Multi-sensor Data Fusion System for Enhanced Analysis of Deterioration in Concrete Structures

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Abstract— Multisensor data fusion provides significant advantages over single source data. The use of multiple types of sensors plays an important role in achieving reasonable accuracy and precision. A novel integrated heterogeneous multi sensor data fusion approach in structural health monitoring is proposed. The study concerns to find a simple and affordable monitoring strategy for Alkali-aggregate reaction (AAR), which is one of the root causes for structural deterioration in concrete. Many researchers have stated the process of gradual structural deterioration to be very complicated because of the random distribution of aggregate, the arising and growth of concrete crack shows remarkable abnormity and discontinuity. Although researchers have developed several test methods to identify potential reactivity of aggregate. There is no universally valid standard testing method for all cases of AAR. The conventional methods namely petrographic examinations, expansion tests, and chemical analyses are cost expensive and require high skilled person to carry out tests. More over they qualitatively determine the possibility of AAR presence but least quantitatively predict whether the AAR will be deleterious. In order to develop a monitoring strategy for AAR in small size concrete structures, it is necessary to simulate the AAR expansion and cracking within reasonable laboratory timescale. A standard method to accelerate AAR expansion is employed on four samples which are prepared with different level of alkali concentrations. Different sensor systems are used at surface and internal level. Acoustic sensor system, electro-mechanical system, optical systems are employed to obtain surface level damage. The internal level of damage is obtained by embedded sensors within the structure. Features extracted from heterogeneous sensors are fed to Decentralized Kalman filter. The fused global estimates and individual source estimates are fed to artificial neural network (ANN), which characterize and quantify the level of damage. The research is focused on establishing correlation among surface damage level, internal damage level and the amount of gel concentration in the structure. To emphasize the expected improved accuracy using data fusion, evaluations are done on efficiency and accuracy of single source data system comparing with the fused heterogeneous data.

1. INTRODUCTION

In recent years, structural health monitoring (SHM) has been an important research area for designing and evaluating reliability of civil engineering structures. SHM is a system, where different kinds of sensors are put in a structure to make it have the ability to sense its structural integrity under various load and environmental conditions. To investigate both local and global damage, a dense array of sensors is anticipated to be required for large-scale civil engineering structures. The type of the sensors is chosen according to the objective of the specific SHM system, and these sensors are then mounted in the structure to measure the static or dynamic structural response.

The study is focused on developing efficient, reliable and affordable monitoring strategy for aging concrete structures which are suffering deterioration from AAR reaction.

Alkali-aggregate reaction is a chemical reaction between the alkali in Portland cement and reactive minerals in aggregate and additives that takes place when moisture is present. This reaction results in the formation of a hygroscopic gel that absorbs water and expands, causing significant expansion and characteristic cracking of the concrete and ultimately failure of the concrete in worst cases.

Mass concrete hydraulic structures such as dams, weirs, locks, and canals come directly in contact with water and water pressure which acts as catalyst in AAR expansion process. AAR problems in mass concrete of hydraulic structures may be considered more serious as they exclusively suffer from AAR problem; moreover they are usually expected to be operational for a long time, owing to their importance, extent, high costs, and long construction periods. Many concrete dams and other hydraulic structures worldwide have suffered from AAR [1]. Construction engineers and real estate owners are demanding better methods of assessing the AAR reaction in structures in order to provide preventive maintenance.

Failures are often addressed after they occur, i.e., by reactive maintenance. This approach is undesirable based on health and environmental considerations, but is often the default practice due to economic and technical considerations. Preventive maintenance, rehabilitation, and replacement are practiced where feasible; however, this is hampered by the difficulty of accessing the system and efficiently inspecting it.

These difficulties can potentially be addressed through the implementation of smart systems. Smart Systems are defined as miniaturized devices that incorporate functions of sensing, actuation and control. They are capable of describing and analyzing a situation, and taking decisions based on the available data in a predictive or adaptive manner, thereby performing smart actions. An ideal, smart system has capability to detect, locate and quantify any change in the structural integrity of the object under study.

With the development of the technologies in sensing, Micro-Electro-Mechanical Systems (MEMS) researchers and developers have demonstrated an extremely large number of micro sensors for almost every possible sensing modality. MEMS based sensors having low installation costs; more reliability and reasonable accuracy have attracted more attention in SHM of civil structures. The paper proposes an affordable monitoring strategy for AAR affected concrete structures using integrated heterogeneous multi sensors.

2. PREVIOUS WORK

In recent years, multi-sensor data fusion method attracts increasing interest to SHM due to its inherent capabilities in extracting information from different sources and integrating them into a consistent, accurate and intelligible data set [2, 3]. Data fusion techniques can combine data from multiple information sources and related information from associated databases to achieve improved accuracies and more specific inferences than by the use of a single source alone. Researchers are engaging in the study of damage identification methods using data fusion techniques to achieve improved accuracies and more specific inferences.

Guo and Zhang [4] and Guo [5] regarded the changes of frequencies and mode shapes as two different information sources and used the data fusion method to detect the damage of two-dimensional truss structures. Basir and Yuan [6] described a multi-sensor implementation of an evidence theory based engine diagnostic system. Bao and Li [7] employed the D-S evidence theory and Shannon entropy to decrease the uncertainty and improve the accuracy of damage identification. Yang and Kim [8] presented an approach for fault diagnosis in induction motors using D-S theory. Guo and Li [9] presented a two-stage method of determining the location and extent of multiple structural damages by using the data fusion technique and genetic algorithm. Shao-Fei Jiang et al. [10] presented 5-phase complex structural damage detection method by integrating data fusion and probabilistic neural network (PNN). In order to demonstrate the capability of the proposed method, a 4-story benchmark framed structure proposed by the American Society Of Civil Engineers (ASCE) Task Group on Health Monitoring was validated by numerical simulation [11]. To extract feature parameters and produce the samples for training and testing, wavelet base function $\psi(t)$ was employed.

Zhao et al. [12] proposed weighted fusion damage index, based on the D-S evidence theory. Weighted fusion damage indices were calculated from data of piezoceramic-based smart aggregates used in the structural health monitoring. Transducers' location information is considered into the approach to improve the damage identification results. A two-story concrete frame instrumented with piezoceramic-based smart aggregates is fabricated as the object for the structural health monitoring test. The experimental result showed that the proposed weighted fusion damage index can detect the severity of the cracks.

The proposed approach is novel of its kind as heterogonous sensors are employed at surface and internal level to study the damage phenomena and evaluate the changes in structural integrity due to AAR reaction. The evaluation of single source damage sensor will be inferior as compared to fused data from heterogeneous damage sensors as it obtains maximum information from multiple sources regarding defect location and characterization. Acoustic sensor system, electro-mechanical system, optical systems are employed to obtain surface level damage. The internal level of damage is obtained by embedded sensors within the structure.

3. RESEARCH METHODOLOGY

3.1. NBRI Test

In order to study the affect of AAR on concrete structures it is necessary to simulate the AAR expansion and cracking within reasonable laboratory timescale. A large number of ultra-accelerated test procedures, for determining the potential alkali reactivity of aggregates, have been developed, particularly in the past 15 years. An ultra-accelerated test method is defined as one which yields results within a few days or; at most, a few weeks. There are two possible selecting criteria for testing aggregates. In the first, testing should be done under severe conditions that will hopefully detect any potentially expansive aggregate. The other is testing under moderate accelerating conditions. We are adopting the second testing criteria as the former method is expensive and requires experts to carry out the procedure. Because of the lengthy lead time required to evaluate adequately aggregate sources for potential alkali-aggregate reactivity, we are using National Building Research Institute (NBRI) standard accelerated method proposed by Oberholster and Davies [13]. Four different samples of concrete bars measuring $160 \times 40 \times 40$ mm are prepared using NBRI standard testing method. Depending on the mixture of alkali concentrations, the four samples prepared are 1) Non reactive 2) Marginal reactive 3) Moderately reactive and 4) Very reactive.

3.2. Integrated Multi Sensor Data Fusion Approach

The methodology adopted is to obtain data from four different systems namely acoustic system, electro mechanical, optical system and embedded sensors and fuse them in order to get more accuracy as compared with the conventional single source sensor systems.

Pulse-echo is one of the simple and oldest acoustic methods for nondestructive evaluation of concrete and masonry. In pulse-echo technique the pulse propagates through the medium and is reflected by material defects or by interfaces between regions of different densities. Thus the deterioration of test object is estimated by change in the velocity of reflected wave. These reflected waves, or echoes, are monitored by a second transducer coupled to the surface of the test object near the pulse source. The transducer output is displayed on an oscilloscope or similar device.

To obtain information from electro mechanical system, low cost and simple, linear variable displacement transformer (LVDT) and an analog data logger were selected for the experiments. Two LVDT sensors are fixed at either side of the specimen. The expansion in terms of displacement is calibrated as change in voltage at the data logger output device. In order to obtain optical information, charge coupled device (CCD) camera is used. CCD is an apparatus which is designed to convert optical brightness into electrical amplitude signals.

In order to obtain the internal dynamic changes due to AAR expansion in the specimen, two PZT piezoelectric sensors are embedded into the mortar specimens. Polymer based waterproof material is used for encapsulation. Impedance analyzer is used to test the electric impedance of PZT piezoelectric sensor. The local rigidity of the mortar specimen decreases with increase in the crack depth, which causes decrease in systemic resonance frequency and increases systemic impedance value. Systemic impedance value under different frequency ranges is collected and analyzed by impedance analyzer.

The challenge for data fusion is to merge heterogeneous data from acoustic system, electro-mechanical system, optical system and embedded sensors in an efficient way to increase the accuracy and consistency of the acquired data. After the data-acquisition step in these four systems, the data is subjected to data cleansing process. Data cleansing is the process of selectively choosing data to accept for, or reject from, the feature selection process. The data-cleansing process is usually based on knowledge gained by individuals directly involved with the data acquisition. Local Kalman filter is used to accomplish the data-cleansing process. The area of the structural damage-detection process that receives the most attention in the technical literature is the identification of data features that allow one to distinguish between the undamaged and damaged structure. The data is condensed and various samples of features are obtained. The various feature vectors sets are analyzed and the features which are redundant and convey least information are discarded and thus the best feature vector sets are retained. Decentralized Kalman filter is used to fuse data to find the global estimates.

3.3. Artificial Neural Network

Further investigation on extracted global estimates is carried out by integrating data fusion technology with ANN approach. ANN is ideally suited to identify non linear system dynamics [14]. A well trained ANN network characterizes and quantifies level of deterioration of the specimen under study. Thus total amount of cracking, total length and width of cracks are evaluated. In depth analysis of damage phenomena at various levels in different alkali concentration samples is made to find correlation among overall surface damage level, internal damage level and AAR gel concentration in the structure.

Artificial neural network (ANN) classifiers are used to obtain damage information such as total amount of cracking, total length and width of cracks. The most popular multi-layer perceptron (MLP) network is used which is having three layers: an input layer, a hidden layer and an output layer. In the input layer, the number of nodes corresponds to the number of input features and the number of nodes in the output layer corresponds to the number of target classes. The number of hidden nodes, however, depends on the type of data. As ANN is ideally suited to identify non linear system dynamics, a well trained ANN network characterizes and quantifies level of deterioration of the specimen under study. Two sets of input and output are used to train MLP network, the first set comprises of feeding the best selected fused features from decentralized Kalman filter to MLP classifier. The second set comprises of individual systems feeding from single source data to MLP.

Finally the results obtained from individual source sensor system and data fusion system are analyzed and compared. The expected improved accuracy using multi sensor data fusion approach is estimated. The integrated approach of damage detection using multi sensor data fusion technique at surface level and impedance spectra of sensors at internal level for four different specimens characterizes and quantifies the level of damage at surface level and at internal level and provides a correlation between them which can render the information on concentration of gel in the structure.

4. CONCLUSIONS

Multisensor data fusion is establishing significant advantages in structural health monitoring application by improving accuracy and precision in evaluation process. The paper proposes a novel heterogeneous sensor based setup which uses data fusion technology and artificial neural network classifier to find an affordable monitoring strategy for Alkali-aggregate reaction, which is one of the root causes for structural deterioration in concrete. The future work using the proposed experimental setup is focused on establishing correlation among surface damage level, internal damage level and the amount of gel concentration in the structure. To emphasize the expected improved accuracy using data fusion, evaluations of single source data system will be compared with fused heterogeneous data.

REFERENCES

1. http://www.renewableenergyworld.com/rea/news/print/article/2010/08/dealing-with-alkali-aggregate-reaction-in-hydraulic-structures.
2. Gros, X. E., J. Bousigue, and K. Takahashi, "NDT data fusion at pixel level," *NDT & E International*, Vol. 32, 283–292, 1999.
3. Hall, D.L., *Mathematical Techniques in Multi-Sensor Data Fusion*, Artech House, Boston, USA, 1992.
4. Guo, H. and L. Zhang, "A weighted balance evidence theory for structural multiple damage localization," *Computer Methods in Applied Mechanics and Engineering*, Vol. 195, 6225–6238, 2006.
5. Guo, H. Y., "Structural damage detection using information fusion technique," *Mechanical Systems and Signal Processing*, Vol. 20, 1173–1188, 2006.
6. Basir, O. and X. Yuan, "Engine fault diagnosis based on multi-sensor information fusion using Dempster-Shafer evidence theory," *Information Fusion*, Vol. 8, 379–386, 2005.
7. Bao, Y. and H. Li, "Application of information fusion and Shannon entropy in structural damage detection," *Proceedings of Health Monitoring of Structural and Biological Systems*, 1–9, San Diego, California, USA, April 2007.
8. Yang, B.-S. and K. J. Kim, "Application of Dempster-Shafer theory in fault diagnosis of induction motors using vibration and current signals," *Mechanical Systems and Signal Processing*, Vol. 20, 403–420, 2006.
9. Guo, H. Y. and Z. L. Li, "A two-stage method to identify structural damage sites and extents by using evidence theory and micro-search genetic algorithm," *Mechanical Systems and Signal Processing*, Vol. 23, 769–782, 2009.
10. Jiang, S., C.-M. Zhang, and C. G. Koh, "Structural damage detection by integrating data fusion and probabilistic neural network," *Advances in Structural Engineering*, Vol. 9, No. 4, 445–459, 2006.

11. Johnson, E. A., H. F. Lam, L. S. Katafygiotis, and J. L. Beck, "A benchmark problem for structural health monitoring and damage detection," *Proceedings of International Symposium on Engineering Mechanics*, 317–324, Austin, Texas, USA, 2000.
12. Zhao, X., H. Gu., G. Song, Y. L. Mo, and J. Xu, "Structural health monitoring with data fusion method," *Proceedings of Earth and Space 2010: Engineering, Science, Construction, and Operations in Challenging Environments*, 2509–2517, Honolulu, Hawaii, March 2010.
13. Oberholster, R. E. and G. Davies, "An accelerated method for testing the potential alkali reactivity of siliceous aggregates," *Cement and Concrete Research*, Vol. 16, 181–189, 1986.
14. Adeli, H., "Neural networks in civil engineering: 1989–2000", *Computer-Aided Civil and Infrastructure Engineering*, Vol. 16, 126–142, 2001.