SENSORS AND BRIDGE MONITORING SYSTEM

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Abstract

Rapid developments of structural sensing and control, data acquisition and processing, and computer technologies have made it feasible to monitor the structural health of large-scale structures in real time. SHM of large-scale infrastructures has increasingly attracted extensive interests from both fields of research and application. Based on recent research achievements of developing smart SHM systems in Ibaraki University, cost evaluation study on introducing bridge monitoring is shown first and then distributed long-gauge FBG (Fiber Bragg Grating) sensing technique is introduced which is one of the distributed sensing technologies such as Brillouin scattering-based sensing and HCFRP (Hybrid Carbon Fiber Reinforced Polymer) sensing.

1. Introduction

Infrastructures are exposed to open air and deteriorating at an astonishing rate due to the natural disasters, lack of maintenance, overloading and other reasons, most of which are in a state of deaf and dumb. Many of them need to be monitored and repaired, especially in many developed countries such as Japan and American (Wu et al. 2003). For this purpose, the SHM has attracted extensive attentions, which is to develop a system similar to human nervous systems through which abnormalities such as pain and itch can be sensed, and provide information for the following actions-judging where the abnormalities are, whether and when to see a doctor. It is clear that the establishment of a distributed sensing system to sense the abnormalities and assess the structural integrity is critically important.

The health management of human beings can be divided into several stages. The first stage is to sense the abnormalities such as fever, pain and itch via the human nervous systems that spread all over the body. The nervous systems can provide an integrity monitoring and assessing of the body, and if there is something abnormal the nervous system will tell the brain where and how the abnormalities are. Then the maintenance enters the second stage where preliminary decisions will be made whether and when to see a doctor according to the integrity monitoring and assessing in the first stage. If the abnormalities belong to familiar symptoms, some simple countermeasures will be taken by the human beings selves. If they are unfamiliar, the maintenance will enter the third stage where ones should have a detailed and particular diagnosis at hospital with some advanced medical devices. The final stage is to take some proper medical counter-measures according to the diagnosis results at hospital.

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In light of health maintenance of human beings, the authors propose the maintenance concepts of large-scale infrastructures (Wu 2003), which may be divided into four stages as well. In the first stage, the monitoring is based on the sensing with a distributed sensor system. For human beings, the distributed sensing system is the nervous system that spread all over the body. For this purpose, large numbers of long-gauge and distributed sensors are needed to be embedded into structures to establish a distributed sensing system similar to the nervous system of human beings for monitoring the global integrity of structures and collecting global information in real time. However, the health monitoring of large-scale infrastructures are more difficult and challenging than that of other kinds of structural systems since they are inherently spatial, distributed and geometrically complex with different materials, joints and sub-structures, and furthermore the sites to be inspected are always extensive, inconvenient, invisible, dangerous or even inaccessible. Consequently, the sensors and sensing system for huge infrastructures should be embedded into structures, and the embedded sensors should have the characteristics of distributed and broad sensing feasibilities as well as long-term durability and low-cost.

In this paper, we introduce first the cost analysis study of adoption of health monitoring system for a bridge and then studies on development of new sensors and systems.

2. Cost Evaluation in Bridge Inspection Strategies

Visual inspection is the first and basic step for maintenance of civil-structures. Visual inspection is a time- and labor-consuming job, though it can provide us with useful information of structural condition. Accuracy of visual inspection generally depends upon inspector's experience and skill. Non-destructive methods are applied for getting further detailed information on damages. In some cases, it cannot be applicable for underground and underwater structures and some structural members which are hard for inspectors to access. Then we need inspection robot to improve accessibility. The inspection robot at the first stage carries CCD camera and/or video camera which act as human eyes. Then inspection robot can be equipped with sensors and data processing function and to get information of structural condition at necessary location and at necessary occasions to evaluate structural health condition.

On the other hand, health monitoring is to monitor structure condition continuously using embedded sensors, data logger and recording system. Health monitoring system is usually installed for special cases, because the cost of the system is expensive. The cost/performance is the critical issue for adopting the health monitoring system. In addition, selection of monitoring items and condition evaluation criterion are also important subjects. There are lot of researches and studies to develop new kinds of sensors and systems to improve the cost and performance using MEMS, optical-fiber sensors, wireless technology and network technology. Especially wireless sensing method is expected to reduce the cost of the system including set up cost. Bridge maintenance is expected to advance in adopting both improved inspection technology and monitoring method based on new technologies.

To support ordinary bridge inspection, bridge monitoring for crack, fatigue and corrosion is introduced (Sumitro et al. 2005, Wu 2003). But, the cost evaluation of the bridge inspection strategies in consideration of the bridge monitoring is not discussed enough in current situation. The important point in planning inspection strategies is uncertainty in future. However, the rigid evaluation method (Amram et al. 1999, Harada et al. 2005, Kurino et al. 2000), such as Discount Cash Flow (DCF) method, commonly used for alternative evaluation, cannot take into consideration of uncertainty that may occur in future. On the other hand, Real Options (RO) method is a new technique that can take this into consideration providing the flexibility of alternatives.

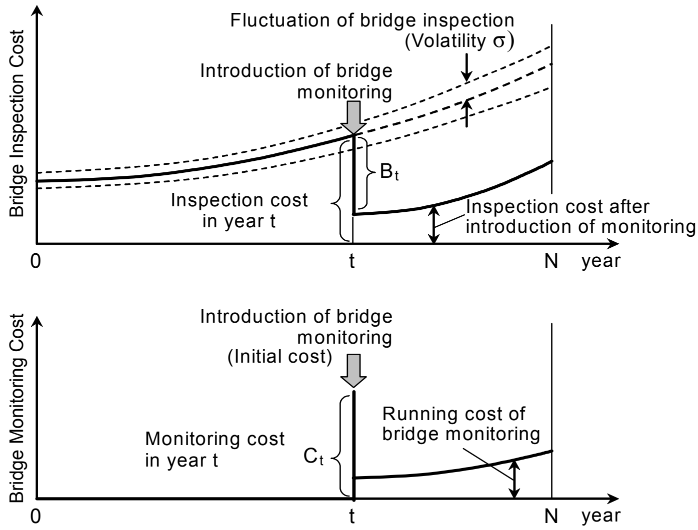

Fig.1 Modeling of bridge inspection and monitoring cost

The cost evaluation study of bridge inspection alternatives by using RO method is conducted (Harada et al. 2006). The inspection cost increases due to aging of the bridge, and the value of cost evaluation is quantitatively estimated based on some possibility that may cause change of inspection cost in the future. The bridge monitoring is introduced instead of inspection. Therefore, instead of the bridge inspection cost being reduced, initial and running cost for bridge monitoring is occurred. Based on the proposed RO cost evaluation method considering change of inspection cost as shown in Fig.1, the role of the monitoring in the bridge inspection is evaluated. The proposed RO cost evaluation method is effective for making proper bridge inspection strategy and has the possibility to reduce bridge inspection cost.

3. Development of Distributed Sensing Techniques

The authors have performed series of studies on the developments of distributed sensors, which are Brillouin scattering based sensing techniques including BOTDR (Brillouin Optic Time Domain Reflectometry) and PPP-BOTDA (Pre-Pump Pulse Brillouin Optic Time Domain Analysis) FOS (fiber optic sensors), HCFRP and distributed long-gauge FBG sensors. The Brillouin scattering based FOS can provide structures a continuous and distributed monitoring in a real time, the spatial monitoring distance may be longer than 10 km. For PPP-BOTDA FOS with a core component of Neurescope system, an accurate and distributed monitoring can be realized in an on-site mode with a spatial resolution of cm-order and strain measuring accuracy of $\pm 25\mu\varepsilon$. The newly developed HCFRP sensors are fabricated with several types of carbon tows, characterized by distributed, broad- and stage-based sensing feasibility as well as long-term durability and low cost. The conventional FBG sensors are known as "point sensors". In our study, the gauge length of FBG sensors are lengthened through a proper packaging and a distributed sensing is realized through arraying proper number of FBG sensors in series. The advantages of FBG sensors are their measuring accuracy and dynamic sensing. In order to measure small strains and vibration, some research activities have performed to enhance the sensitivity of FBG and HCFRP sensors.

The authors have carried out series of studies to develop the HCFRP (hybrid several types of carbon fibers as active materials) sensing technique. The electrical and mechanical model of HCFRP sensor is illustrated in Fig.2 (Wu and Yang 2004, Zhishen Wu et al. 2006). In this model, three types of carbon tows are involved, which are high modulus (HM), middle modulus (MM) and high strength (HS) carbon tows. The HM carbon tows such as C7 and C8 are expected to fracture during a low strain range, and the fracture can lead to a high rate at which the electrical resistance of the HCFRP sensor increases in the low strain range. As a result, the HM carbon fibers can enhance the sensing range where the electrical resistance can be measured accurately and effectively. The MM carbon tows are mainly used to enhance the increase in electrical resistance and the steps of $\Delta R/R_0$ vs. strain curves to meet a stage-monitoring requirement of the practical structures. HS carbon fibers are mainly used to improve the load carrying capacity and

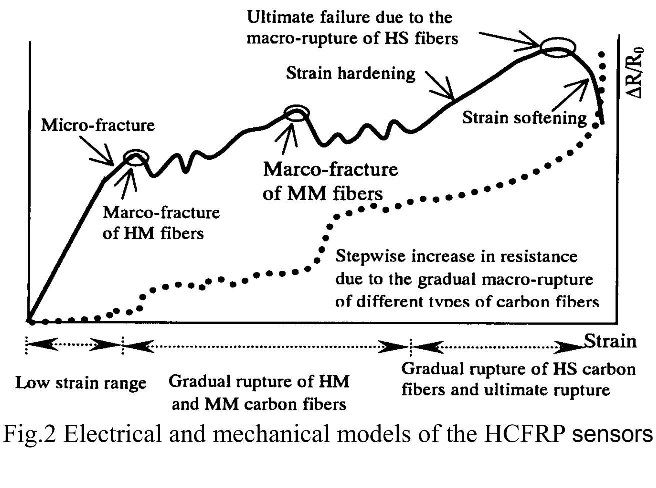

Fig.2 Electrical and mechanical models of the HCFRP sensors

ensure the stability and safety of the HCFRP sensor after the macro-fracture of HM and MM carbon fibers. The hybridization can generate an electrical resistance change as a step-function of strain in a high strain range. Between two steps, the electrical resistance increases nearly in proportion to the strain. Consequently, the hybridization enlarges the strain-sensing ranges and achieves the self-health monitoring serviceability (Wu et al. 2005) using HCFRP sensor.

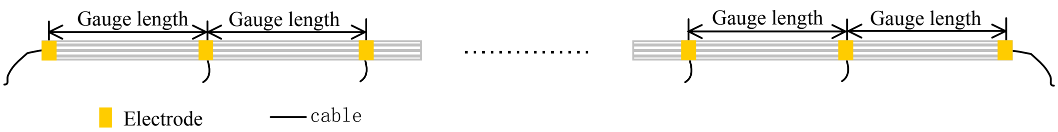

Fig.3 Distributing sensing of HCFRP

For distribution sensing, electrodes are installed in the HCFRP sensor according to specific sensing requirements, as shown in Fig.3. The length between two electrodes is treated as gauge length. The gauge length of every part is optional. The measurement between two end electrodes provides global information. If the measurement is abnormal, the measurements between every two electrodes are performed and the abnormality can be located.

The main advantages of HCFRP sensing are broad and distributed sensing feasibility, low cost and long-term durability. Moreover, the measuring equipment and analysis technique are simple. It is suitable for the monitoring of large-scale structures.

4. FBG Sensing and Long-Gauge Sensors

4.1 Long-gauge FBG sensors

As traditional strain gauges, FBG sensors are known as "point" sensors. A small-diameter FBG sensor consists of core where gratings are carved, cladding and polymer coating. FBG sensors (typical gage length: 5-10 mm) are characterized by a series of parallel gratings (typical grating period: 0.5μm) carved into the core of an optical fiber, and a narrow wavelength range of light is reflected from the sensors when a broadband light is illuminated. Since the wavelength at the peak of the reflected signal is proportional to the grating period, the axial strain can be measured through the peak shift.

The essential of this sensor as shown in Fig.4 is the handling of an embedded tube, inside which bare optic fiber with FBG is sleeved and fixed at two ends. Through special packaging as shown in Fig.5 by composite materials the original Bragg grating with inherent gage lengths on the order of a few millimeters can be extended to effective gauge length up to several centimeters or meters. This FBG sensor can measure average macro-strain that is less susceptible to local stress/strain concentrations and hence more representative of the deformation of the entire structural member. Furthermore, compared with resistive foil strain gauge and other traditional "point" gauges, this sensor can be easily multiplexed at many locations or distributed throughout the structure by using a series connection and permit distributed strain measurements of high precision. The image of distributed long-gage FBG sensors array can be seen in Fig.4.

Single-mode optical fiber of Corning SMF-28 was utilized in this study. All the FBGs available for are passed 100KPSI proof test and could be used to measure strains up to 5000με repeatedly. Meanwhile, an FBG-Interrogation system from NTT-AT with sampling rate of 50Hz was used for data acquisition and signal interpretation.

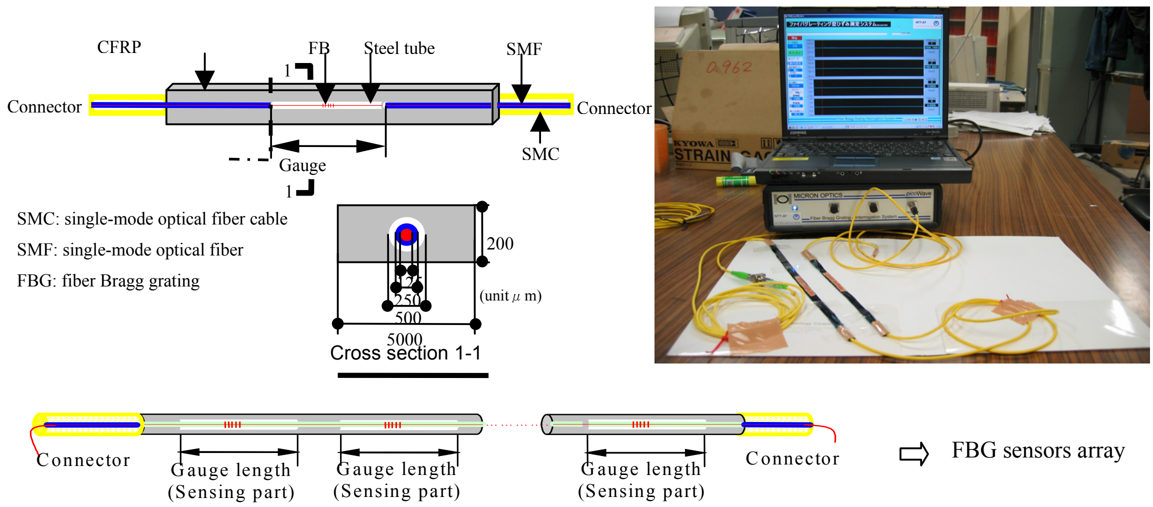

Fig.4 Developed long-gage FBG sensing system

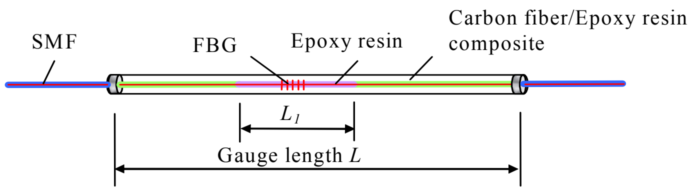

Fig.5 Special packaging for enhancing stain sensitivity

4.2 Local crack and global performance monitoring using long gauge FBG sensors

Health monitoring of RC structures often includes two main aspects i.e. local damage detection and assessment of global structural performance. A RC beam specimen with flexural failure is taken as an example to illustrate the local and global monitoring of structures with the newly developed long-gauge FBG sensors and the concept of distributed sensing (Zhishen Wu and Li 2005). The dimensions of the specimen and distribution of FBG sensors are shown in Fig.6. The specimen was continuously loaded under a load control mode up to its final failure.

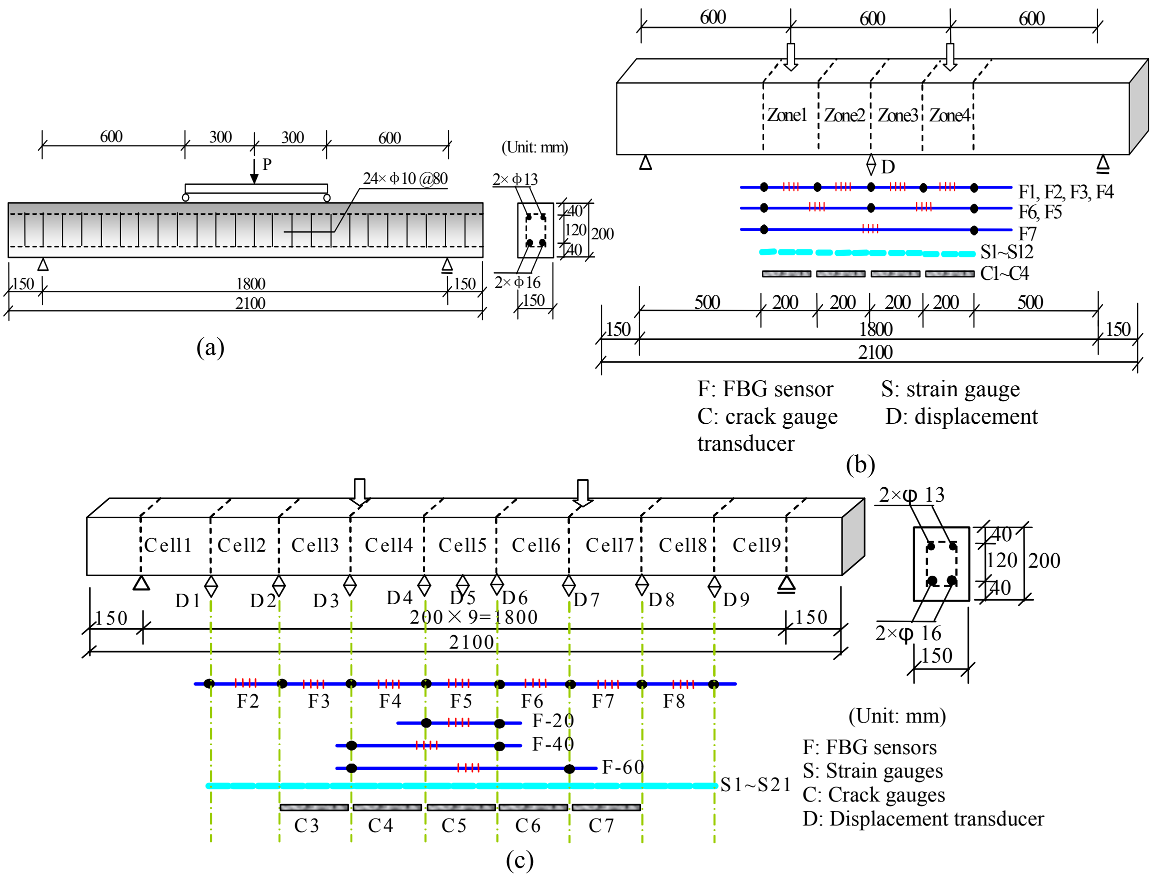

Fig.6 Outline of the RC beam: (a) dimension of the RC specimen; (b) distribution of long-gauge FBG sensors; (c) distribution of long-gauge FBG sensors with high sensitivity

To illustrate the application of long-gauge FBG sensors to RC structures, two RC specimens were fabricated. One is installed with long-gauge FBG sensors, and the other is installed with normal and improved long-gauge FBG sensors.

As demonstrated in Fig.6(b), the area with sensors installation is artificially divided into four zones, denoted by Zone1~Zone4 for the convenience of discussion. Four FBG sensors of 200mm gauge length are arranged onto the bottom surface of the specimen to implement a quasi-distributed measurement. The other two kinds of FBG sensors with gauge length of 400mm and 800mm respectively are attached in parallel to investigate the influence of gauge lengths on the sensor behavior. Traditional foil strain gauges of 60mm gauge length are fixed at the top, bottom and side surfaces of the beam. Crack gauges of 200mm gauge length are also used for comparison. A displacement gauge is installed at the center of the specimen to provide an index to verify the structural global performance.

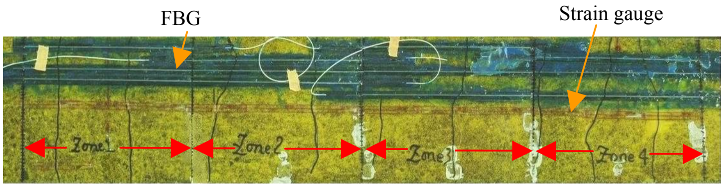

Fig.7 Crack distributions at bottom surface after experiment

The crack distribution of the specimen is shown in Fig.7, with the cracks at the bottom surface of the beam labelled ①~⑨ from left to right. When the load is up to 35KN, six FBG sensors including [F1, F2, F3, F4, F5] failed to work, whereas F6 and F7 worked well until the end of the experiment at a load of about 75KN.

a) Local damage detection

Measured strain with load from FBG sensors of 200mm gauge length are shown in Fig.8. The data from crack gauges and strain gauges are also illustrated for comparison. It can be seen that the first three cracks (④⑥⑧) can be detected easily by FBG sensors from the inflection points after which the slopes of the curves decrease discontinuously.

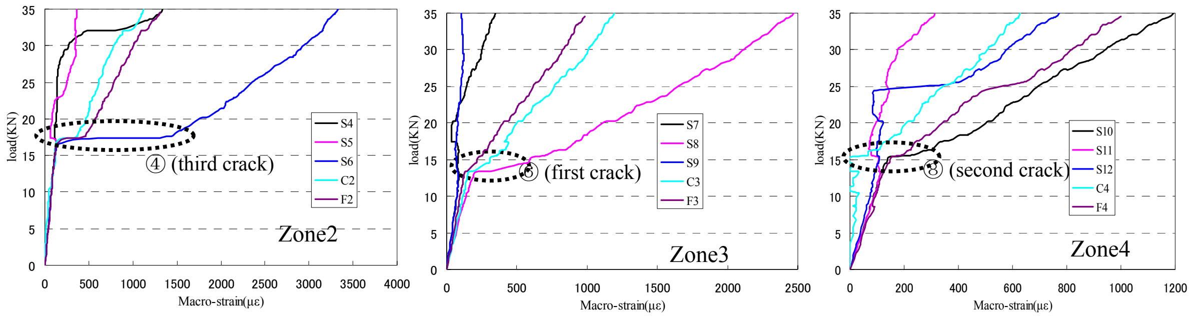

Fig.8 **C**rack detection with long-gauge FBG sensors

Four kinds of long-gage strain sensors are utilized in this study to study the influence of gauge lengths on crack monitoring. These sensors include a strain gauge of 60mm gauge length and three FBG sensors of 200mm, 400mm, 800mm gauge lengths. Now, let us consider crack ⑧ for example. It is obvious from Fig.9 that with the increase of gauge length, the measured macro-strains change slowly after the initiation of concrete cracks. The result reveals an important conclusion that the average macro-strain is less susceptible to the local stress /strain concentration and more representative of the deformation of the entire structural member. Furthermore, it can be concluded that as long as the extent of crack is small or the gauge length of the sensor is long enough, the aberrant changes in the measured data caused by local crack can be reduced to keep the continuity of the final results.

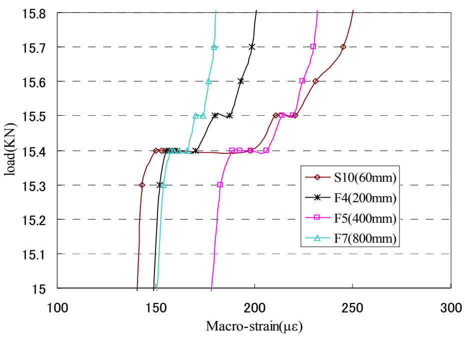

Fig.9 Crack monitoring based on strain sensors of different gauge lengths

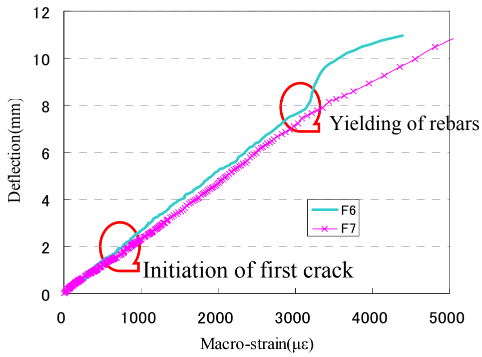

Fig.10 Deflection vs. macro-strain curves from F6 and F7

b) Global structural performance monitoring

The macro-strain responses obtained by F6 and F7 vs. deflection curves are illustrated in Fig.10, where a perfect linear correlation is shown before yielding of steel bars. This conclusion is very valuable in that as long as the gauge length and location of sensors are selected reasonably the long-gage FBG sensor can replace the displacement transducer that is often used for global deflection measurements but difficult to be installed onto the practical civil structures due to the requirement for baseline position. Moreover, it can be seen that the correlation curves maintain the sound accordance before and after cracking, which proved again the above argument that the FBG sensor with enough gauge length can obtain the measurements overlooking the influence of local crack. In addition, compared with those from F6 of 400mm gauge length, the results from F7 of 800mm gauge length matches better with simulation, especially after the yielding of reinforcing bars.

To investigate the effectiveness of the measured average macro-strains, the comparative results from different gauge lengths are illustrated in Fig.11. These results verify the conclusion that in case of RC beam the macro-strain measurements over a certain gauge length can be obtained from the average of those over several gauge lengths. A simulation model is also established in terms of classic bending theory to verify the serviceability of long-gauge FBG sensors to concrete structures. It is confirmed that the measurements from FBG sensors match well with the analytic results before the initiation of the first cracks and have a close agreement with those after cracking. The simulation further verifies the important conclusion that there is a perfect linear correlation between macro-strain and deflection. Through an inverse analysis, the load level and structural parameters can be effectively identified and estimated.

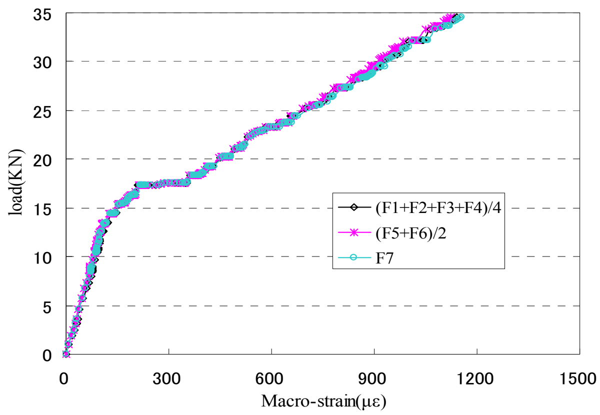

Fig.11 The average macro-strain measurements

4.3 Dynamic sensing with long-gauge FBG sensors

An experimental investigation on beam structures has been carried out to verify the dynamic sensing of long-gauge FBG sensors. Fig.12 gives the outline of experimental specimen and sensors placement. Detailed discussions can be found in (Wu and Li 2006). Taking the case of eight distributed FBG sensors for example, some essential results are shown herein.

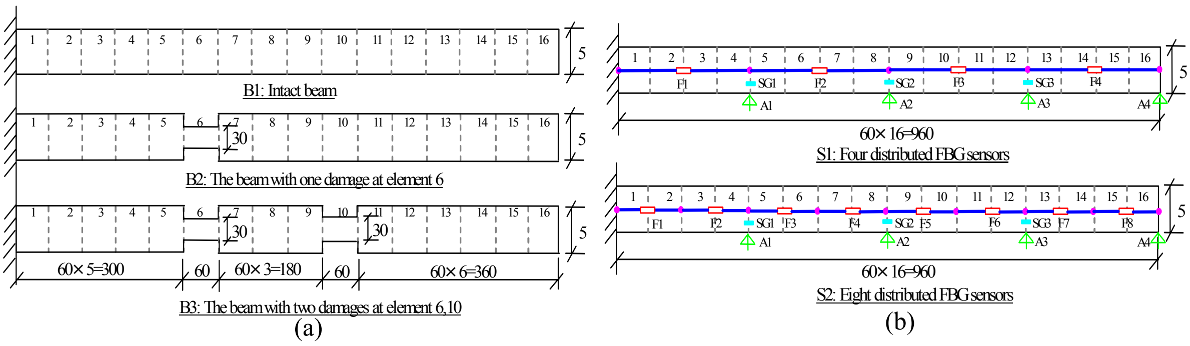

Fig.12 Experimental details about dynastic testing: (a) dimensions of specimen; (b) distribution of long-gauge FBG sensors

Fig.13 is the time-series data of the beams from the distributed long-gage FBG sensors under free vibration. To compare the results of the intact and damaged beams, the initial macro-strains from F1 are set to unit and all the measurements are adjusted proportionally. The dot-dash lines emphasize the responses from FBG sensors which are installed in the region covering the damaged part. It can be found that compared with the time histories from B1, those from S2-B2-F3 and S2-B3-F3&F5 graphically present the obvious difference and detect the damages qualitatively.

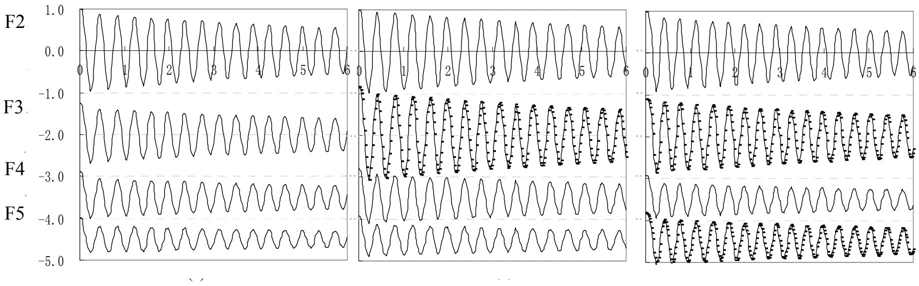

Fig.13 Macro-strain time histories of the beams from F2~F5 in S2

In addition, in order to get detailed information on damages, a two-level damage detection scheme using modal parameters extracted from distributed strain time-series data is proposed, processed by the following phases: (i) Level1-Modal macro-strain vector (MMSV) method for damage localization without a detailed analytical model. (ii) Level2-Damage quantification based on FE model updating.

Concerning the Level1 damage localization, a method named as modal macro-strain vector (MMSV) method with no need for a detailed analytical model is presented. Via experimental modal analysis, the MMSV which has been proved to have a mapping relation with displacement mode shape can be extracted directly from macro-strain time series data, from which a damage evaluating index can be obtained to provide an indicator to damage locations. Many former research works have shown that mode shape curvatures are more sensitive to damage but the differentiation process enhances the experimental errors inherent in mode shapes, yielding a large statistical uncertainty. The application of dynamic strain distribution may bring up a new way for vibration-based damage detection in that this measurement is identical to curvature in a sense and directly provides a modal parameter similar to curvature mode shape without an additional differentiation process

Most of the FE model updating methods has theoretically depended on the sensitivity equations using the relation of changes between structural modal and physical parameters. After the Level1 damage locating, the number of candidate parameters to be identified is sharply reduced, helpful for the further damage detection for exact quantification. 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 the natural frequency is utilized as the initial step in our work for damage quantification. Both simulations and experiments have verified that this two-level scheme holds some merits over traditional methods that implement damage localization and quantification at the same time.

Fig.14 gives an overall view on the structural assessment and damage detection strategy regarding static and dynamic measurements based on distributed strain sensing technologies.

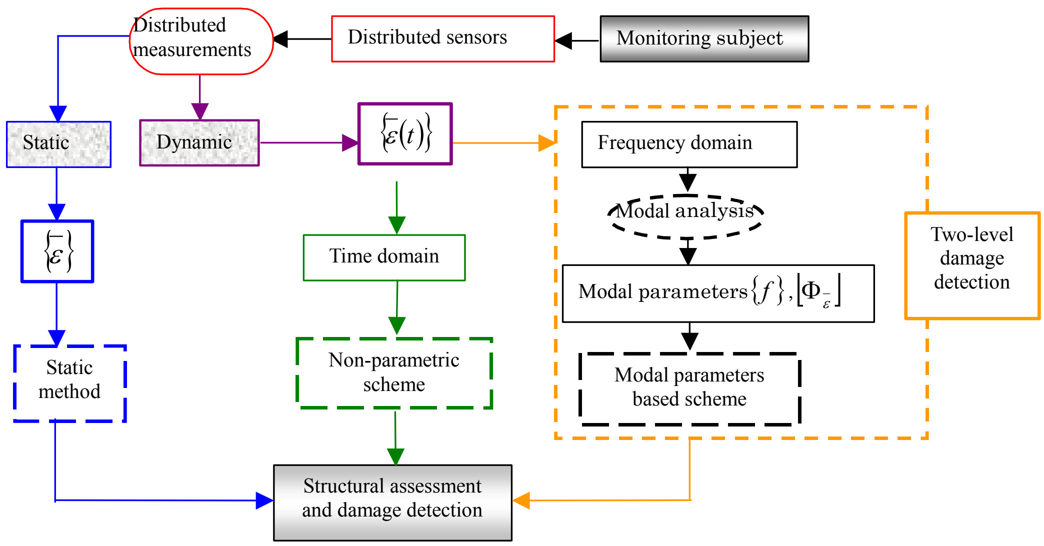

Fig.14 Structural assessment and damage detection strategy

5. Conclusions

In this paper maintenance concepts of large-scale infrastructures in real time have been proposed. For these purpose some newly developed distributed sensors and sensing techniques in Ibaraki University for constructing smart SHM systems have been presented. The following conclusions can be made from this research:

1) The proposed RO cost evaluation method is effective for making proper bridge inspection strategy and has the possibility to reduce bridge inspection cost.
2) Newly developed HCFRP (hybrid CFRP) sensing technique can effectively enhance the measuring range, accuracy and dynamic sensing and can be used as distributed sensing technique for monitoring large structures.
3) Because of hybridization, HCFRP sensor is possible to be low cost, long-term durable and offer self-health monitoring serviceability of the structures.
4) Through special packaging by composite materials, small gauge length (order of few millimeters) of FBG can be extended to the order of several centimeters or meters.
5) This spatial packaged long gauge FBG sensor can measure average macro-strain that is less susceptible to local stress/strain concentration and thereby more representative of the deformation of the entire structural member.

6) Compared with traditional point gauge sensors, this sensor can be easily multiplexed at many locations or distributed throughout the structure with high precision.
7) These FBG sensors can be used for both local crack detection and global performance monitoring as well.
8) By lengthening the gauge length, distributed FBG sensors can be effectively used for dynamic sensing of large structures. Comparing the time history responses from different sensors, damage can be detected qualitatively.

Acknowledgements

The research described in this paper has been carried out by the researchers of Structural Engineering Laboratory of Department of Urban and Civil Engineering, Ibaraki University, Japan. In particular authors are indebted to Dr. C.Q. Yang and S.Z. Li and H. Zhang for their special contribution in developing distributed sensing systems.

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