

# Multidimensional strain field measurements using fiber optic grating sensors

Eric Udd<sup>\*a</sup>, Whitten Schulz<sup>a</sup>, John Seim<sup>a</sup>, Eric Haugse<sup>b</sup>, Angela Trego<sup>b</sup>, Patrick Johnson<sup>b</sup>, Thomas E. Bennett<sup>c</sup>, Drew Nelson<sup>d</sup>, Alberto Makino<sup>d</sup>

<sup>a</sup>Blue Road Research, 2555 NE 205th Avenue, Fairview, Oregon 97024

<sup>b</sup>Boeing Phantom Works, P.O. Box 3999, MS 84-09, Seattle, WA 98124

<sup>c</sup>Sandia National Laboratories, Livermore, CA 94551

<sup>d</sup>Mechanical Engineering Department, Stanford University, Stanford, CA 94305

## ABSTRACT

Fiber optic grating sensors written into polarization preserving optical fiber may be used to monitor multidimensional strain fields in composite materials. This paper provides an overview of the characterization and test of multiaxis fiber grating sensors formed by writing 1300 and 1550 nm fiber gratings into polarization preserving optical fiber. A discussion of the usage of these multiaxis fiber grating sensors to measure two and three dimensional strain fields will be made. A brief review of practical applications of the technology to measure shear strain, transverse strain gradients as well as axial and traverse strain will be made with emphasis on aerospace and civil structure applications.

**Keywords:** advantages, high temperature, transverse, axial, smart structures

## 1. INTRODUCTION

For many structural applications it is highly desirable to be able to measure more than one axis of strain at a single point. For cases where the sensors are to be embedded it is also important to be able to minimize the number of points of ingress and egress. Today many strain measurements are made with electrical strain gages. While most are single axis devices foil gauges can be made that can be used to measure more than one strain component. While single axis electrical foil gauges require two electrical leads the three axis devices in general require six. Other issues associated with electrical strain gauges include, (1) limited temperature ranges, (2) susceptibility to electromagnetic interference, (3) difficulties associated with integrated them into oil field service equipment, (4) limited multiplexing potential and (5) long term durability. Fiber grating strain sensor technology has the potential to overcome all of these issues. In some cases such as immunity to electromagnetic interference and multiplexing potential, the technology itself provides immediate improvements. High temperature operation and long term durability have been demonstrated in the lab and early field tests have been encouraging. The main issues that remain to be solved before successful deployment involve interfacing issues associated with fibers, cables and integration into the structures themselves. Many of these problems have been solved for integration of fiber grating sensors into large civil structures such as bridges<sup>1,2</sup>.

In addition to measuring axial strain and temperature, fiber optic grating strain sensors have another unique capability. This involves the measurement of transverse as well as axial strain by writing fiber gratings into birefringent optical fiber such as polarization maintaining optical fiber<sup>3,4,5</sup>. These sensors have been demonstrated to measure multidimensional strain fields in composite load bearings<sup>6</sup> and multidimensional strain fields interior to adhesive bonds<sup>7</sup> including the measurement of shear strain and transverse strain gradients. These developments allow for the potential to realize embedded or attached fiber grating strain sensors that could measure residual strain, twist and other load factors critical for structural monitoring.

This paper will focus on the multi-axis strain sensing capabilities of fiber optic grating sensors. The paper will begin with an overview of how multi-axis strain sensing may be realized. Selected applications for this technology will be reviewed and details of implementation discussed.

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\* Correspondence: Email: ericudd@aol.com; web: www.bluer.com; Telephone: 503 667 7772 x101; Fax: 503 667 7880

## 2. MULTI-AXIS FIBER GRATING STRAIN SENSORS

When a fiber grating is written into birefringent optical fiber such as commercial polarization preserving fiber the net result is two effective gratings with spacings that depend on the index of refraction along each of the polarization axes. As shown in Figure 1 these axes are orthogonal to the longitudinal axis of the fiber grating. When transverse force is applied along one of the transverse axes the relative index of refraction along each axis changes in response to this force. The net result is that a change occurs in the relative spectral content of the two fiber grating peaks that can be used to measure transverse strain.

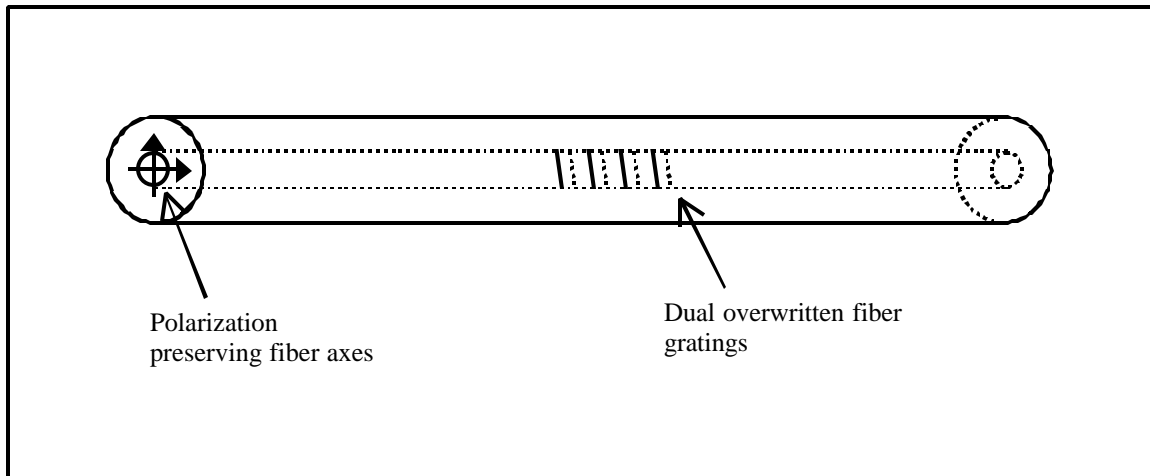


Figure 1. Dual overlaid gratings written onto polarization preserving fiber.

Figure 2 illustrates the situation where the fiber of Figure 1 is subject to axial strain. The two peaks move together in a manner similar to that of an ordinary fiber grating strain sensor. When transverse load is applied the two peaks move together or apart spectrally as shown in the second part of Figure 2.

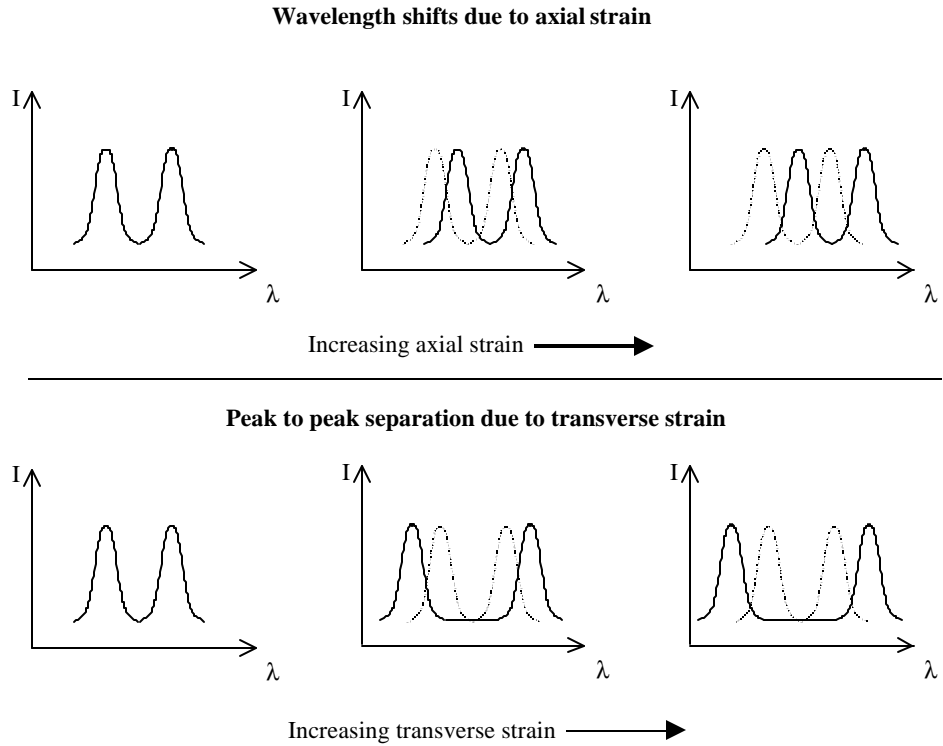


Figure 2. Peak shifts and peak separations due to axial and transverse strains.

Figure 3 shows the case of an actual fiber grating written on polarization maintaining fiber being subject to transverse loading. In this case the loading is applied along an axis that results in the two peaks moving apart spectrally. Loading along the orthogonal transverse axis would result in the two peaks moving closer together.

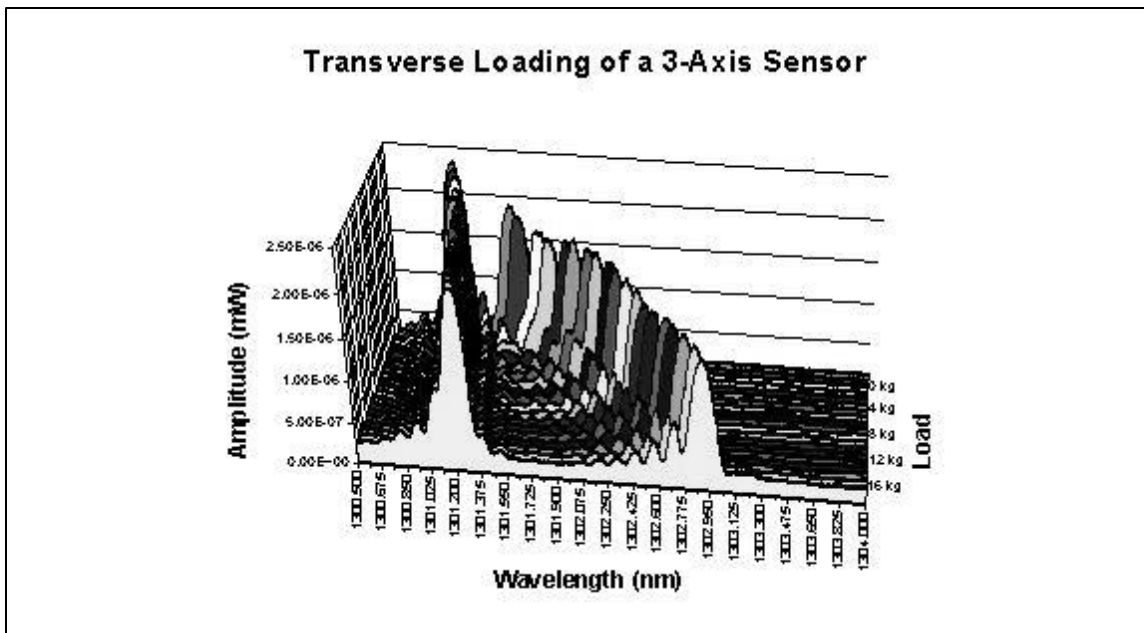


Figure 3. Loading a fiber grating sensor written onto polarization maintaining fiber transversely along a polarization axis results in the spectral peaks moving apart or together in wavelength.

One fiber grating written into polarization maintaining fiber allows the measurement of two parameters simultaneously which might be temperature and a strain component or two strain components. By writing more than one fiber grating into a polarization maintaining optical fiber additional parameters may be measured. In the case of two fiber gratings written at different wavelengths it is possible to generate a matrix of four equations in four unknowns relating the response of the optical fiber to the three axes of strain and temperature. Blue Road Research, Stanford and Sandia have investigated a number of commercial polarization maintaining optical fiber and found that while two and three axes of strain can be accurately measured simultaneously, the matrix is not very well conditioned with respect to temperature in the case of measuring all three axes of strain and temperature at once. By optimizing optical fiber and demodulation techniques significant improvement may be made, and these are being studied.

There are a number of effective means to track all four peaks simultaneously. One method is to use a scanning optical spectrum analyzer similar to that shown in Figure 4. In this particular case light sources at 1300 and 1550 nm are used to illuminate a multi-axis fiber grating sensor written at these two wavelengths. Recently Research International in collaboration with Blue Road Research developed a Ferret III system that can be used to track multiple peaks at 1300 and 1550 nm simultaneously with a scanning Fabry-Perot etalon. The Ferret II+ may be used to track dual peaks for transverse sensing using single fiber gratings written onto birefringent optical fiber.

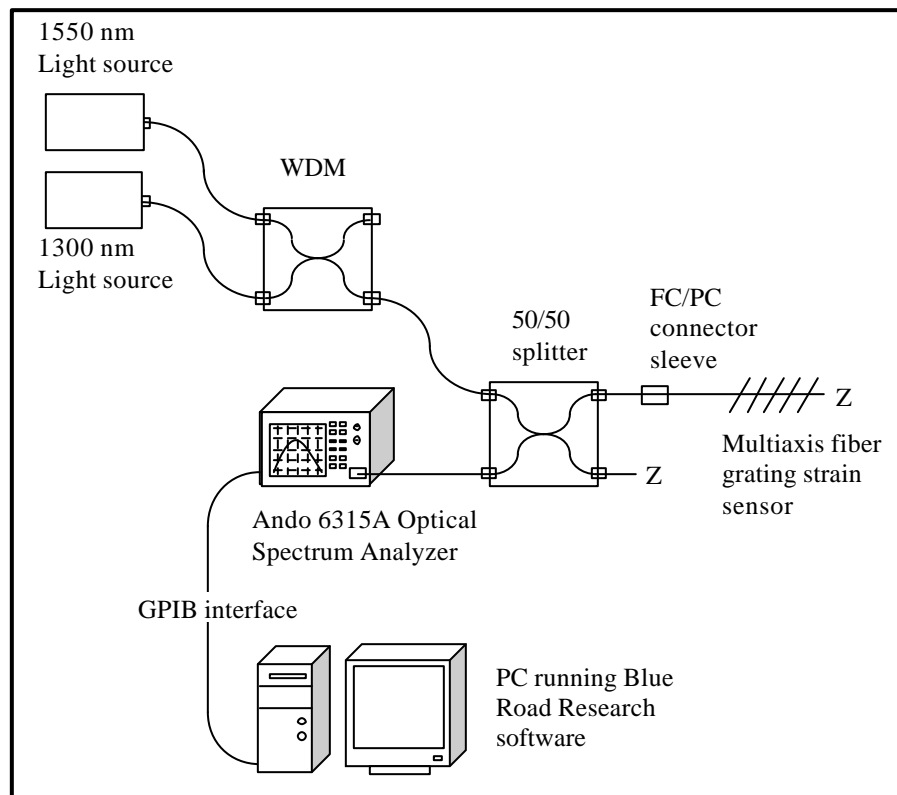


Figure 4. System that may be used to track multiple peaks in multi-axis fiber grating strain sensors

### 3. APPLICATION EXAMPLES

The primary mechanism for bridge failure in the Pacific Northwest involves underscoring of bridge pilings over rivers used to support the bridge deck. Blue Road Research in cooperation with Production Products and the Oregon Department of Transportation have developed and tested a "smart" bridge bearing capable of measuring transverse as well as shear strain fields. Figure 5 shows a panel with four multi-axis fiber grating sensors embedded into it so that transverse and shear strain measurement can be made. Two of the sensors are aligned for transverse strain measurements and two for shear strain. As system similar to that shown in Figure 5 was built by placing the four multi-axis fiber grating strain sensors into a carbon epoxy panel to simulate a steel plate that would be placed between layers of neoprene in an elastomeric bridge bearing.

Figure 6 shows the panel being tested for transverse loading at the Oregon Department of Transportation. The system was shown to operate at loads of 300,000 pounds well in excess of the requirement of 200,000 pounds associated with the break up of concrete.

Aerospace examples of this system would include the usage of appropriately oriented multi-axis fiber grating sensors to perform conformal mapping of a surface such as a wing or the body of an aircraft or spacecraft.

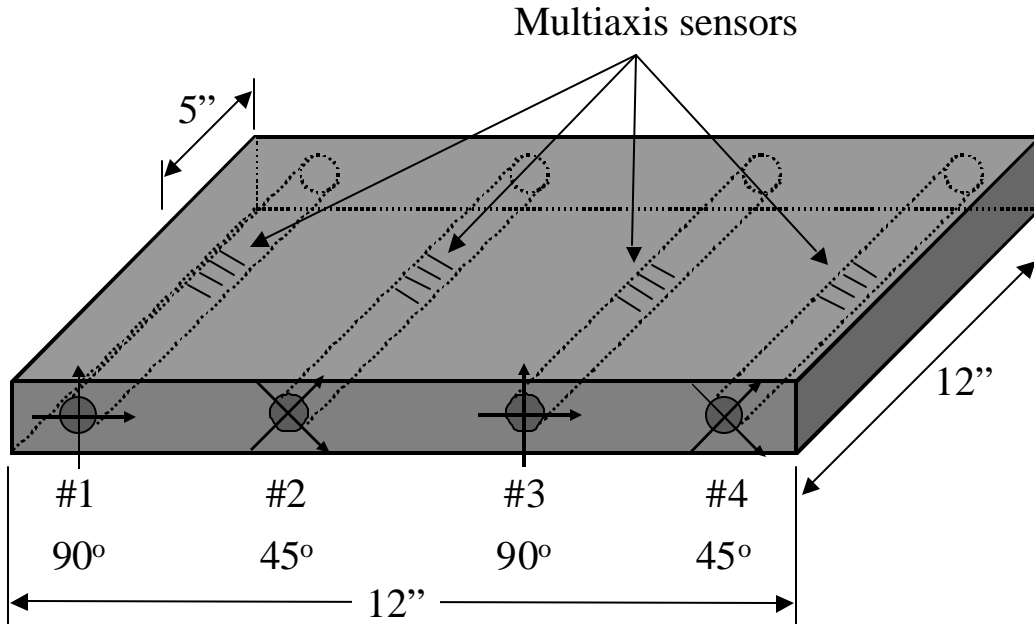


Figure 5. Diagram illustrating the placement of multi-axis fiber grating strain sensors to measure transverse and shear strain

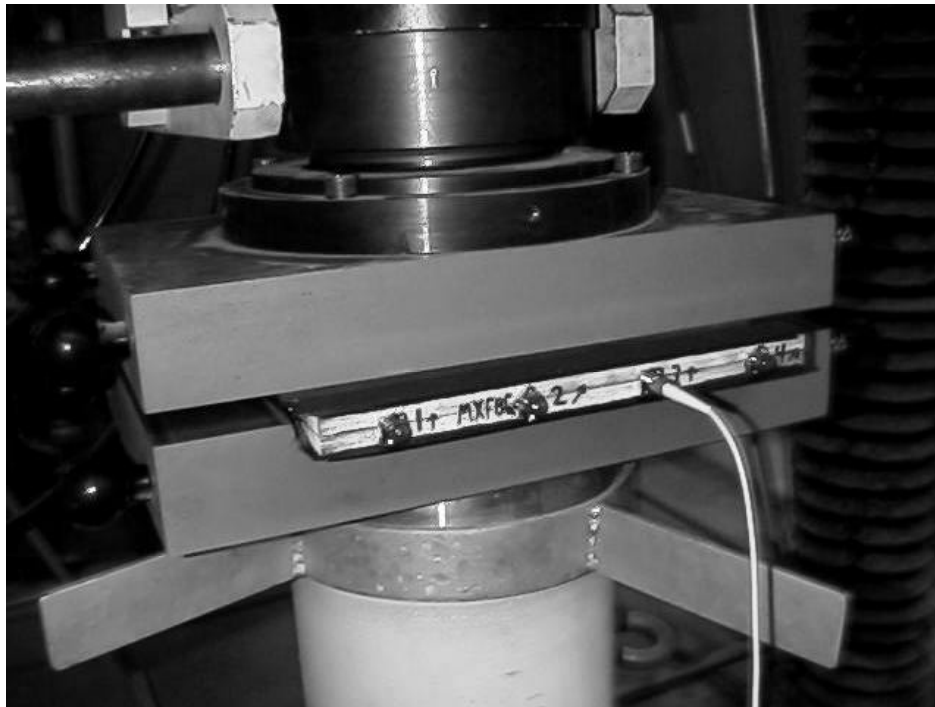


Figure 6. Blue Road Research/Production Products smart bearing under test at the Oregon Department of Transportation.

In addition to measuring transverse strain the multi-axis fiber gratings are capable of measuring shear strain and transverse strain gradients. As an illustration of this Blue Road Research and Boeing have conducted tests of adhesive bonds simulating aircraft joints. When uniform transverse strain is applied along the length of a multi-axis fiber grating sensor the dual peak spectral structure of the fiber grating remains intact as shown in Figure 7. However when the transverse loading is not uniformly applied as would be the case when an adhesive bond starts to break up the spectral peak corresponding to the axis on which non uniform load is applied starts to break up as is shown in Figure 8.

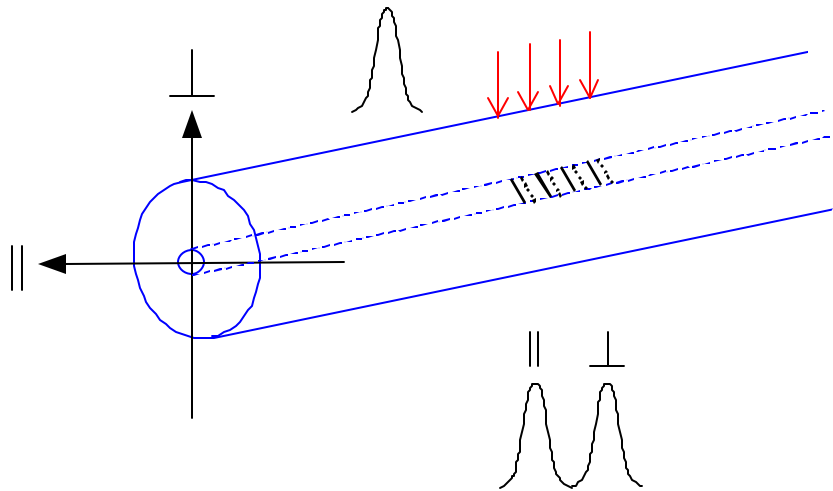


Figure 7. Uniform transverse load across a multi-axis fiber grating strain sensor does not distort the dual spectral peaks.

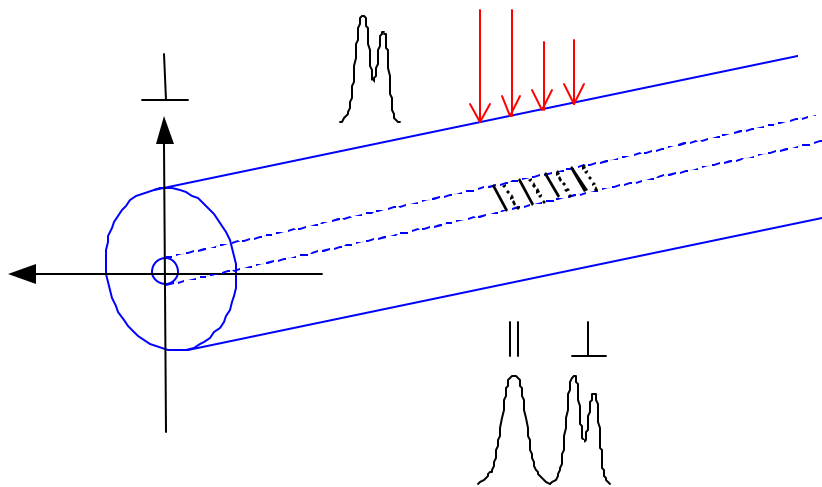


Figure 8. Non-uniform transverse load applied across a multi-axis fiber grating strain sensor results in the multiple peaks forming from the dual peak structure case of Figure 7.

The change in transverse load across the fiber grating can be measure quantitatively by the splitting of the peak. The length of the fiber grating exposed to each load can be determined by the spectral intensity of the peaks.

Figure 9 provides an example of a multi-axis fiber grating strain sensor that has been placed on the edge of an adhesive bond with its transverse sensing axes aligned to detect shear strain. As the bond is strained with increasing load the two principle peaks move apart indicating increasing shear strains. Higher loading results in the longer wavelength peak splitting into two

peaks of approximately equal intensity indicating that transverse strain has been relieved along one of the principle transverse strain axes. A change in wavelength of about 0.1 nm in peak to peak separation corresponds to approximately 300 microstrain of transverse strain. Overall spectral movement corresponds to axial strain or temperature changes. Since in this test the temperature is very nearly constant the movement is axial strain primarily with 0.1 nm changes corresponding to 100 microstrain.

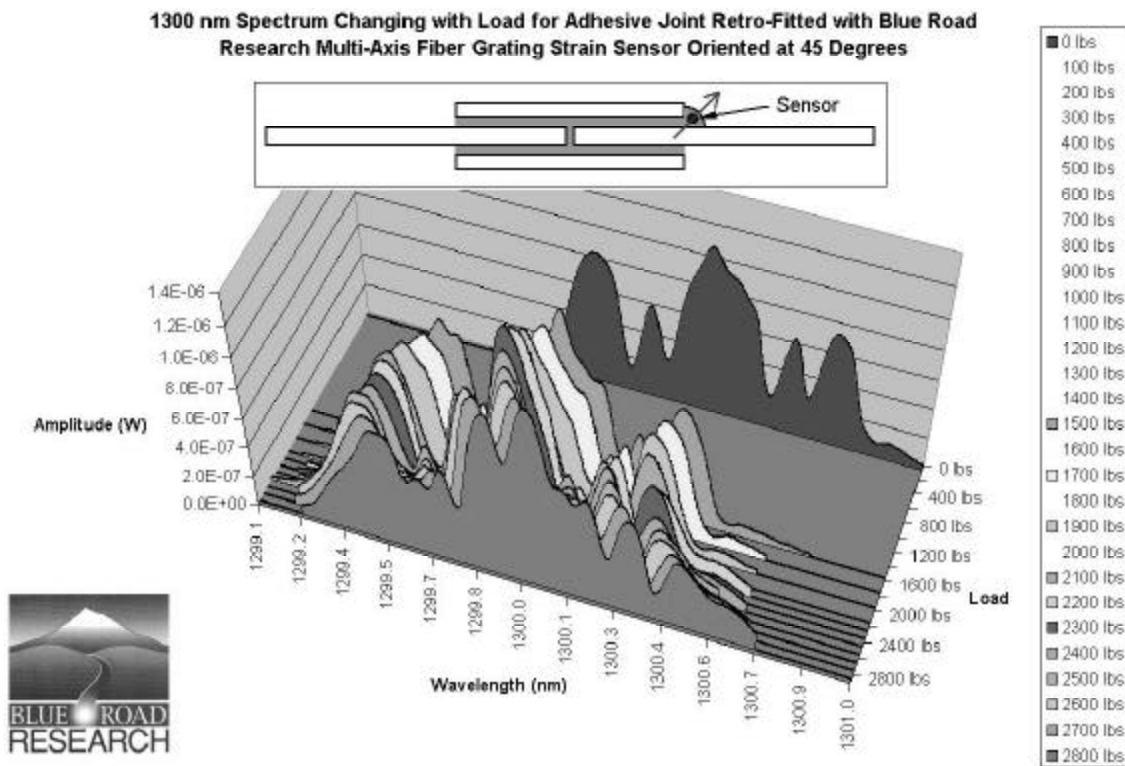


Figure 9. Monitoring an adhesive joint for axial and transverse strain using multi-axis fiber grating sensors. Shear strain and transverse strain gradients may also be detected.

#### 4. MULTI-AXIS FIBER GRATING SENSOR ALIGNMENT

One of the principal issues associated with the multi-axis fiber grating sensor is accurate alignment of the sensor axes within a composite. Blue Road Research has used removable soft epoxy alignment tabs to accomplish this in studies involving adhesive joints. More recently development has been underway in collaboration with Sandia National Labs Livermore on accurate placement of multi-axis fiber gratings directly into short lengths of tow material. Figure 10 illustrates how a fiber can be aligned and inserted in a flat ribbon piece of tow material. The flat ribbon acts as a guide for easy alignment into a composite part. In addition to acting as a guide the procedure allows for better consolidation around the optical fiber as shown in Figure 11. Figure 12 shows the actual alignment and placement of a multi-axis fiber grating sensor into a short length of prepreg material.

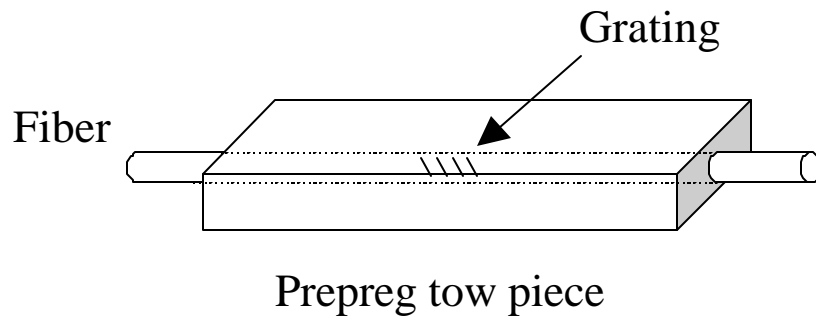


Figure 10. Placement of a multi-axis fiber grating sensor into a piece of prepreg tow material to act as an alignment guide.

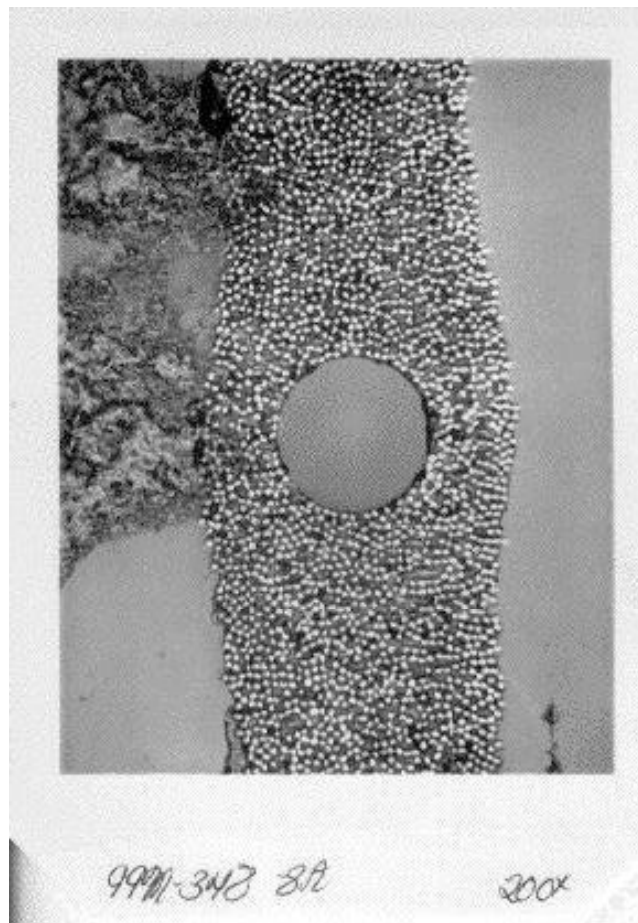


Figure 11. Placement of an optical fiber into a short length of prepreg tow material allowing for good consolidation around the fiber.

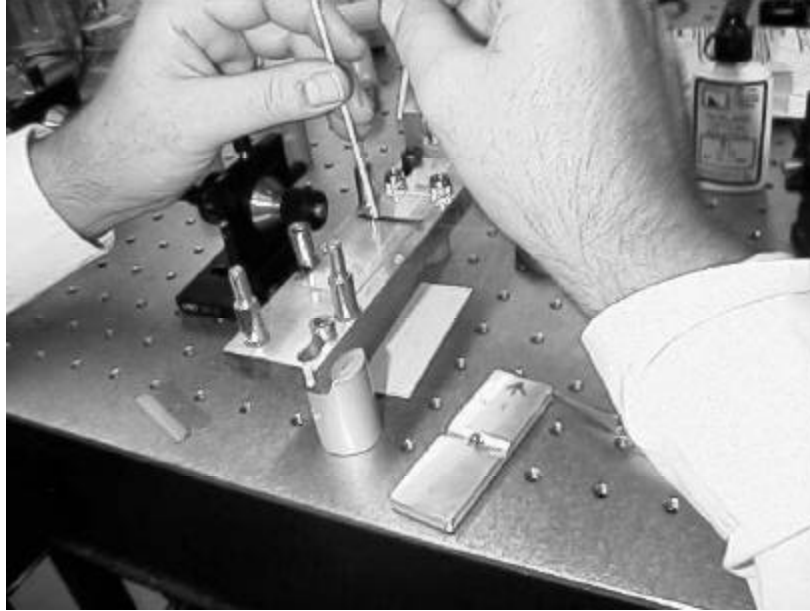


Figure 12. Placement of a multi-axis fiber grating sensor into a short length of prepreg tow material to facilitate alignment into a composite part.

## 5. SUMMARY

Multi-axis fiber grating strain sensors offer the ability to measure transverse strain, shear strain and transverse strain gradients as well as axial strain. These sensors have been used effectively in load cells as well as for monitoring the interior of adhesive bonds. Other applications include monitoring composite parts as they are being formed and to support NDE after completion of the parts. Techniques are being developed to support good consolidation of strength members around the optical fiber and to appropriately orient the optical fiber in composite materials.

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