SEISMIC DAMAGE IDENTIFICATION IN PC COLUMN USING LONG-GAGE FBG SENSORS

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ABSTRACT
Accurate detection of realistic damage in structures is critical for effective condition assessment and structural health monitoring. In this paper, experimental results of pre-stressed concrete columns mounted onto a shaking table and subject to progressively increasing seismic excitations are presented. The study was aimed at investigating the changes in the dynamic parameters in order to detect damage in the concrete column after each post-seismic stage. The dynamic response of the structure was measured using long-gage fiber Bragg grating (FBG) sensors and accelerometers. The post-earthquake damage in the columns were evaluated via modal macro strain ratio (MMSR) based damage identification methods. Results from this study demonstrate the applicability of specially packaged surface-mounted long-gage FBG sensors for detecting the initiation and the progression of cracks due to reverse dynamic loads. The performance of the sensors for structural damage identification is discussed as well.

Keywords: Damage identification, Fiber Bragg grating, Long-gage sensor, Modal macro strain, Strain ratio, Structural health monitoring

1. INTRODUCTION
Civil infrastructures are the essential components of the modern civilization and none of these structures is built for eternity. However, the expected service life of these structures is relatively longer compared to other commercial or manufactured products. Therefore, monitoring of these structures to confirm uninterrupted performance of these structures and increase the safety to human civilization is of prime importance. Recent collapse of the structures has proved that the traditional visual inspection techniques of monitoring the structure regardless of their frequency, are inadequate to detect some damage or to accurately assess the extent or progression of that damage and inspection should employ appropriate non-destructive evaluation technologies when evaluating the critical components (NTSB, 2008). Instrumentation based monitoring of constructed systems has been emphasized by the researching community and numerous sensors for data acquisition and methods or techniques for analyzing the captured data have been proposed for this purpose. The existing approaches proposed in this area can be classified into two major categories-the static identification methods using static test data and the dynamic identification methods using dynamic test data. Compared with the static identification techniques, the dynamic ones have been developed more maturely and the corresponding literature are quite extensive. A detail review on the dynamic identification techniques can be found in Doebling et al. (1998), Carden and Fanning (2004), Sohn et al. (2004) and Montalovao et al. (2006). The basic idea of the vibration based damage identification method is that structural damage causes reduction in stiffness and the intrinsic properties of the structure are changed accordingly. In most of the vibration based damage identification techniques, structural modal parameters or features such as modal frequencies, damping ratios, mode shapes, mode shape derivatives, stiffness matrix and flexibility matrix (Pandey et al., 1991; Pandey and Biswas, 1994; Topole and Stubbbs, 1995; Salawu, 1997) etc., are used. One of the major difficulties with the vibration based damage identification techniques is that the structural properties such as modal frequencies and damping ratios are susceptible to the change of the environmental temperature and damage identification result may not be realistic (Serker and Wu, 2009a). The sensitivity of some vibration-based features to various levels of damage was also evaluated experimentally by Farrar and Jauregui (1998), based on the data collected from the I-40 Bridge in New Mexico by introducing controlled damage to a girder. The study results demonstrate that the modal property based features are not good indicators of damage. Similarly, most of the static test based damage identification techniques utilize static displacement and strain and the health status of the intact structure is a prerequisite (Hajela and Soerio, 1989; Hjelmstad and Shin, 1997). Therefore, different types of structural responses features such as accelerations, velocities, displacements and strains are commonly measured under various excitations for damage identification. Conventional measurements such as accelerations, velocities and displacements are essentially “point” measurements at translational DOF. Among these measurements, strain...
may be the most sensitive to local damage and can be a good candidate measurement for detecting a local damage. One of the significant limitations of the point measurement is that it may not reflect a local damage unless the area where the sensor is fixed exactly covers the damaged region. Since the traditional foil strain gages have very small gage length compared to the length of the structure to be monitored, it will be unwise and expensive to use a large number of sensors to cover the whole structure or important parts. Sensors having distributed sensing capability can be a good choice to overcome this limitation in detecting damage or monitoring large civil structures.

In recent days, fiber optic sensing technology has opened the door of distributed sensing with a gage length up to some meters (Li and Wu 2007). Among the fiber optic sensors, fiber Bragg grating based strain sensors are most suitable with its special features of high precision level, stable sensing capacity, reliability and so on. Adewuyi et. al. (2009) showed that the distributed measured strain responses have better damage identification capability over the point measurement data with the same damage identification algorithm. Li and Wu (2007) developed a long-gage FBG sensor, which can be used to measure the structural response distributed by placing the sensors in series. Serker and Wu (2009b) proposed a damage detection technique, which focuses the application of the long-gage distributed FBG sensor and static macro-strain response. This paper focuses on the application of the distributed modal macro-strain response to detect and localize post earthquake damage in PC column structures. A modal macro-strain based damage identification technique presented by Serker et al. (2010) was also introduced and applied to this purpose. With this technique, damage detection can be accomplished with no requirement for an analytical model.

2. DISTRIBUTED LONG-GAGE FIBER OPTIC SENSING SYSTEM

In spite of high precision and excellent sensing ability, the ordinary FBG faces an unfavourable problem in that its inherent gauge length is around 1-2 cm, which makes FBG work as a traditional “point” strain gauge and difficult for distributed placement. Therefore, enhancement in gage length is required for practical application of the FBG sensor as long-gage sensors. Long-gage FBG sensors developed at the Structural Engineering and Dynamics laboratory of Ibaraki University, Japan was deployed as the sensing device for the distributed strain sensing. The sensor array is shown in Figure 1. After special packaging the gage length was extended to 20–25 cm by using a tube to sleeve the optical fiber and then fixing at two ends of the tube. For a general long-gage sensor, the in-tube fiber has the same mechanical behaviour and hence the strain transferred from the shift of Bragg center wavelength represents the average strain or the macro-strain over the sensor gauge length. A FBG sensors array for distributed macro-strain measurements can be achieved after connecting the long-gage sensors in series as shown in Figure 1(b). The conventional and commonly used transducers, such as accelerometer, velocimeter and displacement transducer essentially provide some kinds of measurements in translational degrees of freedom whereas the long-gage FBG sensors are related with the rotational degrees of freedom as described later.

Figure 1 Long-gage FBG sensors array (Li and Wu, 2007)
3. MODAL MACRO-STRAIN RATIO BASED DAMAGE IDENTIFICATION

3.1 Damage Detection Using the Modal Macro Strain-ratio (MMSR)

For a beam like structure at intact condition and under a certain loading configuration as shown in Figure 2(a), it can be shown that the ratio of the strains between a target and a reference location is constant and can be expressed as the ratio of the distances of the corresponding sections measured from the same reference point as:

$$\frac{\varepsilon_m}{\varepsilon_R} = \frac{x_m}{x_R}$$

(1)

Similarly, the strain ratio between a damaged section and the undamaged reference section can be written as

$$\frac{\varepsilon_m^*}{\varepsilon_R} = \frac{l}{\beta} \frac{x_m}{x_R}$$

(2)

where $\varepsilon_m^*$ is the strain at section $x_m$ after damage, $\beta$ ($0 \leq \beta \leq 1$) is the ratio of the effective flexural rigidity at damaged condition and intact condition. It is apparent from Equations (1) and (2) that the damage can be identified from the change in the strain ratio. In addition, the location of the sensors can be used as a reference for damage identification. The above relationship is valid for a single point time invariant loading. Since every structure has a certain deflected shape under some loading configuration, the above idea can also be applied with a generalized loading. Serker and Wu (2009b) showed the potentials of this approach for damage identification and application for structural health monitoring (SHM) in beam-like structures.

![Figure 2](image_url)

Figure 2 (a) Fundamentals of the strain-ratio approach (b) beam structure model

Although the static test methods have some important features for damage identification, these techniques are not suitable for continuous monitoring of a structure and dynamic measurement is essentially needed. Structure modal properties, such as mode shape, modal frequency etc. are the intrinsic properties and expected to be the same under any condition provided that the structural properties has not been changed. The concept of damage detection presented in the above section can also be applied using the flexural mode shapes. However, mode shape itself is not very sensitive to local damage and mode shape derivatives of different orders have been proposed for damage identification (Pandey et al., 1991). Since strain is very sensitive to local damage, strain mode shapes may also provide excellent damage detection capability.

Strain mode shapes can be obtained from the flexural mode shapes using the well-known moment-curvature relationship

$$\varepsilon = \frac{Mh}{EI} = \frac{l}{\rho(x)} h$$

(3)

where $\frac{l}{\rho(x)}$ is the curvature and $h$ is the distance measured from the neutral axis of the beam to the location where strain will be measured. $M$ and $EI$ have their usual meaning. The curvature of the beam bending can be obtained from the 2nd order differentiation of the displacement mode shape (Pandey et al., 1991) as:

$$\frac{l}{\rho(x)} = \frac{f_{m+1} - 2f_m + f_{m-1}}{l^2}$$

(4)
where $f_m$ is the displacement at section $m$, $l$ is the distance between two measurement points. Combining Equations (3) and (4)

$$
e = h, \frac{f_{m+1} - 2f_m + f_{m-1}}{l^2}$$

(5)

The traditional way of obtaining the displacement mode shape is the use of accelerometers, which essentially correspond to the global behavior of the structure. Another problem with the mode shape derivatives is the high sensitivity to noise. Recently, Li and Wu (2008) presented a robust technique to obtain the strain mode shapes using the macro-strain measurements from the long-gage FBG sensors. A summary of the macro-strain modal analysis is presented here.

Consider a beam-like structure installed with a series of long-gage FBG sensors distributed over the length and each sensor covers at least one element (Figure 2(b)). The average strain or the macro-strain, $\bar{\varepsilon}$, over any sensor with a gage length $L_m$, can be obtained from the rotational displacement with a reasonable assumption that at each element the distance from the inertia axis to the bottom of the beam where sensors are to be installed is the same.

$$\bar{\varepsilon}_m(t) = \frac{h_m}{L_m} \left[ \theta_i(t) - \theta_j(t) \right]$$

(6)

or, in the frequency domain,

$$\bar{\varepsilon}_m(\omega) = \frac{h_m}{L_m} \left[ \theta_i(\omega) - \theta_j(\omega) \right]$$

(7)

where $h_m$ is the distance measured from the neutral axis of the beam to the sensor location. $\theta_i$ and $\theta_j$ are the rotational displacements of the $m$th sensor at $i$th and $j$th node respectively.

The macro-strain FRF, $H_{mp}^{\bar{\varepsilon}}$, between the measurement from the $m$th sensor and the excitation at the $p$th DOF can be achieved by

$$H_{mp}^{\bar{\varepsilon}}(\omega) = \frac{\bar{\varepsilon}_m(\omega)}{P_p(\omega)}$$

(8)

Submitting Equation (7) into Equation (8) with $\eta_m = h_m/L_m$

$$H_{mp}^{\bar{\varepsilon}} = \eta_m \frac{\theta_i(\omega) - \theta_j(\omega)}{P_p(\omega)} = \eta_m \left[ H_{ip}^d(\omega) - H_{jp}^d(\omega) \right]$$

(9)

where $H_{ip}^d$ and $H_{jp}^d$ are the displacement FRFs at the $i$th and $j$th DOF. Equation (9) can be further expressed as:

$$H_{mp}^{\bar{\varepsilon}} = \sum r \frac{\bar{\varepsilon}_r}{\omega_r^2 - \omega^2 + 2\xi_r \omega \omega}$$

(10)

in which the macro-strain modal constant can be written as

$$r \bar{\varepsilon}_r = \frac{\Phi_{pr} \delta_{mr}}{M_r}$$

(11)

and
\[ \delta_{mr} = \eta_{m}\left(\varphi_{r} - \varphi_{f}\right) \]  

is the modal macro-strain at \( m \)th sensor under the \( r \)th mode. By comparing with the traditional displacement FRF, some important conclusions can be drawn about the macro-strain FRF

\[ \frac{rH_{mp}^d(\omega)}{rH_{mp}^r(\omega)} = \frac{rA_{mp}^d}{rA_{mp}^r} \eta_{m}\left(\varphi_{r} - \varphi_{f}\right) \]  

Macro-strain FRF is spatially related with the displacement FRF and not dependent on the load and frequency. Another important feature of the MMS is that there exists excellent correlation among the MMS extracted from various sensors installed on a structure (Li and Wu, 2008). In addition, for a certain condition of the structure and for a particular mode or combination of several modes, MMSR between a target and a reference location will be a constant.

\[ \frac{\delta_{mr}^1}{\delta_{Rr}^1} = \frac{\delta_{mr}^2}{\delta_{Rr}^2} = \ldots = \frac{\delta_{mr}^n}{\delta_{Rr}^n} \]  

If more than one mode is used

\[ \frac{\sum_{r=1}^{N} \delta_{mr}^1}{\sum_{r=1}^{N} \delta_{Rr}^1} = \frac{\sum_{r=1}^{N} \delta_{mr}^2}{\sum_{r=1}^{N} \delta_{Rr}^2} = \ldots = \frac{\sum_{r=1}^{N} \delta_{mr}^n}{\sum_{r=1}^{N} \delta_{Rr}^n} \]  

where \( \delta_{mr}^1 \) and \( \delta_{Rr}^1 \) are the MMS obtained from the measurement of macro-strain data at any time \( t_m \) at a target and a reference location respectively. \( N \) is the number of mode.

### 3.2 Application of the MMSR for SHM

The above-mentioned concept of damage detection will be applied considering that the target structure is instrumented with a series of long-gage distributed sensors. The damage detection technique is presented graphically in Figure 3. In this approach, features (MMS) will be extracted from the measurement over a period of time. Next, the extracted feature of a target location will be plotted against that of a reference location. It is obvious from Equation (1) that all the points of the feature plot will lie on a same line for every condition of the structure and any point lying above the line can be treated as a critical event. However, every structure experiences the varying operational and environmental condition during its life, which may cause some variation in the extracted features. It is considered that only the structural damages can cause a significant and permanent change in the local as well as global behavior of the structure. Therefore, for a damaged section the strain ratio line will shift to a new position and continue shifting for a progressive damage. Statistical approaches can be incorporated to account for the variability in the measured responses due to changing environmental condition. Let the extracted features of a target zone and the reference zone for a set of measurements follow a linear variation and can be expressed as

\[ M_{\text{Target}} = a_1 * M_{\text{Reference}} \]  

where \( a \) is the slope of the regression, \( M_{\text{Target}} \) and \( M_{\text{Reference}} \) are the extracted features from a target zone and a reference zone respectively. Let the statistical model for another set of measurement for a target zone be

\[ M_{\text{Target}} = a_2 * M_{\text{Reference}} \]  

From equation (2) it is obvious that damage causes an increase in the value of the strain ratio. Therefore, damage is likely to be present if the regression line shift to new position with an increased slope i.e. \( a_2 > a_1 \).
4. DAMAGE IDENTIFICATION IN RC COLUMN

4.1 Experimental Set-up and Data Collection

A squared section PC column of 1.40 m length as shown in Figure 4 was used for the experimentation. The concrete column is reinforced with eight 6 mm diameter longitudinal bars with a mean yield stress, $f_y = 325$ MPa and Young’s modulus of 165 GPa, and 4 mm diameter stirrups spaced at 80 mm ($f_y = 180$ MPa, $E = 195$ GPa). The mean compressive strength, tensile strength and Young’s modulus of concrete are 41 MPa, 3.15 MPa and 25.2 GPa, respectively. A concentric axial load was introduced into the column using a steel bar pre-strained to 2240 με via a 10 mm diameter bolt ($f_y = 407$ MPa, $E = 181$ GPa). The PC column was externally mounted on the shake table as shown in Figure 5. Base excitations of different levels with sine and sine sweep waves of different levels were applied. In addition, an earthquake excitation, the 2007 Niigata Chuetsu-Oki earthquake, was applied. Intensity of the load was progressively increased. Description of the load steps are listed in Table 1. The column was divided into six sensing zone as shown in Figure 6. Six FBG sensors one in each sensing zone were installed on the surface of the column to capture the response due to the applied excitations. Five sensors of 20 cm gage length and one sensor of 25 cm gage length were installed on the principal direction of vibration of the column (face A). In addition, three accelerometers were deployed on the same face to capture the acceleration response of the column. Details of the sensor installation and the orientation of the column on the shaking tables are shown in Figure 6. The dynamic responses from FBG sensors have been recorded at a sampling rate of 500 Hz. FBG sensors are attached on the principal direction of vibration marked as face A as shown in Figure 6.

4.2 Damage Identification

Wavelength data recorded during the experiment were processed using a computer. Typical macro-strain responses measured on the column are shown in Figure 8. The first two responses are measured on the intact column and the third response is from the damaged column. Progressively increasing seismic excitations were applied to the experimental column. Therefore, it was possible to identify the load step at which the cracking occurred. The first crack was developed by applying the sine sweep excitation with a frequency of 5 to 25 Hz. The whole data set was then divided into two groups namely intact and damaged column. Data set obtained from the undamaged or intact column was used to train a reference model for damage identification. Rest of the data was used to develop another model and compared with the reference model to identify damage in the column.

Figure 3 SHM in a changing operational and environmental condition
Figure 4 Details of the column specimen

Figure 5 Experimental setup of the column specimen
Figure 6 (a) Sensor configuration (b) Orientation of the shake table

Table 1 List of excitations applied to the column specimen

<table>
<thead>
<tr>
<th>Load steps</th>
<th>Excitations</th>
<th>Before damage</th>
<th>After damage</th>
</tr>
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<td>$\sin (2\pi t)$</td>
<td>$\sin (2\pi t)$</td>
<td>$\sin (2\pi t)$</td>
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<tr>
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<tr>
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<td>$3\sin (2\pi t)$</td>
<td>$3\sin (2\pi t)$</td>
<td>$3\sin (2\pi t)$</td>
</tr>
<tr>
<td>5</td>
<td>2007 Niigata Earthquake</td>
<td>2007 Niigata Earthquake</td>
<td>2007 Niigata Earthquake</td>
</tr>
<tr>
<td>6</td>
<td>$\sin$ sweep 5~10 Hz</td>
<td>$\sin$ sweep 5~10 Hz</td>
<td>$\sin$ sweep 5~10 Hz</td>
</tr>
<tr>
<td>7</td>
<td>$\sin$ sweep 5~20 Hz</td>
<td>$\sin$ sweep 5~20 Hz</td>
<td>$\sin$ sweep 5~20 Hz</td>
</tr>
</tbody>
</table>

Figure 7 Typical excitations (a) sine sweep (b) 2007 Niigata Chuetsu-Oki earthquake
Modal macro strain was extracted from the macro-strain responses through the frequency response function (FRF) technique. Typical FRFs from the intact and damaged column are shown in Figure 9. The first mode of vibration is used for damage identification. The first mode frequency of the intact column was obtained from the accelerometer and FBG as 45.01 Hz. The first mode frequency of the column after the application of the seventh load step (Sine Sweep 5–20 Hz) was obtained as 40.04 Hz. There is a substantial change in the modal frequency of the column after the seventh load step. In fact, the change in modal frequency is due to the reduction in stiffness after cracking which was confirmed through visual inspection. The column specimen after cracking is shown in Figure 10. The first crack was developed very close to the base of the column and supposed to be captured by FBG6 located in this zone. Unfortunately, performance of FBG6 and FBG1 were not good. Therefore, damage produced in zone FBG6 cannot be detected. FBG2 was selected as the reference sensor for damage identification. Through the visual inspection, it was confirmed that the zone of FBG2 was not cracked.

Scatter plot of the extracted MMS from different sensing zones of the intact and damaged column along with the corresponding fit lines are shown in Figure 11. The slope and $R^2$ values are shown in Figure 11 as well. $R^2$ values obtained for all sensing zones are very close to unity. Therefore, the extracted MMS from different sensors are in well agreement. It is obvious from Figure 11 (a) and (b) that extracted features from the intact and damaged columns lie essentially on the same line, i.e. slope of the reference model and slope of the fit line of the damaged structure for FBG3 and FBG4 do not have any significant difference. These zones do not receive any damage during the experimentation. For sensing zone FBG5, slope of the fit lines were obtained as 2.53 and 2.69 respectively at intact and damaged condition. From Figure 11(c) it is also clear that the fit line of the extracted MMS from the damaged column shifted upward. Therefore, damage in this zone can easily be detected from the increase in slope of the fit line as well as visually.
Figure 9 Typical FRFs (a) intact column (b) damaged column

Figure 10 Test column after cracking
5. CONCLUSIONS

In this paper, experimental result of seismic damage identification in a column using the surface-mounted long-gage FBG sensor is presented. The deployed sensors have the capability of obtaining the measurements integrating both local and global information. The experimental results reveal that the long-gage FBG sensors have very good sensing capacity to capture the macro strain response of a column under seismic excitations of different magnitude and the obtained results have very good agreement with the conventional sensors such as accelerometers. The FBG sensor can effectively detect and localize the damage. The initiation and progression of the crack can be determined from the captured data. It is important to note that the location of the damage can easily be found from the spatial information of the sensor. Therefore, the sensors can be deployed to assess performance of structure after some seismic event. The concept of MMSR based damage identification was also applied to detect and localize damage. The MMSR technique could detect the damage accurately. The damage state of the structure was also confirmed by frequency based damage identification technique. One important feature of the MMSR based damage detection technique is that this method does not require any physics based model, therefore, environmental temperature effect on the geometry, boundary conditions etc. or the operational conditions may not affect the damage identification process. The long term sensing capability of the FBG sensors in harsh environment is very promising. Therefore, FBG sensors and the MMSR technique can be applied for continuous monitoring of the structure. However, for better damage identification result the reference model should be calibrated using a relatively large number of data.

REFERENCES


