Online damage identification strategy using distributed macro-strain response

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ABSTRACT: Damage identification in structures is an active field of research and various methodology, techniques and/or algorithm have been proposed to this purpose. In this paper, an online damage identification strategy based on the distributed static macro-strain (MS) response measurements is presented. The basic concept of this technique is that the ratio of the strain measured at a target location and a reference location of a beam-like structure is constant for a given condition of the structure. An array of long-gage fiber Bragg grating (FBG) sensors was installed on a highway bridge in Japan to evaluate the proposed damage identification strategy. Distributed macro strain response under the normal traffic operation was measured. A test vehicle was run at different speed over the bridge and the response was measured to establish a relation between the static and dynamic macro strain measurement. Results from the onsite experiment proof the potentials of the proposed damage identification strategy for online damage identification.

1 INTRODUCTION

In recent years, damage identification in structures has drawn wide attention from various engineering fields and numerous damage identification techniques have been proposed to 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) and Montalovao et al. (2006). In most of the vibration based damage identification techniques, structural modal parameters such as modal frequencies and damping ratios, mode shapes etc., are used. One 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 be false positive or negative (Serker and Wu, 2009). Similarly, most of the static test based damage identification techniques utilize static displacement and strain (Hajela and Soerio, 1989; Sanayei and Onidede, 1991; Hjelmstad and Shin,1997; Liu, 1996; Choi et al., 2004; Caddemi and Morassi, 2007) and the health status of the intact structure is a prerequisite. Therefore, different types of data such as accelerations, velocities, displacements and strains are measured under various excitations for damage identification. Moreover, 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 several 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. Li and Wu (2007) developed a long-gage FBG sensor which can be used to measure the structural response distributedly by placing the sensors in series. Serker and Wu (2007) proposed a damage detection technique which focuses the application of the distributed static strain response. Another problem of the static response based damage identification method is with the application of the static loading which requires involvement of heavy equipment, cost and may need temporary closing of the bridge. This paper focuses on the application of the distributed macro-strain response measured under the normal traffic operating condition to detect and localize damage in RC beam-like structures. A macro-strain based damage identification technique is presented to this purpose. With the proposed technique, damage detection can be accomplished with no requirement for an analytical model and/or health condition of the intact or undamaged structure. Also

2 DISTRIBUTED LONG-GAGE FIBER OPTIC SENSING SYSTEM

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, as shown in Figure 1. In spite of high precision and excellent sensing ability, the ordinary FBG faces an unfavorable 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. After special packaging the gage length was extended to 1.0 meter 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 behavior 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. Macro strain can be defined as the average strain over any sensor with a gage length L_m, and 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.

$$\bar{\varepsilon}_m(t) = \frac{h_m}{L_m}[\theta_i(t) - \theta_j(t)] \tag{1}$$

or, in the frequency domain,

$$\bar{\varepsilon}_m(\omega) = \frac{h_m}{L_m}[\theta_i(\omega) - \theta_j(\omega)] \tag{2}$$

where h_m is the distance measured from the neutral axis of the beam to the sensor location. θ_i and θ_j are the rotational displacements of the m^{th} sensor at i^{th} and j^{th} node respectively. The most important feature is that macro-stain measurements are more sensitive to damage and can be directly applied for damage detection with no requirement for a detailed analytical model.

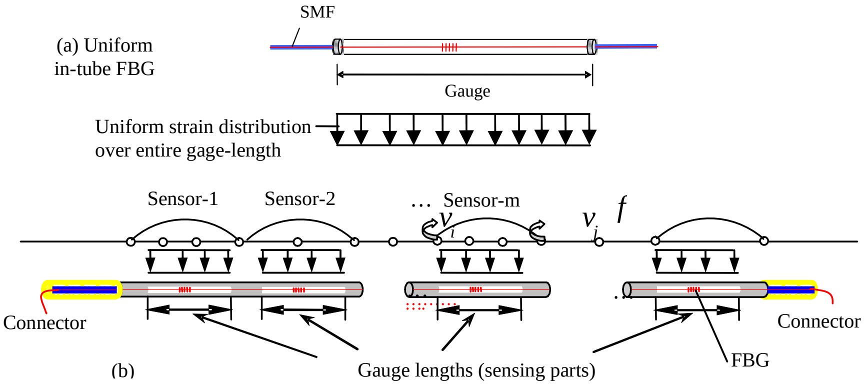


Figure 1. Long-gage FBG sensors array (Li and Wu, 2007)

3 DAMAGE IDENTIFICATION USING MACRO STRAIN RESPONSE

Bending strain of a beam-like structure, Figure 2, at any location *x* from reference can be calculated as

$$\varepsilon_x = \frac{M_x y}{EI} \tag{3}$$

where M_x is the bending moment at any location *x*, *y* is the distance between the target point and the neutral axis of the beam. *E* and *I* are respectively the modulus of elasticity and moment of inertia. For an intact beam the stress or strain at any section solely depends on the magnitude of the moment. For a given configuration and a set of loads, moment at any section depends on the distance measured from a reference section. Therefore, the ratio of the strain between two measurement locations for a given loading configuration is independent of the magnitude of the load and constant. However, the ratio of strain between two measurement locations will be changed if any one of the sections is damaged. The change in the strain ratio will depend on the stiffness reduction of the corresponding section of the beam. Thus this ratio can help detect and quantify the damage.

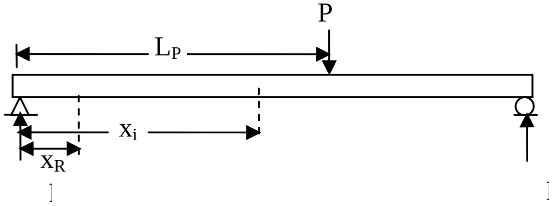


Figure 2. Fundamentals of the strain-ratio approach

3.1 *Damage localization*

Consider the simple supported beam shown in Figure 2 with a point load applied at a distance L_P from the left support. Bending strain at any section x_i :

$$\varepsilon_i = \frac{R_L x_i y}{EI} \tag{4}$$

where R_L is the left support reaction. Similarly, the strain at any reference location, x_R, can be written as

$$\varepsilon_R = \frac{R_L x_R y}{EI} \tag{5}$$

Using Equations (4) and (5), strain-ratio between these two locations can be found as

$$\gamma_i = \frac{\varepsilon_i}{\varepsilon_R} = \frac{x_i}{x_R} \tag{6}$$

From Equation (6), it is clear that for a given configuration of load the ratio of the strain between two measurement locations is equal to the ratio of the distances measured from the same reference point. For other measurement locations similar strain ratios can be obtained as

$$\{\gamma_1, \gamma_2 \ldots\ldots, \gamma_i\} = \left\{\frac{\varepsilon_1}{\varepsilon_R}, \frac{\varepsilon_2}{\varepsilon_R} \ldots\ldots \frac{\varepsilon_i}{\varepsilon_R}\right\} = \left\{\frac{x_1}{x_R}, \frac{x_2}{x_R}, \ldots\ldots, \frac{x_i}{x_R}\right\} \tag{7}$$

These strain ratios are all independent quantities and remain constant for the same loading configuration with varying amplitude of the applied load. If the damage of an element is defined as a reduction of the flexural rigidity, the damage can be expressed as follows:

$$E^* I^* = \beta EI \tag{8}$$

where E^*I^* and *EI* are the flexural rigidity of an element under damaged and undamaged states respectively. Here β $(0 \le \beta \le 1)$ is the ratio of the effective flexural rigidity at damaged and intact conditions. β is 1 with no damage and zero with complete damage in the element.

The strain at any damaged section x_i from the left support can be written as

$$\varepsilon_i^* = \frac{R_L x_i y}{\beta EI} \tag{9}$$

The strain ratio between the damaged section and the undamaged reference section can be written using Equations (5) and (9) as

$$\gamma_i^* = \frac{\varepsilon_i^*}{\varepsilon_R} = \frac{1}{\beta}\frac{x_i}{x_R} \tag{10}$$

where γ_i^* is the strain ratio between the damaged section and the reference section. From Equations (6) and (10) it is obvious that the strain ratio value changes as the measurement location encounters damage. In practice, the target structures may not be found in undamaged condition which demands some alternative to have the intact state response e.g. FEM. The above mentioned technique does not require any reference data of the undamaged structure. Sensor configuration information can be utilized as the substitution to the intact condition information.

3.2 *Damage quantification*

From equation (10) the value of β can be obtained as

$$\beta_i = \frac{\chi_i}{\gamma_i^*}$$

(11)

$$\chi_i = \frac{x_i}{x_R}$$

(12)

is the location ratio which can be found from the sensor configuration and γ_i^* can be found from the measurement data.

4 APPLICATION IN DAMAGE IDENTIFICATION

The above mentioned concept of damage detection will be applied to damage detection strategy considering that the structure to be monitored is instrumented with a series of long-gage distributed sensors and structural response is dominated by the static effect rather than the dynamic effect. By considering such criteria application of the proposed technique will be limited to certain types of structures where the dynamic effect is not prominent. The damage detection strategy is presented graphically in Figure 3. In this approach, macro-strain (MS) response data will be measured at different time instants. Next, the measured macro-strain of different sensors will be plotted against that of a reference sensor. It is obvious from Equation (6) that all points of the feature plot will lay on a 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 to shift 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

$$M_{Target} = a_1 * M_{Reference} \tag{13}$$

where a_1 is the slope of the regression, M_{Target} and $M_{Reference}$ are the extracted features from a target zone and a reference zone respectively. Let the statistical model for another set of measurements for the same zone be

$$M_{Target} = a_2 * M_{Reference} \tag{14}$$

From equation (10) it is obvious that damage causes an increase in the value of the strain ratio. Therefore, damage is likely to be present if $a_2 > a_1$. The damage identification strategy is shown graphically in Figure 4.

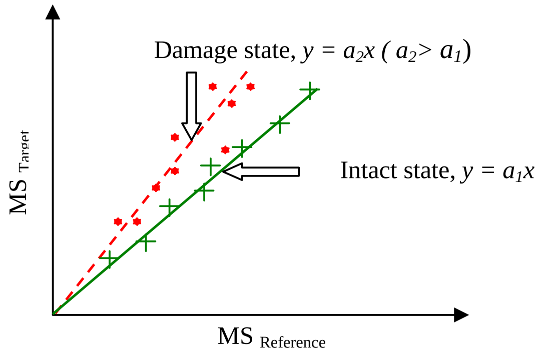


Figure 3. Application of the proposed damage identification technique in civil structures

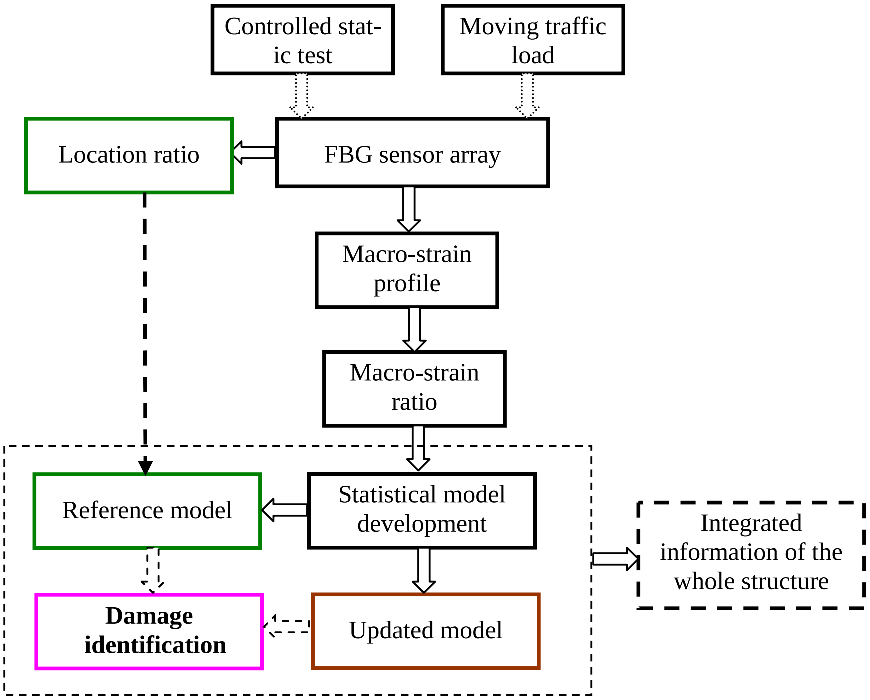
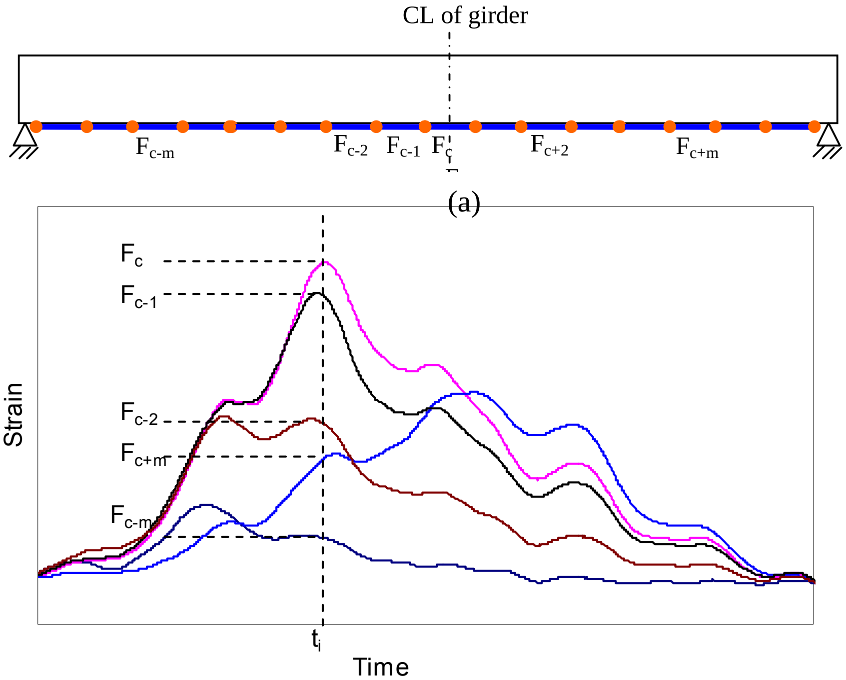


Figure 4 Flow diagram of the damage detection strategy

4.1 *Selection of representative strain*

Consider a beam instrumented with an array of distributed sensors as shown in Figure 5(a). Again, consider that the sensor located at midspan is designated as F_c, sensors located to the left of F_c are designated as F_{c-1}, F_{c-2},……. . F_{c-m} and those to the right are designated as F_{c+1} , F_{c+2} …….F_{c+m}. If vehicular traffics move from left to the right over the beam, macro-strain responses from different sensors with time can be assumed as shown in Figure 5(b). It is obvious that many strain profiles can be obtained from the recorded strain measured by different sensors. However, each strain profile may not be suitable to work with and selection of the best strain profile is very important. It is clear that responses of all other sensors will be large enough corresponding to the peak strain of midspan sensor. Therefore, maximum strain at midspan can be chosen to select the suitable strain profile. In fact, by considering such selection criteria, strain-ratio will automatically remove the effect of loading. Moreover, by considering such selection criteria, the moving load can also be considered as the static moving load, i.e., the strain is dominated by the static effect. For any time instant t_i a set of data can be obtained for different sensors. For another set of data, another peak of the strain-time history of the centrally located sensor should be selected and strain value at the same time instant will be chosen for other sensors.



(a)

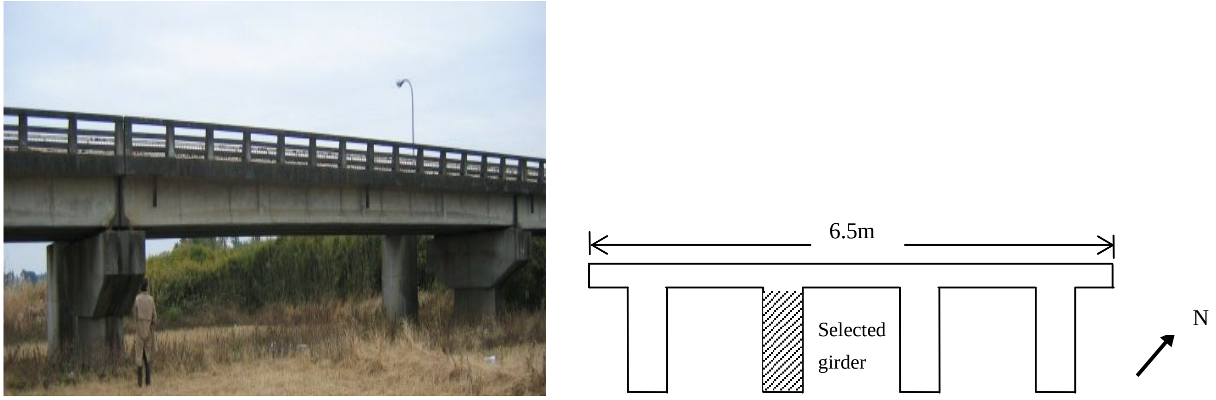
(b)

Figure 5. (a) Beam with distributed sensors (b) macro-strain time series data from different sensors

5 EXPERIMENTAL RESULTS FROM KAWANE BRIDGE

5.1 *Description of Kawane Bridge*

The Kawane Bridge, shown in Figure 6, is located near Mito city in Ibraki Prefecture, Japan. It is approximately aligned in the north and south direction. This RC bridge, constructed in 1963, has six independent spans and each span consists of a concrete deck supported by four girders. The roadway, carrying two traffic lanes, in a span is 6.5 m wide and 21.3 m long. Along the length of each span, five cross-beams are equally spaced. No damage was observed during the visual inspection of the bridge. To investigate the effectiveness of the proposed damage identification technique, the measurement data on Kawane Bridge is considered for assessment.



(a)

(b)

Figure 6. (a) A view of the Kawane Bridge (b) cross section of the bridge

5.2 *Experimental setup and data collection*

Six long-gage FBG sensors of gage-length 1 meter have been installed on one interior girder of the bridge. Details of the sensor installation are shown in Figure 7. Responses were measured using the installed sensors and were recorded in a PC. Four sets of data were collected on four different days. The sampling rate of data collection was different for different days. The sampling frequency was between 250 and 1000 Hz. The first data set was collected on August 19, 2008. The second and third data set were obtained respectively on September 17 and 18, 2008. The final set of data was collected on January 16, 2009. The first and second data collection days were clear and sunny. The weather on the third data collection day was different and it was raining during the data collection period. Air temperature was recorded using a digital thermometer.

Recorded data consist of the responses due to the normal traffic condition as well as the response due to a test bus. The total weight of the test bus was 9740kgf. Total weight on the rear and front axles was 7090 and 2650 kgf respectively. The Bridge is located on the approach road to an expressway. Therefore, the traffic is significantly composed of passenger cars, though the bridge also serves for heavy trucks. The controlled test was run at a speed of 10, 30 and 40 kmph on both lanes. In addition, the bus was stopped on either lane of the bridge to simulate static loading. Measured macro strain responses for some sensors are shown in Figure 8. Figure 9 shows the comparison of the average of the macro strain responses measured when the bus was running at speed of 30kmph along with the simulated strain response by considering the wheel loads as static moving loads. It is obvious from Figure 9 that the maximum strain measured due to the movement of the bus is very close to the maximum value of strain obtained through numerical simulation. Therefore, the assumption of considering the moving traffic as moving static loads holds good.

Response data due to movement of passenger cars as well as small and heavy trucks was collected randomly. In addition, the collected response was due to the vehicles on just each lane as well as on both lanes. Next, the features from the measured responses were selected according to the process described earlier in this paper. Extracted features are plotted in Figure 10.

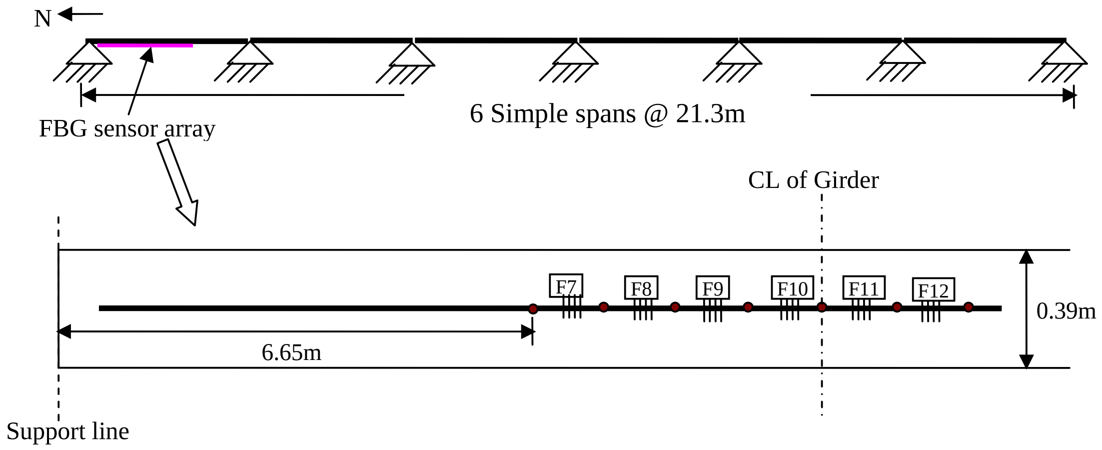


Figure 7. Sensor configuration of Kawane Bridge experiment

5.3 *Experimental results*

Sensor F7 was selected as the reference sensor and different statistical models for damage identification were constructed. The slopes and R^2 values are listed in Table 1. It is obvious from Table 1 that the extracted features from different sensors are in well agreement with that of the reference sensor. Therefore, it can be concluded that the concept of selecting the peaks of the macro-strain time history as feature for damage identification is justified. By considering the measurement data of August 19, 2008 as the reference data set, the corresponding fit lines regarded as the reference to make some comparison among the results extracted from three different data sets. It will be concluded, a sensing zone as a damaged section if the slope of the fit line of a newly measured data set increases or visually if it shifts on the upper side of the reference model. However, it will be concluded, a sensing zone as an undamaged section if the slope of the new model of a sensing zone decreases or if it moves downward From Figure 10 and Table 1, it can be seen that there is no significant change in the slope of the fit lines of different zones. However, slight change in slope was noticed for different sensing zones from day to day measurements. Visual inspection reveals no damage in the bridge. Therefore, the shifting of the fit lines is due to the environmental changes. It is noticeable that the third data set was collected on a rainy day. Since no significant variation in the measured slope of the fit lines is observed, it can be said that the proposed damage identification approach can also accommodate the changing environmental conditions.

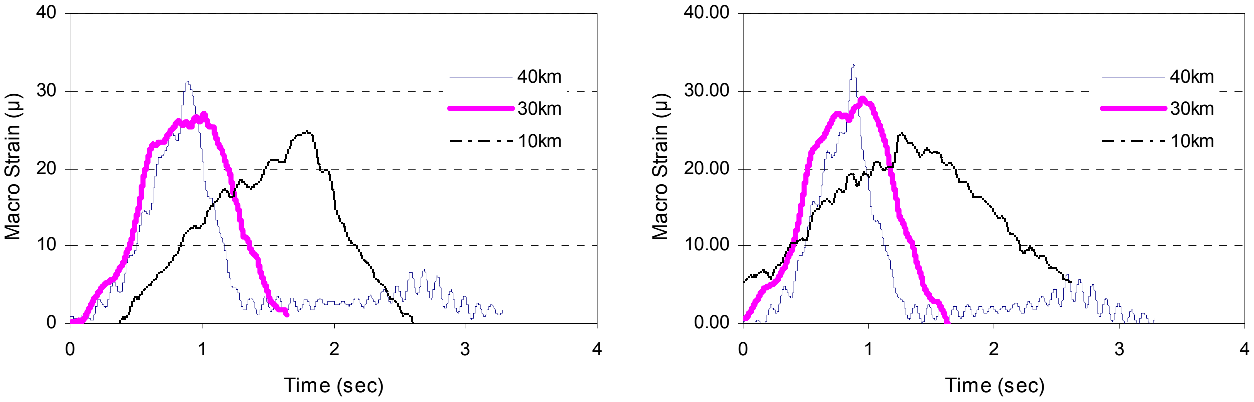


Figure 8. Macro strain recorded at different speed of the test bus (a) sensor F9 (b) sensor F10

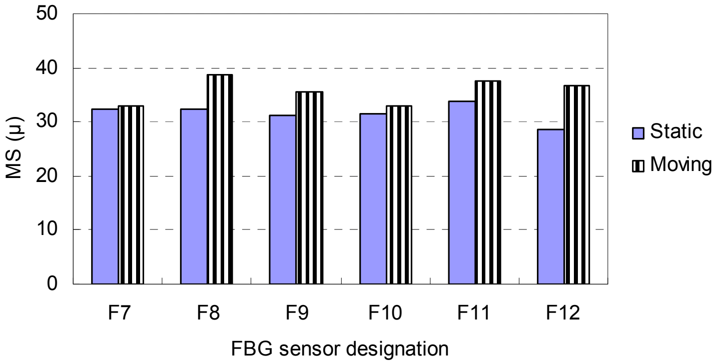


Figure 9. Comparison of the maximum strains obtained from the static and dynamic test under the test bus

6 CONCLUSIONS

In this paper, a damage identification strategy in beam-like structures using the distributed strain response measured using the long gage FBG sensors of one meter gage length has been presented. Onsite measurement data was used to verify the sensing capability of the sensors deployed as well as the applicability of the damage identification strategy. The results of controlled field experiment clearly reveal that the long gage sensors have very good sensing capability. Another important observation is that the strain response of the moving vehicle is very close to that of the static loading upto 30kmph speed of the test bus. Statistics of the evaluated DI shows the consistency of the measured responses as well as the damage identification capability of the proposed technique in normal operation condition under different environmental conditions. The current and future trend of damage identification is the use of continuously measured data under normal operating condition of the structure. Experimental results show that the proposed technique has the potential for the application of online damage identification in civil structures, especially RC bridges. In addition, the environmental changes can easily be incorporated in to the damage identification process without measuring.

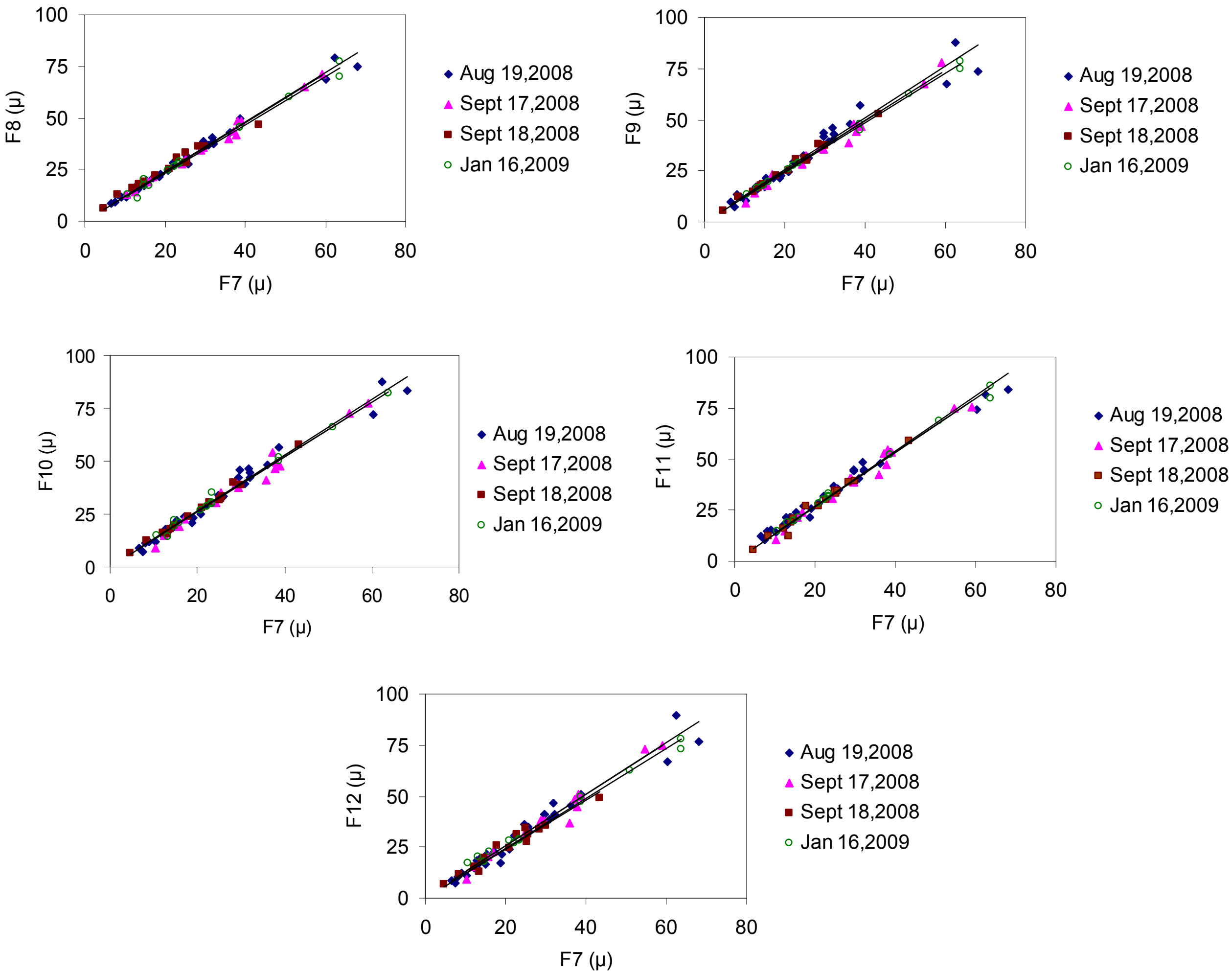


Figure 10. Monitoring results of Kawane Bridge

Table 1. Slope and R^2 values for different sensing zones

Sensing Zone	Date of Experiment							
	Aug 19, 2008		Sept 17, 2008		Sept 18, 2008		Jan 16, 2009	
	Slope	R^2	Slope	R^2	Slope	R^2	Slope	R^2
F8	1.19	0.985	1.19	0.991	1.19	0.953	1.18	0.998
F9	1.26	0.956	1.24	0.980	1.25	0.987	1.25	0.996
F10	1.31	0.978	1.29	0.976	1.30	0.987	1.30	0.996
F11	1.34	0.971	1.33	0.978	1.33	0.980	1.33	0.996
F12	1.26	0.960	1.26	0.973	1.20	0.952	1.22	0.994

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