The 3rd International Conference on Structural Health Monitoring of Intelligent Infrastructure
Vancouver, British Columbia, Canada
November 13-16, 2007

MODEL-INDEPENDENT DAMAGE IDENTIFICATION BASED ON STATISTICAL CORRELATIONS OF DYNAMIC MACRO-STRAIN DISTRIBUTION

Suzhen Li
Department of Urban and Civil Engineering, Japan

Zhishen Wu
Department of Urban and Civil Engineering, Japan

Abstract

A damage locating algorithm with no requirement for a detailed analytical structural model has been proposed in our previous research, named as modal macro-strain vector (MMSV) method, by directly using the modal parameters extracted from dynamic macro-strain data recorded by long-gage fiber optic sensors array distributed throughout the full or some partial areas of beam-like structures. Although this method has been verified to be effective by numerical simulations with different levels of measurements, noise and simple experiments under single-point excitation, the influence of the uncertainty from measuring errors and environmental disturbance is expected to be reduced to ensure it can work in more complex engineering practice. This paper proposes a method for extracting features of MMSV based on the statistical correlations among the distributed macro-strain measurements. Experimental investigations are carried out to verify the effectiveness of the extracted statistical features, based on which the originally proposed MMSV method is extended for damage quantification. Numerical case studies are finally performed to investigate the suitability and universality of the model-independent method for damage identification.

INTRODUCTION

Most vibration-based damage identification strategies developed to date are based on the dynamic responses from accelerometers, velocimeters or displacement transducers. Although large quantities of algorithms have been explored to make the most of these dynamic measurements, many challenges are still in the way of performing an effective strategy for both locating and quantifying damages in large-scale civil structures. On the one hand, damage location is usually implemented by employing model-independent methods that need not require a detailed analytical structural model and can work by directly utilizing features extracted from recorded data. However, frequency holding high measuring precision is too “global” to locate local damage; whereas mode shape and its derivatives, such as curvature mode shape, which are sensitive to damage, are difficult to acquire with enough precision. On the other hand, damage quantifying largely relies on a structural model such as the FE model, and is performed via an optimization-iterative or inverse analysis based on model updating. However, for large-scale structures, model updating requires tremendous work quantification and the effectiveness and reliability of the updated results is difficult to evaluate.

Regarding the state of art on the considerable research works for civil structural health monitoring (SHM), the concept of distributed strain sensing techniques has been employed in our efforts to develop an integrated SHM strategy for civil engineering [1]. As a typical local measurement, strain has been verified to be very sensitive to damage. However, for large-scale civil SHM, strain measurement always serves an auxiliary role, partly due to its locality that the influence of damage on strain measurement cannot be reflected effectively unless the area where the strain sensor is fixed covers the damaged region. Therefore, to detect arbitrary and unforeseen damage in a complicated structure, strain sensors have to be installed in a distributed way.

As one of the essential components in this proposed strategy, an algorithm with no requirement for a detailed analytical model is presented for locating damage in flexural structures by directly using dynamic responses from distributed strain sensors [2], named as modal macro-strain vector (MMSV) method. Although this method has been verified to be effective by numerical simulations with different levels of measurements, noise, and simple experiments under single-point excitation, the influence of the uncertainty from measuring errors and environmental disturbance is expected to be reduced to ensure it can work in more complex engineering practice. This paper proposes a method for extracting features of MMSV based on the statistical correlations among the distributed macro-strain measurements. Experimental investigations are carried out to verify the effectiveness of the extracted statistical features, based on which the originally proposed MMSV method is extended for damage quantification. Numerical case studies are finally performed to investigate the suitability and universality of the model-independent method for damage identification.

DISTRIBUTED SENSING TECHNIQUES

In contrast to the multi-point sensing techniques, distributed sensors are supposed to cover the overall structure. Take a beam for instance. Multi-point sensing means that sensors are placed in multiple special positions of the structure (e.g. at the mid-span and quarter-spans of the beam) where responses are measured. Distributed measurements, on the other hand, are ideally expected to obtain data at any point over the length of the beam.

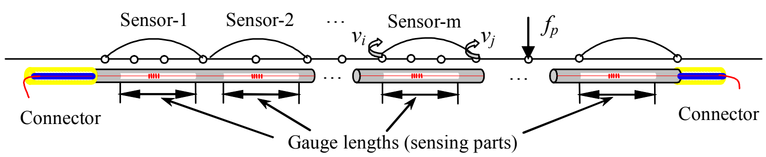

Figure 1. Distributed long-gage FBG sensor.

Fiber optic sensing techniques have been under rapid development in recent years and present a promising tool for this kind of distributed strain measurements. Regarding the on-going development of available fiber optic sensing techniques, fiber Bragg grating (FBG) sensors have better precision and measuring stability, and are currently more suitable for structural damage detection. Thus, in our recent research [3], a novel distributed long-gage FBG strain sensing system for practical adaptation to civil structural health monitoring has been developed (see Fig.1), which is expected to implement both static and dynamic measurements for strain distribution. It should be noted that this sensor array is also included in our definition for distributed sensing, which may fail to obtain the measurement at each point inside a sensor, but can yield the average response over the sensor gauge length.

EXPERIMENTAL INVESTIGATIONS

To emphasize the essential concept of the model-independent damage identification scheme, a typical elastic steel beam is first chosen as a simple illustration for experimental investigations.

Experimental Program

A simple beam with 0.96m length, 50mm width, and 3mm height is used as a beam specimen. To contrast the FE model, the beam is artificially shown in Fig.2 with 16 elements, 17 nodes (1 to 17 from left to right) and 32 DOFs. The set single damage at element 6 and double damages at elements 6, 10 with the width reduction from 50mm to

24 mm are introduced to the beam for damage identification. The geometrical sizes and material properties of the beams can be found in Fig.2. The intact beam and those with different damage scenarios are respectively denoted as [C1, C2, C3]. Distributed sensors with four long-gage FBG sensors array of 24cm gauge length are considered. Four traditional foil strain gauges of 5mm gauge length are installed for comparison.

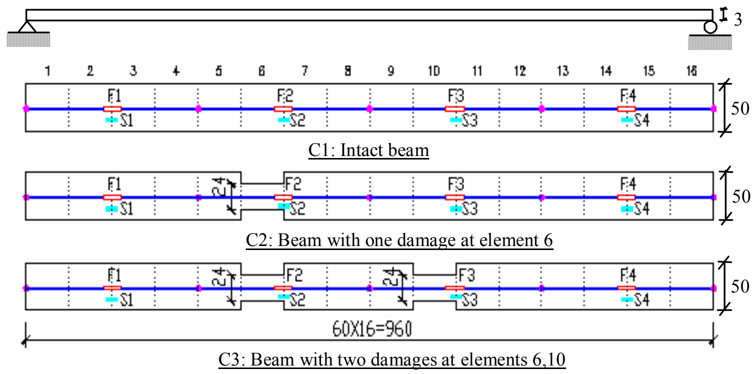

Figure 2. Experimental specimens and sensor placement.

EXPERIMENTAL MEASUREMENTS

Dynamic measurements in time domain

Dynamic tests are performed 15 times for each beam with the single-point impulsive hammer excitation applied at each free node with arbitrary amplitude. Fig.3 illustrates one case of the macro-strain time-series data for the intact and damaged beams. It can be seen graphically from the relative amplitude of strain time-history curves recorded by different FBG sensors that the damaged parts (C2F2, C3F2, C3F3) are relatively magnified.

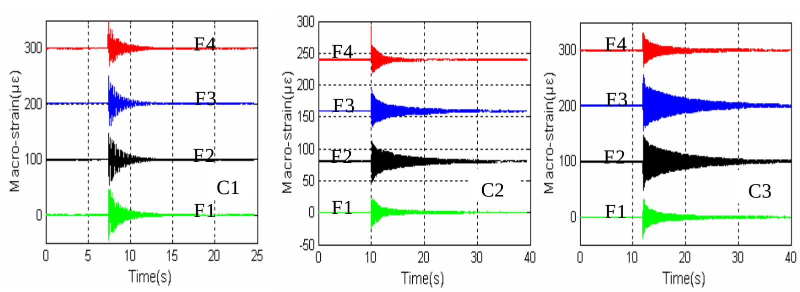

Figure 3. Macro-strain time-series data in different.

Dynamic measurements in frequency domain

Via fast Fourier transform (FFT), the strain frequency response function (FRF) can be obtained by

$$H^{\varepsilon}_{mp}(\omega)=\frac{\varepsilon_m(\omega)}{P_p(\omega)}=\frac{F(\varepsilon_m(t))}{F(P_p(t))} \quad (1)$$

where $\varepsilon(t), \varepsilon(\omega)$ are the strain response in terms of time and frequency, $p(t), p(\omega)$ are the single-point excitation in terms of time and frequency, F is the arithmetic operator for FFT. The magnitude of strain FRF from FBG sensors in a case for C2 is shown as an example in Fig.4 (1), where three obvious peaks can be found for the indications to the first three modes. Taking the first mode for consideration, the frequency spectrums under one excitation case for C1, C2 and C3 are illustrated in Fig.4 (2)-(4). Apparently with the increase of damage extent, the natural frequency and damping ratio reduce. What is more important is that in contrast with the relative value of the peaks from F1~F4 in C1, those from F2 in C2 and from F2, F3 in C3, are relatively larger and potentially offer a reference for damage locating and quantifying.

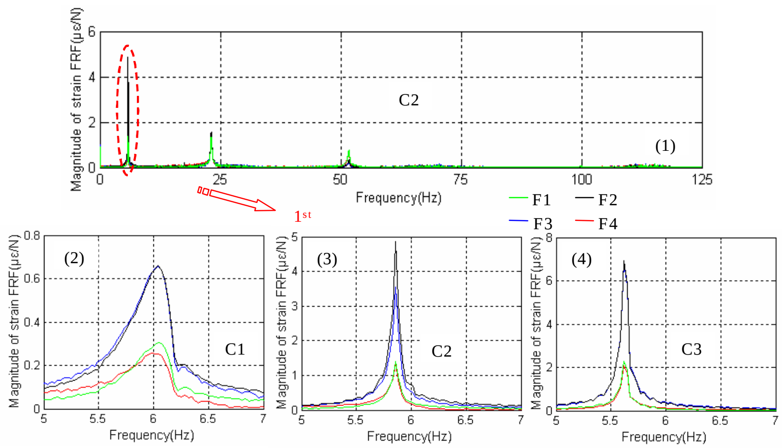

Figure 4. Frequency spectrum and extraction of modal parameters.

By assembling the magnitude of strain FRFs from various sensors, a vector named as modal macro-strain vector (MMSV) for the rth mode can be achieved as

$$\{\delta_{1r}, \delta_{2r}, \cdots, \delta_{mr}, \cdots\}^T = \left\{\left|{}_r H_{1p}^{\varepsilon}(\omega = \omega_r)\right|, \quad \left|{}_r H_{2p}^{\varepsilon}(\omega = \omega_r)\right|, \quad \cdots, \quad \left|{}_r H_{mp}^{\varepsilon}(\omega = \omega_r)\right|, \cdots\right\}^T \quad (2)$$

The component δ_{mr} is correspondingly named as modal macro-strain (MMS). It should be noted that similar to mode shape, this vector ignores the amplitude and only emphasizes the relative ratio of all components.

As FBG sensors and strain gauges employed the different sampling rates, their MMSVs in various cases are constructed respectively. Consider the first mode. The correlations denoted by discrete points between the MMSs from S2~S4 and all FBG sensors and those from S1 including all excitation cases with single-point impulsive load arbitrarily applied in each node, are assembled into Fig.5 (1)-(3). To compare the results of the intact and damaged beams, the correlations between the MMSs from F1~F4 and those from S1 in the cases of C1~C3 are depicted in Fig.5 (4). By fitting these recorded discrete points, perfect lines can be obtained. The slopes of the fit lines obtained by the FBG sensors fixed to the area involving the damages (C2F2, C3F2, C3F3) present evident difference from those from the intact beam (C1). This is valuable for vibration-based damage detection due to the fact the slope of the fit line may provide a more reliable index in view of statistical concept.

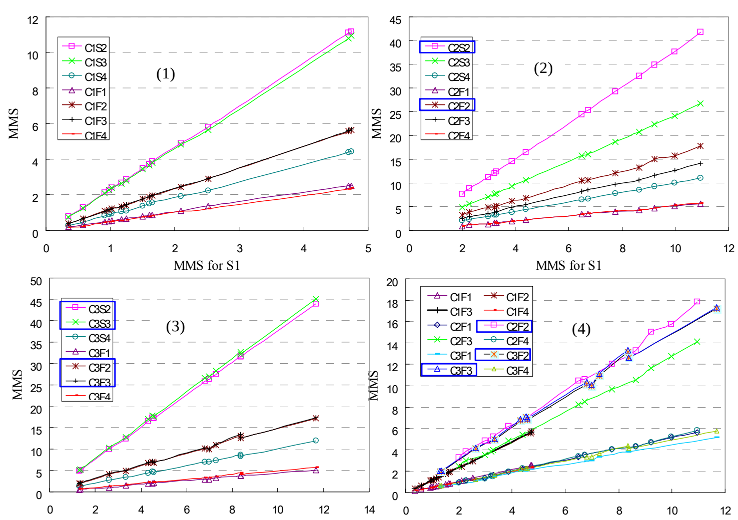

Figure 5. Modal stain measurements under dynamic.

Data Processing and Interpretation

Table 1 gives the correlation coefficients of MMS in various impulsive load cases for each beam. Clearly, perfect linear correlations have been achieved, which verifies the important conclusion that MMSV is a natural property of a structure, independent of external load, and only emphasizing the relation among the vector components, regardless of amplitude. Moreover, the fit line is a type of statistical result, helpful to reduce random errors by fitting the measurements from various load cases.

Table 1: Correlation coefficients of MMS in various impulsive load cases.

Cases	F1	F2	F3	F4
C1	0.9998576	0.9998832	0.9998547	0.9994244
C2	0.9999617	0.9998853	0.9999289	0.9999289
C3	0.999231	0.9991352	0.9989113	0.9992476

What is most important, is the fact that the slopes of the fit lines are actually the components of the normalized MMSV as defined in Eq.(2) by taking the MMS from S1 for reference. The normalized statistical MMSVs (i.e. slopes of fit lines) for each beam are given in Table 2, where the highlighted characters in block emphasize the damaged parts.

Table 2: Normalized statistical MMSV from experiments.

Cases	C1	C2	C3
F1	0.5361	0.5058	0.4547
F2	1.1940	**1.5055**	**1.5039**
F3	1.1975	1.2232	**1.5166**
F4	0.5048	0.5168	0.5017

For the convenience of the later statement, suppose the normalized MMSV as

$$\{\psi_{1r}, \psi_{2r}, \cdots, \psi_{mr}, \cdots\}^T \qquad (3)$$

A damage index vector can hence be defined by the relative error of the normalized MMSV from intact and damaged structures as

$$\{\beta_{1r}, \beta_{2r}, \cdots, \beta_{mr}, \cdots\} \qquad (4)$$

with each component obtained by,

$$\beta_{mr} = \frac{\psi^*_{mr} - \psi_{mr}}{\psi_{mr}} \times 100\% \qquad (5)$$

where the superscript "*" represents the damaged state.

DAMAGE QUANTIFYING BASED ON NORMALIZED STATISTICAL MMSV

It can be found from the above experimental investigations that the damage index based on the normalized statistical MMSV provides a nice indication to damage identification. In the following discussions, numerical case studies will be performed to investigate the relation of this index and damage extent.

Damage Locating

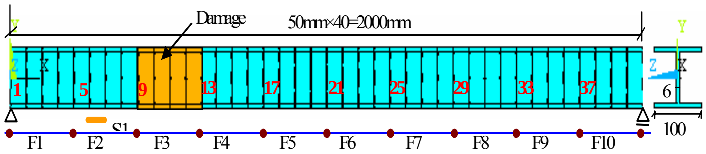

Figure 6. Beam model and sensors placement.

A steel beam of "I" cross section with rollers supported at two points is selected as an object structure. The finite element (FE) model with 40 elements and its detailed dimensions is illustrated in Fig.6. Ten long-gage strain sensors of 200mm gauge length are supposed to be installed onto the bottom surface of the beam in a distributed way, denoted by F1~F10. A sensor of 50mm gauge length shown as S1 is also fixed in parallel at the bottom surface of element 6, which plays the same role as the S1 strain gauge in the above experimental investigations to provide a basis on which the MMS from the distributed sensors can be normalized. In total, 12 cases, denoted as C1~C12, are designed for this study, named by case study 1(CS1). As shown in Table 3, damages are simulated as different levels of the reduction of elastic modulus in the area where F3 is installed (i.e. elements 9~12 in Fig.6). Since the purpose of damage identification is primarily supposed to detect small and medium damage, this work only investigates the damage below 50%.

Table 3: Designed cases for CS1.

Cases	C1	C2	C3	C4	C5	C6
Damage extent	0	1%	5%	10%	15%	20%
E *(E+11)	2.1	2.08	2	1.89	1.79	1.68
Cases	C7	C8	C9	C10	C11	C12
Damage extent	25%	30%	35%	40%	45%	50%
E *(E+11)	1.58	1.47	1.37	1.26	1.16	1.05

The normalized MMSVs for the first mode as well as the damage indexes in all cases are then calculated. It can be found from Fig.7 that damages can be easily located for the β from F3 obviously increase, whereas the β*'s* from the other FBG sensors change little. This feature is very important because in this way the stain sensor only responds to the damage appearing in its gauge length and its inertia to the damages in other locations, which helps to solve the problem facing to traditional transducers such as accelerometers or velocimeters that their responses in translational DOFs are global quantities of structures that are considered being insensitive and having no clear relationship to a specific local damage even near the transducers.

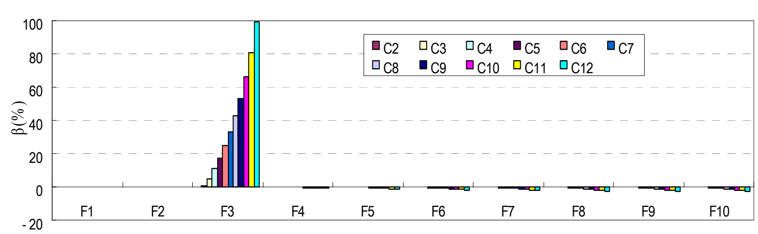

Figure 7. Damage index in CS1.

Damage Quantifying

Aiming at F3 in all above-mentioned cases, a quantitative relation between damaged extent and β_3 in Fig.7 can be achieved. To investigate the suitability and universality of such a relation, considering the same beam model and sensors placement as illustrated in Fig.6, case study 2 (CS2) is performed with the designed cases shown in Table 4. In the cases of single damage including D1~D9, damages are simulated as the reduction of elastic modulus in the area where F1 or F3~F10 is installed with different damage levels from those in C1~C12. The cases of multiple damages are then investigated including D10~D13 with the damaged elements and their respective damage extents in Table 4. It should be noted here that the terms “single” or “multiple” damages depends on the damage that occurs in the area in the charge of a single long-gage sensor or more sensors, rather than structural elements.

Table 4: Designed cases for CS2.

Cases	Single Damage						
	D1	D2	D3	D4	D5		
Damaged elements	1~4	9~12	13~16	17~20	21~24		
Damage extent	C1~C12 (for each case)						
Cases	Single Damage						
	D6	D7	D8	D9			
Damaged elements	25~28	29~32	33~36	37~40			
Damage extent	C1~C12 (for each case)						
Cases	Multiple Damages						
	D10		D11		D12		
Damaged elements	9~12	21~24	9~12	21~24	9~12	21~24	25~28
Damage extent	C1~C12		C4	C2~C12	C5	C3	C2~C12
Cases	Multiple Damages						
	D13						
Damaged elements	9~12	21~24	25~28	33~36			
Damage extent	C7	C2	C6	C2~C12			

Focus on the sensors which are installed in the region involving damages such as F3 in Fig.7. For each sensor in the case of a given damage extent, one point representative of the relation of damage extent vs. β can be plotted. Assembling all the points obtained from the above-mentioned cases (totally 99 points for the cases of single damage and 121 points for multiple damages), it can be seen in Fig.8 that a perfect quadratic curve is obtained. Via polynomial fit, this curve can be expressed as:

$$y(x) = 0.0271x^2 + 0.60374x + 1.458 \qquad (6)$$

with x for damage extent (%) and y for the damage index β (%). So far the fit polynomial Eq.(6) is finally established for damage quantifying.

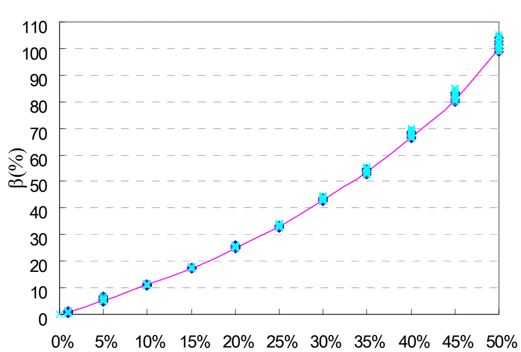

Figure 8. Damage index vs. damage extent in CS2.

Damage in a Certain Location inside the Sensor Gauge Length

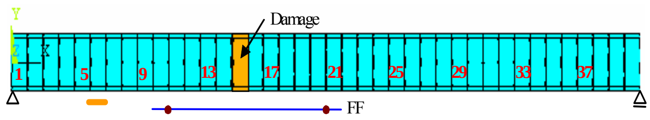

Figure 9. Beam model and sensors placement.

Since damage is a local phenomenon, a long-gage sensor definitely covers a certain length along a structure, hence in many cases, damage is sure to appear somewhere inside the sensor gauge length. Suppose that the beam model in Fig.6 incurs a single damage at element *i* (see Fig.9). Consider a long-gage sensor, denoted FF with the gauge length over *n* elements including element *i*. Based on the above description, the damage index concerning the damaged element can be calculated from Eq.(6), i.e.

$$\beta_i = y(x) \qquad (7)$$

whereas those concerning the remaining intact elements hold

$$\beta_{i+1} = \beta_{i+2} = \ldots = \beta_{i+n-1} = 0 \qquad (8)$$

Thus the relative error of MMS concerning FF should be

$$\beta_{FF} = \frac{\sum \beta}{n} = \frac{\beta_i}{n} = \frac{y(x)}{n} \qquad (9)$$

The relation of β_{FF} vs. damage extent of element *i* concerning different *n's* is shown in Fig.10. This figure provides very important information that if β from a long-gauge sensor is known, the damage extent can be evaluated by giving in-advance estimation on what percentage of the gauge length of the sensor the damage is localized on. For example, if β is 10%, the damage extent is supposed to be 10% based on the assumption that the damage is evenly distributed over the whole gauge length of the sensor, or to be 18% on that the damage does over half of the sensor gauge length, or to be 44% on that the damage is localized to 1/8 of the sensor gauge length.

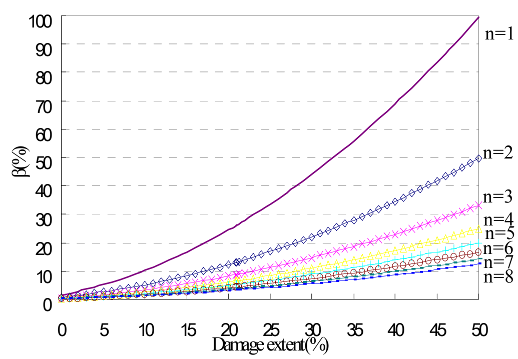

Figure 10. Damage index vs. damage extent.

Damage Identification Based on the Above Experiments

It can be seen directly from the block characters in Table 2 that by comparing the MMSs from the sensors installed on the intact beam, those corresponding to the damaged location change considerably. Recalling Fig. 10, damage quantification can be performed as shown in Table 5. It is obvious that if the estimation on the localized extent of damage is approximate (n=4 here), the damage can be quantified with high precision. Otherwise (i.g.n=1), the damage extent may also be given in an average concept.

Table 5: Damage quantification based on experiments.

Sensor	C1	C2				
	MMSV	MMSV	β	Damage extent		
				n=1	n=4	set
F1	0.5361	0.5058	-5.65%	0	0	0
F2	1.194	**1.5055**	**26.09%**	**21.0%**	**51.5%**	**52%**
F3	1.1975	1.2232	2.15%	1.0%	8.5%	0
F4	0.5048	0.5168	2.38%	1.5%	9.8%	0
Sensor	C1	C3				
	MMSV	MMSV	β	Damage extent		
				n=1	n=4	set
F1	0.5361	0.4547	-15.2%	0	0	0
F2	1.194	**1.5039**	**25.95%**	**20.9%**	**51.3%**	**52%**
F3	1.1975	**1.5166**	**26.65%**	**21.3%**	**52.1%**	**52%**
F4	0.5048	0.5017	-0.61%	0	0	0

CONCLUSIONS

In this paper, a model-independent method for damage locating and quantifying is proposed based on the statistical correlation of modal parameters among the measurements from distributed fiber optic sensors. Some important conclusions are summarized as follows:

(1) On the basis of dynamic long-gage strain distribution, a normalized MMSV can be constructed by taking the MMS from a given sensor for reference. A damage index vector is defined as the relative error of the normalized MMSV from intact and damaged structures.
(2) A polynomial equation representative of the relation of the damage index vs. damage extent is put forward for damage quantifying by fitting the results from numerical case studies. The method for quantifying the damage in a certain location inside the sensor gauge length is presented.
(3) In view of practical applications, the normalized MMSV can be directly constructed by statistically processing the measurements under different load conditions. Experimental investigations on steel beams have verified that based on such normalized MMSV, the presented damage index is effective and accurate to locate and quantify the set damage.

REFERENCES

1. Zhishen Wu and Suzhen Li: "Structural damage detection based on smart and distributed sensing technologies" (Keynote), *Proc. of the 2nd International Conference on Structural Health Monitoring of Intelligent Infrastructure*, pp107-120, 2005

2. S.Z.Li and Z.S.Wu.: "A non-baseline algorithm for damage locating in flexural structures using dynamic distributed macro-strain responses" *Journal of earthquake engineering and structural dynamics* (Published on line: 11 Jan 2007)

3. S.Z.Li and Z.S.Wu: "Development of long-gage fiber optic sensors for structural health monitoring". *Structural Health Monitoring* (In press), 2006