Structural damage detection based on smart and distributed sensing technologies

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ABSTRACT: The essence of structural health monitoring requires an innovative sensing system similar to human nervous system throughout the whole body to catch comprehensive information without losing structural integrity. Strain, which is traditionally regarded as a typical local measurement, has been verified to be very sensitive to damage but fail to detect if the area where strain sensor is fixed doesn't cover damaged region. In this paper, an integrated structural damage detection strategy based on distributed strain sensing technologies is proposed. A typical fiber optic sensing system of developed long-gage FBG sensors for distributed strain measurements is deployed to investigate the feasibility and efficiency of the proposed structural assessment strategy. Some suggestions on the further development of distributed strain sensing technologies are put forward for reference at length.

1 INTRODUCTION

Structural health monitoring (SHM) is to develop a system similar to human nervous system via which various senses like pain and itch can be perceived, reflected and applied for follow-up decisions such as whether and when to see a doctor. It is self-evident that the above-all and foremost task is to establish a sensing system analogous to distributed nerves throughout the whole body to ensure that the information can be aggregated without losing structural integrity.

Most SHM research to date has focused either on global damage assessment techniques using structural dynamic responses, or on limited local independent damage detection mechanisms. Strain, which is traditionally regarded as a typical local measurement, has been verified to be very sensitive to damage. However, for large-scale civil structural health monitoring, strain measurement always serves as an auxiliary role partly due to its locality that the influence of damage on strain measurement cannot act effectively unless the area where 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, which is difficult and even infeasible for conventional foil strain gauges.

Fiber optic sensing technologies under rapid development in the recent years present a promising alternative for this kind of distributed strain measurements. Owing to small size and light weight, optical fiber can be either surface-attached or embedded into structures without changing their original structural mechanical behaviors. Moreover, as a sensor of linear shape, it provides convenience and flexibility for installation and maintenance. The capability of easy multiplexing and distributing in turn reduces the number of leads running through structures.

In this paper, an integrated structural damage detection strategy based on distributed strain sensing technologies is firstly proposed. The newly developed long-gage FBG sensors are then elaborated to investigate the efficiency and applicability of the proposed strategy with experimental and numerical verifications. Finally, some suggestions on the further development of distributed strain sensing technologies are put forward for reference.

2 STRUCTURAL DAMAGE DETECTION STRATEGY BASED ON DISTRIBUTED STRAIN SENSING TECHNOLOGIES

Compared with traditional sensing technologies, one of distinct advantages of distributed strain sensors lies in that they can serve simultaneously as an implement for both static and dynamic measurements. Therefore, on the one hand, more effective and accu-

rate data can be measured under controlled tests including static and forced vibration field tests for periodic monitoring. On the other hand, measurements from ambient vibration under operational conditions can be obtained for real-time and continuous monitoring. Fig.1 shows the structural damage detection strategy regarding static and dynamic measurements based on distributed strain sensing technologies.

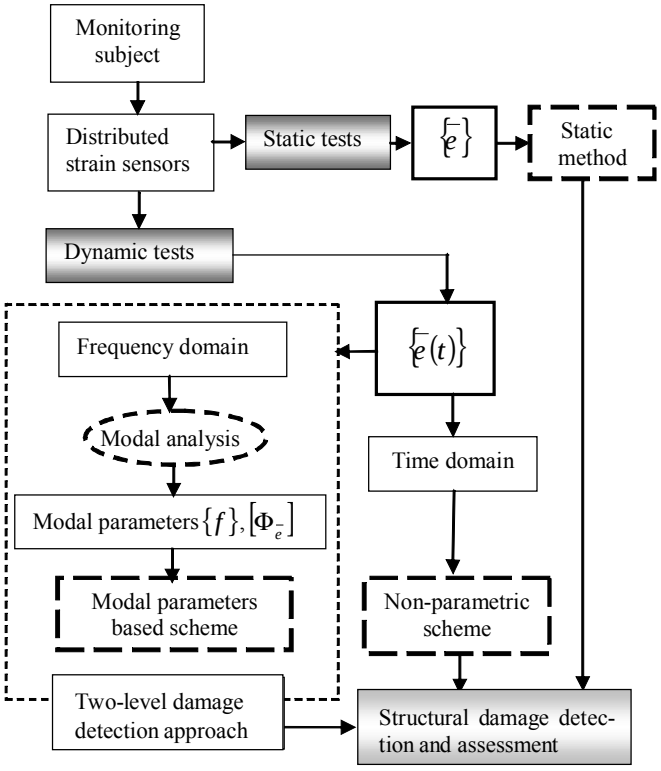


Figure 1. Structural damage detection strategy based on the measurements from distributed strain sensors

2.1 *Static testing and monitoring*

As a conventional manner to study the structural behavior and failure mechanism, static field testing has been in practice for centuries and extends some merits for its application in damage detection due to the simpler theoretical background regardless of mass and damping, more convenient measurements and fewer requests for data processing and signal analysis.

2.1.1 *Static stiffness identification*

In contrast to the early parametric identification methods based on the relation between forces versus displacements and optimal iterative algorithms (Sanayei et al.,1991, Banan et al.,1994, Hjelmstad et al.,1997, Yeo et al.,2000), a new point of view is explored by using distributed strain measurements.

Actually as mentioned above, basic theory is simply grounded on structural mechanics. Suppose quantity and distribution of static loads are known, for a member under uniaxial loading, axial stiffness EA can be calculated directly from strain measurements ε:

$$EA = \frac{N}{e} \tag{1}$$

For a member under bending (in Fig. 2), average bending stiffness $\overline{EI}$ covering the area where a long-gage sensor is attached (from a to b) can be derived by:

$$\overline{EI}_{a-b} = \frac{\int_a^b M(x)y(x)dx}{\bar{e}_{a-b}} \tag{2}$$

Here, $\bar{e}_{a-b}$ is the macro-strain (i.e. average strain) measurement directly from long-gage sensor.

With respect to above discussions, some important

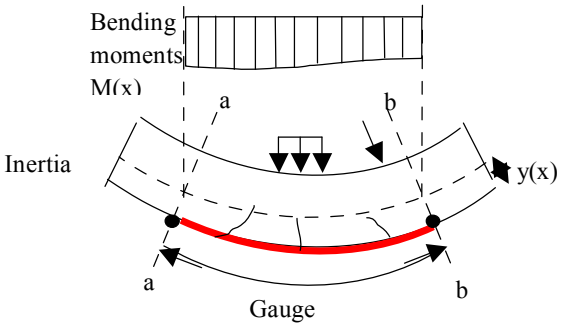


Figure 2. Structural member with a long-gage strain sensor

issues should be noted: (i) Equ.(2) introduces long-gage sensor for macro-strain measurement in the fact that any strain sensor, in a strict sense, inherently has a certain length along which moment and hence strain at every point are generally different under bending. Although traditional "point" strain gauges usually ignore this influence thanks to much smaller size than object member, macro-strain measurement is utilized throughout this paper to keep the convenience and consistency for statement. (ii) For a homogeneous member, $y(x)$ in Equ. (2) can be represented as half height of cross section; otherwise, a few sensors should be fixed at the top side of the member to determine the location of inertia axis. (iii) The influence of boundary conditions may be considered by selecting diversified controlled load cases. (iv) Equ. (1) and (2) show that structural stiffness can be calculated directly from static strain so far as corresponding load is known. (v) A sensor with a certain gauge length only focuses on the stiffness identification in its fixed region while damages at other locations have no weight on its measurement. This information is very useful because the localized method slides over the problem of interactive effect of damages on displacement and stiffness matrix based on which parametric assessment has to be carried out in an optimal and iterative method. (vi) The stiffness of whole structure can be obtained from distributed stain sensors.

2.1.2 *Static damage detection method*

Based on the presented static stiffness identification method, damage denoted by the difference of parameters over various periods can be detected smoothly if it is feasible to carry out controlled static field testing for practical structure pre- and in service. It is worth stressing here that static field testing on a new structure before operation is very meaningful to provide exact stiffnesses that are crucial for FE model updating to set up baseline structure. For existing structure in service, although the information in intact state may be unavailable, damages in structure can still be determined by the difference of stiffnesses from distributed strain measurements at two times.

2.1.3 *Long-term monitoring*

If no zero-shift happens and durability as well as stability can be ensured, distributed strain sensing technologies bring forward a suitable instrument for long-term monitoring by using the absolute shift and development of strain measurements along with time. In contrast to conventional foil strain gauges, fiber optic strain sensors have been testified by many investigations and practical applications to possess excellent performances for long-term monitoring such as electromagnetic noise immunity, resistance to chemical corrosion, adaptability to harsh environments and so on.

2.2 *Dynamic testing and monitoring*

The efforts in vibration based structural health monitoring methods are tremendously extensive. Traditional vibration tests are based on artificially forced excitation and correlated input-output measurements. These methods are limited for relatively small structures. For large-scale civil structures such as cable-stayed or suspension bridges, it often requires heavy equipments and involves important resources to provide a controlled excitation at enough high levels, which becomes difficult and costly. Moreover, controlled experiments often have to shut down the normal working state of structure and lead to serious inconvenience. In the last few years, operational modal testing based on ambient vibration has been proved to be an efficient alternative to classic forced vibration testing for civil structures, especially for bridges. In addition, for some areas like Japan where earthquakes take place frequently, SHM by utilizing small earthquake responses also puts forward a very promising direction.

Based on above-mentioned dynamic testing including controlled forced vibration, ambient vibration and earthquake excitation, two schemes in their respective views of time domain and frequency domain are introduced as follows.

2.2.1 *Non-parametric damage identification scheme using time-series data*

Different from familiar methods which rely on the underlying relations between damages and the changes of structural modal parameters, damage identification schemes without using structural parametric models have been presented recently by some researchers (Wu et al. 2003, Yan et al. 2004, Mita, 2004). These non-parametric methods directly capitalize on structural responses time history and can be looked on as a problem of statistical pattern classification which is often successively followed by two steps: damage locating and then damage quantification.

A structural parametric identification scheme based on neural networks using dynamic measurements in time domain has been developed by Wu et al., and Xu et al. Combined with macro-strain time-series data from distributed long-gage fiber optic sensors, it has been testified by numerical simulations (Wu et al.,2003) and experimental verifications (Xu et al.,2003). Using earthquake response measurements, the feasibility and effectiveness of the neural network based method in stiffness identification have been discussed as well (Xu et al.,2002). For large-scale structures, this scheme is extended for localized and decentralized identification (Wu et al.,2005). Summary of potential advantages in the neural network based parametric identification scheme includes: (i) Without any eigenvalue analysis or optimization computation, structural parameters can be identified by direct use of time history data, which helps to solve nonlinear problems (ii) Off-line trainings shun away the complicated time-consuming inverse analysis and possibly lead to real-time monitoring. (iii) Various errors which acted as damage indices are testified to be very sensitive to damage.

For more detailed information, interested readers can refer to the relevant references. In this regard, a novel two-level damage detection scheme using modal parameters extracted from distributed strain time-series data is presented at length as follows.

2.2.2 *Two-level damage detection scheme using modal parameters*

Vibration based damage detection methods have been expanding rapidly in recent years. Most of them have been focused on the changes in structural modal parameters and can be viewed as falling into the domain of linear model updating. A fundamental difficulty, however, lies in problems of ill-conditioning, slow convergence and sometimes non-uniqueness in inverse and optimal analysis due to the huge quantity of unknown parameters. One potential way to solve these problems is to reduce the number of candidate parameters by restricting suspected portion to the domain where damage is localized.

Based on the above discussion, a two-level damage detection scheme using modal parameters ex-

tracted from distributed strain time-series data is proposed (in Fig. 3), as can be processed by the following phases: (i) Level1-Modal macro-strain vector (MMSV) method for damage location without a detailed analytical model. (ii) Level2-Damage quantification based on FE model updating method.

The existing methods for extraction of modal parameters from time history measurements are generally classified as either time domain or frequency domain method (Maia and Silva, 1997, Ewins 2000). Regarding different dynamic testing cases including controlled forced vibration, ambient vibration and earthquake excitation, the corresponding artifices for modal parameters extraction are diverse. Currently, the stochastic subspace identification (SSI) method seems to be the most advanced method for modal parameters identification under ambient vibration. And wavelet analysis provide a powerful tool for solve the non-linear and non-stationary problem under earthquake excitation.

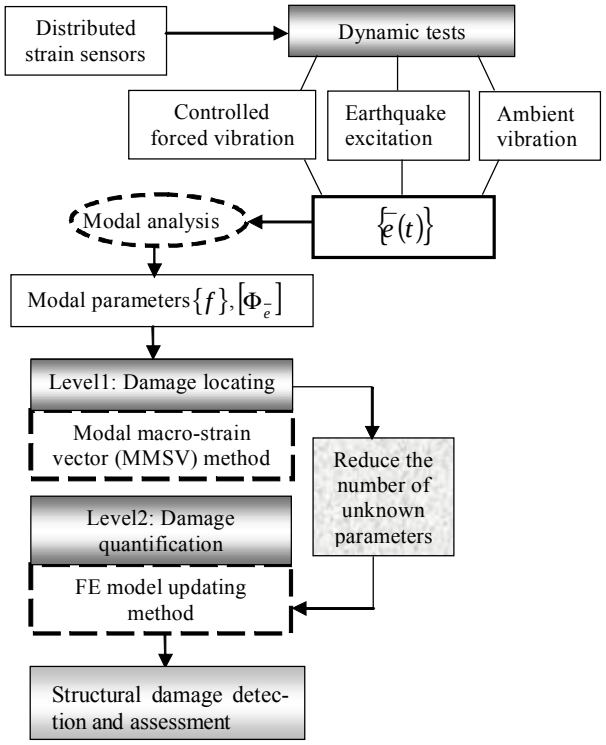


Figure 3. Two-level damage detection scheme using modal parameters extracted from distributed strain time-series data

2.2.2.1 *Non-baseline damage locating--Modal macro-strain vector (MMSV) method*

Methods to localize damage without a detailed analytical model have been traditionally based on the changes in mode shapes and their derivatives from acceleration measurements (Pandey et al.,1991, Aktan et al.,1994, Doebling 1996, Bernal et al.,2002, Gao et al.,2002, Lu et al.,2002). Many investigations have reported that curvature such as mode shape or flexibility curvature is very sensitive to damage and suitable for multiple damage scenarios. But differentiation process enhances the experimental errors inherent in mode shapes, yielding a large statistical uncertainty. Distributed strain measurement, in a sense is identical to curvature and directly provides a modal parameter similar to curvature mode shape. Based on distributed long-gage strain sensing techniques, modal macro-strain vector (MMSV) method has been presented in our previous research for non-baseline damage location, which will be briefly reviewed in this section.

1. Basic concept

For a N-DOF beam structure of two local DOFs (one for vertical translation and the other for rotation) at each node (see Fig.4), macro-strain $\bar{e}_m$ of several

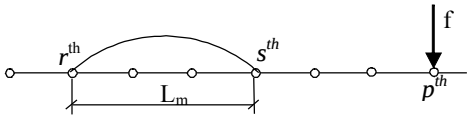


Figure 4. Beam structure

consecutive elements can be obtained from the rotational degree at first node of first element (r^{th} DOF) and that at second node of last element (s^{th} DOF) on a reasonable assumption that the distance from inertia axis to sensor location of each element (demoted as h_m) is same. So theoretically the macro-strains at a certain time or frequency can be obtained respectively from

$$\bar{e}_m(t) = \frac{h_m}{L_m} \cdot [v_r(t) - v_s(t)] \tag{3}$$

$$\bar{e}_m(w) = \frac{h_m}{L_m} \cdot [v_r(w) - v_s(w)] \tag{4}$$

Suppose M long-gage sensors are installed onto the beam, a macro-strain vector of M-dimension with each component from Equ. (3) or (4) can be assembled by left-multiplying a mapping matrix [B] as:

$$\begin{Bmatrix} \bar{e}_1 \\ \bar{e}_2 \\ \vdots \\ \bar{e}_M \end{Bmatrix} = [B]_{M\times N} \cdot \begin{Bmatrix} v_1 \\ v_2 \\ \vdots \\ v_N \end{Bmatrix} \tag{5}$$

Based on experimental modal analysis theory and regarding the fact that the relationship between macro-strains versus displacements is space-dependent but time or frequency-independent, a modal vector $\{d_{mi}\}$ for i^{th} mode, say Modal Macro-Strain Vector (MMSV), can be constructed from time series data of long gage sensors in the same way as mode shape $\{j_{ni}\}$ extraction. The similar mapping relation as Equ.(5) is given by:

$$\begin{Bmatrix} d_{1i} \\ d_{2i} \\ \vdots \\ d_{Mi} \end{Bmatrix} = [B]_{M\times N} \cdot \begin{Bmatrix} j_{1i} \\ j_{2i} \\ \vdots \\ j_{Ni} \end{Bmatrix} \tag{6}$$

Accordingly, the component d_{mi} is named by Modal Macro-Strain (MMS).

It should be noted that MMSV as well as mode shape only emphasize the relative ratio of all compo-

nents but ignore the amplitude. Furthermore in many cases such as ambient vibration under operational condition it is often difficult to normalize MMSV before and after damage under the identical criteria, for example, mass-normalization. So it is necessary to provide an index free from normalized criteria and suitable for any MMSV of intact and damaged structure. Here, taking the original idea from damage index method developed by Stubbs et al. (1992), the other index β is proposed.

According to Stubbs et al. the bending strain energy for a Bernoulli-Euler beam is

$$U = \frac{1}{2}\int_0^l EI\left(\frac{d^2v}{dx^2}\right)^2 dx \tag{7}$$

Damage index at the k^{th} location in structure is given by

$$\frac{\sum_{i=1}^{N} g_{ki}^*}{\sum_{i=1}^{N} g_{ki}} = \frac{\sum_{i=1}^{N}\int_{a_k}^{a_k+l_k}\left(\frac{d^2 j_{ki}^*}{dx^2}\right)^2 dx \Big/ \int_0^l\left(\frac{d^2 j_{ki}^*}{dx^2}\right)^2 dx}{\sum_{i=1}^{N}\int_{a_k}^{a_k+l_k}\left(\frac{d^2 j_{ki}}{dx^2}\right)^2 dx \Big/ \int_0^l\left(\frac{d^2 j_{ki}}{dx^2}\right)^2 dx} \tag{8}$$

Here, Superscript * represents the damaged state. On the other hand, the curvature can be denoted by strain as:

$$\frac{d^2v}{dx^2} = \frac{e}{h} \tag{9}$$

Following the derivation of damage index method and introducing modal macro-strain vector, it holds

$$\int_{a_m}^{a_m+l_m}\left(\frac{d_{mi}}{h_m}\right)^2 dx = \frac{d_{mi}^2}{h_m^2}\cdot l_m \tag{10}$$

Suppose h_m along the structure is same, a damage evaluating index β_m for m^{th} sensor can be defined as

$$b_m = \frac{\sum_{i=1}^{N}\left[\left(d_{mi}^*\right)^2 l_m \Big/ \sum_{m=1}^{M}\left(d_{mi}^*\right)^2 l_m\right]}{\sum_{i=1}^{N}\left[\left(d_{mi}\right)^2 l_m \Big/ \sum_{m=1}^{M}\left(d_{mi}\right)^2 l_m\right]} - 1, \qquad m = 1,2,\ldots,M \tag{11}$$

2. *Damage locating with different sensor placements*

To investigate the MMSV damage location method, a steel cantilevered beam with 1m length, 50mm width and 3mm height is considered as numerical example. Its FE model shown in Fig.5 includes 20 elements and 40 DOFs. Damage is simulated as 10% stiffness reduction at element 8 and 14.It can be found from Equ. (6) that the modal macro-strain vector with different dimension and value will be decided by the number of installed long-gage sensors, their respective gauge length and fixed location. The sensitivity of evaluating index β_m to damage locations with different sensor placements will be discussed in detail as follows.

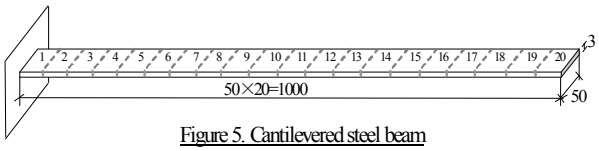


Figure 5. Cantilevered steel beam

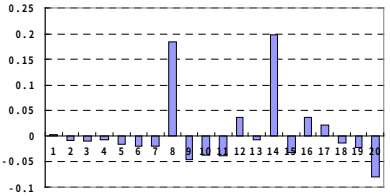
Cross section: a×b=50×3 mm

Elastic modulus: $E=2.10\times10^{11}$ kg F/m^2

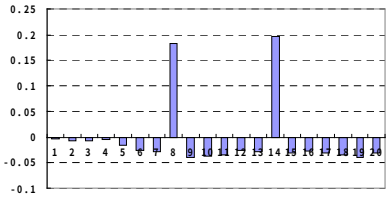
Density: $\rho=7.862\times10^3$ kg/m^3

(1) Sensors distributed throughout the whole structure

It can be seen from Fig.6 (b) that when long-gage sensors are distributed along the whole beam damage index β_m (m=1~20) from MMSV is a nice indicator for damage location and available for different damage scenarios. It is worth stressing here that β_m is positive for the sensor at damaged position while negative for that at intact position owing to the obvious fact that damages lead to the increase of strain measurements.



(a) Mode 1



(b) Modes 1 and 2

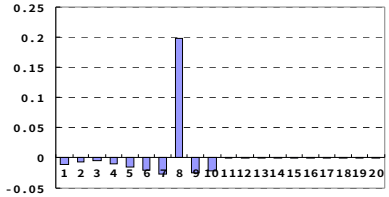
Figure 6. Damage index β_m from MMSV with 10% stiffness reduction at element 8 and 14

In Equ.(11) all modes are included to calculate the damage index β_m . However, it is often infeasible for engineering practice especially for large-scale structures to obtain integrated modes due to the limitation of sensing techniques and measuring difficulty. Furthermore, many researches have shown that the first several modes of a structure, which gather up most of vibrating energy, can represent the structure well enough. Fig.6 (a)-(b) show that the first two modes can locate damages with enough precision.

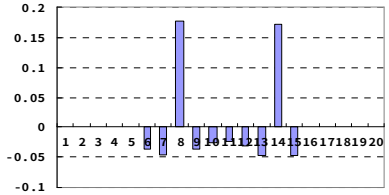
(2) Sensors partly distributed in a certain position of structure

Three groups of sensor placements are considered to investigate the case that sensors are partly distributed in a certain position of structure, including respective elements combination [1~10], [6~15] and [11~20]. It can be found from Fig. 7 (a)-(c) that any damage can be detected as long as the region where a group of sensors are fixed involves the damaged domain,

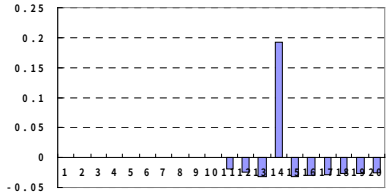
which is crucial to propose the decentralized identification envision as stated in the following section.



(a) 10 sensors from element 1 to 10



(b) 10 sensors from element 6 to 15



(c) 10 sensors from element 11 to 20

Figure 7. Damage index β_m from MMSV with 10% stiffness reduction at element 8 and 14

3. *Decentralized identification envision*

For large-scale structures having a great number of degrees-of- freedom (DOFs), it is difficult to obtain unique estimates of all structural parameters by the conventional optimization search processes that are often computationally inefficient and even numerically unstable. Moreover, dynamic and especially fast dynamic measurements inevitably bring on the problems of excessive time and space for data aggregation, transmission, processing and management. In this section, a decentralized identification envision is presented based on non-baseline MMSV damage location and FE model based damage quantification method. As shown in Fig.8, the cantilevered beam with 20 elements is still employed to illustrate the detailed implementation of the presented envision.

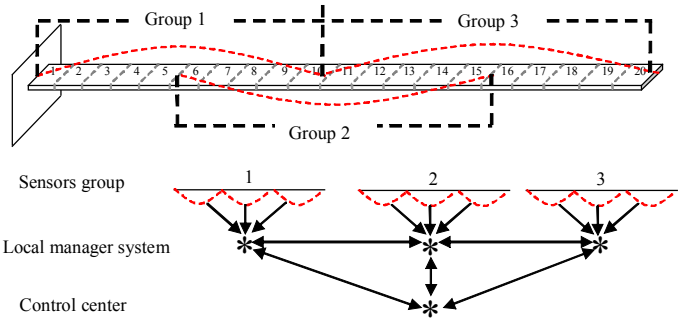


Figure 8. Sketch of decentralized identification envision

(1) Basic organization

Fig.8 shows the sketch of decentralized identification envision, as proceeding by three grades. Some adjacent sensors share one group, from which measurements are aggregated and transferred to a local manager system. Before forwarding information to control center, the local manager system is expected to be "smart" to carry out the non-baseline MMSV based damage location algorithms mentioned before and be competent to implement dialogue with other local manager systems. Wireless technique under rapid development in recent years provides a promising tool to satisfy these requests. In contrast to traditional systems which collect all the measured information in control center, only valuable data revealing the occurrence of abnormity is accessed and maintained, which greatly saves information communication and management.

(2) Sensors grouping and in-group damage location

The cantilevered beam in Fig.8 gives an example to form sensor groups. Three groups of sensors with respective elements combination [1~10], [6~15] and [11~20] are considered. As illustrated in Fig. 7, each group of sensors can locate the damage within its respective fixed domain. It is worth noting here that although damages can be detected by one single group, the overlaps between group 1 and 2, group 2 and 3 ulteriorly confirm the damages at element 8 and 14. Therefore it is recommended to group sensors with overlaps which helps to decrease measured and computational errors.

(3) Information exchange and decision-making

After receiving the report of possible damage occurrence from a local manager system, judgments can be made in control center and then instructions can be issued to drive other local manager systems responsible for adjacent sensor groups or capable for regrouping sensors to focus and confirm damage location. Furthermore, direction can be made to adjust the correlative local manager systems to collect information enough for damage quantification.

2.2.2.2 *FE model-based damage quantification*

Damage in structures is an intrinsically local phenomenon. Therefore, after damage location, the number of candidate parameters to be identified can be sharply reduced. Fig.9 shows the outline of damage quantification based on FE model updating method. It is well-known that frequency measurements hold higher precision and accuracy than corresponding mode shape measurements. Furthermore, most of algorithms including mode shapes have to deal with the problems of FE model reduction or mode shape expansion to bridge the gap between real structure and simulated model. So if damaged location is confined to such a relatively small region as to the number of measured modes can be enough for unknown parameters identifica-

tion, the methods by only using frequency measurements are recommended. Otherwise, MMSVs have to be introduced to construct more equations for solution.

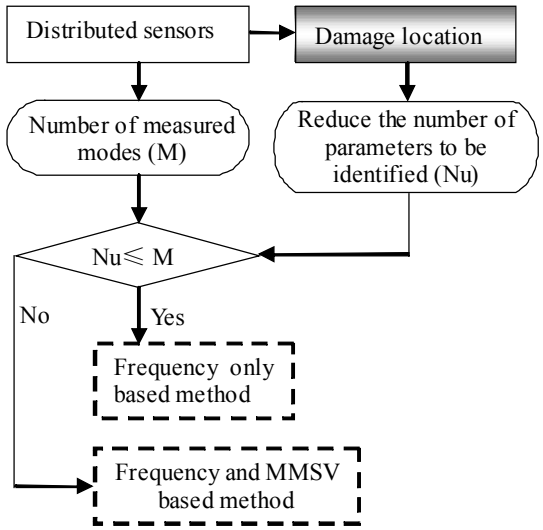


Figure 9. Outline of FE model based damage quantification

1. Frequency based method

The frequency based method (Hassiotis et al.,1995, Wu et al.,2000, Xia et al.,2003, Hwang et al.,2004, Cottin et al.,2005) is not a new concept, which theoretically depends on the sensitivity equations using the relation of changes between eigenvalue or say frequency and structural stiffness or/and mass as:

$$[S]_{M\times Nu}\cdot\{\Delta p\}_{Nu}=\{\Delta l\}_{M}$$
$$S_{ij}=\{f_0^i\}^T\left[\frac{\partial[K_0]}{\partial p_j}-l_0^i\frac{\partial[M_0]}{\partial p_j}\right]\{f_0^i\} \quad (12)$$

where $[S]$ is sensitivity matrix uniquely determined by initial structural models. Δp is change of object parameter. $\Delta\lambda$ is change of measured eigenvalue. It can be found from Equ.(12) that once damage denoted by Δp is located, the number of unknown parameters will be greatly reduced. It is worth noting that Equ.(12) is based on first-order sensitivity and only suitable for small damage degree. If damage increases, second-order sensitivity analysis or step-by-step calculation should be carried out.

2. Frequency and MMSV based method

If there are more suspected damage elements in the structure, information from only frequency is not sufficient for damage quantification and hence mode shape should be included. Researches by use of the combination of frequency and mode shape for constructing sensitivity matrix for linear equations or object function for optimal computation are numerous (Lim et al. 1994, Shi et al.,2000, Ren et al.,2002, Kim et al.2003). Two kinds of indicators generally seem to be promising for practical problems due to their sensitivity to damages and applicability using a few low-order modes: modal flexibility and modal strain energy. In contrast to mode shapes from accelerations that represent deflection degree, MMSVs from macro-strain measurements give the relative rotational degree. So the basic ideas from traditional modal flexibility or modal strain energy based methods can be borrowed for damage quantification using the dynamic measurements from distributed strain sensors.

In the following section, combined with available distributed sensing technologies, the practical application of this proposed integrated strategy in structural assessment will be discussed.

3 DISTRIBUTED STRAIN SENSING TECHNOLOGY

As stated before, fiber optic sensors present a more promising tool than traditional foil strain gauges for distributed strain measurements due to their electromagnetic noise immunity, easy distributing or multiplexing capability, convenient installation manners and so on.

As one of the most attractive distributed fiber optic sensing technologies, Brillouin back scattering based fiber optic sensor is expected to be an achievement in the field of civil structural health monitoring with high feasibility. Some recent pilot investigations have been carried out by Kurashima et al.(1997), Bao et al.(2001), Wu et al. (2002,2003), Ansari (2003). Table 1 summarizes the specifications of AQ8603-BOTDR system from Ando Electric Co. Ltd. and Neubrescope system from Neubrex Co. Ltd. in Japan.

Table 1 Specifications of current Brillouin back scattering based systems

Instruments	AQ8603				Neubrescope			
Readout Resolution	5cm				5cm			
Pulse Width (ns)	10	20	50	100	1	2	5	10
Spatial Resolution(m)	1	2	5	11	0.1	0.2	0.5	1
Dynamic Range(db)	4	8	12	15	1	2	3	5
Max. Measurement distance(km)	10	25	45	55	1	5	10	20
Strain Measurement Accuracy(με)	±100	±100	±50	±50	±25	± 25	± 25	± 25

Although significant progress has been made currently in the development of Brillouin back scattering based sensors, technical challenges including spatial resolution, measurement stability and accuracy are still in the way to put forward this distributed fiber optic sensing technology in practical application. Alternatively, FBG sensors in nature hold better precision and measuring stability, which is more suitable and feasible at present to implement the proposed structural assessment strategy.

In the last few years, FBG sensor has been developed for various purposes of measurements such as

strain, temperature, acceleration, inclination, crack and so on. Although many works (Schulz et al.,2002, Tang et al.,2003, Li et al.,2004, Ansari,2003) have drawn attention to the practical application of FBG sensor in civil structures and some projects have brought it from laboratory to field, most of them focused on the usage of FBG sensor as a localized gauge for point or axial strain measurements, as applied in bridge cables and structural piles. Lately some researchers (Conte et al.,2000, Inaudi et al.,2000, Glisic et al.,2003) have proposed a long-gage fiber optic sensor for macro-strain measurements. Their works have highlighted the potential advantages of such sensor as insensitivity to local stress concentration, capability to obtain global structural behavior and applicability for different topologies or networks, but most of them are limited to brief introduction or conceptual envision. Few works have been done by direct use of macro-strain measurements for structural damage identification.

In our recent study (Li & Wu, 2005), a novel long-gage fiber optic sensor for practical adaptation in civil structural health monitoring has been developed and verified to have the ability to obtain distributed macro-strain measurements for structural assessment. Some related researches will be elaborated as follows.

3.1 *Packaging design*

Typical packaging design for a single long-gage FBG sensor is shown in Fig.10. Distributed packaging sketch is shown in Fig.11. The essential part of this design lies in the hollow tube of gauge length inside the proposed device for sleeving the recoated FBG is essential to ensure that every point within the sensing area to be strained identically and hence the strain transferred from the shift of Bragg center wavelength can represent the average strain along the gauge length. More detailed description can be found in Li & Wu (2005).

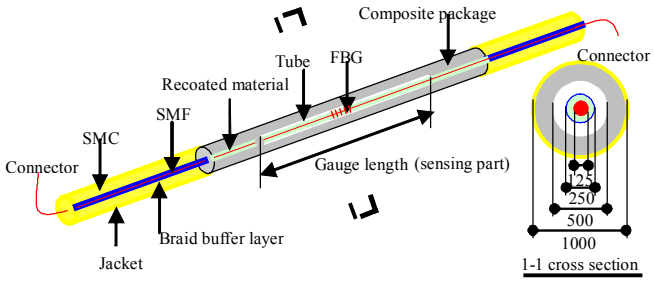


Figure 10. Packaged long-gage FBG strain sensor

SMC: single-mode optical fiber cable

SMF: single-mode optical fiber

FBG: fiber Bragg grating

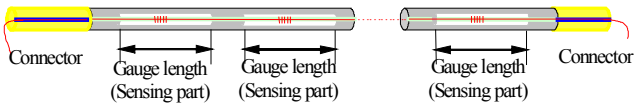


Figure 11. Distributed packaged long-gage FBG sensors

3.2 *Performance verification*

Different from traditional strain sensors, the proposed FBG sensor can obtain some important measurements for local and global structural damage identification: (i) Macro-strain measurements that are less susceptible to local stress/strain concentrations and have a clear relation with rotational degree. (ii) Distributed measurements. (iii) Fast dynamic measurements. The sampling frequency of FBG interrogation systems is newly up to 5KHz.

In order to verify the precision and applicability of FBG sensor, a series of tests have been carried out in both static and dynamic manners.

3.2.1 *Static tests*

3.2.1.1 *Steel specimen under uniaxial tension*

A steel board with rectangular section of 50mm × 3mm and two holes of 7mm diameter was designed. Three strain gauges (SG5-1, SG5-2, SG60) and two packaged FBG sensors (FBG10, FBG25 with gauge length of 100mm, 250mm) were adhered onto the specimen surface. Theoretically, relative to the strains from SG5-1, the ratios of strains from SG5-2, SG60, FBG10 and FBG25 are 1.1450, 1.0146, 1.0088, 1.0070, respectively. Fig.12 shows the same variation trend as well.

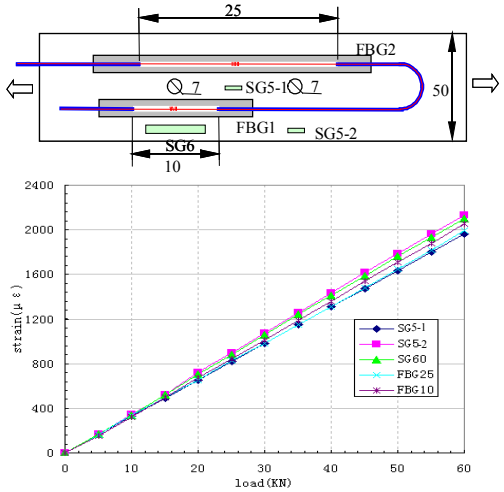


Figure 12. Strain measurements of damaged steel specimen under uniaxial tension

3.2.1.2 *Concrete specimen under uniaxial compression*

A concrete cylinder with 150mm diameter and 300mm height was loaded with a loading rate of

0.1N/mm2/sec. up to the failure of specimen. A packaged FBG sensor and two strain gauges were attached onto the concrete surface, denoted as FBG60, SG60 and SG5 (see Fig.16), whose gauge length is 60mm, 60mm and 5mm respectively. The compressive strains from different sensors versus time are shown in Fig.13. It can be found that the strains obtained by FBG60 and SG60 match well but present some obvious difference, especially after initial stages of loading, from those obtained by SG5 which acted as a point sensor. In other words, the packaged long-gage FBG sensor shows the ability for average strain measurements under compression and persistent efficiency even when the maximum compressive strains amount to 1500με.

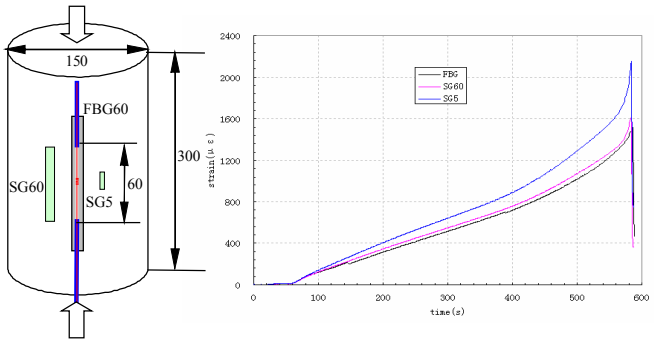


Figure 13. Strain measurements of concrete specimen under uniaxial compression

3.2.2 *Dynamic tests*

3.2.2.1 *Cantilevered beam under impulsive excitation*

A cantilevered steel beam with rectangular section of 50×3mm and 1m length is used. A FBG sensor of 100mm gauge length, as well as an accelerometer of 50Hz response frequency, is bonded onto the surface of specimen. Hammer impulsive loading is applied at free end of the beam and 10s duration of vibration is considered. The sampling rate of FBG sensor and accelerometer is 500Hz and 100 Hz respectively.

The Fourier spectrum of macro-strain and acceleration responses can be obtained via FFT by use of time series data. As shown in Fig.14, the first three resonant frequencies from two sensors have a nice agreement with maximum relative error less than 1%. FBG sensor presents six frequencies thanks to its higher sampling rate.

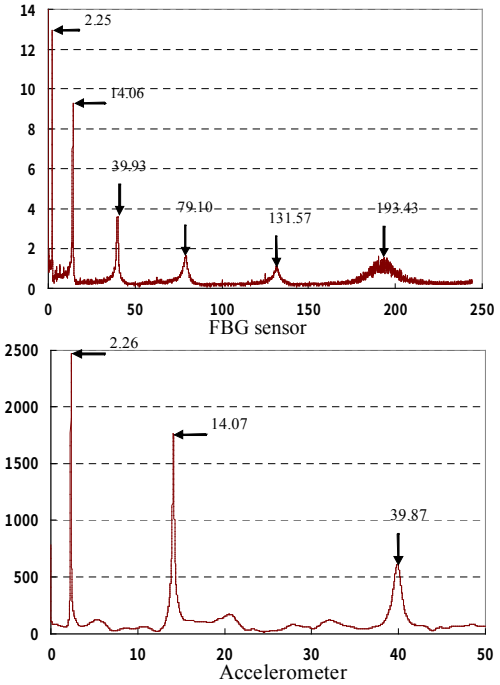


Figure 14. Fourier Spectrum under hammer impulsive excitation

3.2.2.2 *RC column under earthquake excitation*

A shaking table test for a RC column with rectangular section of 45×80cm has been carried out at Public Works Research Institute in Japan. Two FBG sensors of 60mm gauge length were attached onto the top surface of specimen using epoxy resin. Foil strain gauges were placed parallel for comparison.

The shaking table was excited in three-dimensional field and the records observed at JR Takatori Station in 1995 Kobe earthquake (Japan) was chosen as an input ground motion. Three cases including 15%, 90% and 50% amplitude of Takatori earthquake records were carried out in succession. Fig.15 is the macro-strain responses of sensors placed in the direction of column weak axis to 15% amplitude of earthquake records, which shows that FBG sensors work as well as strain gauges under earthquake excitation.

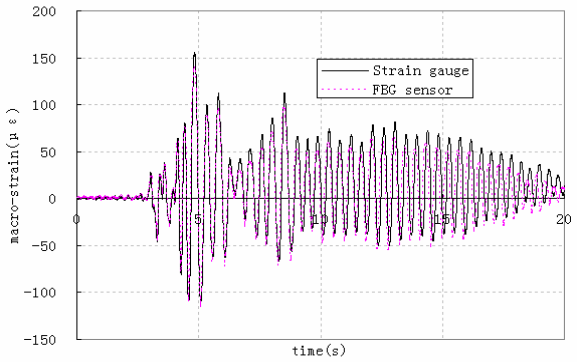
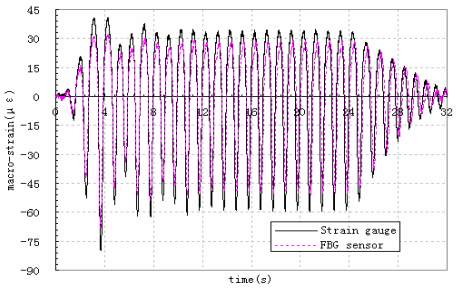


Figure 15. Macro-strain response to 15% amplitude of Takatori earthquake records

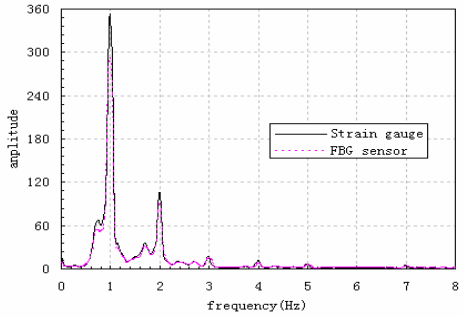
3.2.2.3 *RC column under harmonic excitation*

Following the three loading cases mentioned above, a sine wave was used as a harmonic excitation in the direction of weak axis of the RC column. Fig.16 shows the macro-strain time history curves and frequency spectrums obtained by a FBG sensor and the corresponding strain gauge in the same direction. It can be seen that the macro-strain responses from FBG sensor have a close agreement with those from strain gauge either in time-domain or in frequency-domain under harmonic excitation. A little of discrepancy can result from the difference of gauge

length of the both strain sensors. The responses under earthquake excitation can be found as follows.



(a) time-domain



(b) frequency-domain

Figure 16. Macro-strain response to harmonic excitation

3.3 *Damage detection with experimental measurements*

A steel cantilevered beam in Fig.5 is taken as an object structure for damage identification based on static as well as dynamic scheme mentioned in Section 2.

3.3.1 *Static parametric estimation*

Four cases including intact beam and beams with different damage are considered, as shown in Fig.17. Four FBG sensors of 250mm gauge length are fixed as a kind of distributed sensor. Three strain gauges are used for comparison. The static measurements from these sensors in one loading case are shown in Table 2.

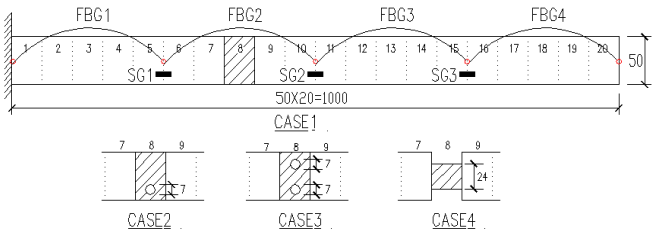


Figure 17. Four cases including intact and damaged beams

Table 2. Static stain in different cases (με)

sensor	FBG1	FBG2	FBG3	FBG4	SG1	SG2	SG3
theoretical	600	429	258	86	515	343	172
case1	592	452	257	83	515	340	170
case2	583	453	258	84	515	325	165
case3	586	463	260	81	520	335	170
case4	581	547	268	81	520	335	170

It can be found that the measurements from strain gauges vary little and in some sense show the weakness of conventional point sensors for damage detection in that local strains are not sensitive to structural damage unless the sensors are placed in the vicinity of damage which is obviously impractical. In contrast, although the strains from FBG1, FBG3 and FBG4 change little, those from FBG2 increase with the occurrence and development of damage.

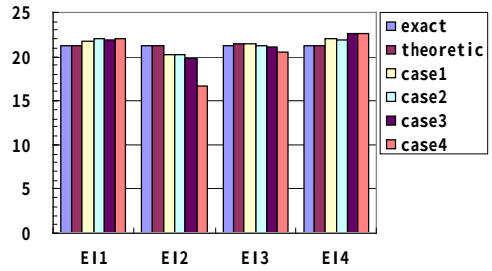


Figure 18. Estimated parameters in different cases

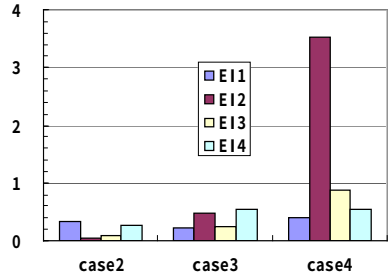


Figure 19. Damage detection by reference to baseline Structure

The flexural stiffness EI of beam elements with known exact value 21.34 is taken as object parameters for identification. All the elements within the gauge length of the FBG sensors (e.g. element 1~6) are arranged to a group and share the same flexural stiffness (denoted as EI1~EI4 for FBG1~FBG4) in common. Identified parameters in different cases are shown in Fig.18. With reference to the identified parameter of baseline structure using the measurements from case1, the damage detection results can be seen in Fig.19. The agreement between exact value and analytical value using theoretical strains shows the high accuracy of algorithm. It can be seen from case4 that distributed macro-strains from FBG sensors present advantage to identify the occurrence, location and extent of damage. However, it should also be noted (see case2 and case3) that average strain, although less susceptible to local stress/strain concen-

trations, can weaken the sensitivity of measurements to damage, which may be merged by noise in measurements. So the number of FBG sensors, their respective gauge length and distributed location should be carefully considered for sensor placements.

3.3.2 *Dynamic damage detection*

The damaged beam in case4 shown in Fig.16 is considered for dynamic damage detection. Three kinds of sensors placements are considered in Fig.20: (1) 4 distributed FBG sensors of 250mm gauge length. The actual stiffness reduction at FBG2 due to damage is 10.4%; (2) 10 distributed FBG sensors of 100mm gauge length. The actual stiffness reduction at FBG4 due to damage is 26%; (3) 20 distributed FBG sensors of 50mm gauge length. The actual stiffness reduction at FBG8 due to damage is 52%.

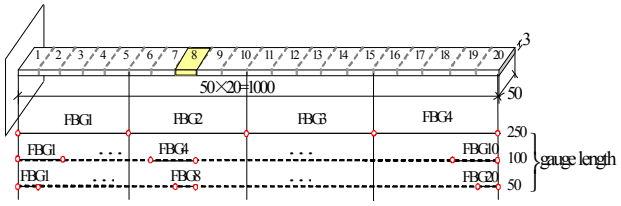


Figure 20. Cantilevered steel beam with fixed FBG sensors

Hammer impulsive loadings are applied at the free end of the beam. The macro-strain time series data before and after damage are then measured from long-gage FBG sensors. Based on the proposed method, MMSV can be directly extracted from the dynamic macro-strain measurements, from which the damage indexes in the three cases may be calculated. For case1, the indexes from FBG1~FBG4 are denoted as β_1~β_4. For case2, suppose the indexes from [FBG2, FBG4, FBG6, FBG8] be denoted as [β_1, β_2, β_3, β_4]. For case3, suppose the indexes from [FBG3, FBG8, FBG13, FBG18] be denoted as [β_1, β_2, β_3, β_4]. As shown in Fig.21, [β_1, β_2, β_3, β_4] in each case locate the damage accurately. With the increase of damage extent, index β_2 presents more distinct indication to damage location.

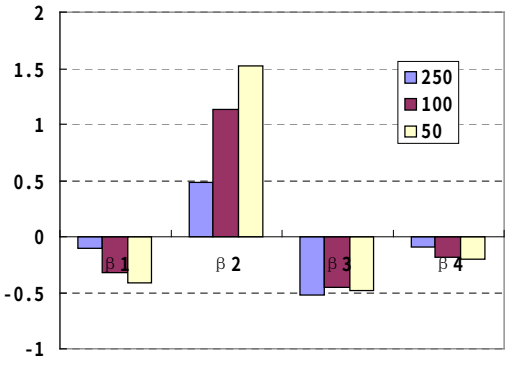


Figure 21. Experimental damage index β_m in three cases

4 DISCUSSIONS AND SUGGESTIONS ON THE FURTHER DEVELOPMENT OF DISTRIBUTED STRAIN SENSING TECHNOLOGIES

In view of the proposed integrated structural damage detection strategy and various experimental as well as numerical validations for the application of available sensors in structural health monitoring, some suggestions on the further development of distributed strain sensing technologies are put forward for reference.

(i) First of all, the accuracy and stability of measurements is still the most important issue for sensors. For BOTDR sensing technique which in deed can carry out continuously distributed measurements, the latest spatial resolution of 10cm can basically satisfy the need of civil engineering practice but strain measurements accuracy of ± 25με seems insufficient for structural health monitoring in respect that any identification method is essentially based on inverse analysis, optimal computation or pattern recognition that is sensitive to measurement errors. In contrast, long-gage FBG sensors are featured with higher precision, so it should be noted to hold it carefully during the process of sensor packaging and installation.

(ii) Maximal measurement distance is also an important behavior for distributed measurements in large-scale structures. For long-gage FBG sensing technology in view of the renovation of interrogation system, this is equivalent to the maximal number of available channels and series-wound fiber gratings.

(iii) Sampling rate is a crucial index for vibration based monitoring which seems as usual to be a more feasible and efficient way for most of civil structures in service.

(iv) The capability of simultaneous measurements and separate storages in static and dynamic cases is expected. Furthermore, whether static or dynamic implement will be under way is also hoped to be controllable and switchable.

(v) If the measured area along a single optical fiber can be adjustable, i.e. only focusing on some interested regions for measurements regardless of other places, it will be very useful for decentralized measurements and monitoring. Anyway, overall and dynamic measurements will bring tremendously huge information. Dividing and rule is a better alternative.

5 CONCLUSIONS

Based on distributed strain sensing technologies, an integrated structural damage detection strategy is proposed. The developed long-gage FBG sensors for distributed strain measurements are employed to investigate the practical applications in structural health monitoring. Some concluding remarks are summarized as follows:

(i) Distributed strain sensing technologies provide a powerful tool to implement the fusion of local strain measurements and distributed global information. Furthermore, diverse measuring manners have the promising potential to carry out both static and dynamic monitoring only using a single instrument.

(ii) Static distributed strain measurements from fielding tests are verified to be efficient for stiffness identification and damage detection based on theoretical background regardless of mass and damping.

(iii) It is worth noting for vibration-based damage identification using modal parameters from dynamic distributed strain measurements that it is significant to perform the two-level algorithm in succession as proceeds by damage location and quantification because locating damage is helpful to reduce the number of unknown parameters and identify damage in a decentralized way.

(iv) MMSV extracted from strain time series data provided by distributed or quasi-distributed sensors gives a nice indicator for damage location, which is crucial to implement decentralized identification for large-scale structure.

(v) Regarding the on-going development of available distributed strain sensing technologies, long-gage FBG sensors possess higher precision and sounder performances such as fast dynamic or online measurements than Brillouin backscattering based sensors for structural assessment and damage detection. However, such a kind of sensing technique, which in deed can carry out continuously distributed measurements and directly utilize the commercial optical fibers without additional packaging, has promising and immense potential for real-time practical application in structural health monitoring.

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