ADVANCEMENT OF BRIDGE HEALTH MONITORING BASED ON DISTRIBUTED FIBER OPTIC SENSORS

Zhishen Wu[1], Suzhen Li[2] and Koichi Yokoyama[3]

Abstract

Over the past few years, our lab has carried out a series of studies based on advanced distributed strain sensing techniques for the development of an integrated structural health monitoring (SHM) system. This paper performs a thorough and systematic review on the important results of this work, including the development of a feasible distributed long-gage strain sensing system for practical adaptation to civil structural engineering, innovative analysis and interpretation of the measured data, as well as use of the generated information to implement effective diagnosis and monitoring.

Introduction

Structural health monitoring (SHM) for on-line diagnosis of damage, assessment of the safety and integrity of infrastructure, and evaluation of the remaining structural service life has received considerable interest in contemporary literature. Most of the existing SHM research has focused either on global damage assessment techniques using structural dynamic responses, or on limited local independent damage detection mechanisms. The amount of literature related to this area is quite extensive [1, 2, 3].

Some of the critical challenges presently facing the development of civil SHM systems that are largely based on traditional, widely-used sensing technologies (e.g. accelerometers, velocimeters, displacement transducers, and foil strain gauges) include the fact that:

(1) Structures are large and complex but structural damage is usually localized;

(2) Static fielding tests require expensive equipments, laborious arrangements, and suspension of the normal working condition of the structures;

(3) The sensitivity of the frequency shift due to local damage is very small despite the relatively high measuring precision of the natural frequency for vibration-based SHM. On the other hand, the mode shape may be more sensitive to damage but easily disturbed by measuring noise. Furthermore, limited by measurement practice, it is often necessary to derive a more reliable and effective index for damage diagnosis from the translational mode shape, such as a second differential to calculate curvature, which in turn greatly enhances the influence of the measuring noise and makes many algorithms theoretically feasible but practically ineffective;

(4) A critical issue regarding FE model updating for civil structures is that although

---

[1] Professor, Dept. of Urban and Civil Engineering, Ibaraki University, Hitachi, Japan
[2] College of Civil Engineering, Tongji University, Shanghai, China
[3] Professor, Dept. of Urban and Civil Engineering, Ibaraki University, Hitachi, Japan

the number of unknown parameters is usually large, the measured responses are so limited that the inverse or optimal algorithms seldom come to convergence and the updated results are hard to evaluate;

(5) Most traditional measurement variables, such as acceleration, velocity and displacement, are essentially “point” measurements at a translational degree of freedom (DOF). Such translational responses are global quantities of structures which are considered insensitive and having no clear relationship to a specific incident of local damage, even for those occurring near the transducers. Moreover, for the case of multiple damage incidents at different locations or for different kinds of damage, the situation will be extremely complicated. The mutual influence of structural damage on the measurements makes it difficult to perform effective structural parametric and damage identification;

(6) Strain may be the most sensitive parameter to local damage. However, the influence of damage on a strain measurement cannot be reflected determined effectively unless the area where the strain sensor is fixed exactly covers the damaged region. However, this is difficult given the fact that structural damage is an arbitrary and unforeseen phenomenon. Actually, traditional foil strain gauges are far from taking the task to monitor a structure not only owing to problems concerning stability, durability, long-term reliability, as well as the difficulty for large area distributed placements.

Therefore, with regard to these existing obstacles which traditional SHM manners may be far from overcoming, as some experts strongly suggested, it is important to introduce some inherently innovative elements to help the current SHM research get out of the dilemma.

Based on advanced distributed strain sensing techniques [4], a series of systematic studies have been carried out in our lab to put forward an integrated SHM system, as outlined in Fig. 1. This work involves three parts: the development of a feasible distributed long-gage strain sensing system for practical adaptation to civil structural engineering, the innovative analysis and interpretation of the measured data, and the use of generated information to implement effective diagnostic and monitoring capability.

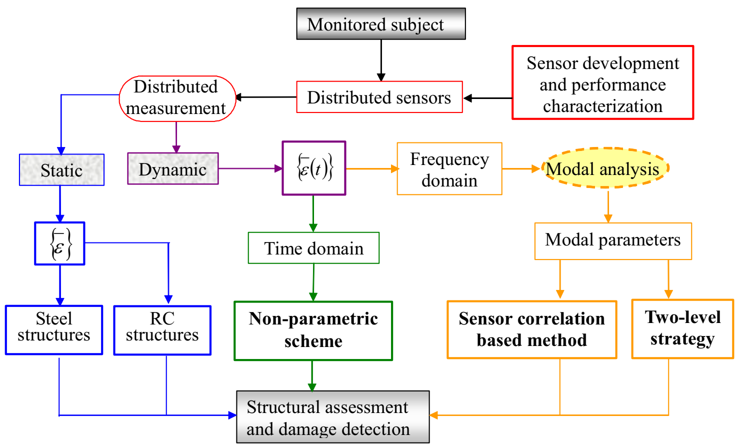


Fig. 1 An overall view of this work

A Distributed Long-gage Fiber Optic Sensing System [5]

A long-gage fiber optic sensor array based on a fiber Bragg grating (FBG) has been developed to implement distributed static and dynamic strain sensing, as shown in Fig. 1. In spite of its high precision and excellent dynamic measuring ability, the ordinary FBG faces an unfavorable problem in that its inherent gauge length is around 1-2cm, which makes FBG appropriate as traditional “point” strain gauge but inappropriate for distributed placement. Our idea is to extend the sensor gauge length by first using a tube to sleeve the optical fiber and then fixing the two ends of the tube.

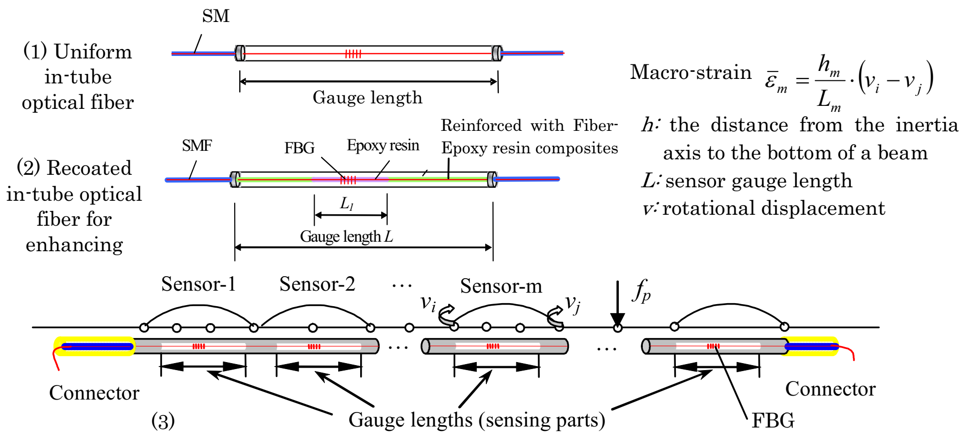


Fig. 2 Long-gage FBG sensor array

For a general long-gage sensor (Fig. 2 (1)), 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 say macro-strain) over the sensor gauge length. In order to obtain effective measurements in the case where the strain response is very small or environmental noise is large, an improved packaging design is proposed to enhance the measuring sensitivity of long-gage FBG sensors (Fig. 2 (2)) by utilizing two materials with different modulus to package the optic fiber and to impose deformation within the gauge length L, largely on the essential sensing part of the FBG L1. After connecting the long-gage sensors in series, an FBG sensor array can be realized, for distributed macro-strain measurements (Fig. 2 (3)). Proof tests have verified the ability of the developed sensors for both static and dynamic measurements.

The developed sensors are characterized by their capability to obtain measurements that integrate both local and global information, which is due to the fact that: (1) strain is typically a local response; (2) distributed sensor placement helps to record the data covering the large region of a structure; (3) a the high sampling rate of FBG interrogator makes it possible to obtain broad-band spectrum and global modal parameters. Widely-used transducers, such as accelerometers, velocimeters and displacement transducers essentially provide some kind of measurement of the translational degrees of freedom (DOFs). In contrast, the macro-strains from long-gage FBG sensors have a clear relation with rotational displacements (see Fig. 2). In light of this feature, the novel sensors can perform similarly to conventional transducers. What is more important 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 or say a baseline structure.

SHM Strategy Based on Static Sensing

Health Monitoring of Steel Flexural Structures [6]

To characterize the ascendancy of the developed sensing system and provide a valuable reference for long-term monitoring, the research concerning practical application of the innovative sensors in SHM begins with experimental investigations of steel flexural structures. Steel beams with "I-shaped" cross-section are designed as the test specimens, supported at two points and installed by various sensors, as shown in Fig. 3. By and large, this part of the work is devoted to the comparison of the newly developed and the traditional sensors from the perspective of SHM.

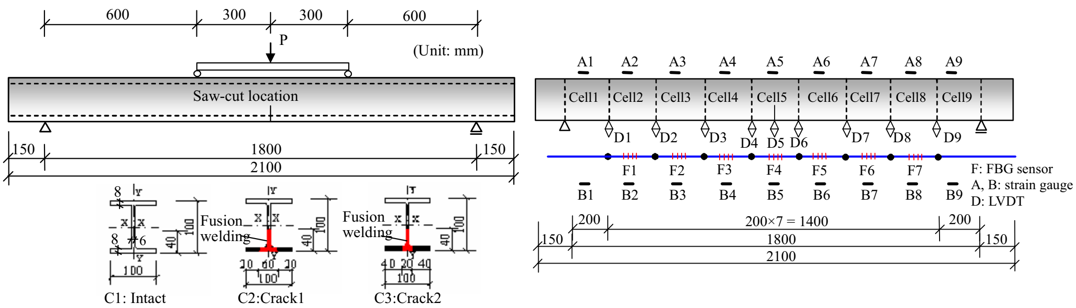


Fig. 3 Steel specimens and sensor placement

Since there is no requirement for an analytical model, damage identification can be performed by directly utilizing the measurements from various sensors. Focusing on the pure bending sections, including Cell4, Cell5 and Cell6, the identified results in the case of small damage (C2) are displayed in Fig. 4. Apparently, the FBG-based method is effective, as the measurements from F3, F4 and F5 for the intact beam agree well, while those from F4 obviously deviate from the data obtained by F3 and F5 for the damaged beam. Comparatively, it seems that the measurements from the strain gauge, which is installed precisely at the location where the crack damages are preset (B5), differ remarkably from the other measurements. However, the strain gauges placed at multiple points face a very unfavorable problem: the measured responses are so concentrated on the local information that they are too vulnerable to localized uncertainties to reflect damage accurately. Moreover, at least one sensor must be fixed exactly to the damaged area, which is difficult to implement by employing such "point" sensors for large-scale structures due to the fact that damage is an arbitrary and unforeseen phenomenon inherent in the structures. For direct measurement of the global displacement parameter, curvatures are usually constructed via central differentiation as the features of interest for damage detection. It can be seen from Fig. 4 (3) that the features obtained in this way are seriously disturbed by measuring noise and fail to identify the damages practically.

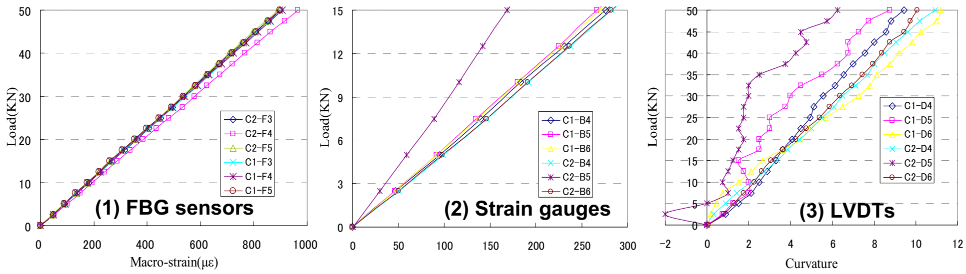
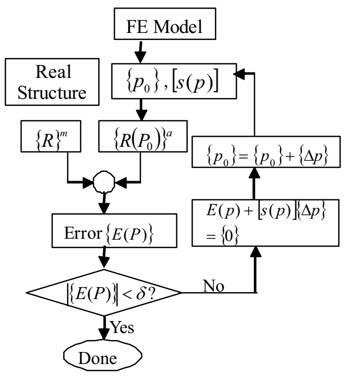


Fig. 4 Model-free damage identification based on various sensors

The intact beam C1 is specially selected for structural parametric estimation. A finite element (FE) model is first established and model updating is carried out to bridge the gap between the numerical model and experimental measurements. The flexural stiffness of the beam corresponding to each cell is considered as an object parameter for identification. An optimization-iterative algorithm (see Fig. 5 (1)) is then employed to estimate structural parameters based on the static macro-strain distribution from the FBG sensor series as well as the displacement responses from LVDTs. As shown in Fig. 5, the satisfied results can be achieved based on a macro-strain distribution with the maximum error below 10%, whereas the algorithm fails to converge to a stable solution in the case of displacement measurements. Therefore, a significant fact can be claimed, which is that distributed long-gage sensors, rather than LVDTs, are more suitable for structural parametric estimation because macro-strain, unlike displacement, only responds to external influences such as loads or structural damages in the area where the corresponding sensor is installed and is inertia to those in the other areas.



(1) Optimal-iterative algorithm for parametric estimation based on static sensing

(2) Parametric estimation based on macro-strain distribution

Iterative times	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Cell 7	Cell 8	Cell 9	$\|E(p)\|^2$
1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	71821.3
10	6.582	7.170	6.683	6.526	6.210	5.998	4.990	3.075	1.962	389.4025
20	6.811	7.419	6.916	6.798	6.561	6.438	5.598	4.482	3.386	117.6589
40	7.152	7.790	7.262	7.201	7.081	7.086	6.478	6.283	5.485	19.20183
60	7.338	7.994	7.451	7.423	7.366	7.441	6.959	7.246	6.634	3.600589
80	7.430	8.093	7.545	7.532	7.505	7.615	7.194	7.715	7.195	0.696298
100	7.473	8.139	7.588	7.582	7.570	7.695	7.303	7.931	7.456	0.136584
150	7.503	8.172	7.618	7.617	7.616	7.753	7.380	8.085	7.641	0.002283
200	7.507	8.177	7.622	7.622	7.622	7.760	7.390	8.105	7.665	4.08E-05
500	7.508	8.178	7.623	7.623	7.623	7.762	7.392	8.108	7.669	3E-07
Exact	7.490	7.490	7.490	7.490	7.490	7.490	7.490	7.490	7.490	
Error (%)	0.23	9.18	1.78	1.78	1.78	3.63	-1.31	8.25	2.39	

(3) Parametric estimation based on displacement measurements

Iterative times	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5-1	Cell 5-2	Cell 6	Cell 7	Cell 8	Cell 9	$\|E(p)\|^2$
1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	4.38142
2	1.490	1.899	1.518	1.800	1.540	1.688	1.464	1.640	0.791	1.041	1.582668
5	4.214	3.964	4.917	5.977	4.300	7.569	2.679	9.768	0.808	1.242	0.116995
8	5.332	4.431	5.858	7.566	5.191	18.967	2.831	339	0.871	1.550	0.049384
10	-502469	2375	-8650	-143	325	5619	-0.056	30088	3.468	1.727	2.73E+01
15	277240	-238471	877831	6212	-1607	12647	-0.747	65278	-83245	1.557	1.15E+00
20	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN

Fig. 5 Model-based parametric estimation based on various sensors

An interesting idea is proposed here for long-term structural health monitoring based on the correlations of the static strain distribution. Consider the above experimental results. At a certain time, seven static macro-strain measurements from F1~F7 can be obtained. Take the data from F1 as a reference, for example. Given a coordinate system with macro-strain values from the reference sensor on the x axis and those from all the sensors on the y axis, seven points are drawn from this measurement. Suppose that the data is recorded at a certain sampling rate. Apparently, as is shown in Fig. 6, if there is no damage, the points corresponding to a sensor are all located on a straight line with a determined slope. When damage happens, the points will severely deviate from the original track and eventually sit on a straight line with another slope. The advantage of this method lies in the fact that the indication to damage is sensitive and statistically reliable, which will greatly reduce the disturbance due to measuring errors and environmental noise. An important issue worth noting is that the reference sensors should be those installed onto the area with the minimum probability of incurring damage during the structural in-service term, such as the parts or members undergoing a relatively small load, having excellent material properties, or serving in a good environmental condition, etc.

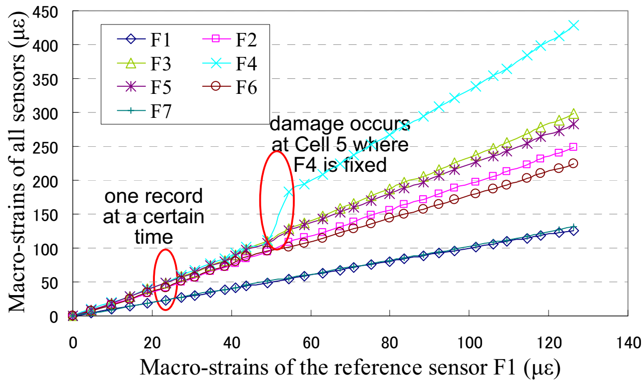
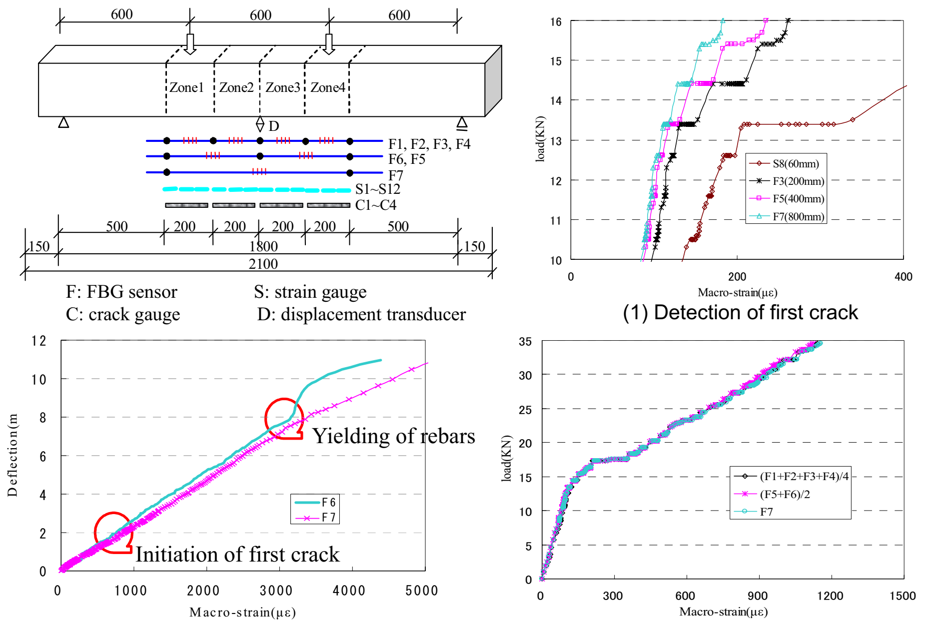


Fig. 6 Long-term monitoring based on the correlations of static strain distribution

Health Monitoring of RC Flexural Structures [7]

Health monitoring of RC structures often includes two main concerns with regard to local damage detection and global structural behavior. A normal RC beam with a flexural failure mode in the design is taken as an example for our experimental investigations. FBG sensors of different gauge lengths are installed onto the bottom surface of the beam, as illustrated in Fig. 7. The important findings concerning the behavior of FBG sensors in the application of RC structures are summarized as follows: (1) The FBG sensor array can effectively detect the occurrence, location and extent of cracks. With an increase in gauge length, FBG sensor may weaken the stress/strain concentration (Fig. 7 (1)); (2) The macro-strains measured by a sensor of gauge length 0.4m or longer present a perfect linear correlation with the deflections at the mid-span from a displacement transducer (Fig. 7 (2)). This leads to the very valuable conclusion that as long as the distributed sensors are reasonably installed, they can replace the displacement transducer, which is often used for global displacement measurements but is difficult to affix to practical civil structures due to the baseline position requirement; (3) The macro-strains over a gauge length of 800mm from the FBG sensors of different gauge lengths are compared in Fig. 7 (3). The nice agreements verify that macro-strain measurements over a certain gauge length can be obtained from the average of those over several sub-gauge lengths. In the other words, the four distributed FBG sensors of 200mm gauge length can also act as the strain sensors of 400mm, 600mm and 800mm gauge length.



(2) Deflection vs. macro-strain curves (3) The average of macro-strain measurements

Fig. 7 Experimental investigations on a normal RC beam

On the other hand, by employing a typical fiber section model (Fig. 8) on the basis of the plane section assumption, the nonlinear behavior of this RC beam is simulated. It is confirmed that the load vs. macro-strain relations match well with the analytic results before initiation of the first cracks and have close agreement with those after cracking. This confirmation is important because it ensures that the macro-strain measurements, unlike traditional "point" measurements, may represent the strain responses for the "plane section." That is to say, by virtue of the distributed long-gage sensors, a solid interrelation of the measured strain response, structural parameters including material and geometric properties, as well as loads can be constructed based on classic bending theory. Any one of them can be estimated as the others are known in advance. Therefore, the method of inverse analysis is proposed for load or parametric identification of RC flexural structures.

Combined with experimental and analytical investigations, an integrated health monitoring strategy for RC flexural structures based on the developed long-gage fiber optic sensors array is finally put forward in Fig. 9, including: (a) local damage identification, (b) parametric estimation, and (c) global behavior evaluation.

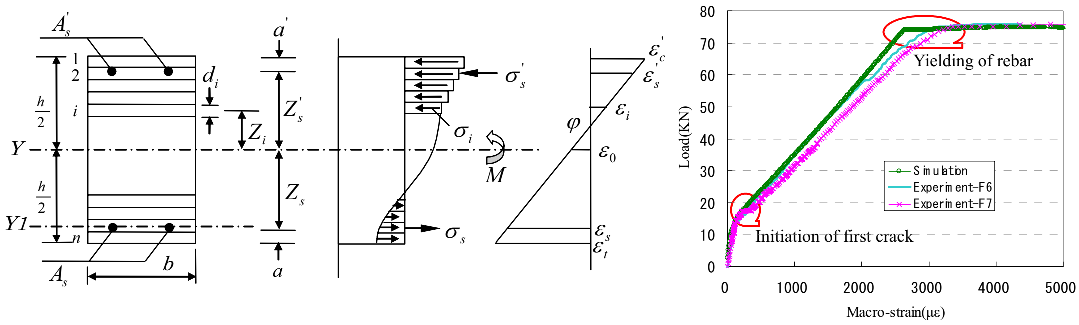


Fig. 8 Fiber section model for simulation

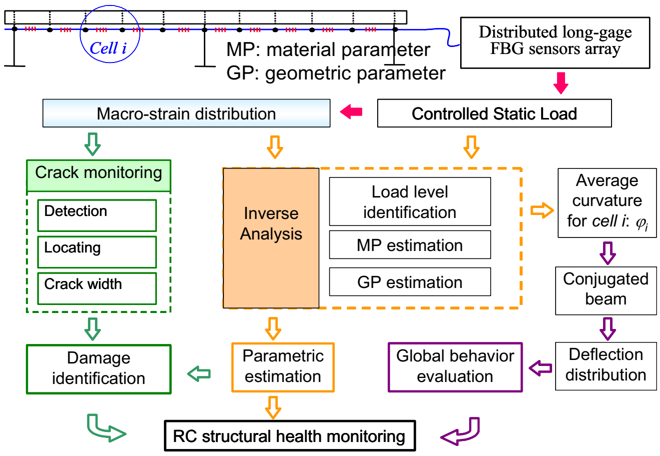


Fig. 9 SHM strategy on RC flexural structures based on static sensing

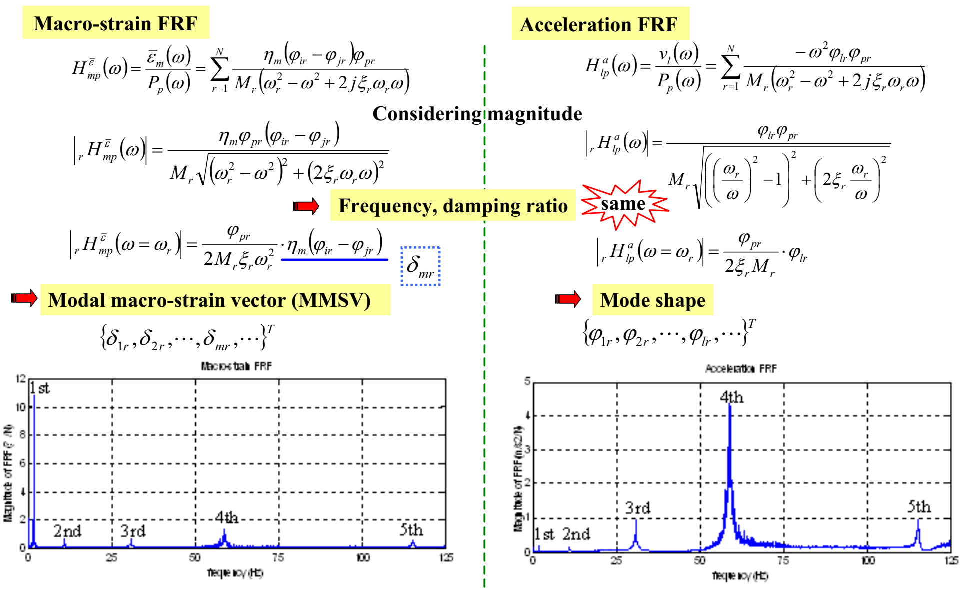
SHM Strategy Based on Dynamic Sensing

As is summarized in Fig. 1, the SHM research based on dynamic sensing is approached from two angles: the time and frequency domain. Many years ago, a neural network based algorithm was proposed for damage identification using time-series data. Interested readers can go directly to the references [8, 9]. Another scheme developed in the frequency domain will be stressed here instead. After performing modal analysis, two damage identification methods are presented by using modal parameters extracted from dynamic macro-strain responses.

Modal Analysis Concerning Distributed Strain Measurements [10]

This part of the work elaborates theoretical and experimental modal analyses on the dynamic strain distribution for the sake of data processing and feature extraction. From the perspective of the time and frequency domains, the macro-strain frequency response function (FRF) more closely resembles a displacement FRF than a velocity or acceleration one, which leads to the result that the relation between the macro-strain FRF versus frequency can provide a more sensitive indicator at low modes, especially when the resonant frequencies are small (see Fig. 10). This feature may be valuable for the on-line monitoring of structures of high flexibility, such as long-span bridges with initial frequencies having very small values (1 rad/s or even 0.1 rad/s) and densely congregating. Although dynamic displacement responses can theoretically play the same role, so far it is still difficult to obtain effective real-time measurements in true civil engineering structures due to the lack of effective displacement sensors.

With respect to modal parameters, the identified resonant frequency and damping ratio from dynamic macro-strain measurements have the same precision as those from conventional transducers like accelerometers or strain gauges, as listed in Fig. 10. In particular, the resonant frequency provides a very high identified precision which is below 0.001.



Sensors	FBG sensor		Accelerometer		Strain gauge	
	Frequency	Damping ratio	Frequency	Damping ratio	Frequency	Damping ratio
case1	0.732	0.0307	0.732	0.0385	0.732	0.0260
case2	6.256	0.0090	6.256	0.0078	6.256	0.0079
case3	11.017	0.0047	11.017	0.0050	11.017	0.0048
case4	25.085	0.0031	25.085	0.0033	25.085	0.0036
case5	30.914	0.0044	30.914	0.0047	30.914	0.0049
case6	115.112	0.0016	115.112	0.0016	115.112	0.0017

Fig. 10 FRFs and modal parameters

It is worth emphasizing that similar to mode shape, a special modal parameter, called modal macro-strain vector (MMSV), can be extracted from distributed macro-strain measurements. It has been theoretically and experimentally verified that the MMSV versus the mode shape have the same mapping relation as the time-series and frequency responses of the measured macro-strain versus displacement responses. This interesting finding confirms that the MMSV is actually a direct measurement of the curvature/strain mode shape and hence has more sensitivity to local damage and is subject to fewer disturbances from measuring errors.

Sensors Correlation based Damage Identification [11]

Based on the correlation within the dynamic macro-strain distribution, a strategy with no requirements for an analytical model has been proposed for damage locating and quantifying. Many numerical simulations on flexural structures yield a quantitative relation of damage index vs. damage severity, as is shown in Fig. 11 (1), where the damage index is given as the relative error of the normalized MMSV. It should be noted that pre-estimation of the percentage of the sensor gauge length subject to localized damage (e.g. "n=2" in Fig. 11 (2) means the sensor gauge length is divided by 2 and the percentage is 50%) can enable more accurate quantification of the extent of damage.

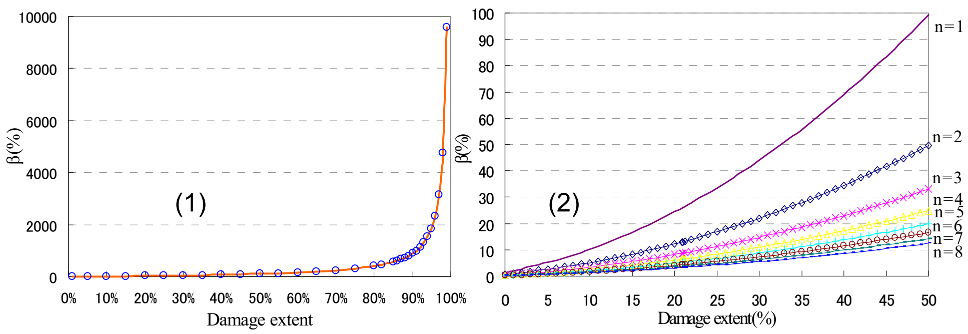
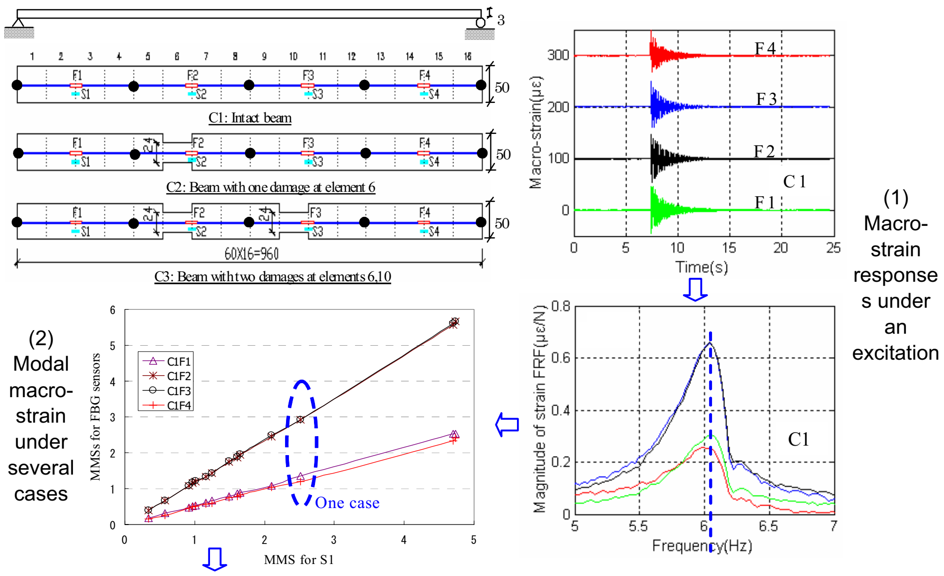


Fig. 11 Damage index vs. damage severity relations based on sensors correlation

Taking a beam structure with four distributed long-gage FBG sensors as an example, Fig. 12 describes the process for feature extraction and damage identification. Under an excitation case, the macro-strain responses from all sensors are recorded (Fig. 12 (1)). Via the FFT, the MMSV can be constructed from the peak values of the strain magnitude FRF. It is obvious from Fig. 12 (2) that the MMSVs from several cases where single-point hammer impulsive excitation is applied at arbitrary locations with arbitrary amplitudes are linearly correlated. The slopes of the fitted lines are then taken as the features for further damage identification. In fact, these features are the normalized MMSV, taking the MMS from S1 as a reference. Moreover, the fitted line is a type of statistical result, which can be helpful in reducing random errors by fitting the measurements from various load cases. As is listed in Fig. 12 (3), the features present a nice indication for damage locating and quantifying.

Two-level Strategy for Damage Identification [12, 13]

Considering the difficulty of identifying damage in large-scale structures (due to such problems as ill-conditioning, slow convergence, and occasional non-uniqueness when there are many unknown parameters for the inverse and optimal analysis), a two-level damage detection strategy using modal parameters extracted from distributed macro-strain data is proposed (see Fig. 13). Level 1 of the MMSV-based damage index method is first performed for locating damage with a spatial resolution of the gauge lengths of fiber optic sensors. Hereafter, the number of candidate parameters to be identified is sharply reduced and level 2 of the natural-frequency-based damage quantification can be then carried out. This step-by-step procedure helps to utilize data with different measuring precisions, i.e., locate the damage using low quality data (e.g. the MMSV) and then to quantify the damage using the parameters of high precision (e.g. frequency). Experimental results of a cantilevered beam have verified the effectiveness and applicability of the proposed two-level strategy.



(3) Feature extraction (slope of the lines in (2)) and damage identification

Sensor	C1	C2					C3				
	MMSV	MMSV	β	Damage extent			MMSV	β	Damage extent		
				n=1	n=4	set			n=1	n=4	set
F1	0.5361	0.5058	-5.65%	0	0	0	0.4547	-15.18%	0	0	0
F2	1.194	**1.5055**	**26.09%**	**21.0%**	**51.5%**	**52%**	**1.5039**	**25.95%**	**20.9%**	**51.3%**	**52%**
F3	1.1975	1.2232	2.15%	1.0%	8.5%	0	**1.5166**	**26.65%**	**21.3%**	**52.1%**	**52%**
F4	0.5048	0.5168	2.38%	1.5%	9.8%	0	0.5017	-0.61%	0	0	0

Fig. 12 Model-free damage identification based on dynamic macro-strain distribution

Conclusions

A series of studies on the development and application of distributed fiber optic sensing techniques in SHM are summarized. The following achievements and contributions show the originality and significance of this work to the existing state of knowledge concerning health monitoring for civil structures.

(1) A feasible distributed long-gage strain sensing system based on a FBG is

developed for practical adaptation to civil structural engineering. The performance of the developed sensors as well as that of the FBG interrogators is characterized on the basis of accuracy, precision, stability and reliability under static and dynamic tests.

(2) An integrated SHM strategy on a steel flexural structure based on static macro-strain distribution has been proposed for structural damage identification, parametric estimation, and global behavior evaluation.

(3) An integrated SHM strategy on a RC flexural structure has been put forward concerning: local crack monitoring, parametric estimation based on nonlinear inverse analysis, and global behavior evaluation in terms of structural deflection distribution.

(4) Modal analysis is specially addressed for dynamic macro-strain distribution. The method for modal testing, response FRF measurement, modal parameter extraction, and data interpretation has been established.

(5) A model-free method based on the correlation among the distributed fiber optic sensors is developed for damage locating and quantifying

(6) A two-level damage detection strategy is proposed by using modal parameters extracted from dynamic distributed strain data to settle the conflict between the large number of unknown parameters and the limited quantities of measured structural responses. It processes using a two–level strategy: (1) level 1 uses an MMSV-based damage index method for locating the damage with a spatial resolution on the order of the gauge lengths of fiber optic sensors, and (2) the level 2 FE model updating method locates and quantifies the damage with a spatial resolution on the order of the sizes of the finite elements.

References

[1] S.W. Doebling, C.R.Farrar, M.B.Prime and D.W.Shevita. Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: A literature review. Los Alamos National Laboratory Report, 1996.

[2] Hoon Sohn, Charles R. Farrar, Francois M. Hemez, Devin D. Shunk, Daniel W. Stinemates, and Brett R. Nadler. A Review of Structural Health Monitoring Literature: 1996–2001. Los Alamos National Laboratory Report, 2003.

[3] Aftab Mufti. Manual No.2 - Guidelines for structural health monitoring. ISIS Canada, 2001

[4] Z.S.Wu and S.Z. Li. Structural damage detection based on smart and distributed sensing technologies. Proc. of the 2nd International Conference on Structural Health Monitoring of Intelligent Infrastructure (Keynote), Shenzhen, China, 2005: 107-120.

[5] S.Z.Li and Z.S.Wu. Development of Distributed Long-gage Fiber Optic Sensing System for Structural Health Monitoring. Structural Health Monitoring [J]. 2007, Vol.6: 133-143.

[6] S.Z.Li, Z.S.Wu and L.L.Zhou. Health monitoring of flexural steel structures based on distributed fiber optic sensors. Structure and Infrastructure Engineering [J]. 2007 (Accepted)

[7] Suzhen LI, Zhishen WU and Watanabe TAKUMI. A health monitoring strategy for RC flexural structures based on distributed long-gage fiber optic sensors. Journal of

Applied Mechanics [J], JSCE. 2007(Accepted)
[8] Zhishen Wu and Bin Xu. Neural networks for localized and decentralized identifications of large-scale structures. Proc. of Neural Networks and Soft Computing 2005 (Keynote), Cracow, Poland
[9] B.Xu, S.Z.Li, Z.S.Wu and K.Yokoyama. Performance of neural networks based damage identification strategy for noise polluted responses. International symposium on Network and Center-based Research for Smart Structures Technologies and Earthquake Engineering (SE'04), Osaka, Japan, 2004: 85-90
[10] S.Z.Li and Z.S.Wu. Modal analysis on macro-strain measurements from distributed long-gage fiber optic sensors. Journal of Intelligent Material Systems and Structures [J]. 2007(Accepted)
[11] S.Z.Li and Z.S.Wu. A Non-baseline Method for Damage Locating and Quantifying in Beam-like Structure based on Dynamic Distributed Strain Measurements. Computer-Aided Civil and Infrastructure Engineering [J]. (In revise)
[12] S.Z.Li and Z.S.Wu. A non-baseline algorithm for damage locating in flexural structures using dynamic distributed macro-strain responses. Earthquake Engineering and Structural Dynamics [J], 2007, 36: pp.1109-1125
[13] Z.S.Wu and S.Z.Li. Two-level damage detection strategy based on modal parameters from distributed dynamic macro-strain measurements. Journal of Intelligent Material Systems and Structures [J], 2007, Vol.18, No.7, pp.667-676