Fiber optic smart bearing load structure

Eric Udd*[a], Whitten L. Schulz[a], John Seim[a], Kelli Corona-Bittick[b], Jim Dorr[c], Kerry Slattery[c], H. Martin Laylor[d], Galen McGill[d]

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

[b]Production Products, 1285 Dunn Road, St. Louis, MO 63138

[c]Duke Engineering Group, Inc., 1285 Dunn Road, St. Louis, MO 63138

[d]Oregon Department of Transportation, Research Unit, 2950 State Street, Salem, OR 97310

ABSTRACT

As proliferation of structures incorporating composite materials occurs, the benefits of in-situ monitoring of the building materials in order to increase reliability and improve maintainability of the overall structure are being recognized. For example, measurement of shear-strain and load within bridge bearings can be directly related to the health and longevity of the structure. In this paper, the embedding of single and multi-axis optical fiber strain sensors within liquid molded load cells for structures such as bridges is reported. Fabrication and testing processes are presented, as well as test results.

Keywords: bridge bearing, shear, transverse strain, composite, elastomeric, embedded

1. INTRODUCTION

1.1. Motivation

Structures such as bridges typically have bearings that provide an interface between load-bearing elements. The bearings allow flexing between load-bearing elements (such as pylons and bridge deck,) and thus are subject to considerable shear and strain. Generally, monitoring of the integrity of these bearings is performed visually (in the case of most highway bridges). As more and more of these bearings are incorporating composite materials in their fabrication, the ability to embed sensors internal to the bearing offer several advantages. Some of these advantages are increased safety, reduced maintenance costs, potentially extending the lifetime of the load-bearing elements, and hence extending the lifetime of the structure.

1.2. Project Objectives

The ability to implement fiber optic "smart structures" such as the embedded composite bearing is evolving rapidly. This is largely due to steady advancements in optical fiber technologies, driven primarily by telecommunications industries. As these technologies rapidly progress, it is increasingly more feasible to cost-effectively embed fiber sensors into structures. At this point, however, much of the requisite work is ground-breaking in nature, and many objectives are of basic engineering nature. That is, while some research and development has been done in laboratories, field-testing is in its earliest stages. As a result, much work needs to be done to transfer research efforts to field-level trials. The primary objectives of this work support the goal of advancing research work towards the field-level application. Specific objectives were (1) select an application that is feasible to implement, (2) design and fabricate a "smart bearing", (3) perform selected tests on the bearing, (4) evaluate the results with a critical eye towards deployment issues such as accessibility and maintainability, as well as overall system performance.

1.3. Project Plan

Successful accomplishment of this work required a team with members having unique expertise from several disciplines. Blue Road Research provided fiber optic sensor technology. Production Products provided composite-structure manufacturing, and Washington University provided test and analysis. The Oregon Dept of Transportation provided design criteria as well as testing and analysis resources. All partners in this project contributed to identifying pertinent objectives, resulting in definition of tasks to be performed. The plan consisted of the following elements:

---

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

1. Select a specific load cell requirement for a known application.
2. Select measurement parameters from which the most information could be obtained.
3. Select appropriate sensors and embedding configuration to optimize acquisition of key information.
4. Select rugged fiber egress solution, eliminating the possibility of losing sensor access.
5. Fabricate the load cell.
6. Test the load cell.

2. FABRICATION OF THE LOAD CELL EMBEDDED WITH FIBER OPTIC STRAIN SENSORS

2.1. Smart Bearing Sub-Systems

There are several sub-systems that comprise a "smart bearing". As seen in Figure 1, the bearing is composed of alternating layers of neoprene, steel, and the composite "load cell". Next, the optical fiber strain sensors embedded into the load cell during fabrication, are complete sub-systems. Being internal to the load cell enables the strain sensors to provide more accurate shear and load data than if the sensors were surface-mounted. (The presence of the sensors within the load cell has been determined to have negligible effect on the function of the bearing.)

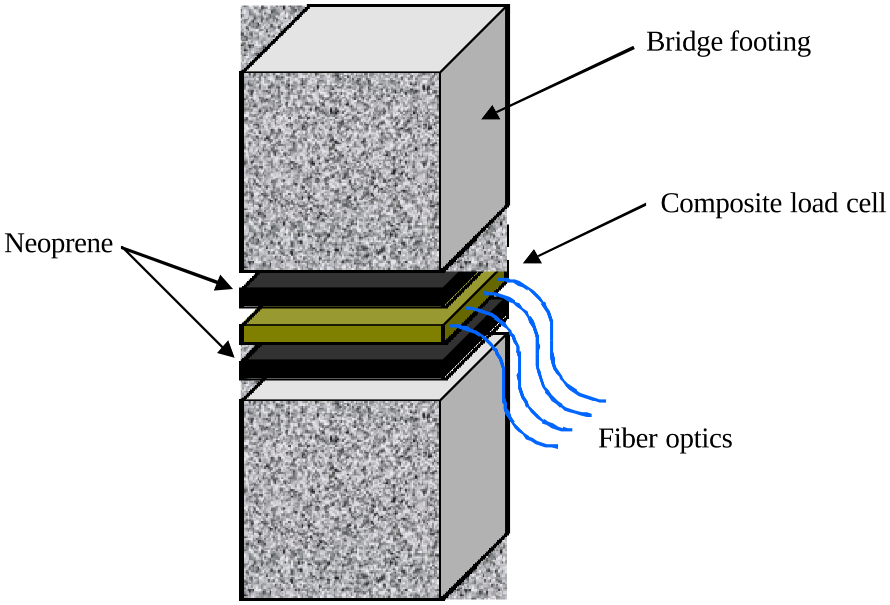


Figure 1. Elastomeric bridge bearing with load cell

2.1.1. Composite Panels

A panel size of 12" x 12" was determined to be an acceptable size representative for most bridge load / bearing pad applications. These elastomeric pads are currently made of laminated steel and neoprene rubber plates. There are approximately 50,000 such pads sold per year for new bridge construction. There also is a considerable retrofit market since bridges often have to be reset every 2 to 3 years. Changes in normal and shear loads over time will give a clear indication of degradation in the bridge substructure - a region difficult to inspect. Typical bearing pressures are 1500 psi maximum. The load cell was sized to meet these requirements. The load cell was fabricated with a total of 4 embedded multi-axis fiber optic strain sensors (Figure 2.) Sensors 1 and 3 are oriented at 90° from the plane of the load cell, and sensors 2 and 4 are oriented at 45° from the plane of the load cell.

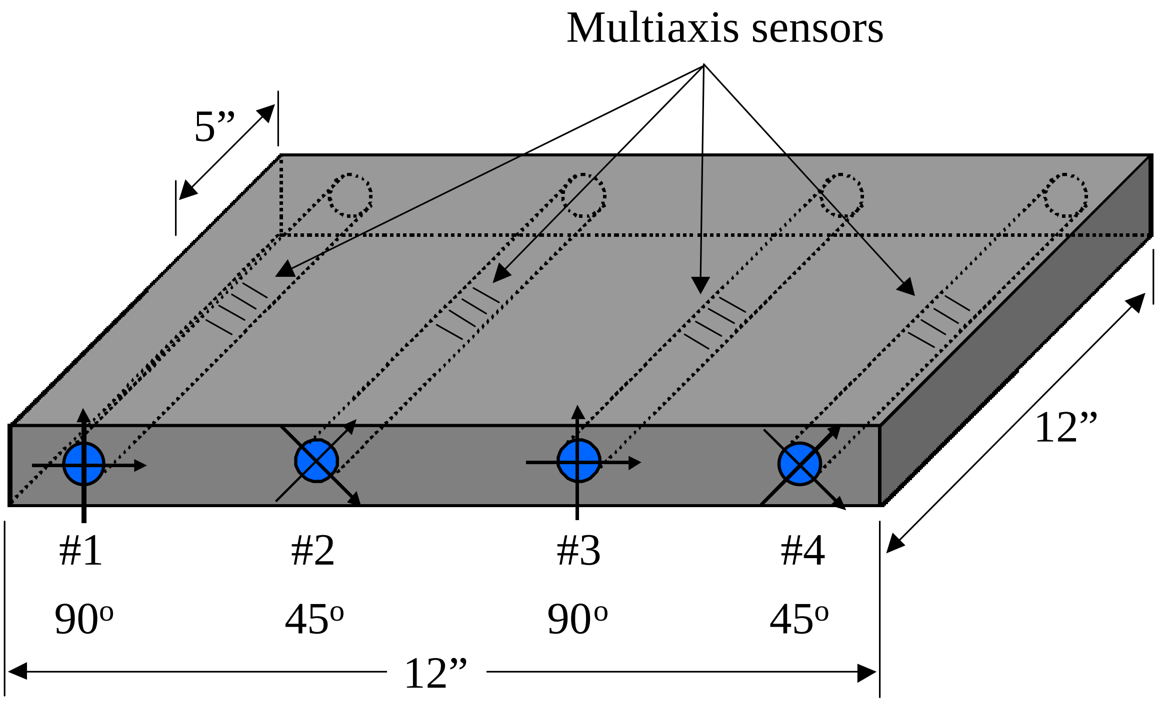


Figure 2. Composite load cell with four embedded multiaxis fiber grating strain sensors

In this configuration, the maximum shear-sensitivity is obtained from sensors with axes tilted at 45 degrees from vertical, and the maximum transverse-strain sensitivity is obtained with sensor axes orthogonal to the plane of the load cell. Also, it was decided that optimum information would result from placement of two sensors at the edges and two in the middle of the cell.

2.1.2. Fiber Optic Strain Sensors

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 3.)

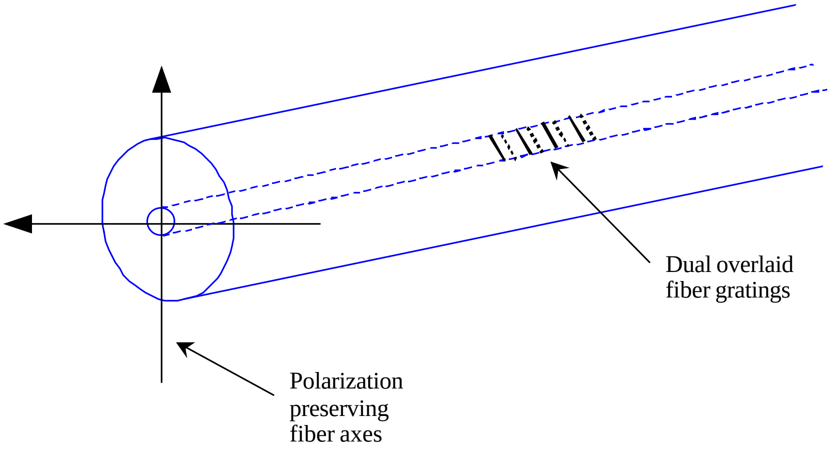
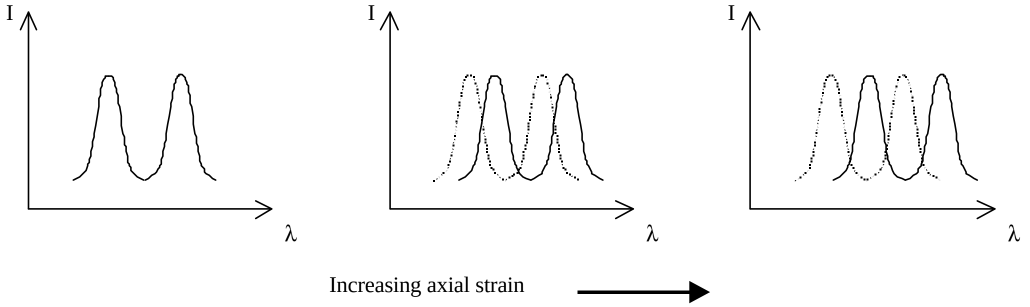


Figure 3. Multiaxis fiber grating strain sensor capable of measuring axial and transverse strains

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 4 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.) 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.

Wavelength shifts due to axial strain



Peak to peak separation due to transverse strain

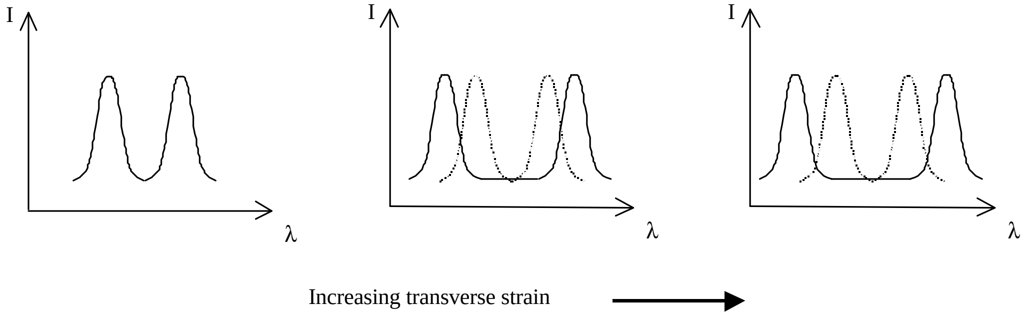


Figure 4. Response of multi-axis fiber grating strain sensor to axial and transverse strains

2.2. Fabrication

In this section, a brief summary of the fabrication process is provided. A key innovation for accessing the sensors is described that increases the reliability of the system considerably, over previous methodologies.

2.2.1. Composite Panels

The load cell was fabricated from a unidirectional carbon fiber prepreg. The material was chosen to allow for precise fiber sensor placement, and due to inherent environmental stability advantages. The resin system selected enabled a curing temperature of 200°F, and minimized shifting of the optical fiber sensors during processing. The fiber optic sensors were sandwiched in the middle of the load cell; that is, with 10 layers of prepreg above and 10 below the layer containing the sensors. Placing the sensors in the middle (thickness-wise) of the load cell eliminates bending effects that are undesirable, since the objective is to measure normal pressure strains and shear strains. The total thickness of each of these panels upon completion was about 1/4".

2.2.2. Embedding of Sensors into Panels

As discussed in the previous section, the fiber optic sensors were embedded into the middle of the load cell. In previous projects of this nature, the optical fibers entering and exiting the composite panels had strain relief provided through various

-type m -relief approaches, extreme care in handling was
-leads entering and exiting the cell. Additionally, such approaches do not
-use as th

incorporating embedded connectors was generated. In this design, upper and lower fiberglass support blocks were fabricated
-connector fittings were permanently installed. This approach has excellent advantages, primarily protection of the
ystem. Since the information
being relayed from the sensors is spectral rather than intensity or phase based, properly cleaned and functioning connectors'
Figure 5 leted panel with embedded sensors and fittings.

Figure 5

3. TESTING

re designed
with the application of bridges in mind, a battery of tests representative of those experienced in the bridge environment were
ad cells,
and are described in the following sections.

3.1.

ODOT testing was performed with a hydraulic press rated to 600,000 lbs as seen 6. Data was obtained in the
owing manner. The first "0" reading was taken with the load cell lying unloaded on a table. Then, the cell was placed in the press, and a measurement was taken with a "zero reading" on the press gauge. Increments of nominally 20,000 lbs were loaded ont
-valued quantities. Next, the load was backed down in 20K lb increments at odd valued quantities. Upon reading zero-
-lbs.

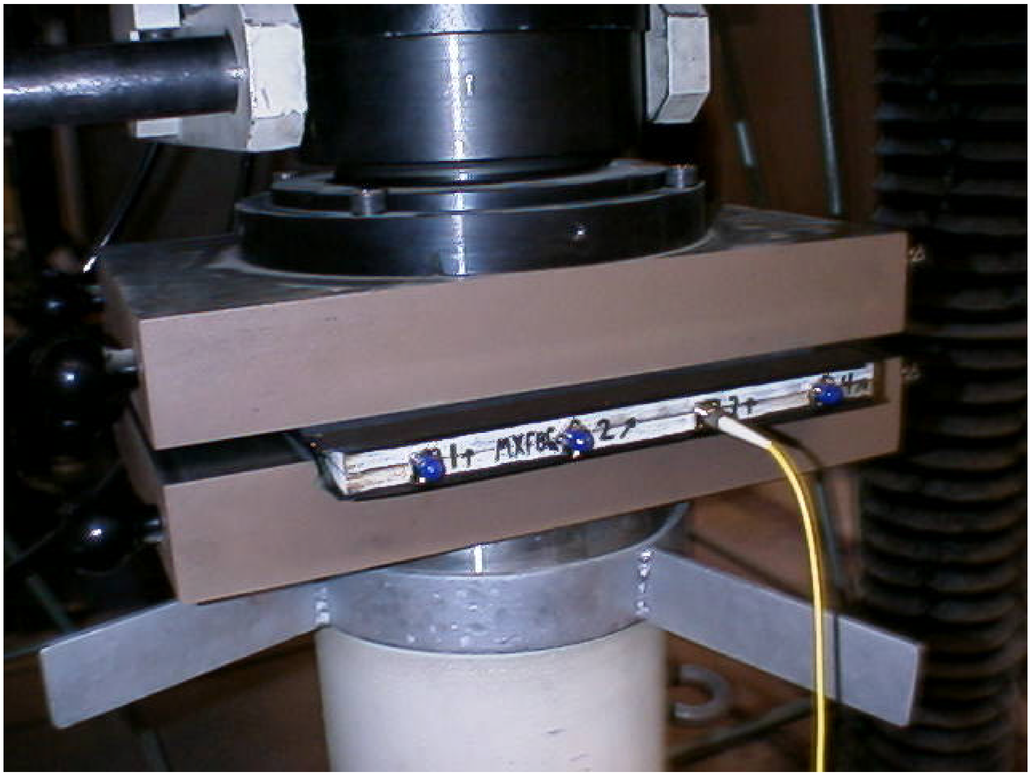


Figure 6. Load testing of composite load cell with embedded multiaxis fiber grating strain sensors

In Figure 7 - Figure 10, two types of spectral information are shown: wavelength-shift and peak-separation. The wavelength plots display how each of the reflected peaks reacted as loading was applied. The peak-separation graphs correspond to the difference between related pairs of peaks and how they respond to the loading. At this point the significance of this data has not been fully investigated, and the results presented here will focus only on wavelength-shift and peak-separation.

Figure 7 shows the wavelength data for a sensor embedded at 45° to the loading direction of the panel. Two traces are shown on the graph, one for each peak associated with the 1550 nm portion of the multiaxis sensor. As the load is increased, both peaks move to higher wavelengths. These peak shifts show the capability of the multiaxis sensor to measure axial strain due to the Poisson effect of the load cell being pressed.

Figure 8 shows the peak separation of the two peaks in Figure 7. This is an indication of transverse strain measurement. As mentioned above, the sensor was embedded at 45° to the loading direction, meaning its transverse strain sensitivity is lowest at this orientation. This is indicated by the small peak separation changes with increasing loads. This 45° orientation has maximum sensitivity to shear strain and will be further explored in future shear tests on the panel.

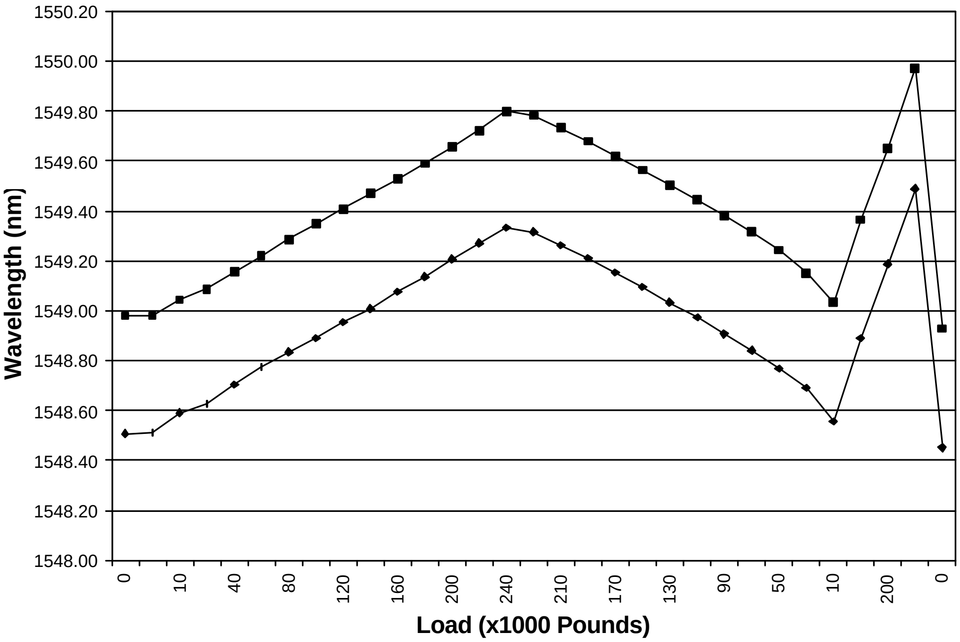


Figure 7. Wavelength data vs. load for sensor oriented at 45° to loading direction

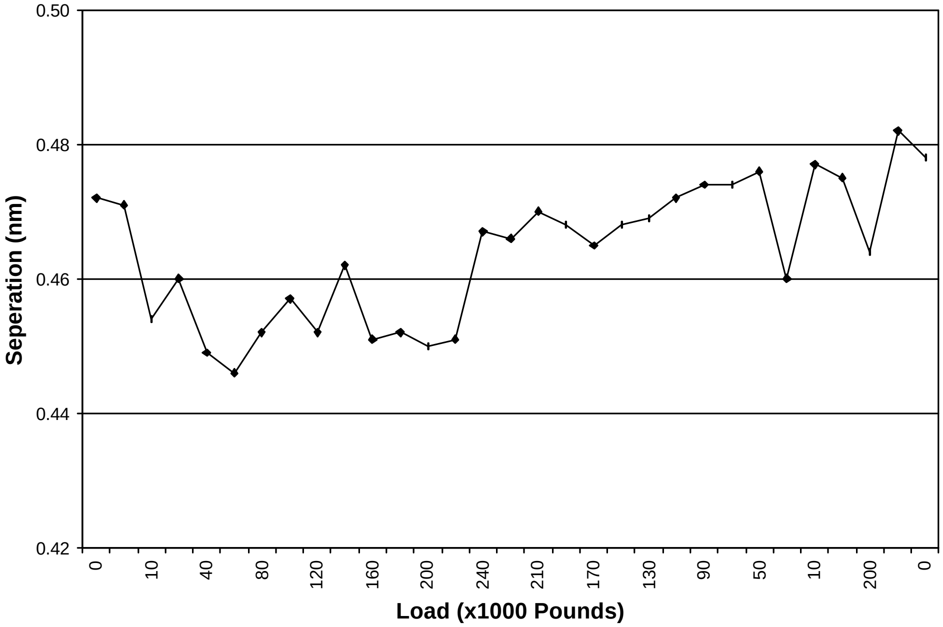


Figure 8. Peak separation vs. load for sensor oriented at 45° to loading direction

Figure 9 shows the wavelength data for a sensor embedded at 90° to the loading direction of the panel. Two traces are shown on the graph, one for each peak associated with the 1550 nm portion of the multiaxis sensor. As the load is increased, both peaks move to higher wavelengths. Again, these peak shifts show the capability of the multiaxis sensor to measure axial strain due to the Poisson effect of the load cell being pressed.

Figure 10 shows the peak separation of the two peaks in Figure 9. This is an indication of transverse strain measurement. As mentioned above, the sensor was embedded at 90° to the loading direction, meaning its transverse strain sensitivity is highest at this orientation. This is indicated by the large peak separation changes with increasing loads.

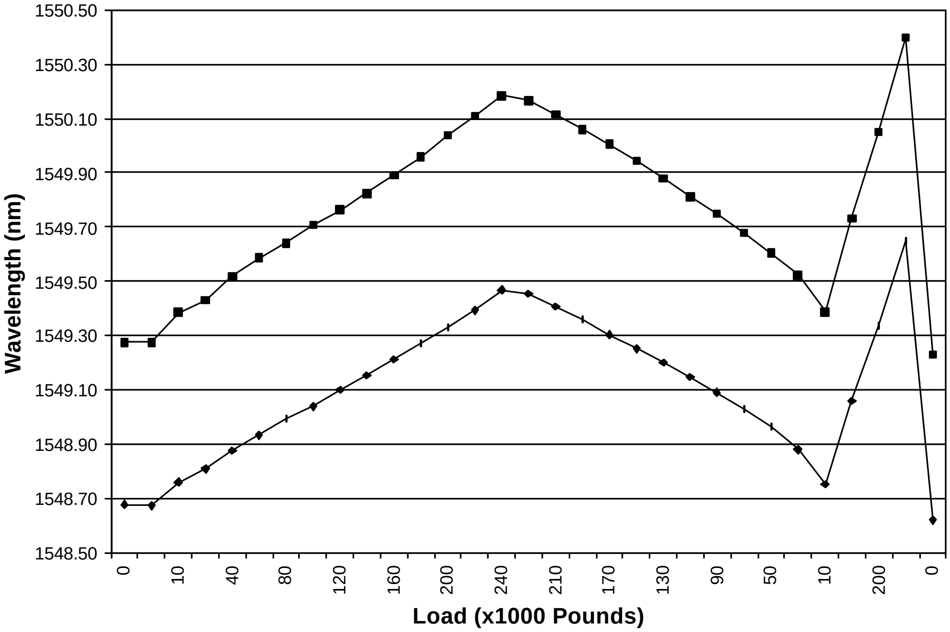


Figure 9. Wavelength data vs. load for sensor oriented at 90° to loading direction

Figure 10. Peak separation vs. load for sensor oriented at 90° to loading direction

4. FUTURE TESTING

Future Shear Tests planned at ODOT

Additional transverse testing and shear load tests are planned at the Oregon Department of Transportation and the University of Washington in Seattle, WA.

5. CONCLUSION / SUMMARY

A composite panel with integrated multi-axis fiber grating sensors has been used to demonstrate the measurement of transverse strain fields in a smart bearing configuration.

6. ACKNOWLEDGEMENTS

Testing support for the smart bearing was made available by the Oregon Department of Transportation. The fabrication of the fiber optic grating smart bearing was supported in part by U. S. Army Phase II SBIR DAAL01-98-C-0034 awarded to Production Products on which Blue Road Research is a principal subcontractor.