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RECENT R&D ACTIVITIES ON STRUCTURAL HEALTH MONITORING FOR CIVIL INFRA-STRUCTURES IN KOREA

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ABSTRACT

Developments and applications of the structural health monitoring (SHM) systems have become active particularily for long-span bridges in Korea. They are composed of sensors, data acquisition system, data transmission system, information processing, damage assessment, and information management. In this paper, current status of research and application activities on SHM systems for civil infra-structures in Korea are briefly introduced by 4 parts: (1) current status of bridge monitoring systems on existing and newly constructed bridges, (2) research and development activities on smart sensors such as optical fiber sensors and piezo-electric sensors, (3) structural damage detection methods using measured data, and (4) a test road project for pavement design verification and enhancement by the Korea Highway Corporation. Finally the R&D activities of a new engineering research center entitled Smart Infra-Structure Technology Center at Korea Advanced Institute of Science and Technology are also briefly described.

1. INTRODUCTION

Developments and applications of bridge monitoring systems have become active in Korea, since the early 1990's. The number of the deteriorated infrastructure systems, mostly built in the rapidly industrialized period of 1970's, has increased rapidly and the recognition of the potential devastating disruption of the infrastructure systems due to natural and man-made hazards has also increased. Particularly after the tragic collapse of Sungsu Bridge crossing Han River in Seoul in 1994, the Korean governmental authorities have issued more stringent requirements on bridge management and operational programs. They include systematic visual inspection, instrumentation, load capacity tests and field measurements for design and construction verification, and long-term performance monitoring and assessment.

The structural health monitoring (SHM) systems are generally composed of two major parts: (1) hardwares such as sensors, data acquisition equipment, data transmission systems, etc, and (2) softwares such as signal processing, information processing, damage assessment, information display and management, etc. The first part of the SHM system involves the observation of the structure using periodically sampled response measurements from arrays of sensors, the storage of the measured data, and the transmission of data to the control center. In the second part, the extraction of the damage-sensitive features from the measurements is performed using various signal/information processing techniques, and then damage assessment algorithms are applied to determine the current state of the structural integrity. Recently the web-based integrated SHM system has become an important research topic in conjunction with the on-line monitoring system.

In this paper, current status of bridge monitoring systems on existing and newly constructed bridges in Korea is reviewed. Then the research and development (R&D) activities on optical fiber sensors for smart health monitoring and structural damage detection methods using the measured data are summarized. Finally the test road project for pavement design verification and enhancement by the Korea Highway Corporation is described.

2. CURRENT STATUS OF BRIDGE MONITORING SYSTEMS

2.1 Bridge Monitoring Systems on Existing Bridges

The bridge monitoring systems were recently installed on several existing bridges, especially on long-span bridges in Korea. The purposes of the monitoring systems are to monitor the structural integrity based on the measured data for cable tension, tilting of main tower, vibration of girders and local strains, and to construct the database on the bridge responses and the characteristics under various loading conditions such as traffic, wind, earthquake, and temperature. Fig. 1 shows several bridges with such monitoring systems. Jindo bridge, built in 1984, is a three-span cable-stayed bridge. The monitoring system was installed to monitor both of the short-term and long-term behaviors of the bridge. It is composed of 66 sensors for static and dynamic measurements, 3 data loggers for dynamic data, and 1 data logger for static data to construct the database and to give a warning. In Dolsan bridge, another cable stayed bridge built in 1984, the database program including 3-dimensional computer graphics makes it possible to give the engineers instantaneous information of the bridge. Namhae bridge, constructed in 1973, is a three-span suspension bridge with a main span of 404m and side spans of 128m each. The stiffening girders consist of welded steel boxes. Fig. 2 shows the types and the locations of sensors installed in Namhae bridge. 74 channels are used to measure the static data such as bi-axial tiltmeters, submersible tiltmeters, and static strain gauges. 36 channels are used to measure the dynamic data such as dynamic strain gauges, accelerometers, and anemometers. Fig. 3 shows the long-term monitoring system of Namhae bridge.

(a) Jindo Bridge (b) Dolsan Bridge (c) Namhae Bridge

Fig. 1 Long-span bridges on which monitoring systems are installed

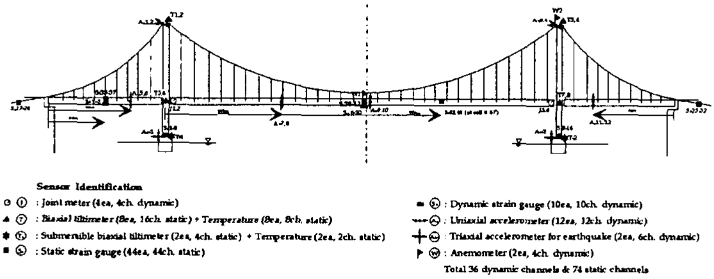


Fig. 2 Sensors installed in Namhae Bridge

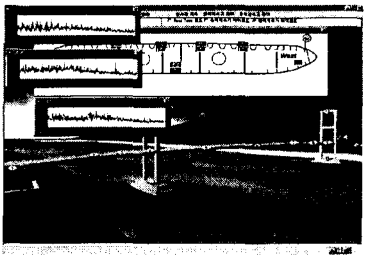


Fig. 3 Long-term monitoring system of Namhae suspension bridge

2.2 Bridge Monitoring Systems on New Bridges

Recently a number of long-span bridges were built in Korea and most of those bridges are equipped with modern monitoring systems. Unlike those installed in existing bridges, many sensors and acquisition systems for measuring behavior under construction become a part of the long-term health monitoring system. The monitoring systems are integrated into the network of the bridge management systems including inspection, evaluation, estimation and rehabilitation. The system utilizes advanced techniques such as sensing, communication by fiber optic cable, wireless data transmission, and Internet-based remote acquisition and control. Currently, Seohae Bridge, Banghwa Bridge and Youngjong Bridge (Fig. 4), all completed in 2000, are on the network of the integrated bridge management systems, which are developed and operated by the Korea Highway Corporation (KHC). The bridge monitoring systems on Seohae Bridge and Youngjong Bridge are briefly introduced below.

Seohae Bridge: It is a cable-stayed bridge with stiffened steel girders and precast concrete slabs. The main span is 470m long and two side spans are 260m each. 120 sensors were installed: 21 for static and 99 for dynamic data. Various types of sensors are installed on the main towers to monitor the tilt, accelerations, temperature, etc. Tensiometers and thermometers are mounted on the main cable. Accelerations, deflections, static/dynamic strains are monitored in the girders. Besides of monitoring the bridge behaviors, various loadings such as earthquakes, winds, temperatures, etc. are also being monitored.

Youngjong Bridge: It is a self-anchored suspension bridge(125m+300m+125m) with double-deck warren truss girder carrying both railway and roadway. A total of 380 sensors were installed as shown in Fig. 5 and Table 1. Measured data are transmitted to the control center, which is 20km apart from the site through the optical communication networks. The functions of the monitoring systems are acquisition/storage of the measured data, control of the data acquisition equipments, on-line monitoring of the bridge behavior, and analysis of long term behavior.

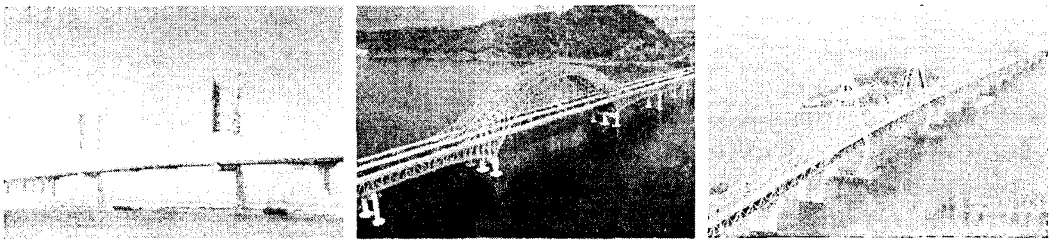

(a) Saehae Bridge (b) Banghwa Bridge (c) Youngjong Bridge

Fig. 4 Recently constructed long-span bridges with monitoring systems

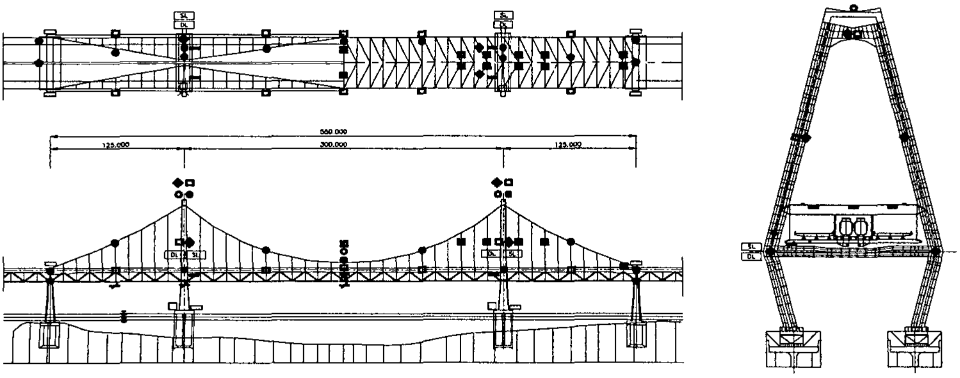


Fig. 5 Sensor locations of Youngjong Bridge

Table 1 Sensors installed in Youngjong Bridge

Symbol	Sensor	Quantity	Behavior	Symbol	Sensor	Quantity	Behavior
●	Thermometer	21Ea	Cable & Member	■	1-D Accelerometer	12Ea	Cable
		12Ea	Tower	◘	2-D Accelerometer	4Ea	Tower Top & Deck
==	Static Strain Gage	8Ea@4	Anchor Bolt			10Ea	Deck
		42Ea	Deck. Cross Section	□	3-D Accelerometer	3Ea	Tower Foundation
		10Ea@4	Anchor Plate	○	Anemometer	4Ea	Wind
		8Ea	Link Shoe	×	Laser Disp. Sensor	3Ea	
—	Dynamic Strain Gage	76Ea	Deck. Cross Section	⬢	Potentiometer	4Ea	Expansion Joint
		99Ea	Etc.	SL	Static Data Logger	2Ea	
◆	2-D Tiltmeter	10Ea	Tower Inclination	DL	Dynamic Data Logger	2Ea	

2.3 Integrated Operating and Management Systems

Data collected at each bridge can be processed exclusively at each field station for real-time monitoring and alarming the sudden abnormal behavior. But data that are useful for long-term evaluation of bridge condition as well as the periodical inspection data of the bridge are transmitted through high speed Internet lines to the management center that is located far from the site as shown in Fig. 6. Once data are collected at the center, the integrated bridge management software (Fig. 7) handles them to classify, store and retrieve. This integrated BMS itemizes bridge maintenance details not only physical information but knowledge, such as detailed rating category for all members. And, based on the inspection results, it manages status assessment, rating, repair and retrofitting activities. Although the health monitoring system itself plays an important role to study the behavior of structures in real environment and to reduce uncertainties in further design process, it can be combined with other technologies such as system identification and damage detection theory, bridge management system and artificial intelligence to give an overall estimation of the bridge condition, to make a proper maintenance decision, and finally to lengthen the service life of the structure. Current researches are focusing on implementing decision algorithms for repair and retrofitting methods, priority and budgeting as well as improvement of the hardware performance of the health monitoring system.

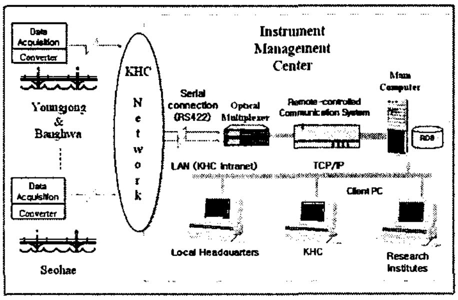


Fig. 6 Integrated Operating System

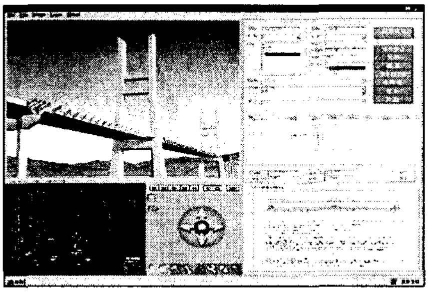


Fig. 7 Integrated BMS software

3. R&D ON SMART SENSORS

3.1 Optical Fiber Sensors

Optical fiber sensors (OFSs) have many advantages for real-time health monitoring of civil-infra structures. They can be easily embedded or attached to the structures and are not affected by electromagnetic fields. They have the flexibility of sensor size (μm-km) and very high sensitivity. Sensor developments have been carried out mostly by the researchers in the fields of mechanical engineering and materials science. However, close collaborations with the structural engineers recently began for application to civil infra-structures particularly with the Smart Infra-Structure Technology Center (SISTeC) which was established at KAIST under the sponsorships of Korea Science and Engineering Foundation (KOSEF). Recent development activities on FBG sensors in Korea are summarized here.

3.1.1 Interrogation Methods for FBG Sensors

Wavelength Division Multiplexing (WDM) Method: Fiber Bragg grating (FBG) sensing based on wavelength division multiplexing (WDM) technology appears to be ideally suited for structural health monitoring. Since the strain is wavelength en-coded in this method, the sensed signal is independent of the power intensity of the light source and the loss in the fiber optic network inter-connecting the sensors. In the case of Bragg gratings, sensor arrays for multiplexing are easily made by connecting several Bragg gratings written at different wavelength serially in a line along the length of a single fiber and addressing each sensor individually using WDM techniques. In order to monitor the load capability and brittle failure of the retrofitted structure, FBG sensors are embedded and attached to the repairing sheets and the smart WDM system is applied to the structure as shown in Fig. 9 [1].

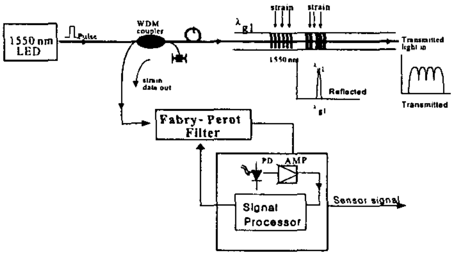


Fig. 8 FBG Sensor Using WDM Method

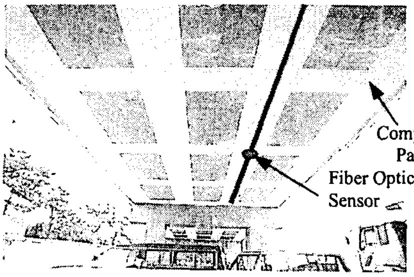


Fig. 9 Example of Self Diagnostic Retrofitted Structure

Wavelength swept fiber laser (WSFL): Recently, an interrogation technique based on the wavelength-swept fiber laser (WSFL) was developed [2]. This technique offers several attractive features compared to previous ones. First, it provides for high signal powers, since the full source output is available during the measurement of a given grating's Bragg wave length. Second, the wide tuning range of the source and its narrow instantaneous spectral line width allow for a large number of individual sensors within the array. However, this technique has a lack of linearity through the tuning range.

Code Division Multiple Access (CDMA) Method: For better multiplexing capability, FBG sensors with the code division multiplexing (CDM) technique are extensively studied [3]. Current activities have been mostly at research level, and the number of the applications to real civil infra-structures still remains limited. However, this type multiple interrogation system has high speed response time and can be used for dynamic measurement of strain.

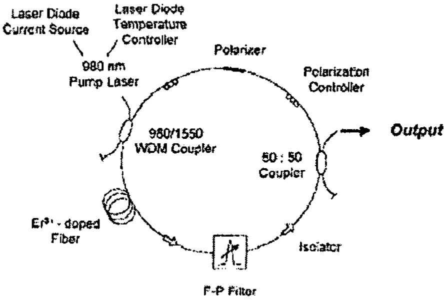


Fig. 10 Wavelength-Swept Fiber Laser (WSFL)

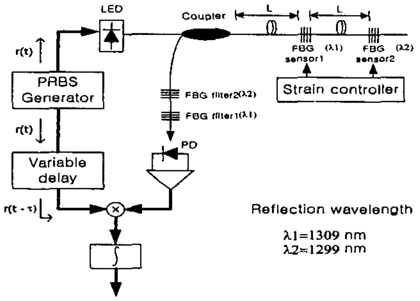


Fig. 11 Experimental configuration for multi-FBG sensor system using CDMA

3.1.2 Weigh-in Motion with Optical Fiber Sensors

The high speed weigh-in motion (WIM) system with FBG sensors has been developed [4]. Multiple Bragg gratings with same wavelengths and same bandwidths are straightly connected each other. Among the multiple gratings, the gratins under the truck load regardless their positions shift the center wavelength of the reflected light. The light is overlapped to the reflected light from the rest of the gratings. The resultant bandwidth of the total reflected light under the load is broader than the initial reflected light without load. Therefore, simple photo detector can catch the variation of the intensity of the reflected light. A new high speed signal processing system which employs bandwidth filter is proposed, a new sensor package design of bridge type is also proposed. The proposed fiber optic WIM system was tested at the laboratory and in the field with actual trucks, as shown in Fig. 12. The test results show that the new WIM system can accurately measure the truck weight under ordinary traffic speed.

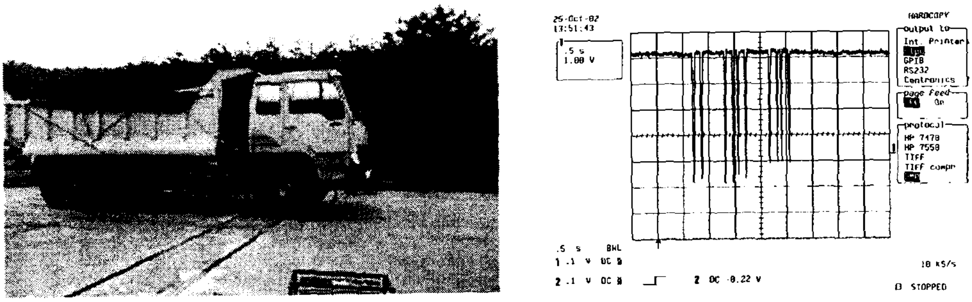


Fig. 12 Truck test of fiber optic WIM system and the signals from the WIM sensors

3.1.3 Structural Integrity Test of Nuclear Power Plants with Optical Fiber Sensors

Nuclear Power Plants should be designed and constructed to prevent leakage of the radioactivity in accidents. So, the structural integrity of the nuclear containment structure should be confirmed by imposing 1.5 times of the design internal pressure and by checking deformation of the containment before commencing operation. To overcome various problems with the existing measurement system using conventional extensometers, optical fiber sensors were used to measure the deformation of a newly built containment structure during the pressure test as shown in Figs. 13-14.

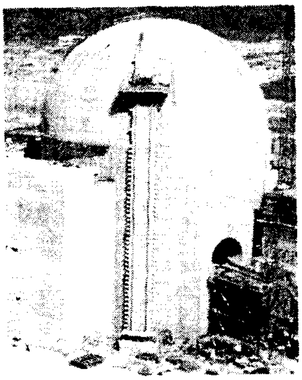


Fig. 13 Nuclear Plant

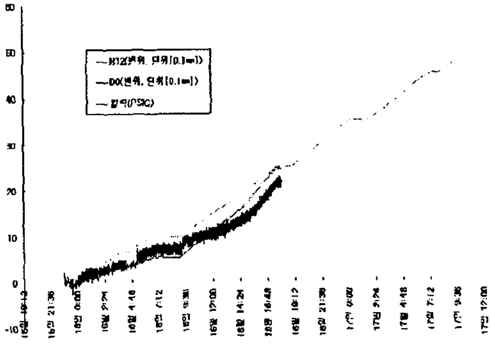


Fig. 14 Optical Fiber sensor Measurement

3.2 Piezoelectric Sensors

Conventional NDE techniques such as ultrasonic testing and X-radiography can provide significant details about the nature of damage. However, these techniques usually require direct access to the structure being investigated and involve bulky equipment. Moreover, these techniques usually require disruptions of the operation of the structures/equipments, which is not attractive for on-line structural health monitoring.

Smart piezoelectric (PZT) transducers, which act as both actuators and sensors in a self-analyzing manner, can be very effective for non-parametric health monitoring of structural systems. The PZT transducers can be very attractive and economical for large civil-infra structures, since a few number of PZT transducers may be required, while a large number of fiber optic sensors may have to be laid through the entire length of the structure.

3.2.1 Piezoelectric impedance-based structural health monitoring

This technique is based on the principle of electromechanical coupling between the host structure and the bonded PZT transducer. The change in structural impedance due to the occurrence of damage modifies the effective electrical impedance of the PZT. This effected change in the driving point impedance of the PZT transducer is used to identify incipient damage in the structure. Soh *et al* (2000), Tseng *et al* (2000) and Bhalla (2000) [5-6] have reported on the successful application of this method on concrete and other civil engineering structures. Experimental setup for the verification of the proposed method is shown in the Fig. 15.

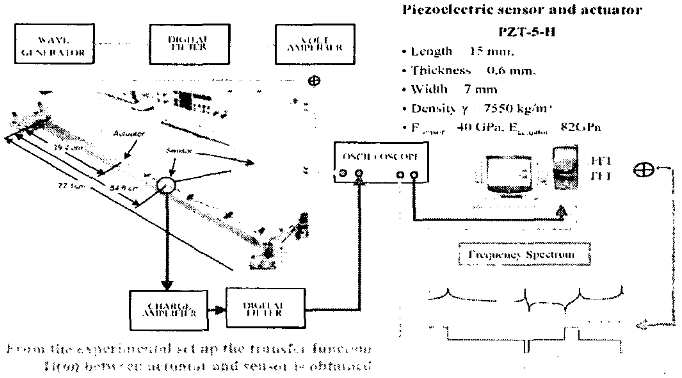


Fig. 15 Experimental test setup

3.2.2 Lamb wave propagation in an integrated piezoelectric transducers

Lamb waves have been used in ultrasonic testing and material evaluation for several decades, and numerous research endeavors have been undertaken to study the feasible methods of generating and receiving these kinds of waves and their propagation characteristics in plate-like structures. Recently, many researchers have studied the technology of integrating piezoelectric sensors/actuators into the structures for the purpose of generating and collecting diagnostic Lamb waves and thus realizing continuous monitoring of their structural integrity. The scheme of this method is shown in the Fig. 16.

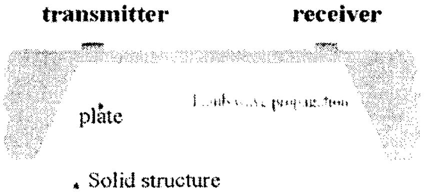


Fig. 16 The scheme of diagnostic lamb waves

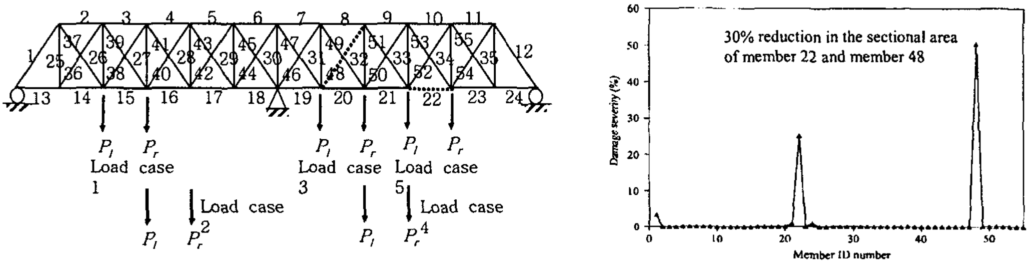
4. RESEARCH ACTIVITIES ON STRUCTURAL DAMAGE DETECTION

Damage detection methods for civil infra-structures based on the measured data from the monitoring system have been studied by several groups in Korea. The methodologies may be classified as (1) the least square error-based identification incorporating various techniques to reduce the ill-posedness of the inverse problem; (2) the soft computing techniques for damage identification; and (3) the damage indicator method based on the modal strain energy.

Verifications of the methods have been carried out through laboratory tests on various bridge models and field tests on real bridge structures.

4.1 Least Square Error-Based Identification for Damage

The damage detection methods based on the minimization of the least-squared errors between the measured and the calculated responses by the finite element model have been studied. Several regularization techniques are introduced to alleviate the ill-posedness of the system identification problem. A geometric mean scheme is presented to determine an optimal regularization factor for Tikhonov regularization technique in the system identification problems of linear elastic continua. The characteristics of non-linear inverse problems and the role of the regularization are investigated by the singular value decomposition of a sensitivity matrix of responses [7]. Hjelmstad and Shin proposed an adaptive parameter grouping updating scheme to localize the damage zones in the structure and utilized a Monte Carlo method with a data perturbation scheme to provide a statistical basis for assessing damage [8]. Lee et al. presented a system identification scheme to determine the geometric shape of an inclusion in a finite body. A variable regularization factor scheme is proposed for a consistent regularization effect [9]. Numerical simulations and laboratory experiments have been performed on various kinds of model structures such as Figs 17-19.



(a) 2-Span Continuous Truss Model

(b) Damage Severity by Averaged Displacements

Fig. 17 Numerical simulations for damage detection of 2-span continuous truss

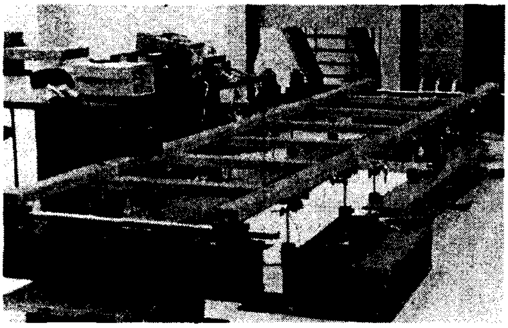


Fig. 18 Model for laboratory tests

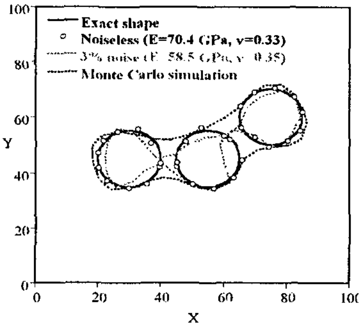


Fig. 19 Identification of Shapes and Material Properties of Inclusions

4.2 Soft Computing Techniques for Damage Identification

Soft computing techniques such as genetic algorithms (GA) and neural networks (NN) have been utilized increasingly for the damage estimation due to their excellent pattern recognition capability. Especially, the NN-based identification approach has great advantage for on-line health monitoring, since it needs very short time to assess the structural integrity based on the measured data [10-12]. Yun et al. presented a NN-based damage estimation of a bridge structure using ambient vibration data caused by the traffic loadings [11]. An improved algorithm to consider the modeling errors in the baseline finite element model was also presented [12]. An experimental study was carried out on a bridge model subjected to vehicle loadings as shown in Fig. 20 and a field test on a span of Hannam Grand Bridge over Han River in Seoul, Korea was also performed to confirm the applicability of the NN-based approach. (Fig. 21).

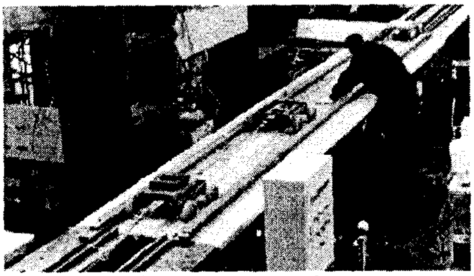


Fig. 20 Laboratory Test

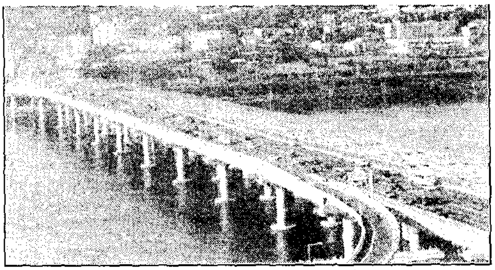


Fig. 21 Hannam Grand Bridge

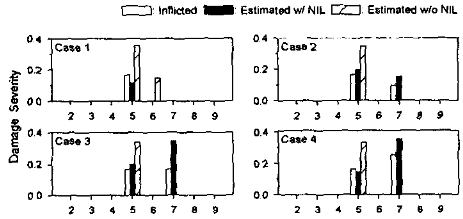


Fig. 22 Damage Estimation for Laboratory Test

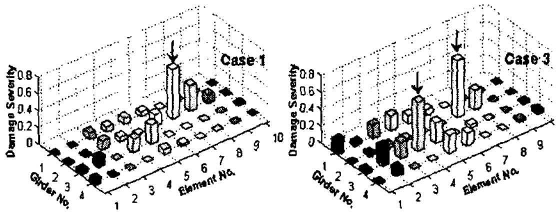
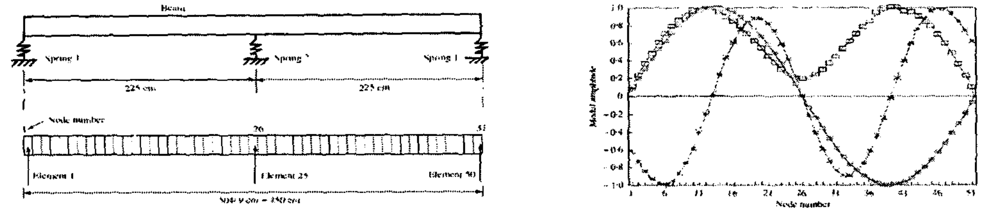


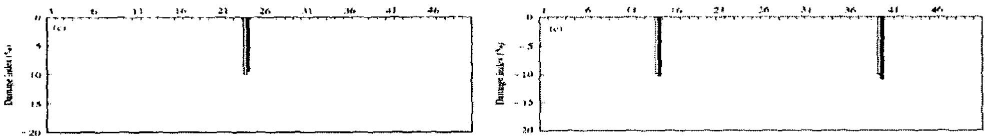
Fig. 23 Damage estimation for Hannam Grand Brdige

4.3 Damage Indicator Method Based on Modal Strain Energy

Kim and Stubbs recently proposed an improved damage indication method to predict locations and severities of damage in structures using changes in modal strain energy [13]. The damage prediction accuracy was numerically assessed for a two-span continuous beam using a few vibration modes as shown in Fig. 24. Kim et al. presented a methodology to nondestructively locate and estimate the size of damage in structures for which a few natural frequencies or a few mode shapes are available. A frequency-based damage detection method and a mode-shape-based damage detection method were developed, and numerical simulations were performed on a prestressed concrete beam [14].



(a) Schematic of two-span continuous beam (b) Mode shapes of two-span continuous beam



(c) Damage prediction results (⊙ : True, □ : Predict)

Fig. 24 Damage indicator method for two-span continuous beam

5. KHC TEST ROAD PROJECT

Korea highway coporation (KHC) built a test road to verify and enhance the pavement design guides based on the measured data in the real traffic and environmental conditions. It is an ordinary two lane expressway of 7.7 km long constructed along the Joongbu Inland expressway, as shown in Fig. 25. It consists of 40 Portland cement and asphalt concrete test pavement sections. The research objectives of the KHC test road project are (1) to develop the Korean pavement design guides, (2) to optimize the pavement thickness design procedures, and (3) to reduce the construction and maintenance costs.

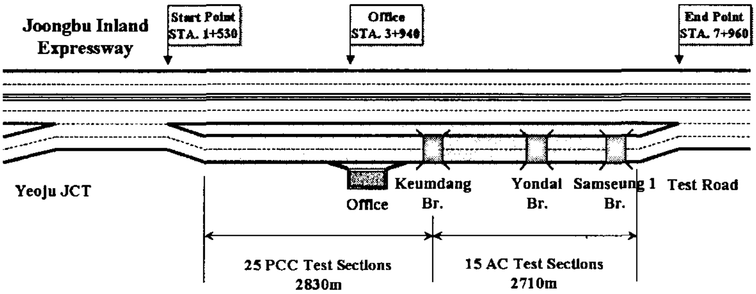
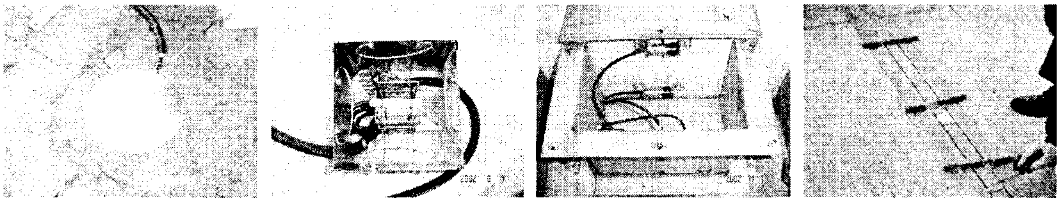


Fig. 25 KHC Test Road Project

Measurement systems installed are classified into two groups: automatic and manual systems. The automatic system is for monitoring the pavement responses due to the environmental change; such as weather, water content, and accumulated traffic volume. In the automatic measurement systems, which are installed on 15 sections along the test road, data loggers and circuit boxes are installed on site and the data transmission is made through fiber-optic cable networks. On the other hand, the manual measurement systems are for measuring the pavement responses for stationary or moving vehicle loads. Various types of sensors are installed to monitor the effect of the traffic loads and the environmental conditions. They are strain gauge, soil pressure gauge, crack gauge, thermocouple, water content gauge, and WIM sensors. 1261 sensors are installed at the 25 Portland cement concrete pavement sections, and 636 sensors at the 151 asphalt concrete pavement sections.

There are 3 test bridges constructed in the test road. They are a steel plate girder bridge with precasted bridge deck, a steel open flange box girder composite bridge, and a high strength prestressed concrete girder bridge. Bridge monitoring systems will be also installed and the performance of the bridge under real traffic load will be examined.



(a) Soil Pressure Gauge (b) Strain Gauge (c) Crack Gauge (d) WIM Sensor

Fig. 26 Type of Sensors Installed on the Test Road

6. SMART INFRA-STRUCTURE TECHNOLOGY CENTER

Smart Infra-Structure Technology Center • (SISTeC) was established at Korea Advanced Institute of Science and Technology (KAIST) in July 2002, as an engineering research center (ERC) sponsored by Korea Science and Engineering Foundation (KOSEF). The research goal is the development of smart structure technologies relevant to the assurance of operational and structural safety and the improvement of life-cycle cost effectiveness for large civil infra-structures. The key technologies include smart materials, smart sensors, structural health monitoring, integrity assessment, structural control, smart repair/retrofit, integrated design and analysis of smart structural systems, and smart geo-technologies. The research team consists of 18 senior investigators who are professors and senior researchers at KAIST and other institutions. Cooperative research projects are carried out in cooperation with various government-sponsored research institutes and leading construction companies. The researchers in SISTeC consist of those from various fields of engineering, such as civil, architectural, mechanical, aerospace engineering and material science.

There are four groups. The research of Group I aims at the development of smart sensor technologies applicable to the large civil infra-structures and smart concrete materials having the characteristics of self-diagnosis/self-healing and environment-adaptivity. Group II aims at the development of analysis/design technologies for smart structures by integrating finite elements/damage models developed for analyzing damage behaviors of smart structural members/systems. Group III aims at the development of the integrated smart maintenance system by using advanced technologies related to health monitoring, damage assessment, vibration control and smart repair/retrofit of large infra-structures. Group IV aims at the development of an integrated smart system for analysis, design, construction and maintenance of earth and geotechnical structures.

SISTeC hosts regular and special seminars and organizes technical courses by inviting experts in the field of smart structure technologies to provide opportunities to communicate and cooperate among the participating members and the researchers/engineers in industries and academia. Besides, SISTeC offers inter-disciplinary courses on smart structures technologies. In addition, SISTeC is making an effort to cooperate with international research centers for developing smart structure technologies. For example, Asia-Pacific Network of Centers for Research in Smart Structures Technologies (ANCRiSST) was established in September 2002. Currently, it consists of 6 centers in Korea, the U.S., Japan, and China. The major purpose of establishing ANCRiSST is to develop joint research projects, exchange of researchers/students, and develop education programs on the advanced smart materials and smart structure. The first activity of ANCRiSST is the 1st International Workshop on Smart Structure Technology to be held in Hawaii, USA, in January 2004. The 2nd Workshop will be held in Seoul, Korea in late 2005.

7. CONCLUDING REMARKS

In this paper, the recent R&D and application activities on structural health monitoring in Korea are reviewed. The development and application of the SHM systems have been very active particularly on long span bridges in Korea. However, the current system is limited to the development and installation of the monitoring systems for collection of the bridge responses under various operational and environmental loadings. They utilized advanced technologies such as data transmission by optical cables and web-based data display and management. However, further improvements are needed for information process for assessment of structural integrity.

The R&D activities have been carried out on smart sensors such as optical fiber sensors, piezoelectric sensors, and MEMS for the application to civil infra-structures. Researches have been performed to develop methods for assessment of structural integrity based on the vibration data under ordinary traffic loadings and under test loadings.

A newly established engineering research center entitled "Smart Infra-Structure

Technology Center" has been played a key role for the R&D activities for structural health monitoring in Korea. It is expected that further advancement in the SHM system may result in through such multi-disciplinary researches on smart sensors, monitoring, and assessment technologies.

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REFERENCES

[1] K. S. Kim, C. Chung and H. J. Kim, "Fiber Optic Structural Monitoring of Concrete Beam Retrofitted by Composite Patches", SPIE Proceedings 5050-24, SPIE's 10th Annual International Symposium on Smart Structures and Materials, 2-6 March 2003.

[2] C. G. Kim, D. H. Kim and C. S. Hong, "Development of FBG Sensor System for Measuring the High Frequency Vibration of Structures and the Natural Frequency of Composites", Proceedings of US-Korea Workshop on Smart Infra-Structural Systems, 3-10, August, 2002.

[3] K. S. Kim, H. Yoo and H. Lee, "Economical and Multiple Fiber Grating Sensor System with Rapid Response using CDMA", OFS2000, 14th International Conference on Optical Fiber Sensors, SPIE Vol.4185, pp712-715, 2000.

[4] K. S. Kim, S. K. Cho and B. Bae, "High-speed Weigh-in Motion Measurement with Bragg Grating Sensors", SPIE Proceedings 5024-30 SPIE's 10th Annual International Symposium on Smart Structures and Materials, 2-6 March 2003.

[5] Soh C K, Tseng K. K-H, Bhalla S and Gupta A 2000 Performance of smart piezoceramic transducers in health monitoring of RC bridge *Smart Master. Struct.* 9 553-42

[6] Tseng K K-H, Soh C K, Gupta A and Bhalla S 2000 Health monitoring of civil infrastructure using smart piezoceramic transducers *Proc. 2nd Int. Conf. on Computational Methods for Smart Structures and Materials* (Madrid, Spain, June 2000) pp 153-62

[7] H. W. Park, S. Shin, and H. S. Lee, "Determination of an Optimal Regularization Factor in System Identification with Tikhonov Regularization for Linear Elastic Continua", International Journal for Numerical Methods in Engineering, 2001, 51, 1211–1230

[8] K. D. Hjelmstad and S. Shin, "Crack Identification in a Cantilever Beam from Modal Response", Journal of Sound and Vibration, 1996, 198(5), 527-545

[9] H. S. Lee, Y. H. Kim, C. J. Park, and H. W. Park, "A New Spatial Regularization Scheme for the Identification of the Geometric Shape of an Inclusion in a Finite Bodies", International Journal for Numerical Methods in Engineering, 1999, 46, 973–992

[10] C. B. Yun and E. Y. Bahng, Substructural identification using neural networks, Computers and Structures, 2000, Vol.77, No.1, 41-52.

[11] J. W. Lee, J. D. Kim, C. B. Yun, J. H. Yi, and J. M. Shim, "Health-Monitoring Method for Bridges under Ordinary Traffic Loadings", Journal of Sound and Vibration, 2002, 257(2), 247-264

[12] J. J. Lee, C. B. Yun, J. W. Lee, and H. Y. Jung, "Neural Networks-based Damage Detection for Bridges Considering Errors in Baseline Finite Element Models", Journal of Sound and Vibration, submitted

[13] J. T. Kim, and N. Stubbs, "Improved Damage Identification Method Based on Modal Information", Journal of Sound and Vibration, 2002, 252(2), 223-238

[14] J. T. Kim, Y. S. Ryu, H. M. Cho, and N. Stubbs, "Damage Identification in Beam-Type Structures: Frequency-Based Method Vs Mode-Shape-Based Method", Engineering Structures, 2003, 25, 57-67