Long Gage Fiber Optic Bragg Grating Strain Sensors to Monitor Civil Structures

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ABSTRACT

Fiber optic Bragg gratings packaged in long gage configurations are being used to measure static and dynamic macro-strains in structures and structural models to monitor structural health and detect and identify macro-damage incurred from a seismic event. These long gage sensors are being used to experimentally verify analytical models of small-scale structural models in their pre- and post-damage states using system identification techniques. This fiber optic deformation measurement system could play a significant role in monitoring/recording with a higher level of completeness the actual seismic response of structures and in non-destructive seismic damage assessment techniques based on dynamic signature analysis. This new sensor technology will enable field measurements of the response of real structures to real earthquakes with the same or higher level of detail/resolution as currently in structural testing under controlled laboratory conditions.

Keywords: Macroscopic strain, dynamic strain measurements, seismic damage assessment

1. INTRODUCTION

Determination of the actual nonlinear inelastic response mechanisms developed by civil structures such as buildings and bridges during strong earthquakes and post-earthquake damage assessment of these structures represent very difficult challenges facing the earthquake structural engineering. Presently, there is an unbalance between the analytical capabilities for predicting various nonlinear structural response and damage parameters and the incompleteness (lack of richness) of the information on the actual seismic response of structures measured in the laboratory and, more importantly, in the field. Furthermore, this unbalance impedes the full deployment of the new and very appealing philosophy of performance-based earthquake engineering.

The research being performed aims at filling the gap defined above through studying the feasibility, through physical experimentation at small scale, of using long gage fiber optic Bragg grating sensors for monitoring directly the "macroscopic" internal deformation response of structures to strong ground motions and for non-destructive post-earthquake evaluation of structures. These fiber optic sensors can be either embedded inside a reinforced concrete or composite structure or bonded to the surface of a steel structure and monitored real-time at speeds from DC level to over 10 MHz with strain resolutions from 0.02 microstrain (DC to 10 kHz) to 25 microstrain (10 MHz.)

1.1. Fiber Bragg Grating Sensor

The core sensor technology for this project is the fiber Bragg grating. A Bragg grating consists of a series of perturbations in the index of refraction along the length of a fiber (Udd, 1991.) This grating reflects a spectral

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peak based on the grating spacing, thus changes in the length of the fiber due to tension or compression will change the grating spacing and the wavelength of light that is reflected back. Quantitative strain measurements can be made by measuring the center wavelength of the reflected spectral peak. Fig. (1) shows a Bragg grating and the effects of a broadband light source impinging on the grating.

Transmission spectrum

Broadband light
directed toward grating

Grating
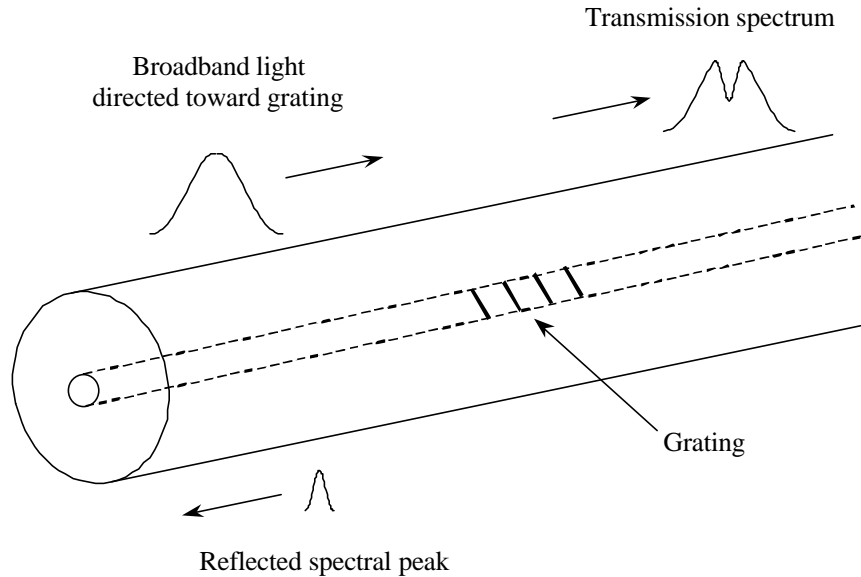
Reflected spectral peak

Fig. 1 Transmission and reflection spectra from fiber Bragg grating

In its basic form, a typical Bragg grating has a gage of approximately 5mm. For most civil structure applications this gage is too short, so a method of effectively increasing the gage length was developed.

1.2. Long Gage Fiber Bragg Grating Sensors

In order to increase the gage length of the Bragg grating to provide a more macroscopic strain value useful in civil structure applications, the grating is packaged in a tube with the tie points defining the effective gage length. Fig. (2) shows a long gage sensor with optional brackets for surface mounting.
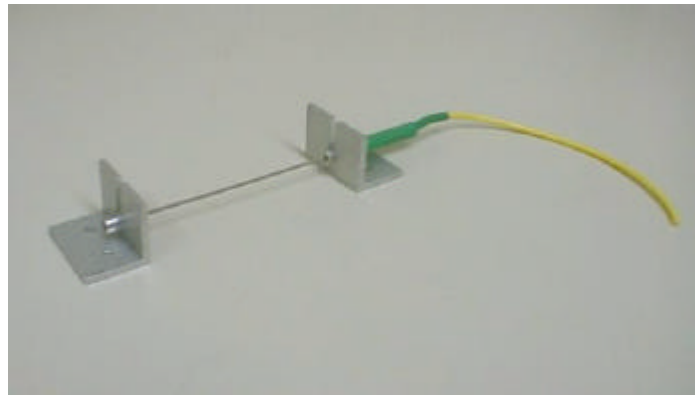
Fig. 2 Long gage grating sensor shown with optional brackets for surface mounting capability

This packaging, shown in Fig. (3), provides a gage range from 2.5 to 100 cm. The maximum diameter of the grating package is less than 7 mm, making it non-obtrusive and ideal for embedding into composites, placing into grooves in concrete, etc.
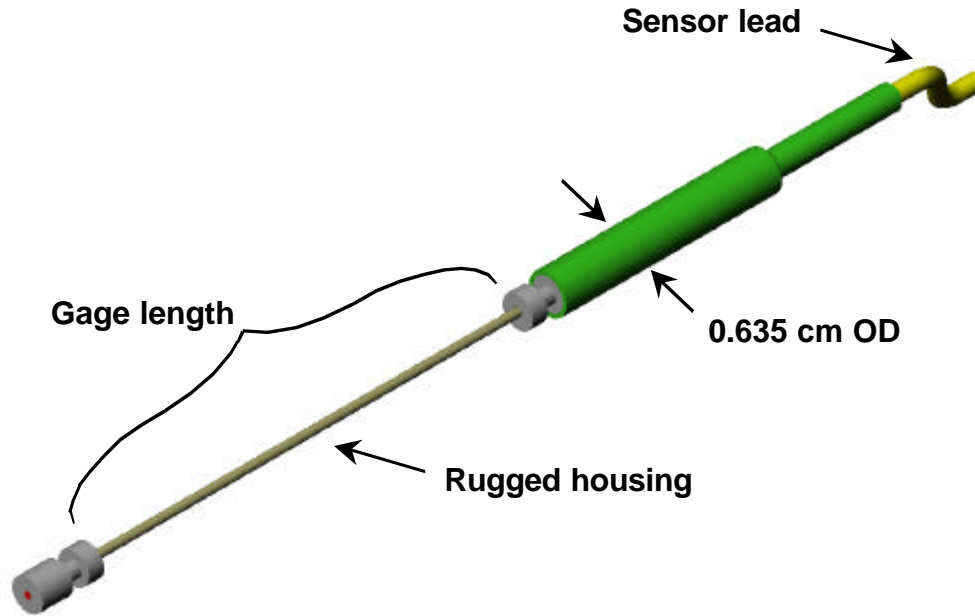
Sensor lead

Gage length

0.635 cm OD

Rugged housing

Fig.3 Long gage sensor packaging

1.3. Dynamic Strain Measurement

The analytical models in this project require dynamic strain measurements for experimental verification. A high-speed fiber grating demodulation system has been developed that can measure strain from DC levels up to 10Mhz (Seim, 1998.) For this project, the system has been optimized for 1 kHz, which provides sufficient oversampling. This demodulation system consists of a grating filter that converts the spectral information from the grating sensor into an amplitude based signal measurable by photo detectors. Fig. (4) shows this system where light is directed into the sensor through the first beam splitter, reflected in the grating and directed into the second beam splitter where it is divided into the filtered and reference legs and then into the high speed detector. The reference leg compensates for amplitude losses in the system.
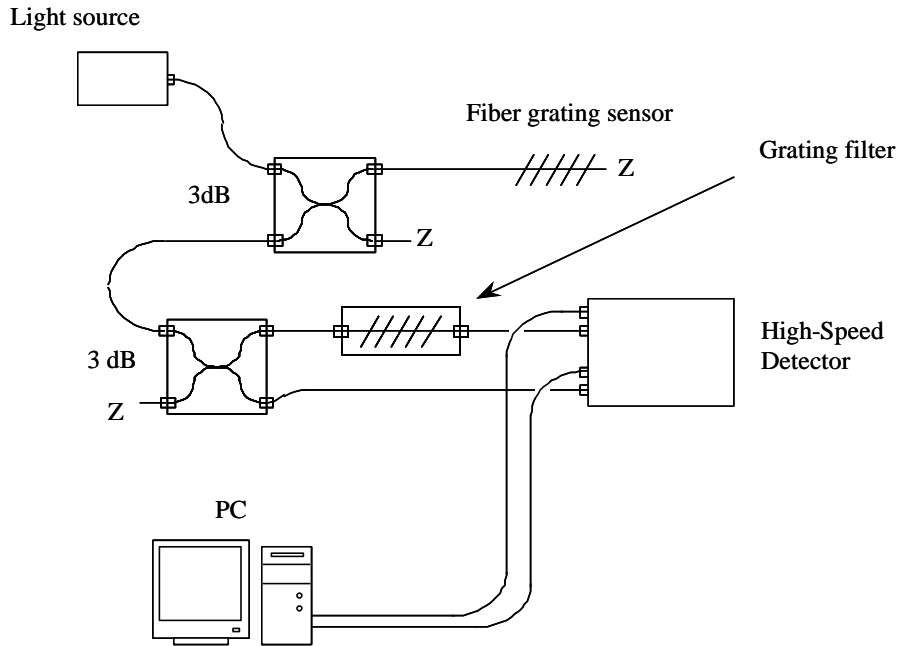
Fig. 4 High-speed demodulation system

This high-speed system can also be expanded to support more than one grating sensor as represented in Fig. (5).
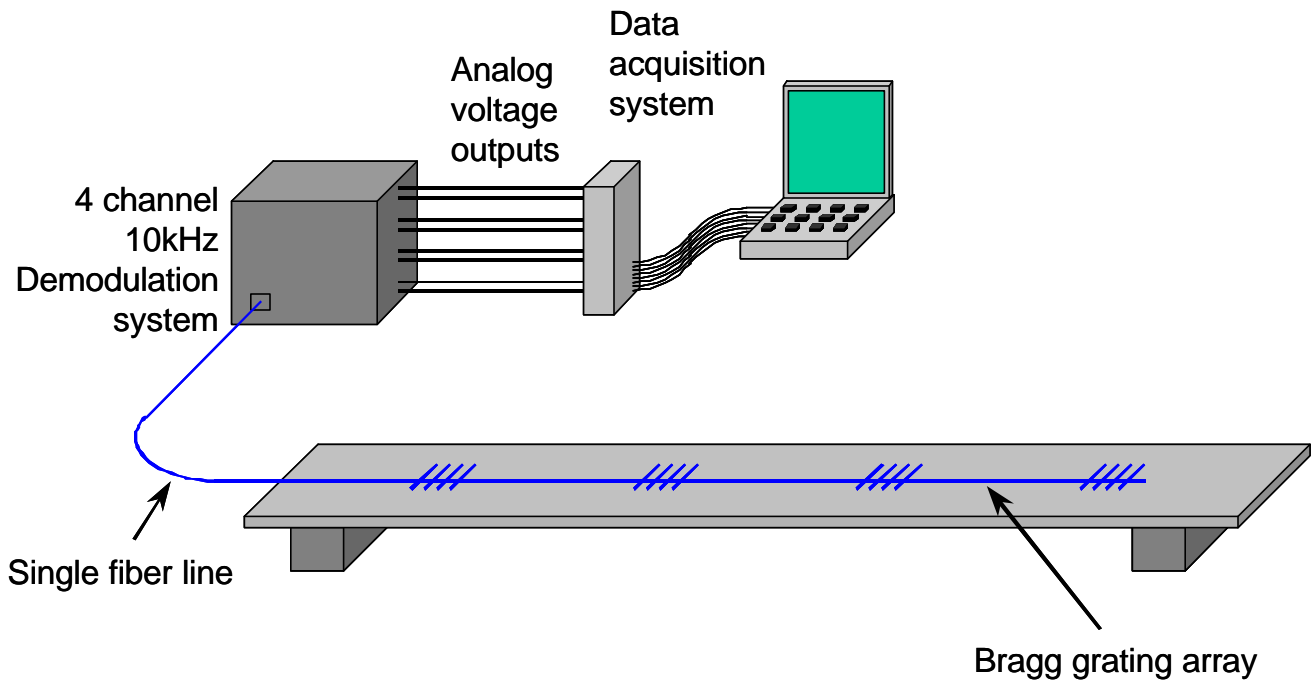

Fig. 5 High-speed measurement of a series of fiber gratings along a single fiber line

2. CIVIL STRUCTURE EXAMPLES

Feasibility is an important aspect of introducing new technology and the sensors and the system described above have been used successfully on real structures. One example below has been providing long-term survivability and sensor performance data for over two years.

2.1. Horsetail Falls Bridge

Twenty-six sensors have been successfully monitoring the Horsetail Falls Bridge in Oregon for over two years (Seim, 1999.) The bridge, shown in Fig. (6), was built in 1914 and in 1998 underwent a strengthening procedure where composite wrap was placed over the concrete beams.

Fig. 6 Horsetail Falls Bridge before being strengthened by composite wrap and instrumented with 26 long gage fiber grating strain sensors

To verify that the composite wrap was adding strength to the bridge, long gage fiber grating strain sensors were placed in grooves cut into the concrete and in the wrap itself. Fig. (7) shows the sensors being embedded into the concrete and composite wrap.

Fig. 7 Sensors being placed into grooves in the concrete (left) and embedded into the composite wrap (right)

Using the high-speed demodulation system, the bridge motion was monitored during several dynamic tests. Fig. (8) shows results from one of the tests focusing on one sensor as traffic was monitored.

Fast Demodulation of Sensor T1FC (Transverse Beam, External to Composite, Flexure, Center) on Horsetail Falls Bridge, Demo
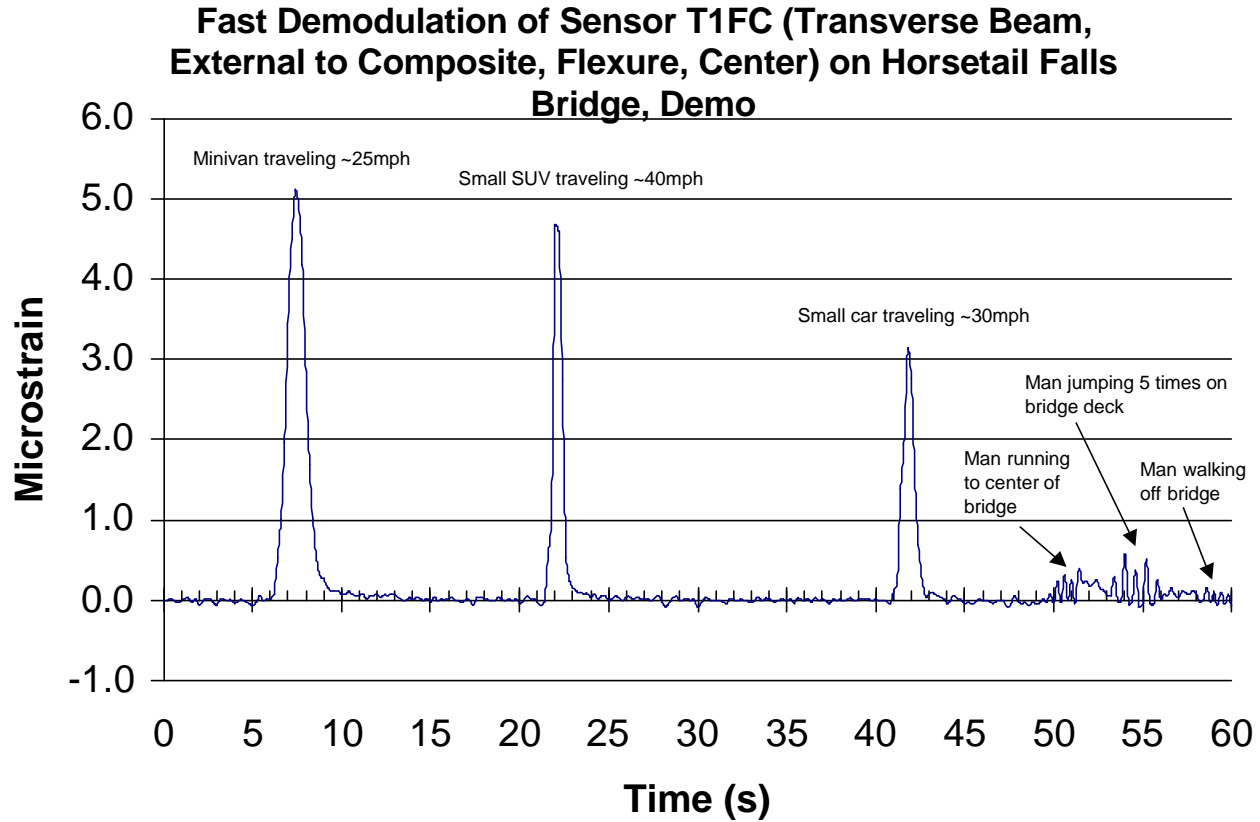

Fig. 8 Dynamic data from a sensor installed on the Horsetail Falls Bridge

The high-speed demodulation system has a high sensitivity as demonstrated by the resolution of less than 0.05 microstrain.

2.2. Sylvan Bridge

In mid July, 2000, 14 long gage sensors were installed on another Oregon bridge shown in Fig. (9). This bridge also received composite wraps, but in strips as opposed to sheets. This could be an important part of this seismic damage assessment project as the bridge is tentatively scheduled to be demolished in 3-5 years. This will allow for increasingly severe damage states to be monitored with the sensors and compared to analytical predictions.

Fig. 9 Sylvan Bridge in Oregon instrumented with long gage sensors in July 2000

3. EXPERIMENTAL VERIFICATION OF AN ANALYTICAL DAMAGE IDENTIFICATION ALGORITHM

While the applications listed above provide excellent structural health and feasibility information, it is still necessary to use small-scale physical models of structures to verify existing analytical structural damage identification algorithms based on changes in vibration characteristics (Conte et al. 2000.) These small-scale experiments will be conducted in two main stages, free and forced vibration. Damage will be inflicted "manually" during this dynamic testing and compared to damage locations predicted using system identification based on the dynamic measurements provided by the long gage grating sensors.

3.1 Free Vibration

The first set of experiments will employ an aluminum beam with various combinations of boundary conditions and mass distributions. The beam will be 100 cm long and have three sensors with gages of 15 cm. Fig. (10) shows a representation of the beam and the various configurations. Several long gage sensors will be placed at key locations on the beam to measure macro strain during free vibration. These strain values will then be compared to results from an analytical (finite element) model.
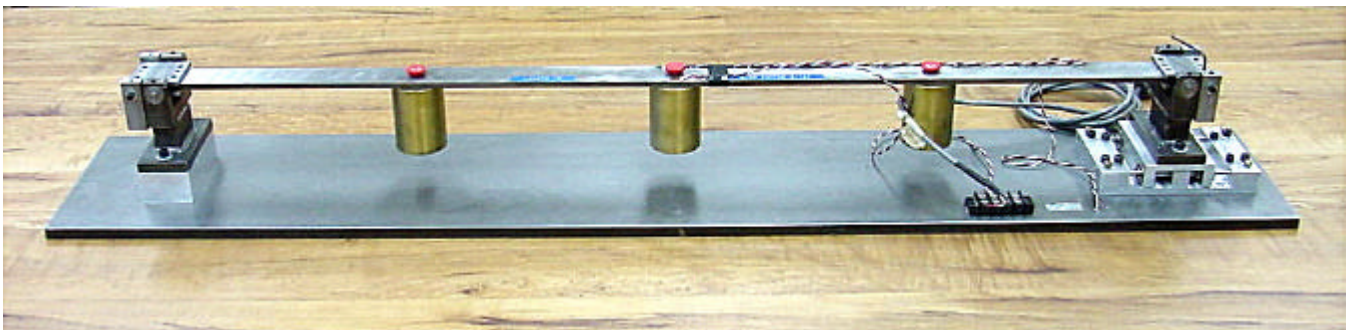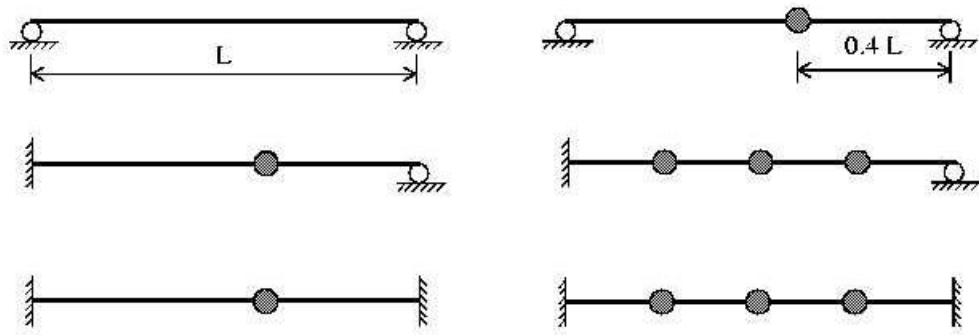
Fig. 10 Different mass distributions and boundary conditions for test beam in free vibration

This rigorous set of free vibration experiments will contribute to verify the analytical models and the long gage sensors.

3.2 Forced Vibration

The second main set of experiments will involve forced vibrations with more complex models better representing real structures. Fig. (11) shows the forced vibration setup with a shaker table and examples of potential models.
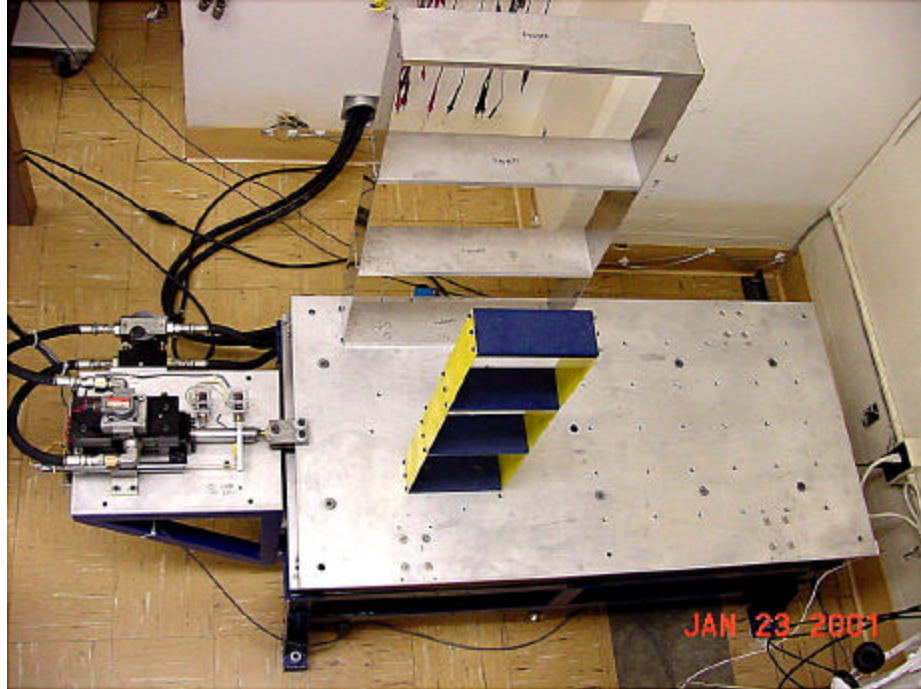
Fig. 11 Servo-hydraulic shaker table and structural models of forced vibration tests

3.3. Damage Identification

A damage detection, localization, and quantification algorithm has been developed and verified through numerical simulation (Conte et al. 2000). This algorithm makes use of a linear finite element model of the structure before and after damage and vibration measurements obtained from a set of long gage strain sensors before and after damage as well. This algorithm will now be verified experimentally through the above small-scaled experiments. During dynamic testing, damage will be simulated by reducing the cross sectional area of the models at known points over an extended length to see if the analytical models are able to capture the known inflicted damage.

4. SUMMARY

Long gage fiber optic Bragg grating sensors are being used to monitor the structural health of structures and to provide experimental verification of a seismic damage identification method. The long gage length is to provide a macroscopic strain value more useful in structural monitoring. These sensor systems have the capability of measuring dynamic strain from DC levels to over 10 MHz with strain resolutions from 0.02 microstrain (DC to 10 kHz) to 25 microstrain (10 MHz.)

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