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Composite Fan Exit Guide Vanes for High Bypass Ratio Gas Turbine Engines

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Various composite materials were identified for reduced weight applications as fan exit guide vanes in high bypass ratio gas turbine engines. These exit guide vanes turn fan discharge air in an axial flow direction to reduce drag and improve efficiency. Candidate materials, airfoil geometry, and ply orientation were evaluated using NASTRAN finite-element analysis. A vane core and shell design approach utilizing several different fiber orientation concepts was selected and variations in bending and torsional stiffness were documented. Material suppliers and airfoil fabricators were selected to provide panels and airfoils which were inspected, environmentally conditioned, and tested. Static and dynamic airfoil tests established durability characteristics for a range of composite material/design approaches. All composite fan exit guide vane configurations and materials tested exhibited fatigue strain capability in excess of requirements. For the 3.6-in. chord vane design, the fiberglass shell material/ply orientation combinations exhibited increased fatigue capability compared to graphite shell configurations.

Introduction

HIGH bypass ratio engine fan exit guide vanes, Fig. 1, turn fan discharge air in an axial flow direction to reduce drag and improve efficiency. Currently, high bypass ratio gas turbine engines utilize a significant quantity of aluminum vanes, varying between 84 and 108 parts per engine. Considerable weight reduction of 40-50 lb per engine is possible by replacing aluminum with composite vanes. The subject program evaluated the static and fatigue behavior of 17-in.-span, 3.6-in., and 4.0-in. chord vanes, Fig. 2. Other variables considered in the evaluation were the effects of different core and shell construction fiber materials, fiber orientation, fabrication procedures, and resin matrix material on vane static/dynamic test performance.

Design

Vane Geometry

Vane external dimensions and shape were selected to provide for easy incorporation into existing or advanced models of high bypass ratio engines. A core/shell design was selected with core fibers oriented in the vane span (radial) direction and bidirectional shell fibers angled to the core. Shell fibers were wrapped around a thicker core trailing edge (0.080 in.) as compared to an earlier configuration which terminated shell fibers at the thin trailing edge (0.020 in.).

Design Criteria

Vane strength requirements were established by static and dynamic aerodynamic engine stresses. Static stress was primarily due to gas bending loads exerted on the pressure side of the airfoil, whereas dynamic stress was a result of natural frequency vibration of the vane during engine operation. Part design criteria were established to provide sufficient bending and torsional stiffness to avoid excessive vibratory stress in either bending or torsional modes. Early composite vane experience on thin 0.020-in. fiber-reinforced trailing edge parts identified the first bending mode as the potential problem vibration mode under selective flow conditions. Occasional part failures initiating from the trailing edge were experienced. The primary objective of the design effort was to select vane section size and material/ply configurations which would increase the bending stiffness of the airfoil, provide for more uniform load distribution, and thereby decrease first bending mode strain levels primarily at the trailing edge. Another design consideration was to maintain sufficient torsional stiffness to avoid introduction of a first torsion mode. Finally, it was necessary to maintain sufficient vane frequency differences between first bending and torsion to avoid bending/torsion coupling.

Structural Analysis

Four candidate 3.6-in. and one 4.0-in. chord vanes with different core and shell materials were selected for detailed design, fabrication, test, and evaluation. All vane candidates contained a high modulus core with either of two different 50 million modulus materials; six different shell materials were evaluated.

NASTRAN finite-element analysis was used to predict vane static strains, first bending and first torsion frequencies, and bending/torsional spring rates. Finite-element analyses were performed for 3.6-in. chord vanes with elemental properties determined by classical laminate theory. The NASTRAN element used in the analysis was a two-dimensional compatible bending membrane element in three-dimensional space (Clough element). The model breakup consisted of 48 elements along the vane chord and 20 stations spanwise along the 17-in. vane span, making a total of 960 elements. The individual element properties were generated by a preprocessor which calculated membrane, bending, and in-plane shear properties based on the ply layups. These calculations were based on classical laminate theory.[1] Mechanical property data obtained in the subject program at 60 ± 5% volume composite fiber as well as properties extracted from the literature were used as input to the NASTRAN analyses.[2] Bending spring rates (K_B) were higher for candidate thick trailing edge vanes compared to thin vanes, where as torsional spring rates (K_T) decreased

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proportionately to shell fiber modules (Table 1). In addition to stiffness, a comparison was made between experimental first bending and first torsion frequency test data for the thin trailing edge vane and NASTRAN dynamic data for the thick trailing edge vane. The differences between bending and torsion frequencies were considered sufficient to avoid mode coupling during vane excitation. Chordwise distribution of radial strain was compared for both thick and thin trailing edge 3.6-in. chord vanes and for 4-in. thick trailing edge vanes under maximum static load on the airfoil at the vane midspan, as shown in Fig. 3. Strain gage data obtained during the experimental program provided good agreement to NASTRAN analysis. A thickening of the airfoil, starting at midchord and gradually continuing to the trailing edge, provided additional high modulus core fiber which decreased the average strain in the core. The use of the trailing edge shell wraparound concept in conjunction with the thick trailing edge permitted the unidirectional core to move approximately 0.30 in. closer to the trailing edge outer surface, which also contributed to increased bending stiffness. These additive effects resulted in decreased trailing edge strain from −2800 to −1720 $\mu\epsilon$. Additional reduction in trailing edge strain to −900 $\mu\epsilon$ was obtained for the 4-in. chord vane. Furthermore, the wraparound shell concept was expected to provide a twofold benefit of improved fiber/resin homogeneity and an improved shear tie in the shell around the trailing edge radius. The earlier thin trailing edge vane was designed with concave and convex shell fibers which terminated at the trailing edge.

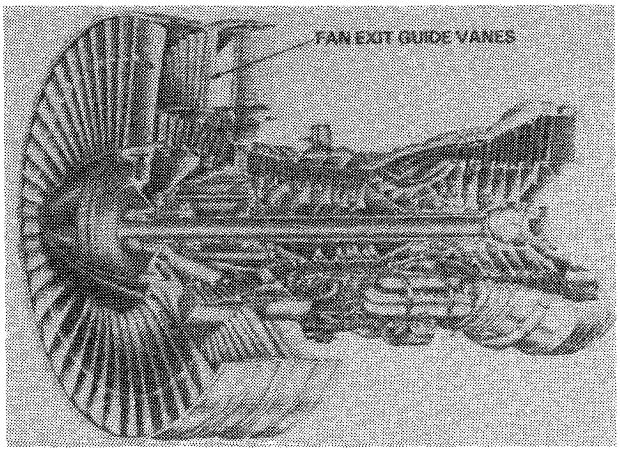

Fig. 1 JT9D turbofan engine.

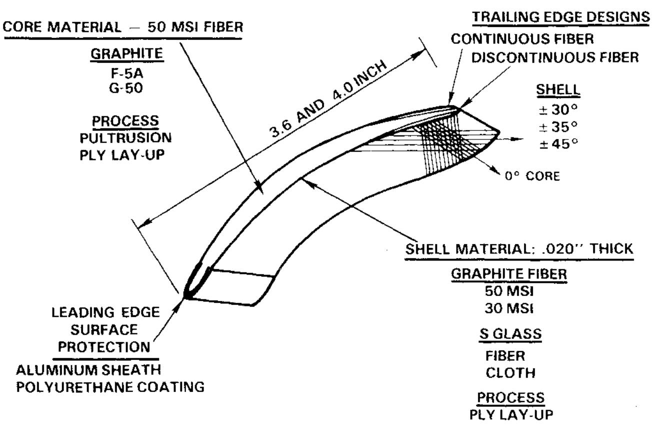

Fig. 2 Composite fan exit guide vane material/fabrication variables.

Material Properties

Composite Mechanical Properties

Material acceptance data were obtained for all of the fiber, cloth, and resin materials used to fabricate vanes. Critical mechanical and physical properties of Great Lakes Carbon, Hercules, and Celanese graphite composite panels showed excellent repeatability when tested by the vane manufacturer and Pratt & Whitney Aircraft. Additional data were obtained directly from sections of vanes. This test approach was taken to ensure that test panel and vane mechanical properties would be representative of the material and process specification established for this part. The critical properties for a material specification were established as shear, flexure strength, and modulus of the composite material in dry and wet conditions at room and elevated temperature. A summary of graphite and fiberglass composite mechanical property data is presented in Figs. 4 and 5.

Results for "dry" composite specimens indicated that short beam shear strength was most affected at 250°F for all candidate materials. Fortafil 5A short beam shear strength decreased approximately 30%, whereas AS-2, S-glass cloth, and S-glass fiber shell decreased 50, 50, and 65%, respectively. The flexural strength of Fortafil 5A did not change significantly at 250°F; however, the other three materials experienced a flexure strength decrease of between 30 and

Table 1 NASTRAN calculated properties of thin and thick trailing edge fan exit guide vanes—concave surface

							Radial static strain	
	K_B, lb/in.	K_T, in.-lb/deg	E_{11}, msi	G_{12}, msi	f_B,[a] Hz	f_T,[a] Hz	Maximum thickness, % strain	Trailing edge, % strain
Trailing edge								
Fortafil 5 0-deg core/ Fortafil 5 ±35-deg shell	1374	29.1	19.6	2.75	220[b]	565[b]	0.1000	−0.2800
Thick trailing edge								
Fortafil 5A 0-deg core/ Fortafil 5A ±35-deg shell	1885	23.4	19.9	2.15	244	535	0.0955	−0.1910
Fortafil 5A 0-deg core/ AS-2 ±30-deg shell	1825	16.1	21.3	1.45	240	468	0.0985	−0.1980
Fortafil 5A 0-deg core/ S-glass fiber ±45-deg shell	1575	11.4	17.7	1.07	220	382	0.1100	−0.2285
Fortafil 5A core/ S-glass cloth ±45-deg shell	1570	10.6	17.6	1.02	220	368	0.1095	−0.2295

[a] Frequency data based on beam theory using bulk vane modulus properties. [b] Experimental data.

40%. Modulus remained relatively constant for three of the four materials; however, S-glass cloth experienced a drop of approximately 40% at 250°F.

Mechanical property test specimens of similar thickness to the vane trailing edge (0.08 in.) were exposed to moisture for from 3 to 4 weeks at 140°F/95% relative humidity to simulate the moisture level which would be absorbed by the composite vane after achieving equilibrium in a worst condition ground/flight environment. Moisture absorbed by specimens during this period ranged from 0.4 to 0.9 wt.%. Flexural strength, modulus and short beam shear strength were not significantly affected by moisture added to specimens. The basis for moisture level addition is described in the Environmental Effects section.

Environmental Effects

Two environmental factors, long term erosion resistance and the influence of moisture, were considered in establishing a durable composite fan exit guide vane operating between 10 and 190°F.

Earlier tests, prior to this program, in both vibration rigs and engines had shown that the combination of a 0.01-in.-thick leading edge aluminum sheath on the airfoil covered by 0.01-in.-thick polyurethane coating over the entire airfoil provided the required protection from foreign object damage and erosion/corrosion.

Concern for long term durability of nonmetallic matrix composite material under varying temperature conditions, cyclic load and moisture environment established the need for suitable static mechanical property data of "wet" composite material. Both specimens and vanes were exposed to environmental conditions which resulted in moisture levels typical of service operation.

Vane moisture absorption and drying cycles in an engine environment were determined based on two factors: worst case average temperature and percent relative humidity at airports (75°F at 87% relative humidity) and service reported data for the lowest JT9D powered aircraft utilization rate during the past eight years reported by one operator. The lowest utilization time, using this conservative approach, was determined to be approximately 20% flight time. When converted to a daily cycle, this was equivalent to ground exposure for approximately 19 of every 24 h, and flight drying conditions for the remaining 5 h. Typical drying conditions for this period would be approximately 60°F, 0% relative humidity at pressures encountered at 35,000 ft altitude. A one-dimensional computerized analytical diffusion model developed by Springer and additional experimental data presented by Bohlman were used to determine the equilibrium moisture content in the 0.080-in.-thick trailing edge section of the vane for the most conservative condition.[3,4] Moisture content in the trailing edge was considered to be the controlling factor, since this airfoil section was most highly stressed. Calculations for a typical graphite/epoxy (3501-6 Hercules resin) system indicated that equilibrium moisture in the trailing edge section of the vane would be approximately 0.8 wt.% after 9 months. This moisture value was then used as the average quantity of moisture added to test specimens.

The magnitude of fan exit guide vane stress associated with residual fabrication stress, operational thermal gradients and part volume increase due to moisture absorption was estimated to be small.[5]

Resin Properties

Epoxy novalac systems were selected to meet processing and vane operational requirements. Samples of neat resin material, cut from 0.1-in.-thick slabs fabricated by both vendors, were exposed to 140°F/95% relative humidity conditions for various periods of time. Glass transition temperature (T_g), using the Perkin Elmer TMS-1 Thermal Mechanical Analyzer in the penetration mode, was determined for increasing levels of moisture in both epoxy systems. The T_g of both resin systems respond similarly to moisture gain, Fig. 6. However, these reductions in T_g were not expected to affect material performance, since the lowest wet glass transition temperature was well above the maximum expected operating vane temperature of 190°F.

Characteristic infrared spectra were obtained for each of the resin formulations for potential use in raw material process control testing. The spectra signatures confirmed the similarities of the two candidate epoxy novalac systems. One different peak grouping, in the 1105-1145-cm^{-1} frequency range, was noted between the two variations of epoxy novalac. This peak grouping can be related to the presence of an aromatic sulfone (S-0 stretch). Aromatic sulfones in epoxy novalac systems contribute to higher glass transition temperatures.

Neat resin mechanical properties were obtained from cast slabs fabricated by both vendors and tested by Pratt & Whitney Aircraft. Data are summarized in Table 2.

The mechanical and physical property data obtained during material acceptance and characterization testing were used to establish a model specification (PWA 125) for graphite fiber epoxy composite materials.

Vane Fabrication

Introduction

During the period between 1978-1980, several engine sets of vanes were fabricated for static and dynamic testing. A select group of these vanes were "bench" tested and provide the basis for this report. At the outset of the program, four of the initial vanes with different shell fiber were fabricated with

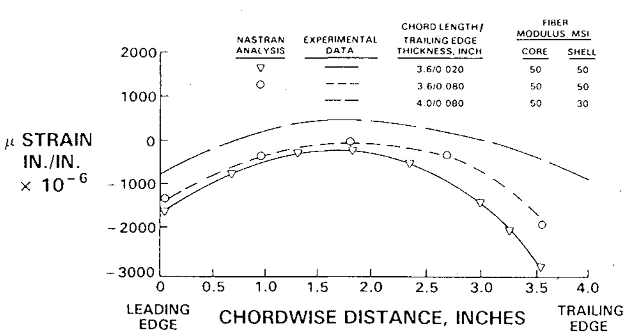

Fig. 3 Graphite composite fan exit guide vane—chordwise distribution of radial strain on concave side at 5-psi maximum steady-state load.

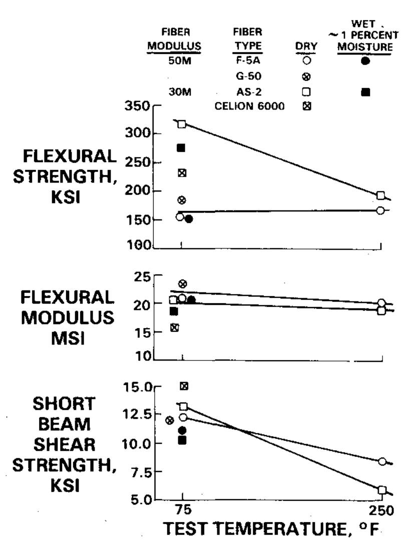

Fig. 4 Effect of temperature and humidity on mechanical properties of graphite epoxy fan exit guide vane material—average data.

intentional flaws of various types and sizes at different locations. These flawed vanes were subjected to a variety of nondestructive inspection techniques to determine inspection sensitivity levels.

Vane Fabrication Sequence

Vane cores were fabricated by either pultrusion or prepregged ply layup and the shell, in all cases, was fabricated by ply layup, Fig. 2. After materials acceptance, graphite fibers for the core section of vanes were prepregged by pultrusion through a liquid resin bath. The pultruded unidirectional core was then partially preformed to airfoil shape, cut to length and laid up with either four bidirectional 0.005-in.-thick cross-ply shells of prepregged graphite or two bidirectional 0.010-in.-thick S-glass cloth or fiber shell plies. A 0.010-in.-thick AMS 4015 aluminum leading edge was included in the one step compression molding operation in a heated tool. Unidirectional fiber and cloth test panels were fabricated and evaluated for each batch of resin used for vane fabrication.

Dimensional Requirements and Weight Control

Dimensional readings at a minimum of three vane sections were obtained on typical vanes for chord length. Although some variation did exist, the effect of these deviations on ''tructural integrity was considered insignificant and no dimensional effect was noted on the fatigue strain capability of the part. In addition to dimensional analysis, each vane was weighed as a further indicator of quality control. One vendor's vanes showed less scatter than the other's product. Comparison of the average weight of a graphite/epoxy vane (0.617 lb) to an aluminum vane (1.174 lb) of similar geometry 'ndicated a difference of 0.557 lb. For an engine with 96 vanes, weight saving of composite materials over aluminum was 53 lb.

Nondestructive and Microscopic Evaluation

The objective of the nondestructive evaluation (NDE) portion of the program was to determine detection sensitivity for various size and shape flaws located in different sections of the airfoil by using currently available inspection techniques. This baseline of flaw detection sensitivity was established by intentionally introducing flaws into four airfoils which represented different materials and ply layups. Flaw patterns were repeated on opposite ends of each vane midspan so as to permit inspection sensitivity evaluation under uncoated and polyurethane-coated conditions. Schematic diagrams showing flaw types and location are illustrated in Fig. 7. Some foreign nonmetallic materials, Teflon, glass microspheres and syntactic foam were introduced to simulate intentionally flawed regions. However, whenever possible, efforts were made to introduce flaws without foreign material. Low voltage radiography at 16 kV and 3 mA appeared to offer the most promise and was selected for evaluation of intentionally flawed vanes. The balance of vanes fabricated in the program were then inspected prior to and after fatigue testing and nondestructive test results were compared to data obtained from the NDE standard vanes.

Table 2 Neat epoxy resin mechanical properties[a]—minimum values

	Ultimate tensile, ksi	Modulus, msi	Elongation, %
Vendor A resin[b]	10.0	0.52	2.5-3.6
Vendor B resin[c]	7.4	0.47	1.7-4.8

[a]Specimen size 1.2-in. gage length; 0.4 in. wide; 0.1 in. thick. [b]Minimum of three specimens. [c]Minimum of seven specimens; epoxy novalac composition: DEN 438/50 parts; DER 331/50 parts; TONOX 60-40/20 parts.

Microstructure examination of pretest vanes was performed by removing a 0.375-in. section from the end of the vane to evaluate porosity, ply layup, fiber/resin homogeneity and fiber continuity at trailing and leading edges of the airfoil. Vanes were sectioned again after fatigue test to evaluate failure mode.

Airfoil Tests

Static Mechanical Tests

To determine bending spring rate, each vane was supported on the convex surface by two contoured knife edges located 15.7 in. apart. A uniform pressure load was applied to a 14.7-in. span of the vane concave surface. The bending stiffness determined experimentally for 60 vol.% fiber was consistently higher than the predicted analytical data, Fig. 8. In addition, experimental data showed considerable vane-to-

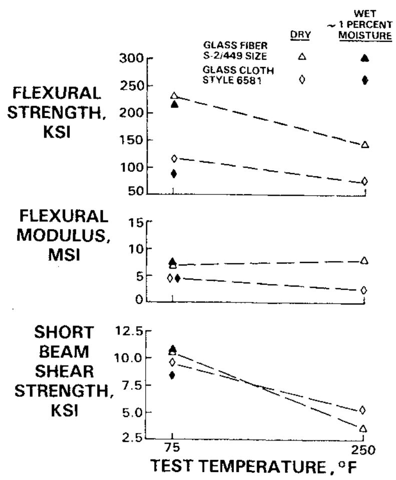

Fig. 5 Effect of temperature and humidity on mechanical properties of glass epoxy composite fan exit guide vane materials—average data.

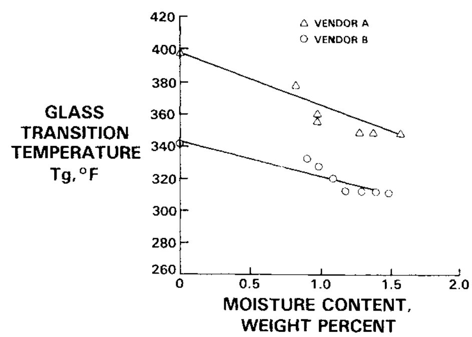

Fig. 6 Effect of moisture on glass transition temperature of epoxy novalac resin systems.

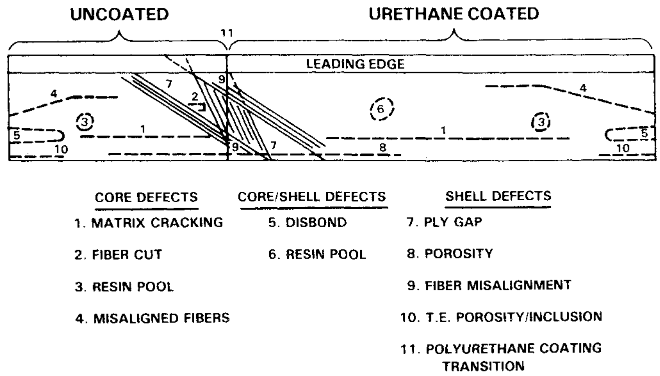

Fig. 7 Defect vane flaw location and identification map.

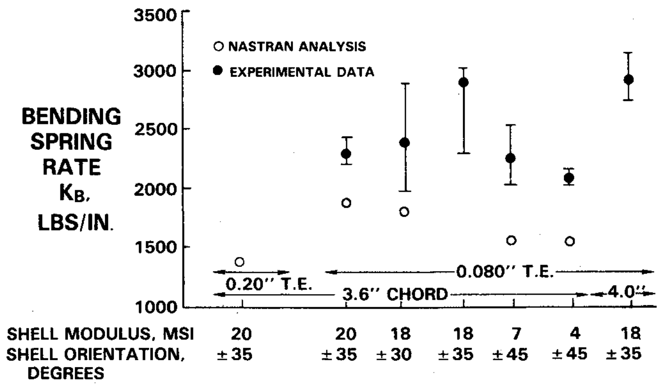

Fig. 8 Bending stiffness of composite fan exit guide vane—core modulus: 20-22 msi.

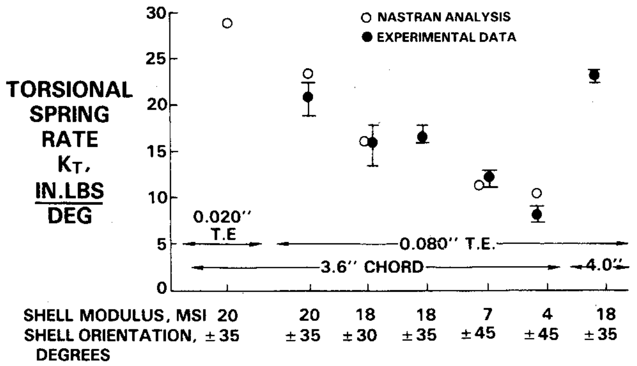

Fig. 9 Torsional stiffness of composite fan exit guide vane—core modulus: 20-22 msi.

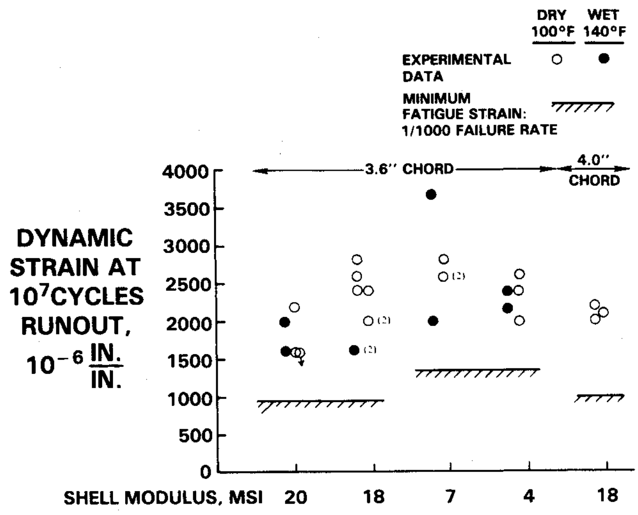

Fig. 10 Composite fan exit guide vane fatigue strain capability—simulated engine static compressive load—core modulus: 20-22 msi.

vane bending stiffness variation. Microscopic evaluation and composite density measurements confirmed that variations in fiber volume between 55 and 65% were a primary factor which influenced differences in bending spring rate. Another trend was noticed in that vanes fabricated with lower modulus shell material experienced a lower net bending stiffness than those vanes fabricated with higher modulus shell material. Shell construction material comprised approximately 20% of total airfoil composite material. Strain gage measurements were taken on the trailing edge of the six different vane constructions to establish the static strain levei to be imposed during subsequent fatigue tests.

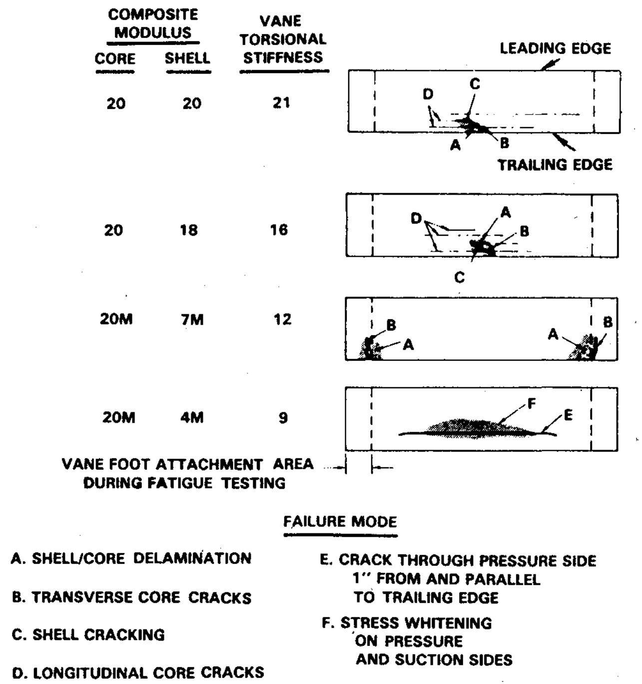

Fig. 11 Composite fan exit guide vane failure mode summary.

Vane torsion spring rate was determined separately in another fixture up to a total torque of 60 in.-lb. Torsional stiffness of the six different vane material/design configurations spanned the range 7-23 in.-lb/deg, Fig. 9. Shell material modulus exhibited a more dominant role in deter mining vane torsional stiffness as compared to bending stiffness. Furthermore, as one would expect, the torsional stiffness of the 4.0-in. chord vane was higher than the 3.6-in. vane with the same shell modulus material. NASTRAN analysis for 3.6-in. chord vanes was in excellent agreement with experimental data in predicting torsional stiffness.

High Cycle Fatigue Tests

After completion of static mechanical testing but prior to fatigue testing, two vanes from each of four groups of varying material/configuration were exposed to a 140°F/95% relative humidity environment for 4 and 3 weeks, respectively, for graphite and fiberglass shell parts. This accelerated moisture inoculation conditioning was required to duplicate the equilibrium moisture level expected in the trailing edge section of the vane during service operation. Analytical determination of weight gain resulting from the same moisture exposure conditions for a similar graphite/epoxy system (AS/3501-6) using the Springer, Bohlman moisture diffusion approach provided excellent agreement with experimental data.[3,4]

Vanes were prepared for fatigue testing by bonding each vane at both ends into aluminum fixtures using a silicon rubber potting compound. Strain gage instrumentation was installed by removing a 0.250×0.250 in.^{2} of polyurethane coating from the vane at each planned gage location to allow installation of strain gages directly on outer shell fibers. Prior to the application of vibratory loading, the aluminum end fixtures on the vane were turned to provide an airfoil static bending load which simulated the magnitude of aerodynamic loads experienced in the engine. Static loads were increased until the preselected trailing edge radial compressive static strain of $-1750\ \mu\epsilon$ was reached.

After static loads were stabilized, vibrational loading in the first bending mode was introduced. When the test vane successfully completed 10^7 cycles at any one vibrational strain level, strain was progressively increased until a frequency loss indicated failure. Strain at failure was considered quite conservative, since many vanes were tested at 10^7 cycles at increasing strain levels for up to six times before failure occurred.

The fatigue test program showed that for 3.6-in. chord airfoil, the glass shell/high modulus graphite core vanes failed at higher strain levels than graphite shell/high modulus, graphite core vanes; 2000 vs 1600 $\mu\epsilon$, respectively. The increase in chord dimension to 4.0 in. for an all-graphite vane appeared to raise the minimum dynamic strain to failure to 2000 $\mu\epsilon$, similar to glass shelled vanes, Fig. 10. Fatigue data for vanes in this program were Weibull treated to establish a minimum fatigue strength capability for each of the material/design configurations. Minimum fatigue strain capability was defined as a one-in-one-thousand vane failure rate. All the vanes within each of these two material groups (graphite vs glass) appeared to have a similar minimum fatigue strength range although chord dimension, shell and core material sources, fiber orientation, fabrication process, moisture and part quality variations existed. The insensitivity of vane fatigue strength to these variations is testimony to the adequacy of vane design and improvements in materials since the early 1970s. The difference between the minimum fatigue strain and the anticipated engine dynamic strain for the thick trailing edge vane provided significant fatigue margin. Several different failure modes were noted for the material configurations tested. The patterns and locations for failures were essentially consistent within any one material configuration, Fig. 11. However, shell fiber modulus appeared to be the most important factor in determining the torsional and uncamber stiffness of the airfoil and a relationship was apparent between failure location, mode, and torsional stiffness.

Conclusions

All composite fan exit guide vane configurations and materials tested exhibited fatigue strain capability in excess of requirements. For the 3.6-in. chord vane design, the fiberglass shell material/ply orientation combinations exhibited increased fatigue strain capability compared to graphite shell configurations.

A correlation was shown to exist between vane fatigue failure mode and torsional stiffness.

The presence of up to 0.8 wt.% moisture in composite vanes did not affect fatigue performance.

Graphite/epoxy vanes provided a 53-lb weight savings compared to aluminum vanes in a typical high bypass ratio engine.

Mechanical property tests of two 50-msi and two 30-msi modulus graphite fiber source materials revealed good repeatability and acceptable properties.

Infrared signature and glass transition temperature characteristics were established for resin systems.

Low voltage radiography in combination with visual examination was effective in identifying most of the defects in intentionally flawed vanes and cracks in postfatigue test vanes.

Experimental laboratory data substantiated the computer model developed for predicting moisture weight gain expected from service operation of composite fan exit guide vanes.

Acknowledgments

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