against selected structural design criteria. Test experience is described along with recommendations for future testing of these materials if required.

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