Health monitoring of an adhesive joint using a multi-axis fiber grating strain sensor system

Whitten L. Schulz[*a], Eric Udd[a], Mike Morrell[a], John Seim[a], Ignacio Perez[b], Angela Trego[c]

[a]Blue Road Research, 2555 NE 205th Avenue, Fairview, OR 97024

[b]Naval Air Warfare Center - Aircraft Division, Bldg. 2188, M/S 3, Patuxent River, MD 20670

[c]Boeing Phantom Works, P.O. Box 3999, MS 82-97, Seattle, WA 98124

ABSTRACT

The use of adhesive joints in aerospace structures is becoming increasingly important. From this, arises the problem of assessing joint integrity quickly, non-intrusively, accurately, and inexpensively. Current methods of assessing joint integrity, such as ultrasonics and x-rays, are time intensive and difficult to interpret. Blue Road Research's solution to monitoring adhesive joint integrity quickly and accurately is to embed non-intrusive, multidimensional optical fiber grating strain sensors into or adjacent to the joints. Aluminum double lap adhesive joints were instrumented with the multi-axis sensors and subjected to tension and fatigue tests. Each specimen contained one sensor located either near the bond, embedded at the edge of the bond, or embedded towards the inner bond area. The joints with sensors embedded into the adhesive showed minimal strength degradation. Basically, the multiaxis fiber grating strain sensors were found to provide information about transverse strain, axial strain, and transverse strain gradients that can provide important information throughout the adhesive joint. By changing the orientation of the sensor, shear strain and its effects can be clearly measured.

Keywords: aluminum joints, transverse strain, shear, embedded, adhesively bonded, fiber optics

1. SHEAR STRAIN MEASUREMENT

The Blue Road Research multi-axis fiber grating strain sensor has the capability to measure both axial and transverse strains when embedded into a structure. The multi-axis sensor is formed from dual overlaid gratings written onto polarization preserving fiber (Figure 1.)

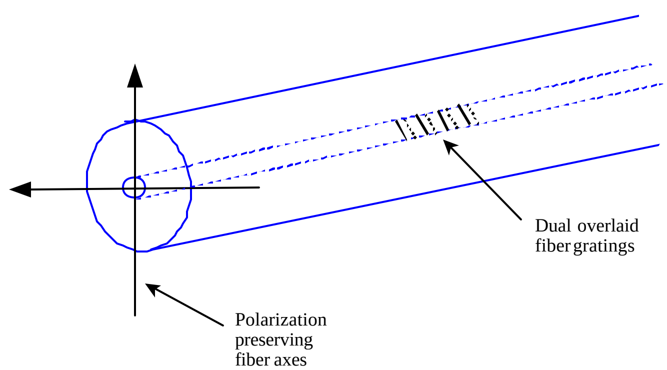

Figure 1. Multiaxis fiber grating strain sensor capable of measuring axial and transverse strains

The shear strain measurement capability comes from the orientation of the transverse strain sensing axes of an embedded multi-axis strain sensor being aligned with the shear direction of the parent material. This relates the shear strain to a measurable transverse strain on the sensor.

Figure 2 shows how the multi-axis fiber grating strain sensor responds to axial and transverse strains. When a broadband light source is directed into the sensor, four spectral peaks are reflected (one peak for each grating and polarization axis.)

[*] Correspondence: Email: Whitten@teleport.com; web: www.BlueRR.com; Telephone: 503 667 7772 x102; Fax: 503 667 7880

Axial strain is measured by calculating the amount of wavelength the peaks shift. Transverse strain is measured by the amount of peak to peak separation.

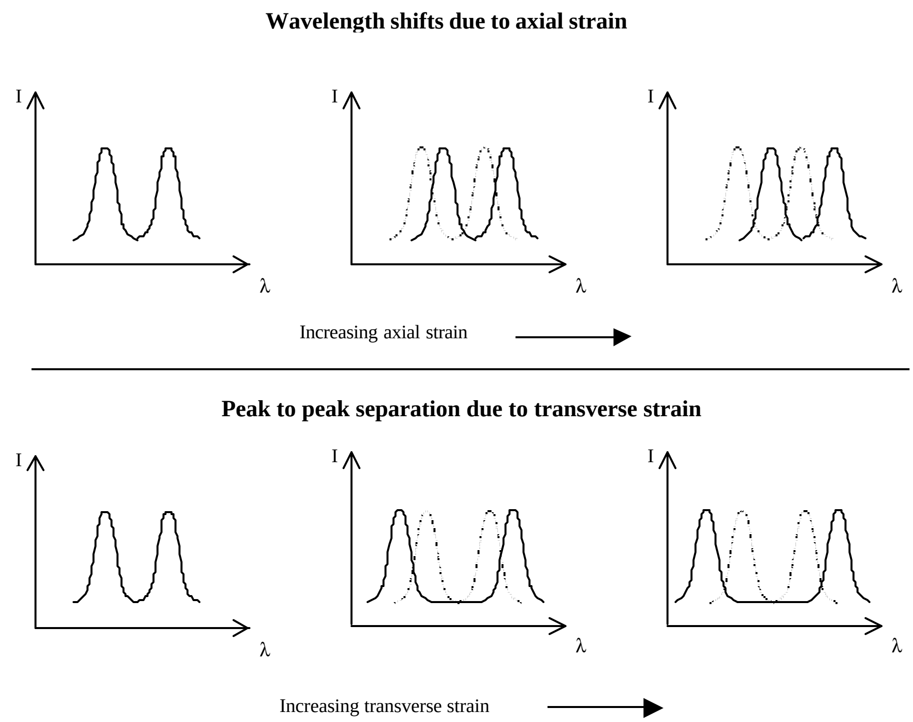

Figure 2. Response of multi-axis fiber grating strain sensor to axial and transverse strains

2. ADHESIVE JOINT INSTRUMENTATION

The test specimen baseline in this work was a double lap adhesive joint (Figure 3.) This symmetric configuration was chosen to simplify joint modeling.

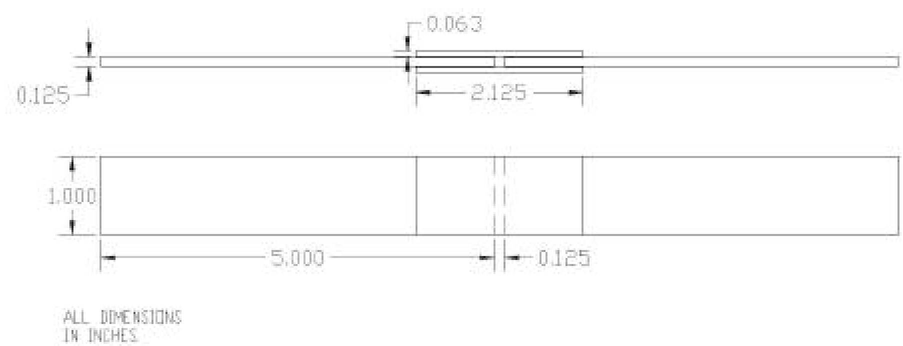

Figure 3. Double lap adhesive joint specimen geometry

The dimensions of the test specimen are from the ASTM standard D 3528 "Standard Test Method for Strength Properties of Double Lap Shear Adhesive Joints by Tension Loading." Fourteen joints were fabricated using Al7075 with 9394 adhesive (curing time: 1 hour at 200^{o}F.)

2.1. Embedding multi-axis fiber grating strain sensors

Three basic locations were used to perform diagnostics on the adhesive joints and are illustrated by Figure 4. Multi-axis fiber grating strain sensors were placed interior to the joint, at the edge of the adhesive joint and just outside the joint to simulate a retrofit.

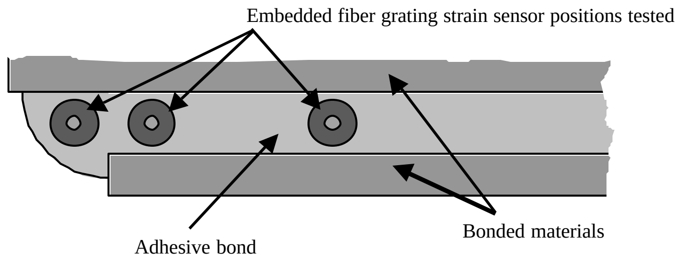

Figure 4. Locations of embedded multiaxis fiber grating strain sensors tested

For the specimens where the fiber sensor was embedded at the edge of the joint and the interior of the joint, a piece of fiber the same diameter as the sensor was used to control the bond height (Figure 5.)

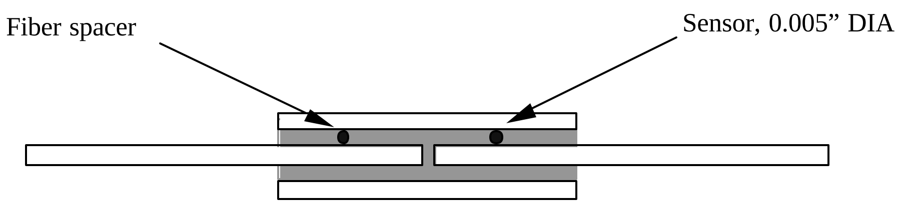

Figure 5. Fiber with the same diameter as the strain sensor was used to provide an even bond height

2.2. Orientation of embedded multi-axis fiber grating strain sensors

To determine the effects of different orientations, the multi-axis strain sensors were oriented in three different directions in relation to the loading direction. These orientations were at 45, 90 and 135° from the loading direction (Figure 6.) The main mechanical action in an adhesive joint is shear, and the 45° orientation was expected to give the greatest sensitivity for shear measurements.

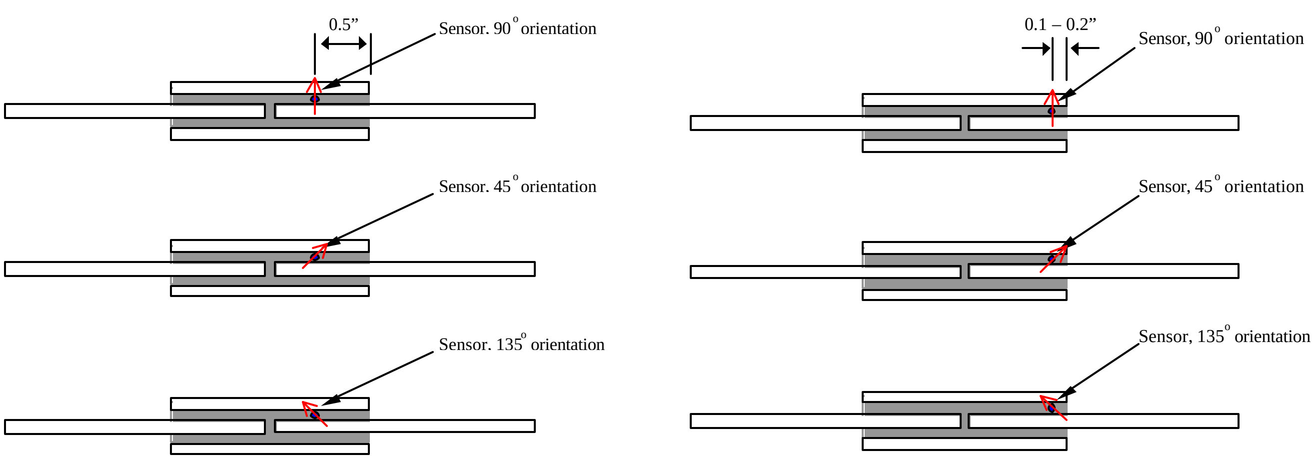

Figure 6. Multi-axis strain sensors embedded into inner (left) and edge (right) locations of adhesive bond with different orientations

The 135° orientation also provides highest sensitivity to shear, but will have the opposite spectral response from the sensor as the 45° case (i.e., if the spectral peaks separate with increasing shear at a 45° sensor orientation, the 135° orientation should result in the peaks coming together.)

In order to control the sensor orientation during embedding, tabs were placed on the fiber to create an asymmetric shape (Figure 7.) This ensures that the two mutually orthogonal transverse strain sensing axes are aligned in the direction of desired sensitivity.

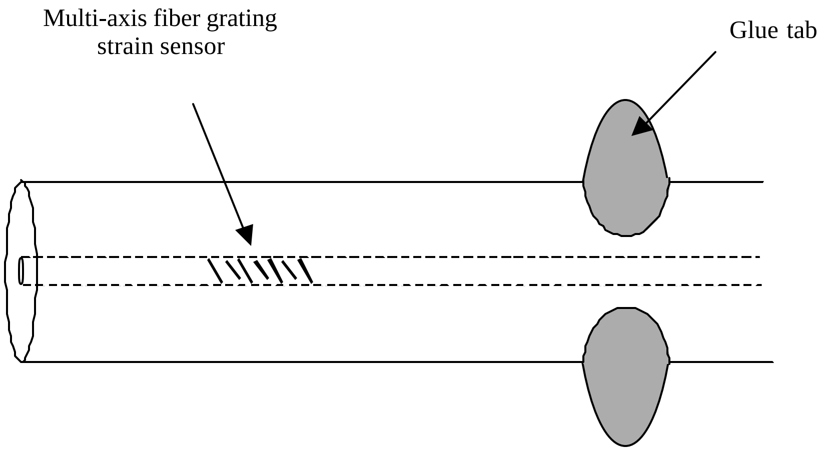

Figure 7. Glue tabs on fiber to control orientation of transverse strain sensing axes

2.3. Inner embedded

This configuration consisted of the multi-axis sensor being embedded approximately 0.5 inches from the edge of the bond (see Figure 6 above.) The mechanics in this area of the joint should be mainly shear effects, so this location was chosen for easy correlation to any future modeling of the joint.

2.4. Edge embedded

This configuration consisted of the multi-axis sensor being embedded approximately 0.1 – 0.2 inches from the edge of the bond (see Figure 6 above.) This is a more complicated loading area due to combined loading and also where the bonds typically start to fail first. This location was chosen for its potential to provide early diagnostics on joint degradation.

2.5. Retrofit

The retrofit configuration shown in Figure 8 is the case where a multi-axis strain sensor was attached to an existing joint with adhesive. This provides the capability to add sensors to existing joints, not just during the fabrication of new ones.

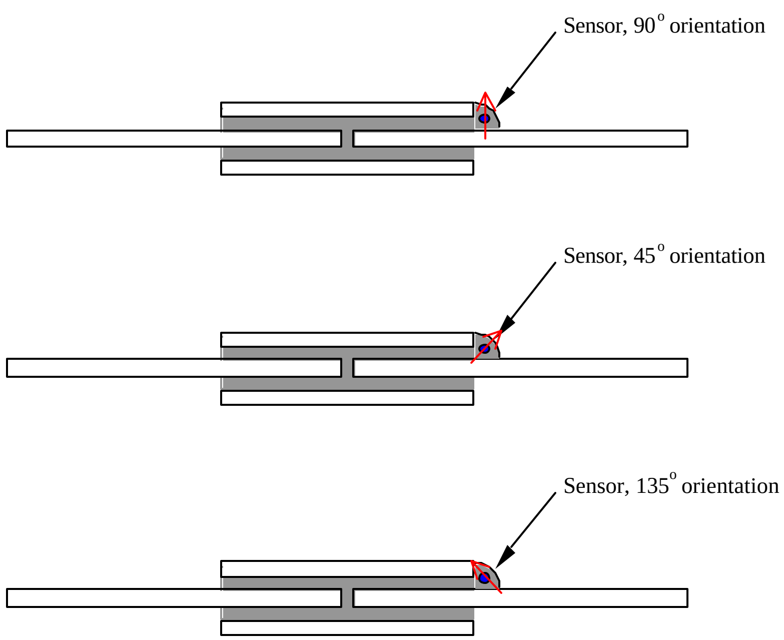

Figure 8. Retrofit of multiaxis sensor to existing adhesive joint

3. TESTING

3.1. Demodulation

An optical spectrum analyzer was used to obtain the spectra from the embedded multi-axis strain sensor (Figure 9.) Two broadband ELED light sources were used to obtain four reflected spectral peaks from the sensor, although only two peaks are required for transverse strain and hence shear measurement.

3.2. Tensile

The joints were loaded at 1,000 lbs/min in a tensile tester with the following load steps:

Step #	Load (lbs)	Step #	Load (lbs)
1	0	9	2500
2	1500	10	2600
3	1700	11	2700
4	1900	12	2800
5	2100	13	2900
6	2200	14	3000
7	2300	15	3100
8	2400		

Table 1. Tensile Loading Levels

Figure 9 shows the test setup and demodulation system used. At each load level, the spectrum analyzer was used to obtain the spectra from the multi-axis sensor.

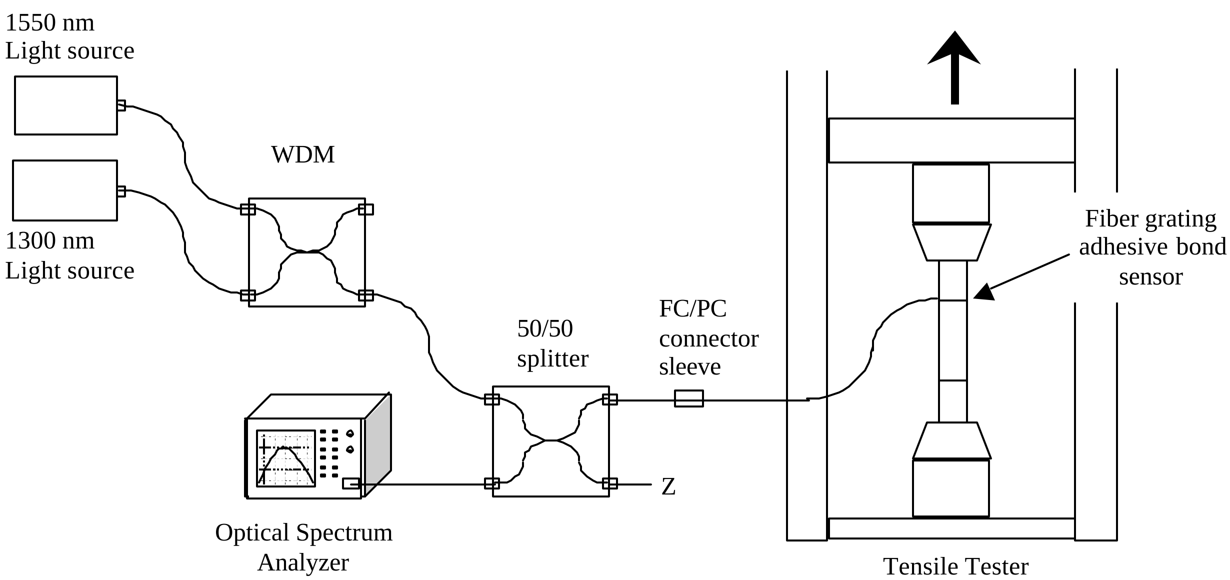

Figure 9. Loading and demodulation setup during tensile testing of instrumented adhesive joints

3.3. Fatigue

In addition to the ten shear tested joints, one joint with a retrofit multi-axis fiber grating strain sensor was fatigue tested in tension. The first part of the test consisted of loading the double lap adhesive joint to approximately 50% of its ultimate strength at 4Hz. The spectrum analyzer was used to acquire the spectrum during pauses every 2,500 cycles while the joint was held at a mean load of 674 lbf. Because no noticeable change had occurred after 10,000 cycles, the second part of the test was to load the joint to 80% of its ultimate strength and again capture the spectrum during pauses at a mean load of 1,078 lbf. The pauses required to take the data were approximately 30 seconds.

4. RESULTS

4.1. Joint strength

One of the first concerns to be addressed was possible degradation of the strength of the adhesive joint due to the presence of the fiber grating within or near to it. Figure 10 shows in graphical form the results of testing adhesive joints to failure in shear with and without fiber sensors. The first two adhesive joints had no fiber in the joint and three of the adhesive joints were retrofitted with fiber sensors in an adhesive bead outside the joint area. The average load for failure for these five adhesive joints was 2802 pounds and is the Baseline Strength used in the graph of Figure 10. Of the seven joints tested where the fiber grating was placed inside the joint, all but two are within plus or minus 15 percent of the Baseline Strength. One of the adhesive joints survived the load test beyond 114.2% of the Baseline Strength and the other failed at 74.9%. These results strongly indicate that the effect of embedding the multiaxis fiber grating sensors into the adhesive joint are minimal.

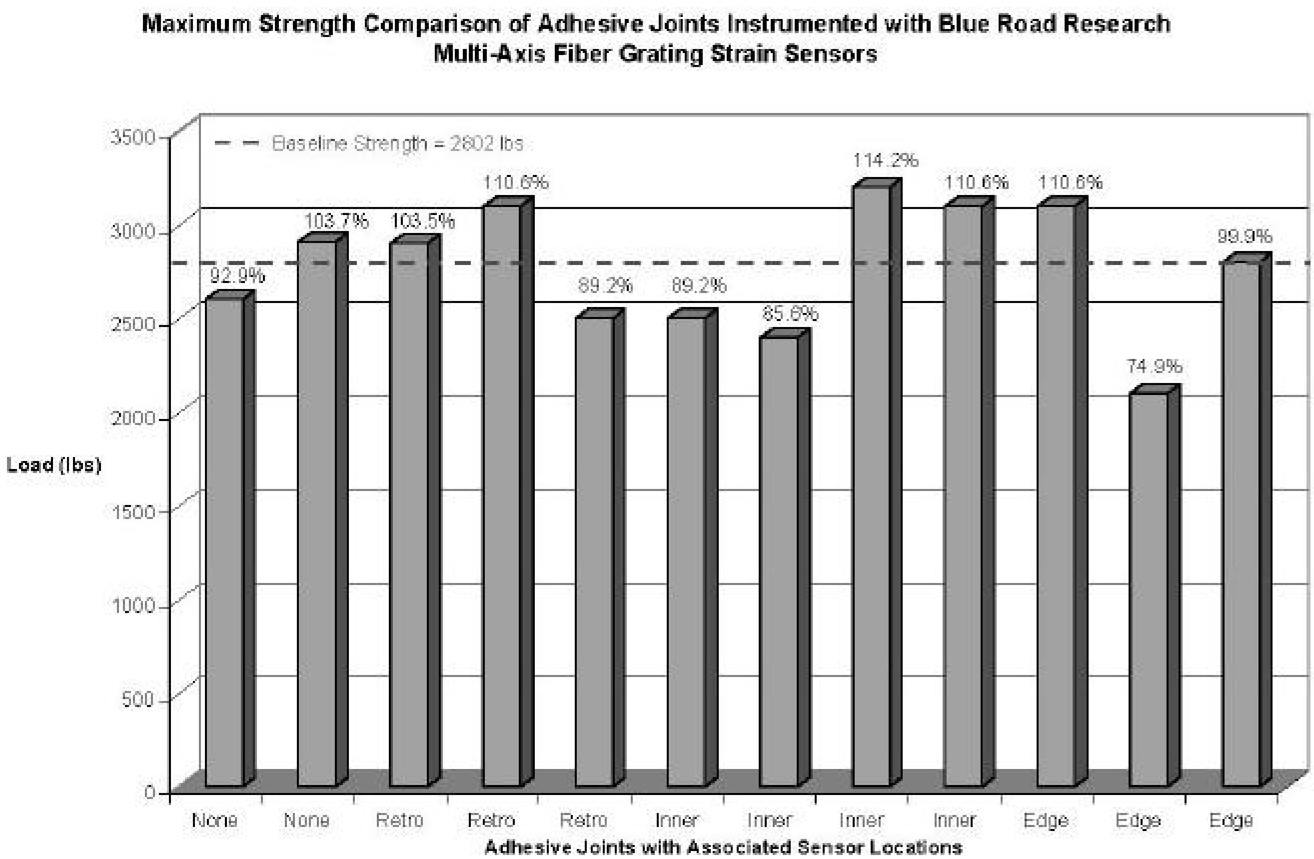

Figure 10. Strength comparison of instrumented joints with embedded fiber grating sensors to joints without embedded sensors.

4.2. Sensor Robustness

In four of the test cases, the fiber grating sensor survived the joint failure. In all of the remaining cases, the sensor survived until joint failure. This is very encouraging towards showing that a fiber grating sensor embedded into an adhesive will survive even with large strain fluctuations which will allow potential failure detection before actual joint failure.

4.3. Retrofit of multiaxis grating sensor

Of the three locations tested, locating the multiaxis fiber grating sensors outside of the joint area is perhaps the most interesting for field use as it allows adhesive joints to be monitored using easily applied retrofits. Figure 11 shows the results of testing an adhesive joint to failure with a multiaxis fiber grating strain sensor placed in an adhesive joint retrofit. The transverse sensing axes are aligned at 45° with respect to the plane of the joint. This procedure allows the measurement of shear strain as load is applied to the joint.

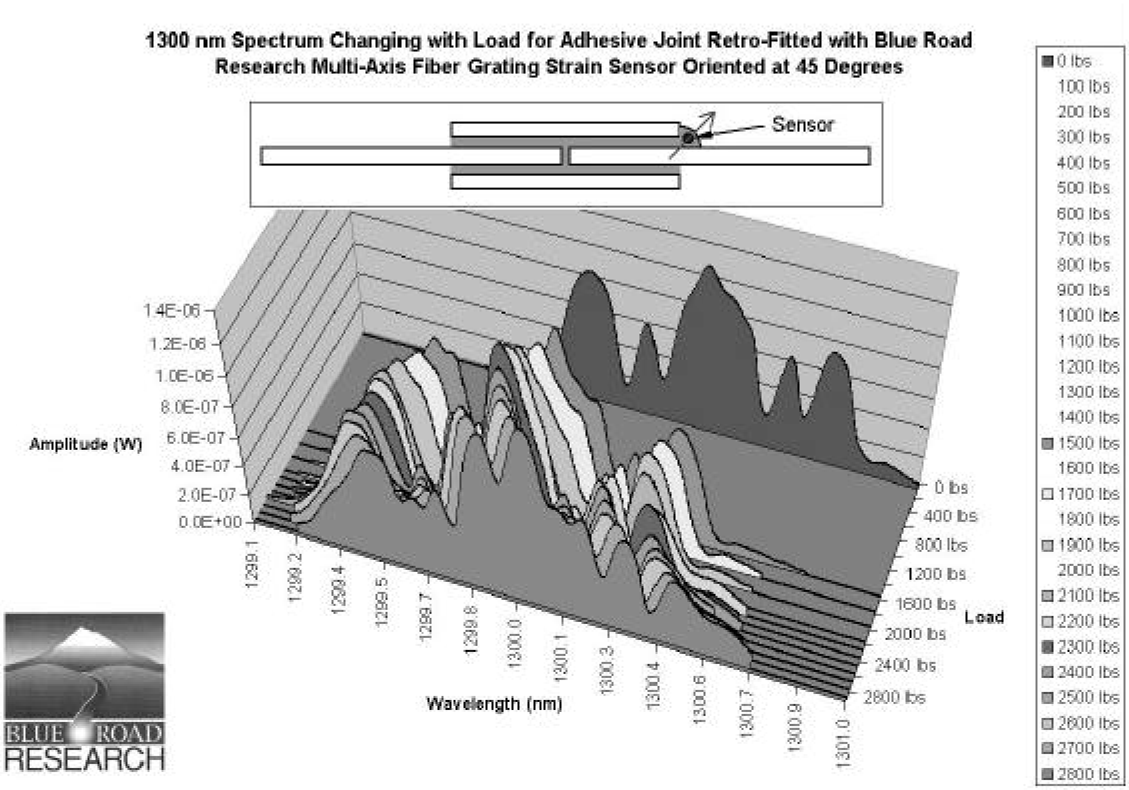

Figure 11

Also, when the adhesive starts to degrade and transverse forces are unloaded, this results in changes in transverse strain gradients that can be measured. Figure 12 illustrates how shifts in transverse load along one of the axes affect the output spectrum. When transverse loading is uniform, a clean single peak structure occurs along each axis. Partial adhesive bond failure shifts transverse loads on one or more of the axes of the multiaxis fiber sensor as shown in Figure 13, resulting in a single peak moving to a multiple peak structure. Returning to Figure 11, the first chart at zero load corresponds to the spectral output of the multiaxis fiber grating strain sensor in the 1300 nm wavelength region. The two largest peaks correspond to the two transverse strain sensing axes. The smaller peaks indicate there are transverse strain gradients and the multiaxis fiber grating strain sensor is not uniformly loaded. Since the intensity of these peaks are much smaller, it indicates that these transverse gradients are very local possibly due to bubbles or impurities in the adhesive. When the adhesive joint is loaded, the two principle peaks are separated initially by a fixed spectral distance. At approximately 2400 lbs of loading, the peak to peak spectral separation of the spectral peaks increases indicating that transverse strain is increasing in the retrofitted multiaxis fiber grating sensor along its principal transverse strain sensing axis. As load is increased, transverse strain increases and is measured by increasing peak to peak separation. At about 2700 lbs of loading one of the principle peaks separates into two. This separation indicates a sudden shift in transverse loading over a portion of the grating and a degradation of the adhesive bond. The overall transverse strain continues to increase after this event until failure of the part.

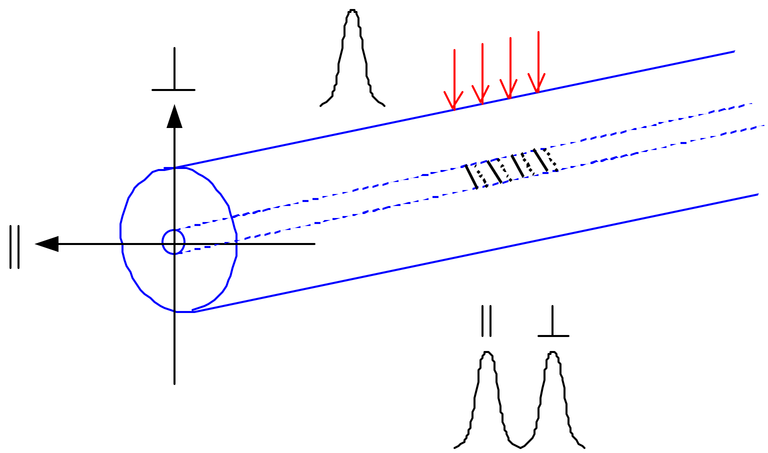

Figure 12. Primary transverse axes of multiaxis fiber grating strain sensor with one peak for each axis. The peak associated with the perpendicular axis is unaltered in shape due to uniform transverse load.

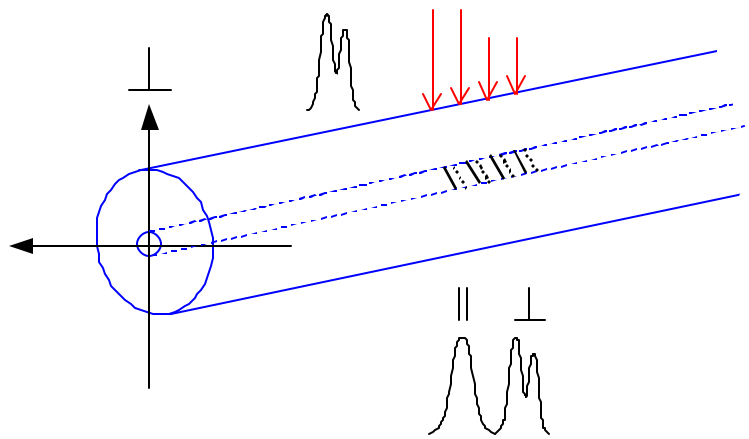

Figure 13. Primary transverse axes of multiaxis fiber grating strain sensor with one peak for each axis. The peak associated with the perpendicular axis has split into two peaks due to a transverse gradient.

Figure 14 illustrates a second adhesive joint that was tested using a multiaxis fiber grating strain sensor with its principle transverse strain sensing axis aligned orthogonal to the plane of the joint. In this case when the adhesive joint is loaded the principle direction of strain is along the area of the sensor with no transverse sensitivity and there should be no peak to peak separation change between the principal peaks at 1300 nm. This is clearly the case in Figure 14 as through the entire test there is no significant change in the spectral profile. For this particular run the multiaxis fiber grating strain sensor survived the failure of the adhesive joint and the profile after failure closely matches that of the no load condition.

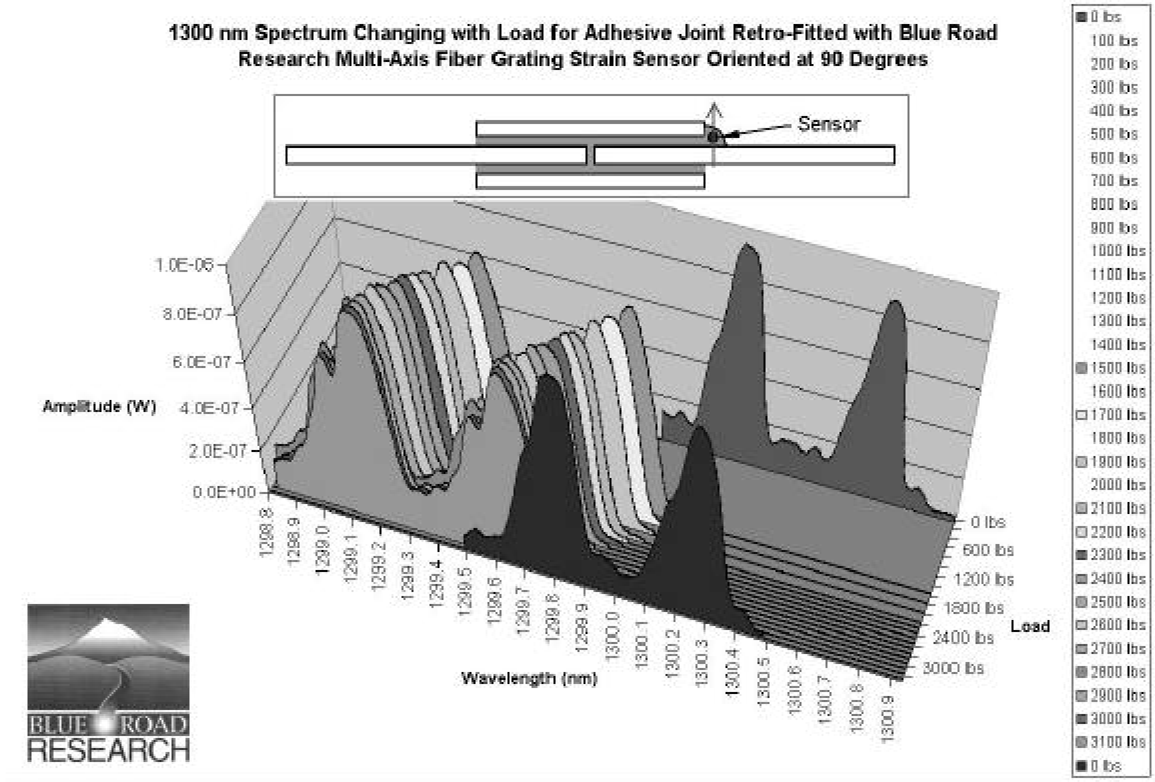

Figure 14

Basically the multiaxis fiber grating strain sensors were found to provide information about transverse strain, axial strain and transverse strain gradients that can provide important information throughout the adhesive joint. By changing the orientation of the sensor, shear strain and its effects can be clearly measured.

4.4. Edge embedded

The highlighted data in this section is from a specimen which was loaded to 3200 lbf, and then unloaded to zero lbf without failure. Figure 15 shows the load and deformation of the joint.

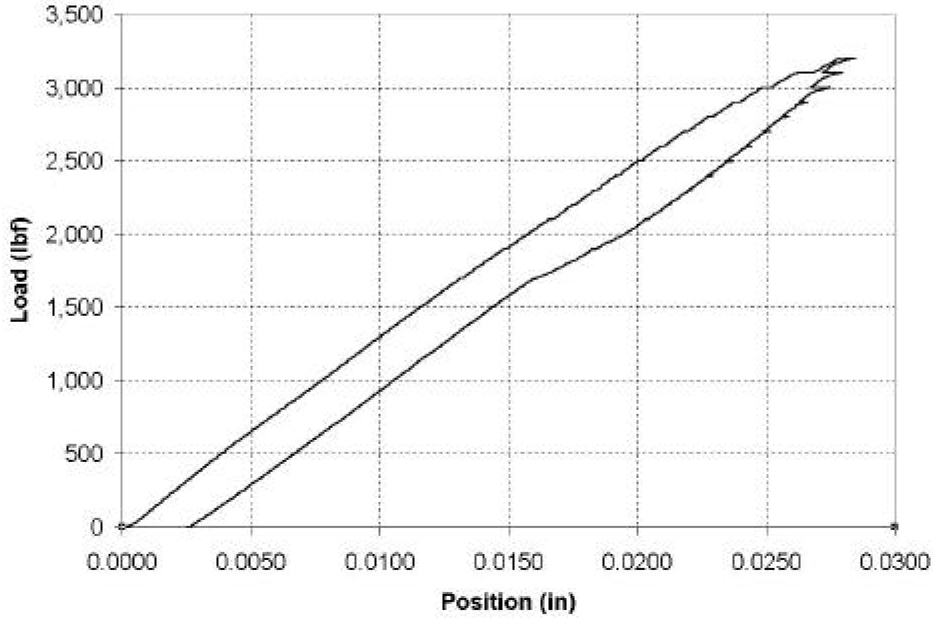

Figure 15. Load versus position for specimen #14

Figure 16 shows the spectrums obtained through loading and unloading of the joint. From Figure 15, it can be seen that the joint was plastically deformed during the loading and unloading process. This can also be seen in Figure 16, by comparing the beginning and end spectrums and noting the changes.

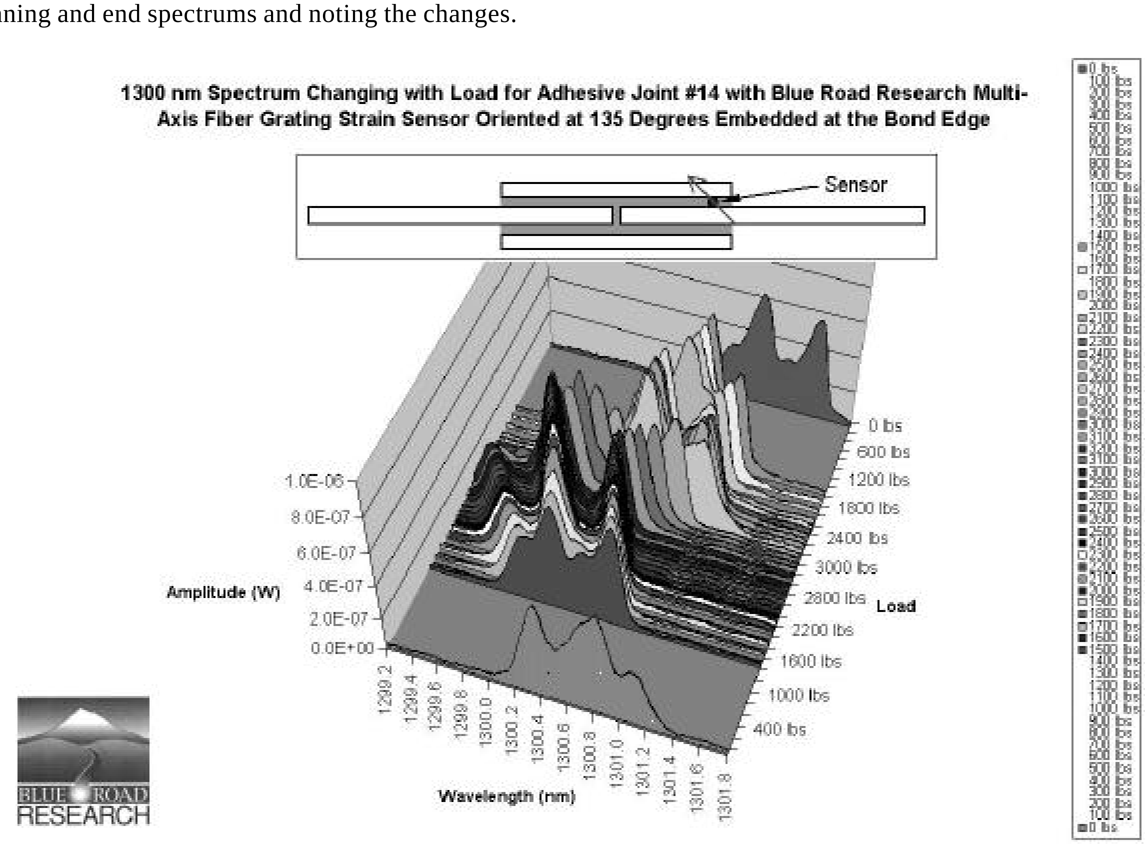

Figure 16

Also, because the strain sensor was oriented at 135° from the loading direction, the peak separation can be noted as decreasing as the load is increased up to 3200 lbf and increase as the joint is unloaded. If the sensor was embedded at 45° from the loading direction, the peak separation would increase with load, as evident from the 45° orientation data for Figure 11.

4.5. Inner embedded

Figure 17 shows data obtained from a specimen with a sensor embedded in the inner bond area. As compared to Figure 11, this data set has fewer sidelobes which indicates fewer transverse strain gradients. This is a result of the adhesive bonding more evenly to the sensor and evenly transferring strain to the sensor. Another reason for fewer transverse strain gradients may be from the location of the sensor in the bond. In this inner bond area, the primary mechanism is shear, which is less complex than the strain field expected at the edge of the bond or in a retrofit case.

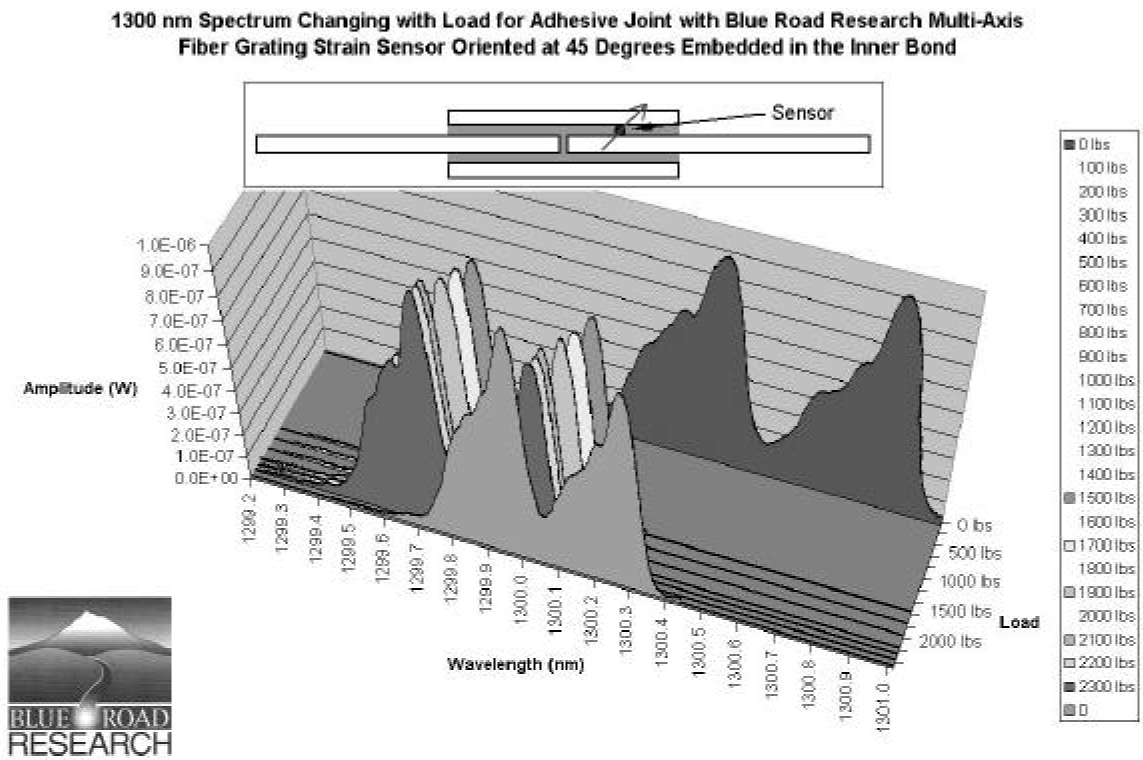

Figure 17

4.6. Fatigue

The fatigue test was inconclusive as the joint failed at a bondline opposite to where the sensor was embedded. Future fatigue tests could be based on a single lap joint, guaranteeing that the embedded sensor is located in the critical bond area.

5. APPLICATIONS

The main application for embedding these multi-axis strain sensors into adhesive joints is in-service health monitoring of aerospace structures where the need for lighter and more advanced configurations is increasing the use of non fixed fastener joints. Visual inspection of bonded joints cannot be performed in-service and can be time consuming, expensive, inconclusive, and in some cases not possible. It is believed that embedding these non-intrusive fiber grating shear sensors can provide critical information to the current health of an adhesive joint and be connected to other fiber grating sensors throughout the structure to form a complete structural health monitoring system.

Another application of this technology is monitoring the joint during manufacturing. Information on cure time (the strain state will change as the adhesive sets), and residual stresses can be very useful in optimizing manufacturing processes and identifying out of spec parts.

6. CONCLUSIONS

1. Embedded multi-axis fiber grating strain sensors into an adhesively bonded joint can measure shear strain when the transverse sensing axes are aligned with the shear direction.
2. The introduction of the sensors into the adhesive bond area does no significantly reduce joint strength.
3. The multiaxis sensors can be retrofit to existing adhesive joints and provide strain information.
4. The strain information from the embedded sensors can be used to identify the state of the part and predict joint failure.
5. The sensors proved to be robust with four surviving joint failure and the rest surviving until joint failure.

7. FUTURE WORK

Future work to this effort could include:

1. More shear and fatigue testing to achieve statistically valid data.
2. Monitoring the curing process of the adhesive.
3. Introducing intentional disbond points to further test the sensor's health monitoring capabilities.
4. Develop faster demodulation systems to further show the potential of in-service health monitoring.

8. ACKNOWLEDGEMENTS

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