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Development of an Embedded Fabry Perot Fiber Optic Strain Rosette Sensor (FP-FOSRS)

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ABSTRACT: In this paper we investigate the feasibility of utilizing a Fabry-Perot Fiber Optic Strain Rosette Sensor (FP-FOSRS) for the evaluation of the internal strain state of a material system. We briefly describe the manufacturing process for this sensor and point out some potential problem areas. Results of an embedded FP-FOSRS in an epoxy matrix with external resistance strain gauges applied for comparative purposes are presented. We show that the internal and external strain measurements are in close agreement. This work lays the foundation for embedding this sensor in actual composite laminas.

I. INTRODUCTION

It has been shown [1] that embedded Fabry-Perot Fiber Optic Strain Sensors (FP-FOSS) provide accurate and reproducible measures of strains within a material system containing complex damage states. This unique form of internal strain measurement provides the technical community a tool to interrogate the structure's health and gives researchers an instrument to study the basic physical behavior of material systems. The prospect of utilizing these sensors in this manner has sparked a high degree of interest in the scientific community. One advantage that the FP-FOSSs have over their resistance strain gauge counterparts is that their measurements are unaffected by the presence of surface shears. Therefore, accurate measurements of strain in the presence of high surface shear, such as between plies in a composite panel, is easily accomplishable with the FP-FOSSs. For this reason, as well as the sensor's ability to give accurate measurements in the presence of EM fields, one can readily understand that the FOSS's are an attractive alternative to resistance strain gauges.

While fiber optic sensors do provide useful data, their applications have been limited by the inherent nature of the 1-dimensional measurements (i.e. only along the axis of the FOSS). In terms of health monitoring, a full 3-dimensional state of strain is required to quantitatively assess the material's damage state. We present in this investigation the philosophy of using multiple FP-FOSSs oriented in chosen directions to experimentally determine the full strain tensor at a point within a material. Past researchers have utilized this approach to investigate surface strains [2]. In particular three sensors oriented within a plane at 0, 45, and 90°(see Figure 1) are embedded in an epoxy coupon for testing. The Fabry-Perot Fiber Optic Strain Rosette Sensor FP-FOSRS has a gauge

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length of approximately 4mm and thus constitutes point measurements of strain with respect to the size of the coupon. The material is subjected to variety of loading conditions to investigate the ability of the internal sensor to monitor different states of internal strain. The data obtained from the embedded FOSRS are compared to classical experiment techniques to demonstrate the accuracy of the device. This measurement methodology gives researchers a important tool to understand the nature of internal strain redistribution near damaged region for both homogeneous and in-homogeneous systems.

2. MANUFACTURING

The Fabry-Perot fiber optic strain rosette is comprised of three separate Fabry Perot fiber optic sensors. Each of these sensors is manufactured with a gauge length of 2-7mm. The reader is referred to [2] for details on the manufacturing process and on the strain measurement technique of the FP-FOSS. The three FP-FOSS which comprise the rosette are initially positioned in an alignment fixture to orient the sensors at nominal angles of 0° , 45° , and 90° . Once positioned, the sensors are adhered together with a standard epoxy applied at their intersection defined by point "A" as shown in Figure 1. The epoxy prevents movement of the sensors relative to one another once the rosette is assembled.

The initial design and manufacture of the rosettes involved placing the hollow core portion of the FP-FOSS (the portion which essentially defines the gauge length) as close as possible to the intersection "A" of the three sensors. The hollow cores were placed at this position in an attempt to produce a sensor capable of measuring point strains as compared to a sensor which would monitor strains over a finite region. For health monitoring purposes point strains are a more useful quantity. However, due to the formation of an air bubble produced by outgassing of the epoxy (discussed in results section), the hollow core has been repositioned outside of this intersection in subsequently manufactured sensors. Presently the single mode portions of the sensor intersect at this location, and the three hollow cores are approximately 5mm from this point. Furthermore, in an attempt to eliminate the presence of the air bubble, the epoxy has been replaced in the more recent sensors with with an AE-10 epoxy.

3. TEST SETUP

The validation of strain measurements obtained from embedded FP-FOSRS can be accomplished by several different methodical approaches. However, we believe the most efficient and revealing approach is to investigate the response of the FP-FOSRS in a homogeneous matrix material. This technique eliminates any extraneous parameters which might influence the results, such as strain gradients caused by local disturbances. By utilizing a transparent epoxy as a test matrix, we have the ability to visually inspect the embedded FP-FOSS to determine if any anomalies are present which might influence the results. This would not be possible in an actual composite. Nonetheless, by using an epoxy system similar to that of a graphite/epoxy composite, we expect adhesion characteristics present in the homogeneous test specimens and the actual composite system to also be similar.

In our investigation, the FP-FOSRS are embedded in a homogeneous PLM-9 epoxy material and cured near room temperature (i.e. 37°C). By curing the test specimen at

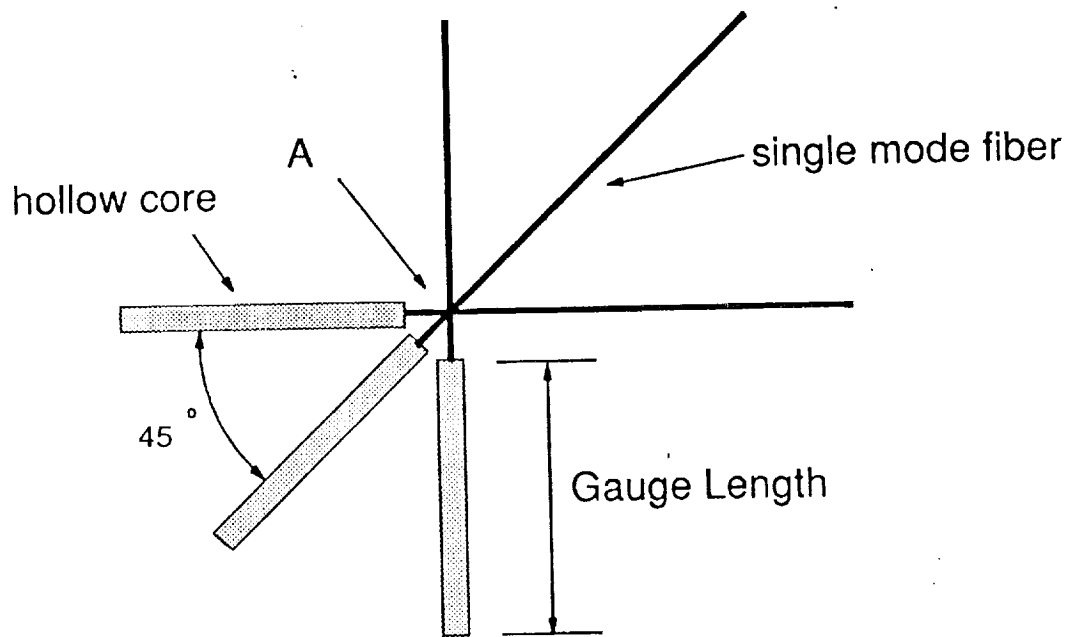


Figure 1: Illustration of a Fabry-Perot Strain Rosette sensor.

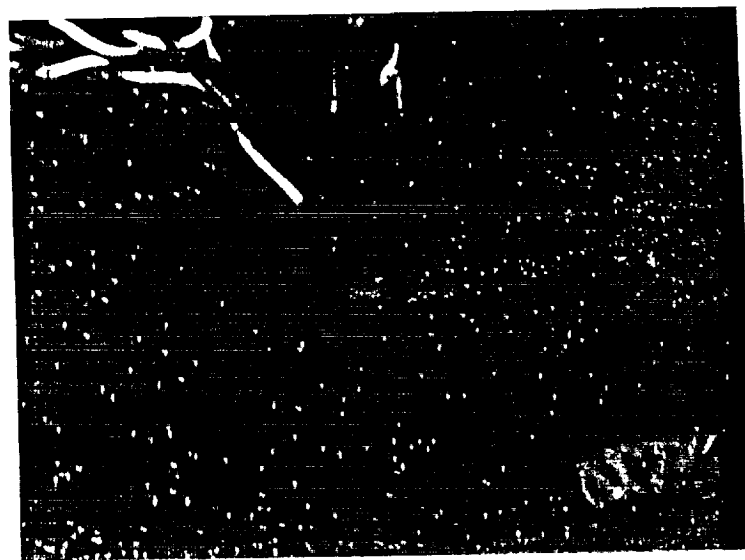


Figure 2: Picture of the air bubble around the intersection of the hollow core fibers.

a relatively low temperature, we have decreased the amount of load transfer due to thermal stresses. If, after testing, we discover that the load transfer is insufficient, the material can be cured at a higher temperature. The size of the test coupon is sufficiently large enough to prevent boundary conditions such as grip effects from influencing the strain field present in the region around the the FP-FOSRS.

Once the test coupon is cured, three resistance strain gauges are carefully attached to the surface of the test coupon. Each gauge is positioned on the specimen directly over and aligned with a FP-FOSS. The data obtained from the resistance strain gauges are compared to the data from the FP-FOSRS to validate the internal measurements. The test specimen is mounted in a servo-hydraulic test frame with tensile and compressive loads applied along the axis of the specimen. This loading introduces a state of plane stress in a homogeneous material system at distances sufficiently far from the grips. Within the gauge section, the strains are constant. This statement, of course, assumes the FP-FOSRS is unobtrusive. Therefore, the strain measurements obtained from the embedded FP-FOSRS gauge should be identical to measurements obtained from the surface mounted resistance strain gauges.

We wish to point out that the current test methodology also provides a worst case scenario for the embedded FP-FOSRS sensor (not considering damage). For our test setup, the modulus of the FOSRS is significantly larger than the modulus of the matrix (i.e. 20 times larger). As a result, we would expect the FOSS sensors to slightly effect the strains being measured. On the other hand, in an actual composite the modulus of the sensor and host have similar magnitudes. As a result, the FP-FOSRS embedded in an epoxy resin is a more obtrusive measurement than a composite structure. So, if the FP-FOSRS provides accurate data in the homogeneous system we would also expect it to provide accurate results in a epoxy/graphite composite.

4. RESULTS

The initial FP-FOSRS gauge was manufactured with the hollow core tube attached at the intersection "A" as stated in the manufacturing section. We performed uniaxial compression and tension tests on this coupon. In both loading sequences the FP-FOSRS provided erratic data. The strain to load was found to be different for each loading cycle. Furthermore, the 0° gauge provided strain data comparatively larger than the external strain gauge. The 45° and 90° gauges exhibited little to no strain, a contradiction of the data obtained from the resistance strain gauges. Initially, this discrepancy was thought to be due to inadequate adhesion between the FOSS and the matrix. The coupon was subsequently cured at an elevated temperature (90°C) to induce higher residual thermal stresses. However, this did not alter the output obtained from the FP-FOSRS.

Upon closer inspection of the composite (see Figure 2) an air bubble, larger than the hollow core's diameter was detected at the intersection "A". The formation of this air bubble was believed to be due to the type of epoxy utilized in the manufacturing process of the FP-FOSRS. This air bubble would theoretically alter the gauge length (since it encompasses the hollow core) and the load transfer of the FP-FOSS. For this reason, the manufacturing process was altered slightly for subsequent sensors. The next sets of FP-FOSRS were manufactured with a different epoxy resin system and the location of the hollow core fibers was changed. The hollow core fibers were placed approximately 5mm outside of the intersection point "A" (see Figure 3).

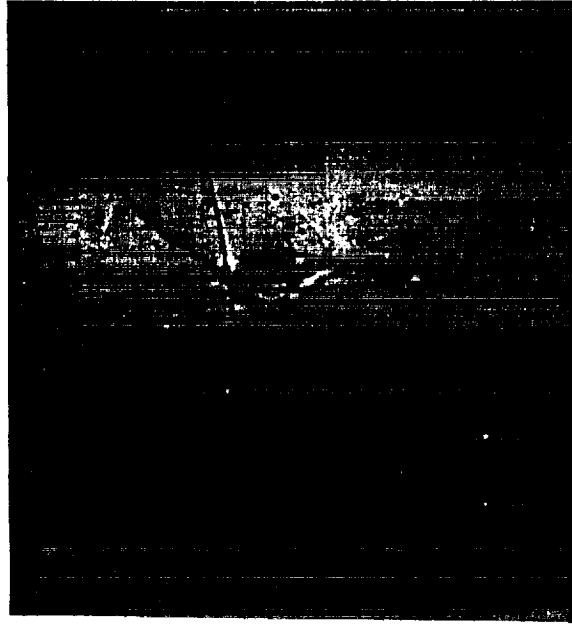


Figure 3: Picture of the modified Fabry-Perot Strain Rosette sensor.

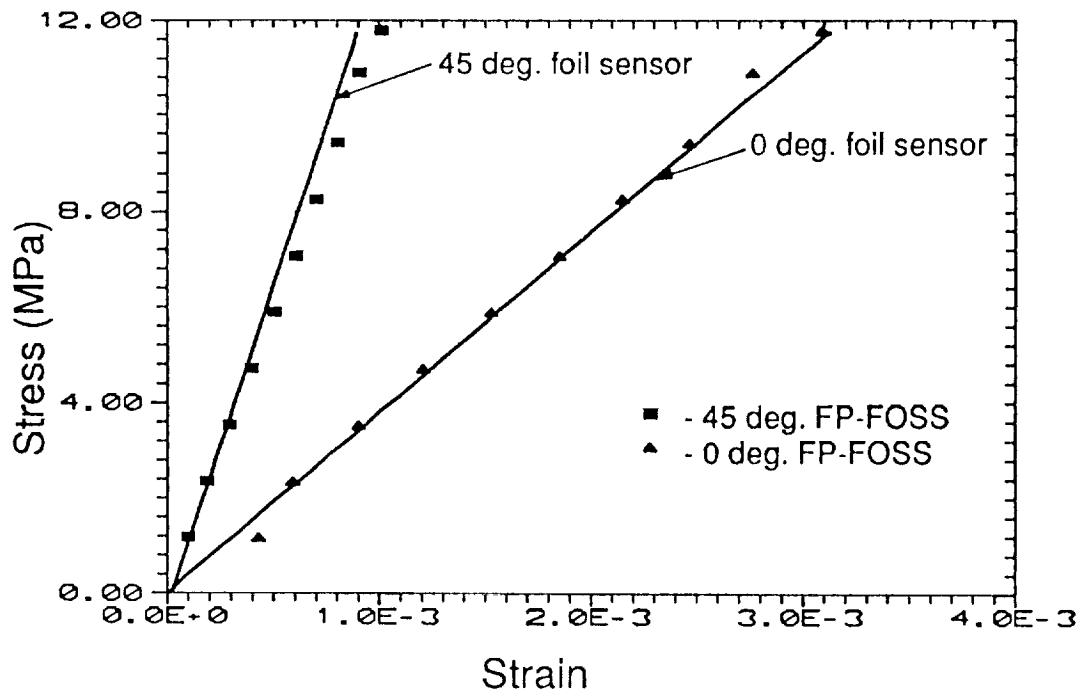


Figure 4: Comparison between strain data obtained from the external resistance strain gauges and the internal FP-FOSS.

While mounting the modified FP-FOSRS in the mold, the single mode portion of the 90° sensor was inadvertently broken. However, the decision was made to still attempt to use the sensor. In an effort to reduce the number of extraneous parameters in the measurement process, the test specimen was cured at 90°C to ensure sufficient load transfer. Results of the tension tests performed on this specimen are presented in Figure 4. The maximum tension applied to the specimen was 1000 lbs. Strain data obtained from the FP-FOSRS was recorded at various load levels and are presented in this figure as symbols. As can readily be seen, the two different sensing methods are in excellent agreement. These results validate the ability of the embedded sensor to monitor internal strains accurately.

5. CONCLUSIONS

The manufacturing process utilized in the development of the FP-FOSRS was described. Potential problem areas such as out-gassing near the intersection region of the hollow core fibers were identified. These problem appeared to be easily solvable by either the removal of the hollow core from the intersection region or utilizing a different adhesive in the intersection region. We demonstrated that good agreement between the embedded sensors and the external strain gauge were obtained once the problem areas were remedied. Tests in the near future will involve embedding the FP-FOSRS between plies of an actual graphite/epoxy composite.

6. REFERENCES

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