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Fatigue Testing of a Composite Propeller Blade Using Fiber-Optic Strain Sensors

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***Abstract*—The performance of surface-mounted extrinsic Fabry–Perot interferometric (EFPI) sensors during a seventeen-million-cycle, high-strain fatigue test is reported. Fiber-optic strain measurements did not degrade during the test. The sensors were applied to a composite propeller blade subject to a constant axial load and a cyclic bending load. Strain measurements were taken at four blade locations using two types of EFPI sensors and co-located electrical resistance strain gages. Static and dynamic strain measurements were taken daily during the 65 days of this standard propeller-blade test. All fiber-optic sensors survived the fatigue test while most of the resistive gages failed. The suitability of fiber-optic monitoring for fatigue testing and other high-cycle monitoring is demonstrated.**

***Index Terms*—Aerospace systems, fatigue testing, fiber-optic strain sensors, smart structures.**

I. Introduction

FIBER-OPTIC sensors are becoming important tools in material and structural testing. They are used for measurement of strain and temperature to assess load performance, structural integrity, and cure conditions [1], [2]. Their advantages include environmental ruggedness which offers the potential of long-term monitoring and operation in extreme conditions [3], [4]. Also, fiber-optic sensors are well suited for use with composite materials due to their small size and temperature tolerances. The resulting smart-composite-structures technology is an active area of research. In particular, Fabry–Perot interferometric fiber-optic sensors have been used in many composite applications [5], [6]. Their performance and accuracy have been favorably compared to that of traditional electrical resistance strain gages in both static and dynamic applications [7]. The information from these smart systems [8] can monitor structural performance [9], control composite cure processes [10], assess delamination damage [11], [12], and characterize wing behavior [13]. Coupon tests of embedded Bragg-grating fiber-optic sensors have shown that the sensors do not degrade through one million cycles for less than 250 μstrain deltas [9]. The fatigue characteristics of intrinsic Bragg-grating sensors may not be representative of Fabry–Perot sensors since the latter sensors require bonding of optical fibers and capillary tubes. Some work has been done evaluating Fabry–Perot fiber-optic sensors for aerospace fatigue tests [14] and for civil engineering structures [15]. In the latter test, the Fabry–Perot interferometric fiber-optic sensors survived 100 000 cycles. However, more work is needed to establish confidence in the fiber-optic sensors themselves with regard to fatigue life-time and performance.

One aerospace application of composites is in the manufacture of propeller blades from Kevlar® and carbon-graphite. Composite propeller blades offer many advantages over more common aluminum blades including lighter weight, lower inertia, better reparability, and longer service life. Fatigue testing of propeller blades is required per FAA regulations [16] and follows a standard test method. Strain sensing is required to establish the required loads for a fatigue test and can be used to monitor the part during the test. However, cycle life for resistive strain gages decreases dramatically as the strain delta increases. Strain deltas of 2000–4000 μstrain are not uncommon. Consequently, traditional resistive strain gages often fail early in testing and the general structural performance is inferred from load and deflection control. The ability to directly measure local strains throughout a test, and particularly during failure, can provide valuable insight into the blade behavior.

In this study, an experimental investigation of the sensor performance is done during a fatigue test of a composite propeller blade. The blade was subject to a constant axial load and a cyclic bending load. The loading and test parameters were the same throughout the test, i.e., the blade did not fail during the test. Strain measurements from surface-mounted extrinsic Fabry–Perot interferometric (EFPI) fiber-optic sensors are presented and compared to measurements from electrical resistance gages. The sensors at different locations on the blade experienced a variety of strain conditions. The extreme case was a cyclic strain of roughly 0–4000 μstrain. The fiber-optic measurements were consistent with the electrical measurements and their response suffered no apparent degradation during the 17 725 000-cycle fatigue test. None of the fiber-optic sensors failed, however most of the electrical resistance gages did fail. These fiber-optic sensors can enhance the procedure for propeller fatigue tests and serve reliably in other high cycle applications. EFPI sensors have already been shown to provide strain information during structural failure [17]. The suitability of fiber-optic sensors, especially EFPI sensors, for structural testing and monitoring applications is demonstrated. In particular, the sensors excelled in a high-strain environment and provided consistent measurements multi-million cycles.

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Previous work, as noted in the literature, was limited to one-million-cycle, low-strain testing of Bragg-grating fibers [9] and to 100 000-cycle applications of Fabry–Perot sensors [13].

II. Fiber-Optic Strain Instrumentation

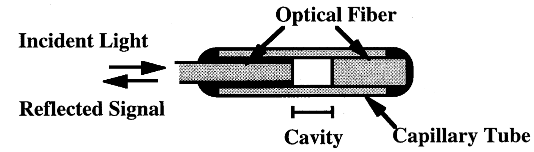
A. Commercial Implementation Issues

Fiber-optic-based smart instrumentation for composite propellers has three potential areas of commercial application. The first is quality control during cure. Cure consistency can be improved by direct in-situ measurement of internal conditions [10]. Preliminary experiments show that fiber-optic sensors satisfy measurement needs in an industrial setting and that they do not impose significant manufacturing and testing concerns [18]. The second application is developmental testing such as the fatigue test described in this work. The required fatigue and failure tests produce high cycle and high strain levels. The time and effort needed to carry out these tests could be reduced by use of sensors with longer fatigue life. Implementation and the associated instrumentation investment require confidence that the sensors have the needed performance. The third application is long-term health monitoring. A permanent sensing system could reduce maintenance costs by reducing the labor involved with periodic inspections while providing pilots an early indication of a structural problem before the onset of a catastrophic failure. Again, the sensors must be shown to have good fatigue and environmental characteristics, as well as other technical solutions for signal processing and spinning platform issues, for commercial implementation and regulatory acceptance.

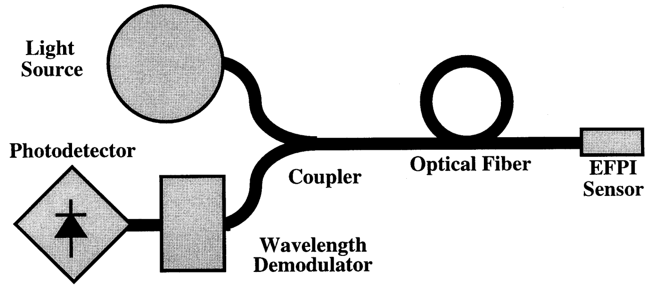
B. EFPI Fiber-Optic Sensors

An EFPI fiber-optic sensor is schematically shown in Fig. 1(a). The EFPI fiber-optic sensor utilizes multiple-beam interference [19] between two polished end-faces of a single mode fiber and a multimode fiber [20]–[25]. A capillary tube is bonded to the two fibers and maintains the alignment of their end faces. The tube is bonded to a material under strain. As the material and attached tube is strained, the reflected interference signal varies in response to changes in cavity spacing. The sensor has little transverse coupling and effectively evaluates the axial component of strain [26]. The gage length is determined by the length of this capillary tube rather than the cavity and can be built to varying lengths. A variation of this configuration is an extensometer in which the capillary tube is not bonded to the optical fibers. Instead, the fibers are bonded to the material under test at discrete points. The gage length is then determined by the effective distance between bonding points. The extensometer can measure a larger strain than the standard EFPI sensor, but the extensometer requires special handling during installation and its accuracy depends on the bonding characteristics.

Fig. 1(b) displays the schematic of source/detector system for the EFPI fiber-optic sensors. An LED source provides the input light beam into the single mode fiber. A coupler and wavelength demodulator branches the reflected interference fringes to a detector. The interference response at several wavelengths can determine the absolute cavity displacement and hence the absolute strain.



(a)



(b)

Fig. 1. (a) Extrinsic Fabry–Perot interferometric (EFPI) sensor with an external air-gap cavity and coated high-reflectance fiber surfaces. (b) EFPI fiber-optic sensor and support instrumentation for absolute strain measurement.

The fiber-optic instrumentation used in this experiment was manufactured by Luna Innovations (formerly F&S, Inc.). Standard EFPI AFSS sensors and prototype EFPI extensometer sensors were used. The first type were high-finesse sensors with gage lengths of approximately 8 mm. The second type were also high-finesse sensors. The effective gage lengths for the extensometer-type sensors were set during installation and were calculated as approximately 4.5 mm. Both sensors used a multiplexed AFSS system. Absolute strain was demodulated for each sensor from multiple measurements at several different wavelengths around 830 nm. The system was capable of scanning multiple sensors at 1 Hz per sensor channel.

C. Propeller Instrumentation

A Kevlar® composite propeller blade was the focus of this fatigue study [27]. The blade is typical of a design used on commuter turbo-prop aircraft and its length was roughly 1.5 m. The blade consists of a composite laminate shell formed around a foam core and bonded to an aluminum plug. Retention of the composite to the metal plug is strengthened by using a glass wrapping over the Kevlar® in the plug region. To simulate expected flight forces, the FAA fatigue test [16] subjects the blade to a steady, centrifugal load along the blade's center axis coupled with a steady, vibratory bending load.

Strain sensors were surface mounted on both sides of the propeller, i.e., camber and face. Standard EFPI sensors, EFPI extensometer sensors, and electrical resistance strain gages were applied with epoxy according to manufacturers' instructions. They were grouped at six locations near the base of the propeller and aligned as near the center of radius as possible. In total, four standard EFPI sensors and two prototype EFPI extensometers were surface mounted to the composite propeller blade. Fig. 2 illustrates sensor placement. Note that the tip of the propeller blade was removed and a special fixture attached for load application.

A resistive strain gage was co-located at each station with fiber-optic sensors for strain comparison. Electrical resistance strain gages are the typical instrumentation for fatigue tests

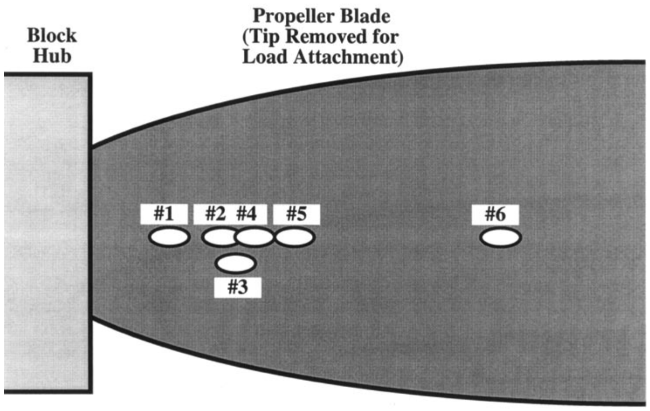


Fig. 2. Sensor locations on propeller blade during fatigue test. Resistive sensors were located on the camber and the face of the blade at all six positions. Standard EFPI sensors were located on the camber at positions #4, #5, and #6 and on the face at position #6. Extensometers were located on the camber at position #4 and the face at position #6.

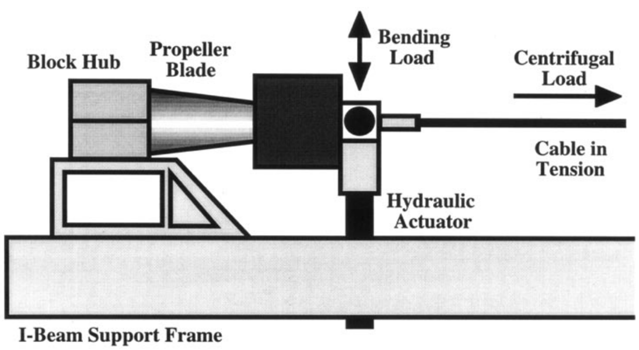


Fig. 3. Propeller fatigue test apparatus showing directions of applied loads.

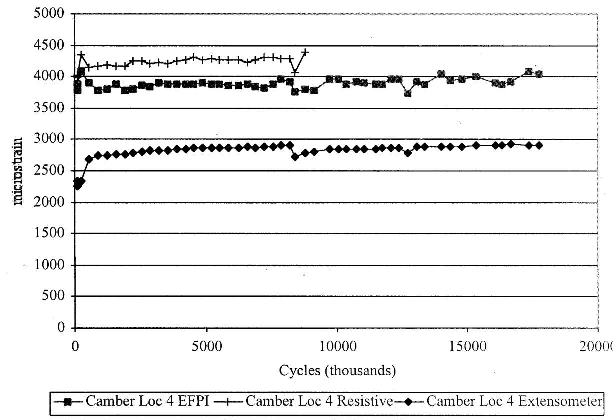


Fig. 4. Static strain at camber location #4 for minimum bending load.

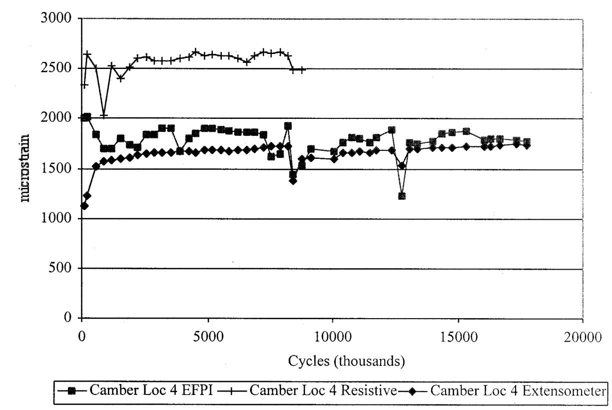


Fig. 5. Static strain at camber location #4 for maximum bending load. All sensors show good correlation.

and are used primarily during the beginning of the tests. They are not expected to survive the entire test. These sensors were Micro-Measurements model EA-13-250-BF-350 strain sensors. They had a nominal resistance of 350 Ω and a gage length of 6.35 mm. The measurement instrumentation was a Hewlett Packard Wheatstone bridge system. Besides the four resistive gages co-located with fiber-optic sensors, eight other resistive gages were used at other station locations to calibrate the test.

III. Propeller Fatigue Test

A. Fatigue Test Setup

Fig. 3 is a diagram of the fatigue test setup. The propeller was mounted horizontally in a test hub. A grip box was attached to the tip end so that both axial (or centrifugal) and bending loads could be applied. A steady centrifugal load was used in conjunction with a steady and alternating bending load. The sensors were zeroed with only centrifugal loading, i.e., no bending load. The bending loads were maintained using the Hewlett Packard control system in load-control mode. The hydraulic actuator used to induce the bending loads operated at 4 Hz.

The test was conducted over 65 calendar days during which 17 725 000 cycles were applied to the propeller blade. The test ran continuously as much as possible. When down time was required, the propeller remained in the test fixture. A standard fatigue test is conducted to 5 000 000 cycles, but this test was allowed to run past 17 000 000 cycles. The propeller blade did not fail.

Static and dynamic strain measurements were taken every business day for which the test was running. Static readings were taken for both fiber-optic sensors and resistive gages while the cyclic loading was interrupted. These readings were taken for two conditions: strain with maximum bending load applied and strain with minimum bending load applied. Dynamic readings were also recorded once per day for 4-Hz cyclic loading.

B. Strain Readings at Camber Locations #4 and #5

Figs. 4 and 5 show the total static strain measurements at camber location #4 for minimum and maximum bending loads. Fig. 6 shows the delta strain for each sensor, i.e., the difference in the strain for maximum and minimum loading conditions. The resistive gage at this station failed near 8.8 million cycles. Examination of the plots shows that all sensors correlated well in terms of trends and order of strain magnitude. Since all sensors could not be exactly co-located, i.e., placed on the center radius, some variation in strain magnitude and delta was expected. Measurements for camber location #5 are not shown as they are similar to those of camber location #4 and the resistive sensor at camber location #5 failed too early in the test for any meaningful comparison.

The results of dynamic strain measurement at the camber location #4 for the standard EFPI sensor are shown in Fig. 7. This

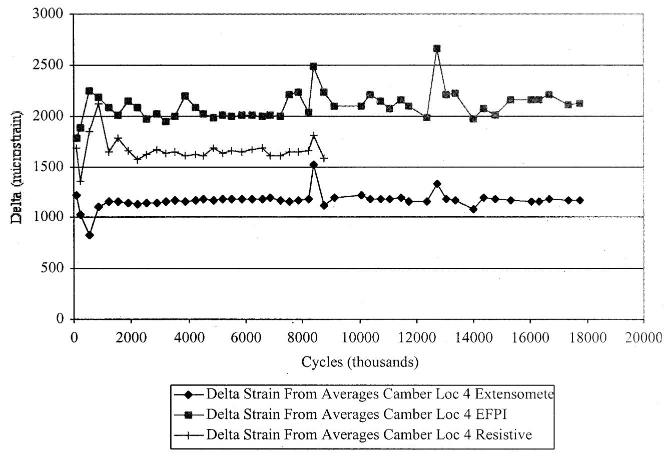


Fig. 6. Strain deltas for camber location #4. The EFPI and resistive measurements are well correlated and the extensometer and resistive measurements are somewhat correlated.

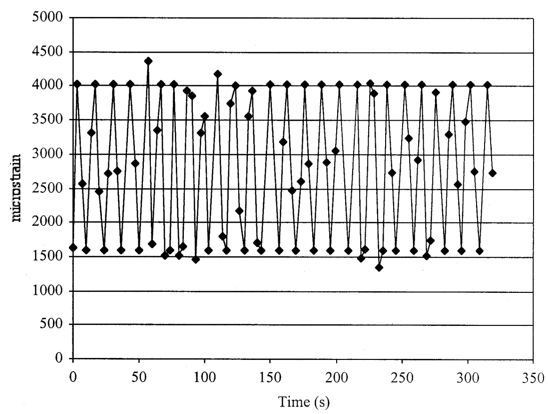


Fig. 7. Dynamic strain for standard EFPI sensor at camber location #4 (7.878 million cycles). The envelope of the dynamic data gives the maximum and minimum strain.

data was taken at about the 7.9 million cycle point in the test. Note that the data envelope defines the maximum and minimum strains over time. Some stray data points were caused when the automatic gain control failed to adjust properly in the dynamic environment and the instrumentation returned full-scale strain readings erroneously. The AFSS-PC instrumentation recognized the problem and returned errors for these points. These data points are not included in the figure and represented less than five percent of the data points taken dynamically. Comparison of the dynamic data for the standard EFPI sensor at camber location #4 to dynamic data from other stations showed that the frequency of error readings decreased with decreasing delta strain. While the AFSS-PC system is not designed for high-speed cyclic testing, the results show it can be adapted for such work—albeit with some limitations.

C. Strain Readings at the Camber and Face Location #6

Figs. 8–10 show the total static strain measurements for minimum and maximum bending loads and the delta strains at the camber location #6. The former measurements show minor trends in opposite directions. However, the strain deltas closely

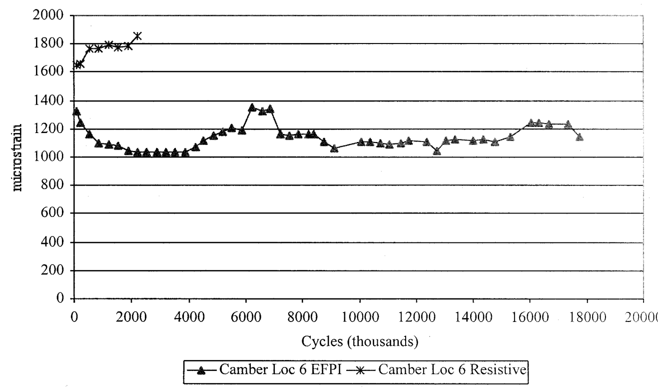


Fig. 8. Static strain at camber location #6 for minimum bending load.

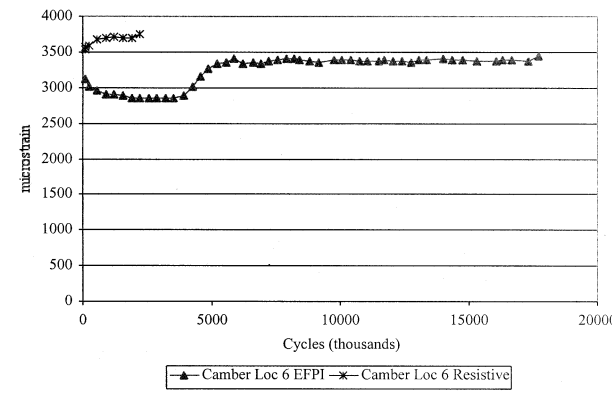


Fig. 9. Static strain at camber location #6 for maximum bending load.

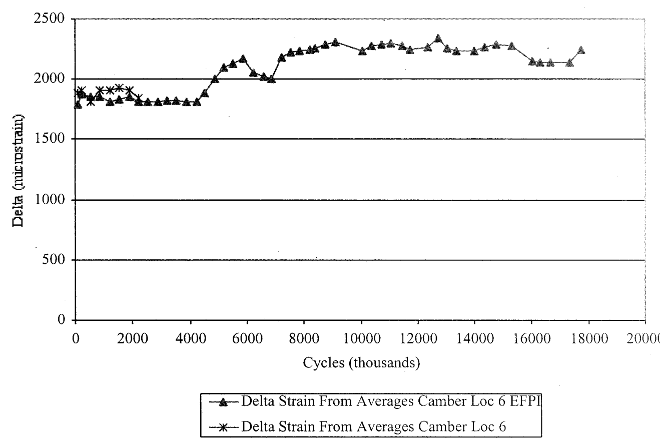


Fig. 10. Strain deltas for camber location #6. The resistive gage failed at about 2.5 million cycles. The standard EFPI and resistive measurements show excellent correlation until resistive gage failure.

matched while the resistive strain sensor was operating. The resistive gage failed at about 2 500 000 cycles.

Three sensors were positioned at face location #6. The resistive gage at this station survived the entire test. As can be seen in Figs. 11–13, the extensometer sensor and resistive gage had very good correlation in strain deltas, but a large offset in absolute measurements. The standard EFPI sensor does not show good correlation to the other sensors and appeared to under report strain changes. This behavior was evident from the beginning of the test and consistent throughout.

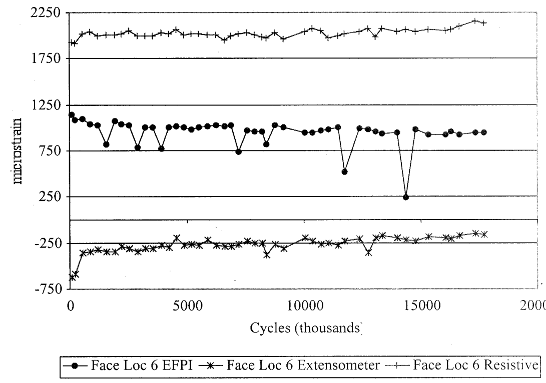


Fig. 11. Static strain at face location #6 for minimum bending load.

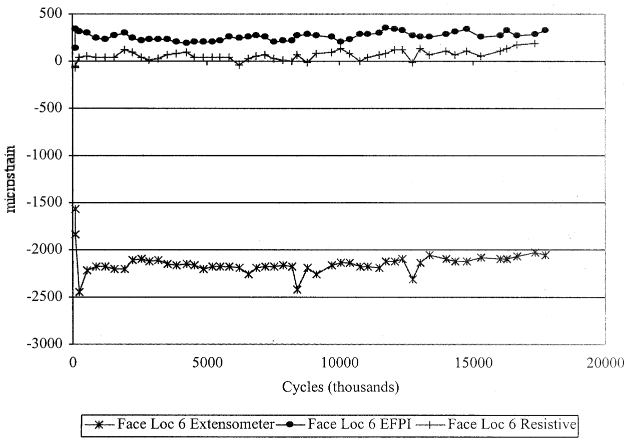


Fig. 12. Static strain at face location #6 for maximum bending load.

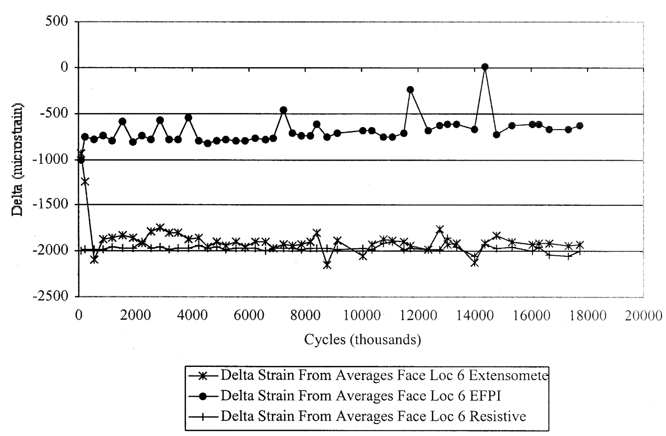


Fig. 13. Strain deltas for face location #6. The extensometer and resistive measurements show excellent correlation.

IV. Discussion

A. Performance of Electrical Resistance Gages

Four resistive gages were placed at stations with fiber-optic sensors. Only one survived the entire test. Failures occurred at less than 80 000 cycles for the sensor at camber location #5, at 2 542 249 cycles for camber location #6, and at 8 776 959 cycles for camber location #4. The surviving gage at face location #6 had an average delta strain of 2000 μstrain and maximum strain of 2100 μstrain. The fatigue test had eight other resistive gages at other locations. Only two of these additional gages survived the entire test. Of the two, one gage was in the lowest strain (delta and absolute) portion of the blade at camber location #1 (average delta of 1400 μstrain and maximum of 3000) and the other was at face location #4 (average delta of 2300 μstrain and maximum of 2500). Table I shows the breakdown of gage failures. Note that the sensor lifetime generally depended on both the average delta and maximum strain. Those sensors subjected to a higher maximum strain were more likely to fail than another sensor subject to a similar delta but lower maximum. This failure behavior is typical for this type of test.

TABLE I
SUMMARY OF ELECTRICAL RESISTANCE GAGE FAILURES

Cycles at Failure (thousands)	Position of Resistive Gage	Average Delta / Maximum Strain (microstrain)	Number of Failed Gages (Total 12)
<80	Camber location 5	2250 / 4100	1
2542	Camber location 6	2000 / 4000	2
3519	Camber location 3	1900 / 4000	3
4240	Camber location 2	1800 / 4100	4
4856	Face location 2, Face location 5	2200 / 2300 1800 / 2300	6
8777	Camber location 4	1650 / 4000	7
9419	Face location 3	2200 / 2400	8
13673	Face location 1	1800 / 2000	9

TABLE II
AVERAGE STANDARD DEVIATION AND VARIANCE AT MAXIMUM AND MINIMUM DISPLACEMENT FOR EFPI SENSORS

Fiber Optic Sensor	Std. Dev Maximum	Std. Dev Minimum	Variance Maximum	Variance Minimum
Camber Location 4 Extensometer	1.07	0.22	2.61	0.10
Camber Location 4 Standard EFPI	0.56	0.23	1.02	0.22
Camber Location 5 Standard EFPI	0.32	0.33	0.47	0.10
Camber Location 6 Standard EFPI	0.23	0.20	0.13	0.07
Face Location 6 Extensometer	1.03	0.28	3.44	0.36
Face Location 6 Standard EFPI	6.99	0.63	61.30	0.68

B. Performance of Fiber-Optic Sensors

All of the fiber-optic sensors survived this high-cycle fatigue test with no apparent degradation. The measured strain shows only small variations over the course of the test even for the maximum bending loading. Since the blade did not fail, uniform strain results are expected. In a load-controlled test, any changes in the blade stiffness would cause strains to change as the controller maintains applied load.

Standard deviation and variance were calculated for each set of fiber-optic sensor readings and average values are given in Table II. Standard deviation and variance were highest for the maximum bending load data and significantly lower for the minimum bending load data. Although the maximum-load standard deviation values were higher, the averages are quite acceptable and agree with the resistive data available, particularly in terms of delta strain.

The fiber-optic strain values generally agree with the corresponding resistive gage values. The strain deltas were consistent. Some of the absolute maximum and minimum bending strains do show discrepancies. The small strain offsets can be attributed to slight positional differences and to time differences. The fiber-optic and resistive measurements were taken within a few seconds of each other, but, even in the static case, some drift always occurs in the applied load. A large offset of about 2000 μstrain occurred for the prototype extensometer and the resistive gage at face location #6. This offset is too large to be a matter of position. However, the strain deltas for this case had one of the best correlations. The cause is unclear, but it may be related to errors in the gage attachment or to the effective gage length calculation.

V. Conclusion

EFPI fiber-optic strain sensors and resistive strain gages were compared in a fatigue test of a composite propeller blade. The test followed a standard method that meets FAA regulations and exceeded the standard cycle count by a factor of three. Both static and dynamic data between fiber-optic sensors and co-located resistive gages showed good correlation. All strain deltas were comparable, although some absolute strain offsets occurred. Most offsets were attributed to small positional differences and to load variations. Furthermore, the most significant result was that all fiber-optic sensors gave consistent measurements throughout the long-term fatigue test. The testing and qualification procedures of composite aircraft propellers must follow prescribed guidelines to ensure safety and performance. The ability of fiber-optic sensors to directly measure local strain up to and during failure can provide valuable insight that is not typically available from traditional sensors. This work is a demonstration of fiber-optic instrumentation in an industrial setting.

The investigation showed that EFPI fiber-optic sensors can provide reliable measurements during a high-cycle, high-strain fatigue test. During this 17 725 000-cycle test, none of the fiber-optic sensors displayed any apparent degradation in performance. The most extreme case was a constant strain of 2000 μstrain in conjunction with a cyclic strain of 2000 μstrain. In comparison, nine of twelve resistive strain sensors failed completely. Previously published studies of sensor fatigue performance were done for significantly lower cycle counts. This study provides a needed encouragement for fiber-optic-sensor implementation in industrial processes and products. For fatigue tests and other high-cycle applications, fiber-optic sensors can provide monitoring for the duration of a test or the lifetime of the structure.

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