

**Structural Damage Assessment Via Modal Property Identification using Macro-Strain Measurements with
Fiber Bragg Gratings as an Alternative to Accelerometers**

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Fiber gratings packaged to provide long-gage strain measurements were attached to test articles with varying degrees of induced damage. Dynamic strain measurements during free vibration were used to identify the damage through modal macro-strain vectors.

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Introduction

Past research in the area of nondestructive damage detection in structures has shown that modal frequencies and modal damping ratios may not be sensitive enough indicators to detect damage, while changes in mode shapes are significantly more sensitive to structural defects or local damage, with the greatest change occurring in the vicinity of the structural defect. In general, local damage corresponds to a local loss of stiffness of some structural element(s). Therefore, damage identification methods based on changes in vibration mode shapes such as changes in mode shape curvature have encountered some success. However, the changes in mode shape curvature are traditionally obtained through double numerical differentiation of "noisy" mode shapes identified using accelerometer data. Thus, the identified mode shape curvatures may be too noisy to identify (i.e., detect, localize, and quantify) low to intermediate level of local structural damage.

On the other hand, the effective modal macro-strain vectors used in this effort, which are equivalent to curvature mode shapes, are identified *directly* from the long-gage fiber grating sensor measurements. Thus, they are in general much less noisy and therefore significantly more reliable than the curvature mode shapes identified using accelerometer data. This is exactly where the advantage lies of using long-gage fiber optic deformation sensors for structural health monitoring and global damage identification of structures.

In this effort, funded in part by the National Science Foundation (Grant No. 9961268), the use of long-gage fiber Bragg gratings to provide dynamic strain measurements in conjunction with this damage detection algorithm is investigated.

Long-Gage Fiber Bragg Grating Strain Sensors

For larger structures, such as bridges, there is a need to provide long-gage (macro) strain measurements that are less susceptible to local stress concentrations, such as cracks. This gives a strain value more representative of the entire structural member. To provide these long gage lengths, fiber Bragg gratings, with inherent gage lengths on the order of a few millimeters, are packaged to extend the effective gage length up to 1.5 meters. This long gage package can be seen in Figure 1.

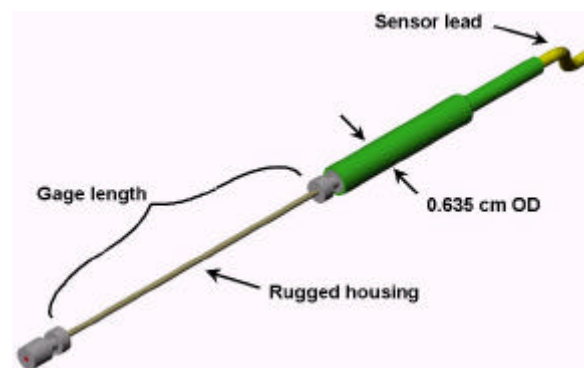


Figure 1. Packaging of the fiber Bragg grating into a long-gage strain sensor.

These sensors provide axial strain (along the length of the fiber) and can be pre-strained to provide compressive measurement capabilities. Used in conjunction with the Blue Road Research high-speed demodulation system,

these sensors are capable of providing long-gage, dynamic (DC up to 2Mhz) measurements. Sensors of this type have been successfully monitoring an Oregon bridge for over three years [1].

Testing

To demonstrate the use of long-gage fiber grating strain sensors in identifying damage in a structure, a test fixture was fabricated into which a 1 meter aluminum beam could be placed while controlling the end support conditions and distribution of masses on the beam. Three long-gage (10 centimeter) fiber grating strain sensors were surface mounted to the test beam using brackets (Figure 2.)

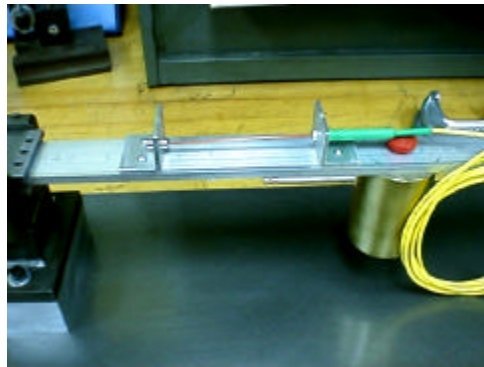


Figure 2. Long-gage strain sensors attached to surface of test specimen.

The demodulation system for the grating sensors consisted of a high-speed system [2] shown in Figure 3. This system provided a measurement speed greater than 500Hz, a dynamic range of $\pm 4,500$ microstrain, and a resolution on the order of 10 microstrain. The system uses a grating filter to convert the wavelength information from the Bragg grating sensor into an amplitude based signal measurable by a high-speed detector. Each of the three sensors on the test article had a separate demodulation system, but shared the same light source and data acquisition system.

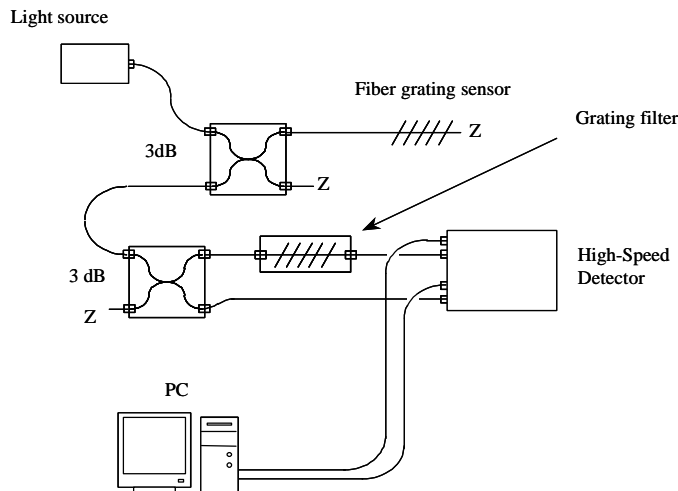


Figure 3. Dynamic measurement system for the grating sensors.

The tests consisted of inducing free vibration in the beam under multiple support conditions and mass distributions while capturing the dynamic macro-strain response from the fiber grating sensors. These tests were repeated with several damage cases (reductions of cross-sectional area) as shown in Figure 4.

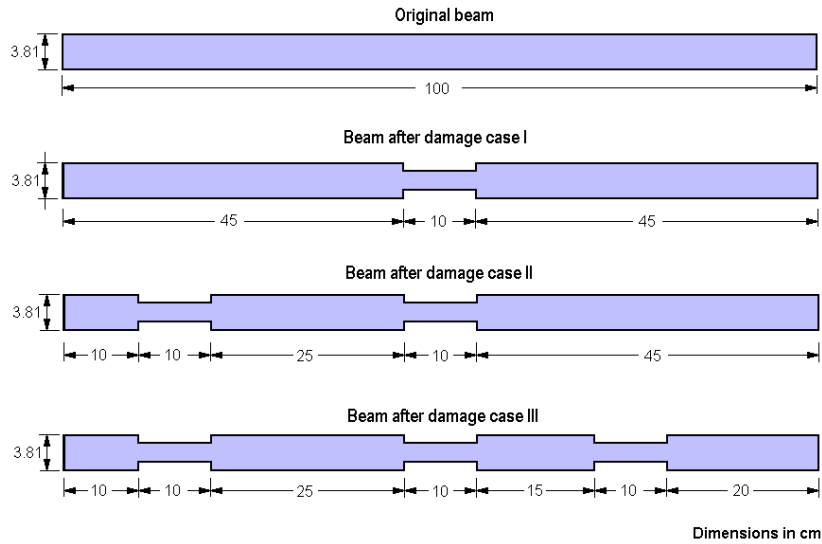


Figure 4. Manufactured damage cases (reduction in cross-sectional area) in the test article used to verify the damage identification capabilities of the system.

Results

In order to predict the macro-strain response of the beam, a numerical simulation package was developed to discretize a 2-D frame-type structure using the finite element method and to compute the dynamic response of the linear elastic finite element model of the structure to a specified dynamic load. The finite element formulation developed also includes the long-gage fiber optic sensors installed on the structure and computes their measurements of the structure dynamic response. This numerical response, when compared to the experimental response of the fiber grating sensors, shows the feasibility of using the grating sensors to detect damage using modal macro-strain vectors.

Referring to Figure 5, the correlation between experimental measurements of macro-strains and their numerical simulations is very good (within 3%.) An earlier analytical study by Conte and Liu [3] at UCLA indicated that global structural damage modeled as local loss of stiffness in structural frames can be identified using a two-stage element-by-element sensitivity-based damage identification algorithm using macro-strain responses. Since macro-strains measured using the fiber Bragg sensors correlate very well with their numerical simulations, it is expected that the fiber Bragg sensor measurements will offer the same damage identification capability.

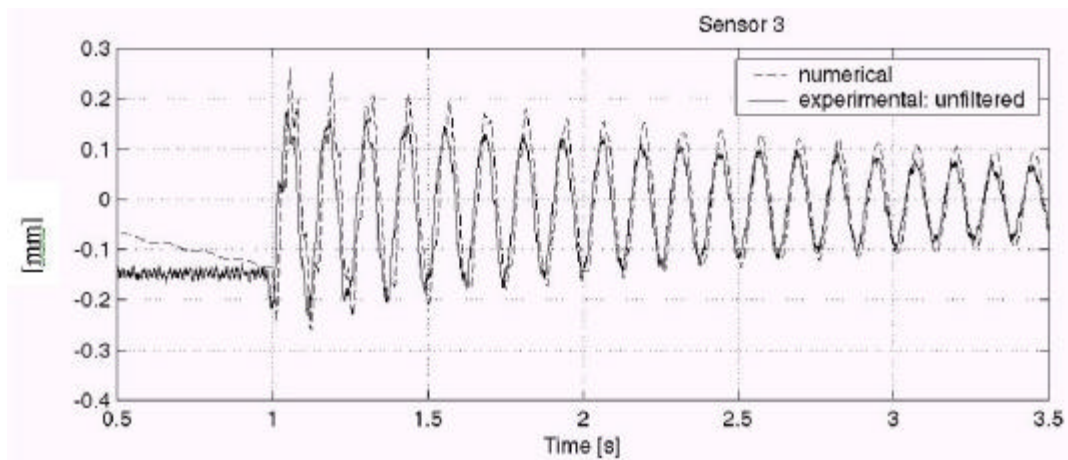


Figure 5. Comparison of numerical and experimental macro-strain response.

Figure 6 shows a sampling of the numerically simulated effective modal macro-strain vectors [3,4] of the beam for different support conditions and for every damage level. Referring to Figure 4, Sensor #1, is closest to the damage site on the left, Sensor #2 is closest to the damage site in the middle, and Sensor #3 is closest to the damage site on the right.

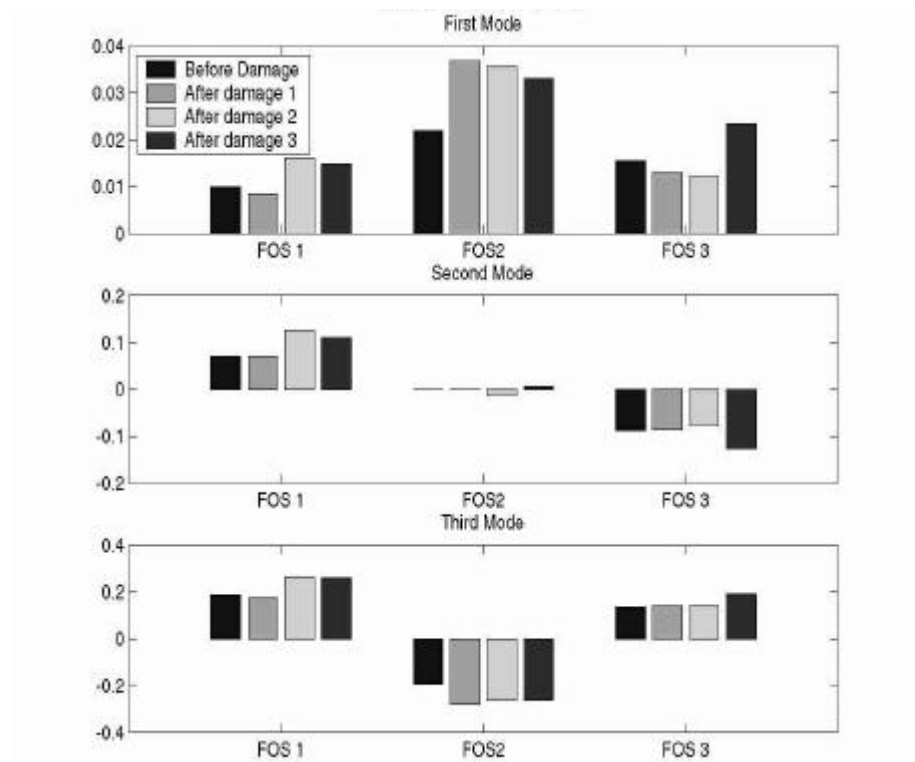


Figure 6. Numerically simulated modal macro-strain vectors for all damage cases and the first three free vibration modes of the test article.

Observe that when progressing from one damage level to the next, only the component of the modal macro-strain vectors close to the new damage location changes significantly. This provides clear indication that the numerical macro-strain vector technique, and thus the measured macro-strains using long-gage fiber grating strain sensors can be used to effectively detect location and severity of damage in a structure. As this technique uses a direct measurement of strain, it is in general much less noisy and therefore significantly more reliable than the curvature mode shapes identified using accelerometer data.

Summary

In summary, long-gage fiber Bragg strain sensors combined with system identification techniques using a finite element model of the structure have been shown analytically and experimentally at the small-scale level to hold very strong promise for effective and reliable structural health monitoring and damage identification of civil structures.

References

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