Evaluation of Structural Integrity and Performance Using Nondestructive Testing and Monitoring Techniques

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ABSTRACT

In this paper, the necessity of developing effective nondestructive testing and monitoring techniques for the evaluation of structural integrity and performance is described. The evaluation of structural integrity and performance is especially important when the structures are subject to abrupt external forces such as earthquake. A prompt and extensive inspection is required over a large area of earthquake-damaged zone. This evaluation process is regarded as a part of performance-based design. In the paper, nondestructive testing and monitoring techniques particularly for concrete structures are presented as methods for the evaluation of structural integrity and performance. The concept of performance-based design is first defined in the paper followed by the role of evaluation of structures in the context of overall performance-based design concept. Among possible techniques for the evaluation, nondestructive testing methods for concrete structures using radar and a concept of using optical fiber sensor for continuous monitoring of structures are presented.

Key words *: monitoring, nondestructive testing, optical fiber sensor, performance-based design, radar*

1. Introduction

Demand for the development of reliable evaluation techniques for structural systems is ever increasing with a growing concern about the deteriorating condition infrastructures worldwide (Chong, et. al.[3]; Korea Concrete Institute[6]). The evaluation of structural integrity and performance is especially important when the structures are subject to external forces abruptly such as earthquake. Either by normal deterioration process during life cycles of structures or by sudden damage by earthquake, effective evaluation techniques which can be used for accurate assessment of the condition of structures are needed prior to any replacement or rehabilitation action (Rhim[12]).

Efforts also have recently given to the development of high-performance infrastructure facilities and implementation of performance-based design concept as compared to traditional structural design approach. As the productivity of the construction industry which directly influences every segment of the world economy represents between 10 and 20 percent of the Gross National Product (GNP) in many countries, such efforts will benefit every aspects of construction industry worldwide. One of the goal of performance-based design is to develop a methodology to evaluate structural integrity and performance.

This paper presents a brief description of performance-based design as well as the concept of evaluation of structural integrity and performance as a part of overall design process. Then, the research work presented here focuses on the nondestructive testing techniques using radar for concrete structures,

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followed by a study of monitoring techniques for concrete structures using optical fiber sensor.

2. Performance-based design

Research on performance-based design or engineering is actively pursued during last 10 years as a new and more rational design paradigm (Massachusetts Institute of Technology[10]; Building Research Institute[1]). The research seeks to analyze the performance of structures by optimizing the selection of materials in design with the objective being to minimum weight and cost, and by predicting the durability or service life of structures due to the aging and deterioration of materials. In addition, rational methods are being developed to help in designing for constructability. The goal is to evaluate the compatibility of the structural design and the construction process and to minimize total cost and construction time.

The performance-based design is also defined as the integrated effort of design, construction, and maintenance needed to produce engineered facilities of predictable performance for multiple performance objectives (Krawinkler and Fajfar[7]). The performance-based approach would result in proper recognition of high-quality technologies, and would ultimately improve the performance and quality of building structures.

Building engineering has undergone rapid progress in recent years, accompanied by various technological innovations such as development of new materials and improvement of structural systems and design procedures. On the other hand, the present building codes remain of the prescriptive type which specifies materials and dimensions based on established structural solutions. As a result of that, the present framework cannot explain the building performance and is becoming increasingly inappropriate for new technologies and indication. There is thus a need to establish a new performance -based design frame work. Such a frame work a would encourage the application of new materials and technologies by simply prescribing performance requirements and allowing flexibility in selecting precise measures to meet them. The present structural design frame work prescribes the design load and external force, as well as the allowable stress and deformation, but does not necessarily specify performance requirements, target performance or archived performance (Fujitani[4]).

3. Evaluation of structural integrity and performance

A building structure designed in the new framework is subjected to a performance evaluation. The principle of performance evaluation is to compare the response values against assumed loads and external forces and the critical values of the structure's engineering properties, on which the target performance is based. Here, the level of performance is determined by both the levels of assumed loads and external forces and the critical values of engineering properties. In other words, the principle of performance evaluation is to confirm that the response values against the assumed loads and external forces are below critical values with a certain margin. In Fig. 1, a flow chart of performance based design for building structures is presented.

It is ought to be mentioned that the valuation is divided into two categories of methods that involve "inspection" and the methods involve "monitoring". Inspection techniques concern cracks or other defect characterization while monitoring techniques look at changes in the behavior of the structure or components under loading. One of the emerging research demands for civil infrastructure is the development and application of long-term continuous monitoring which can be helpful for evaluating structures, making decisions of preventive maintenance, and further examining new design approaches. An effective continuous monitoring or

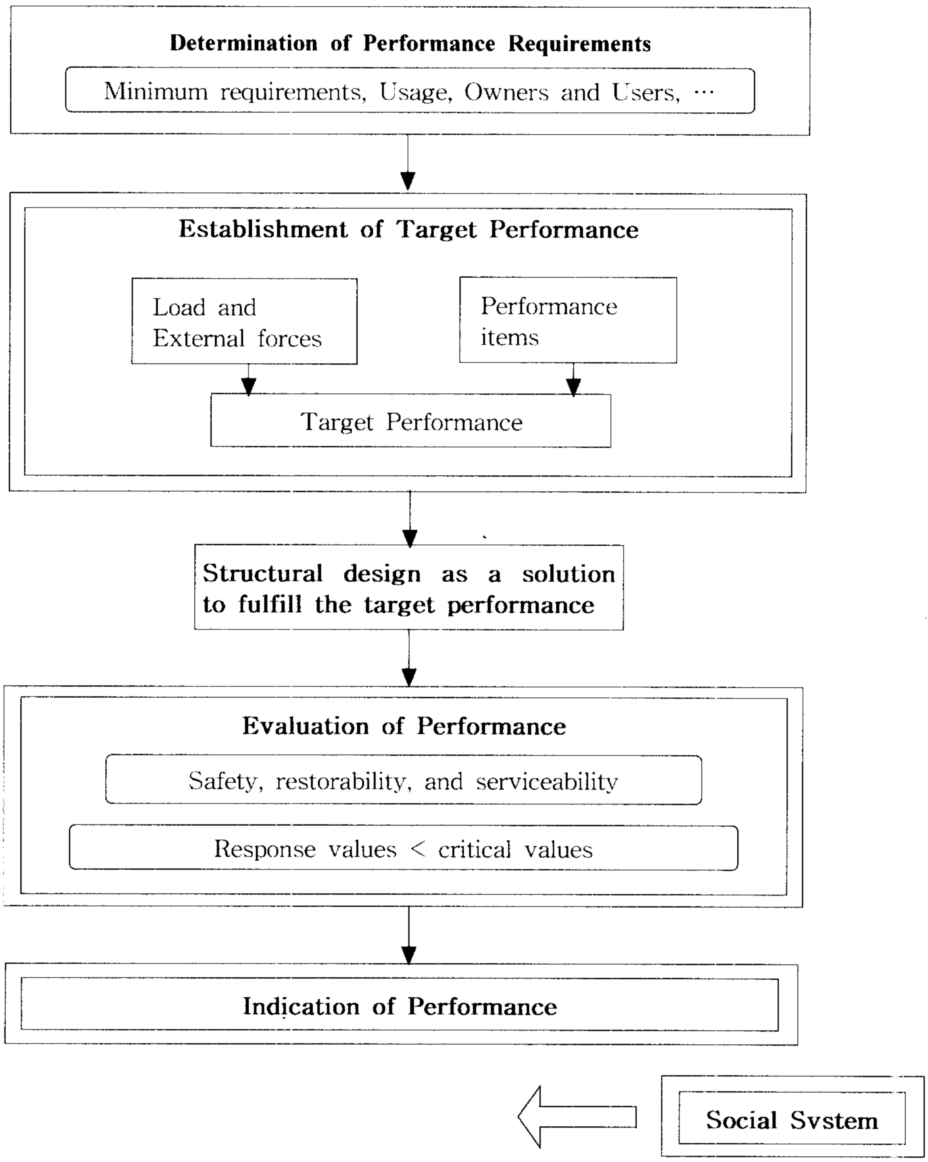


Fig. 1 Flow of performance-based design for building structure and social environment (Fujitani[4])

surveillance system is required to identify damage and deterioration state of the structure and then issue early warning signals when the extent of damage exceeds certain threshold, to eliminate or minimize the possibilities of sudden collapse of the structure (Wooh[15]).

Thus, in the following nondestructive testing techniques using radar and monitoring techniques using optical fiber sensors are presented. A focus has been given to the development and application of the techniques for concrete structures.

4. Nondestructive testing using radar

The objectives of conducting radar measurements are to determine characteristics of concrete specimens upon radar measurements and to develop an appropriate measurement technique for nondestructive testing of concrete. Radar measurements are affected by measurement parameters such as center frequency, frequency bandwidth, and polarization of incident waves, geometric and material properties of concrete, and inclusions embedded inside concrete.

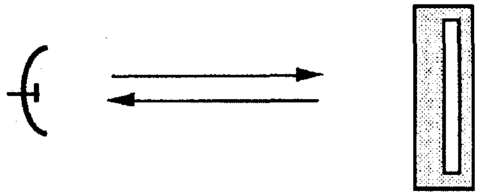
A successful application of a radar method to concrete structures for nondestructive testing requires a clear understanding of the electromagnetic properties of concrete. Many aspects of electromagnetic wave pro- pagation in a material are dependent on the electromagnetic properties of that material. Generally, the interaction of electromagnetic waves with a given material is frequency- dependent, and furthermore, this interaction at a given frequency strongly depends on the electromagnetic properties of the material.

This necessitates the need to develop a data base for electromagnetic properties of concrete as a function of frequency. In addition to the frequency dependency of the electromagnetic properties of concrete, the inherent characteristics of concrete such as moisture content and density variations further complicate the problem requiring an in depth study of the material behavior in its interaction with electromagnetic waves (Rhim[14]).

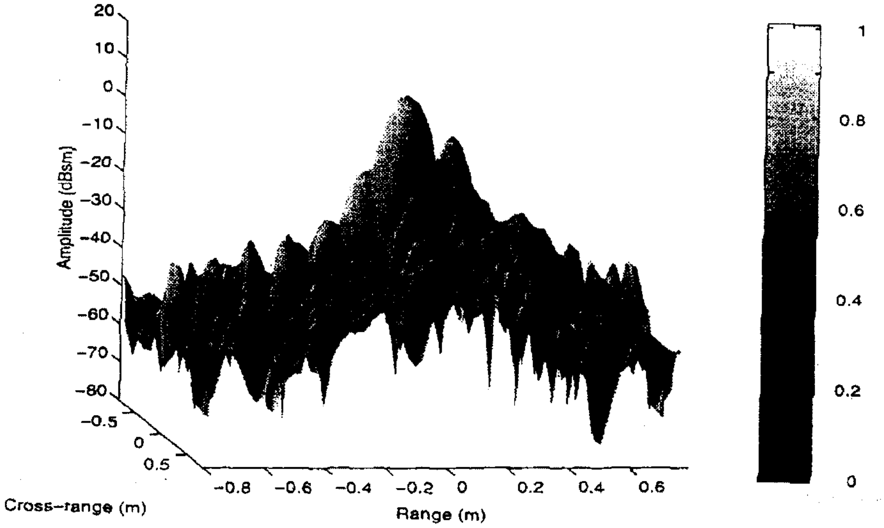
Throughout the measurements, emphases are given to three areas of interest for nondestructive testing applications: i) determination of penetration and detection capabilities of a radar system in connection with plain concrete specimens with different thickness and dimensions with inclusions, ii) monitoring of deterioration in side concrete which involves small holes and delaminations in different sizes at different locations, and iii) detection of inclusion embedded inside concrete such as steel reinforcing bars and bars in combination with delaminations.

In Fig. 2, a sample result of radar measurement of a concrete target with a delamination inside laboratory size concrete specimen is shown. The imagery was obtained by sending a radar signal at 3.4 to 5.8 GHz. Measured data is processed to produce a two-dimensional image (Fig. 2b) and a one-dimensional image (Fig. 2c). The front surface of the concrete specimen is clearly seen as the largest peak in the Fig.s. The second largest peak represents the reflection from the delamination.

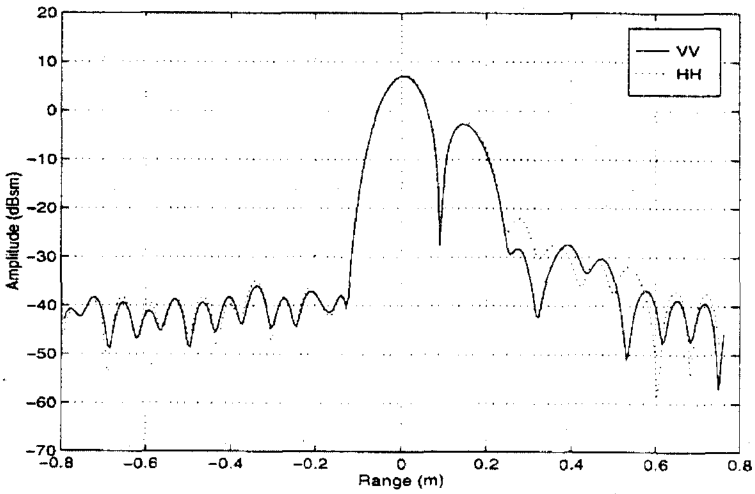
The detectability of various inclusions with different size, location, and orientation can be investigated through parametric study using radar measurements (Rhim, et. al.[13]) and by performing computer simulation of electromagnetic wave propagation and scattering



(a) A laboratory size concrete specimen with a delamination inside



(b) Two-dimensional image of the specimen



(c) One-dimensional image of the specimen

Fig. 2 A sample result of radar measurement of a concrete target

(Buyukozturk and Rhim[2]).

5. Monitoring concept using optical fiber sensor

A novel optical fiber sensor has a potential of being a powerful tool to detect and monitor flexural cracks in concrete structures. For the sensor to be useful in practical applications, its sensitivity, range, and loss have to be optimized. A combination of micromechanics and electromagnetic wave theory can be used to predict guidelines for the choice of design parameters in the optimization of sensor performance (Nanni, et. al.[11]; Fuhr, et. al.[5]; Leung, et. al.[9]).

Although sensors have been developed during the past 15 years for initial specialized applications in aerospace, hydrospace, and biomedical systems, recent attention has been given to the transitioning of these methods to the evaluation of civil structures. Properly installed fiber-optic strain gauges not only can survive the harsh environment involved in the embedment process, but can also yield accurate quantitative strain information from reinforced concrete structures.

Optical-fiber systems have been developed during the past 25 years for primary applications in long-distance, high-speed digital information communication. Optical fibers may also be applied to the measurement of environmental parameters such as strain, temperature, vibration, chemical concentrations, and electromagnetic fields. Optical fibers are typically cylindrical and fabricated from polymer, glass, or ceramic materials. They consist of central core regions of material surrounded by concentric cladding regions. Typical outer dimensions of fiber claddings are more than 100 microns; core dimensions are, in part, determined by the desired waveguiding properties of the fiber.

The existing condition of many important concrete structures can be assessed through the detection and monitoring of cracks. For example, in concrete bridge decks, crack openings beyond 0.15 to 0.2 mm will allow excessive penetration of water and chloride ions, leading to corrosion of steel reinforcements. Crack opening of the order of mm's, which may occur after a major earthquake, is a sign of severe structural damage.

Conventionally, crack detection and monitoring for bridges have been carried out by eye inspection. The procedure is time consuming, expensive, and yet unreliable. For buried structures like the grouted columns, no reliable techniques is available for the detection of slightly opened crack. Recently, various researchers has developed fiber optics based crack sensors for concrete structures. Compared with other sensors and transducers, optical fibers have several advantages including non-conductivity (hence not vulnerable to lightning), immunity to electromagnetic interference and low weight. Also, with the parallel developments in the telecommunications industry, the cost of fibers and opto-electronics equipment can potentially drop significantly with time (Leung and Elvin[8]).

The concept of a novel sensor for the detection and monitoring of cracks in a concrete structure is introduced. The principle of the sensor is illustrated in Fig. 3, which allows a 'zig-zag' sensor at the bottom of a bridge deck.

6. Conclusion

The significance of evaluating structural integrity and performance as a part of performance-based design process is examined. The evaluation involves both nondestructive testing and monitoring of structures, which can be made over discrete time intervals and continuous time, respectively.

Nondestructive testing using radar has shown a potential to be used as an effective tool for probing concrete structures. A

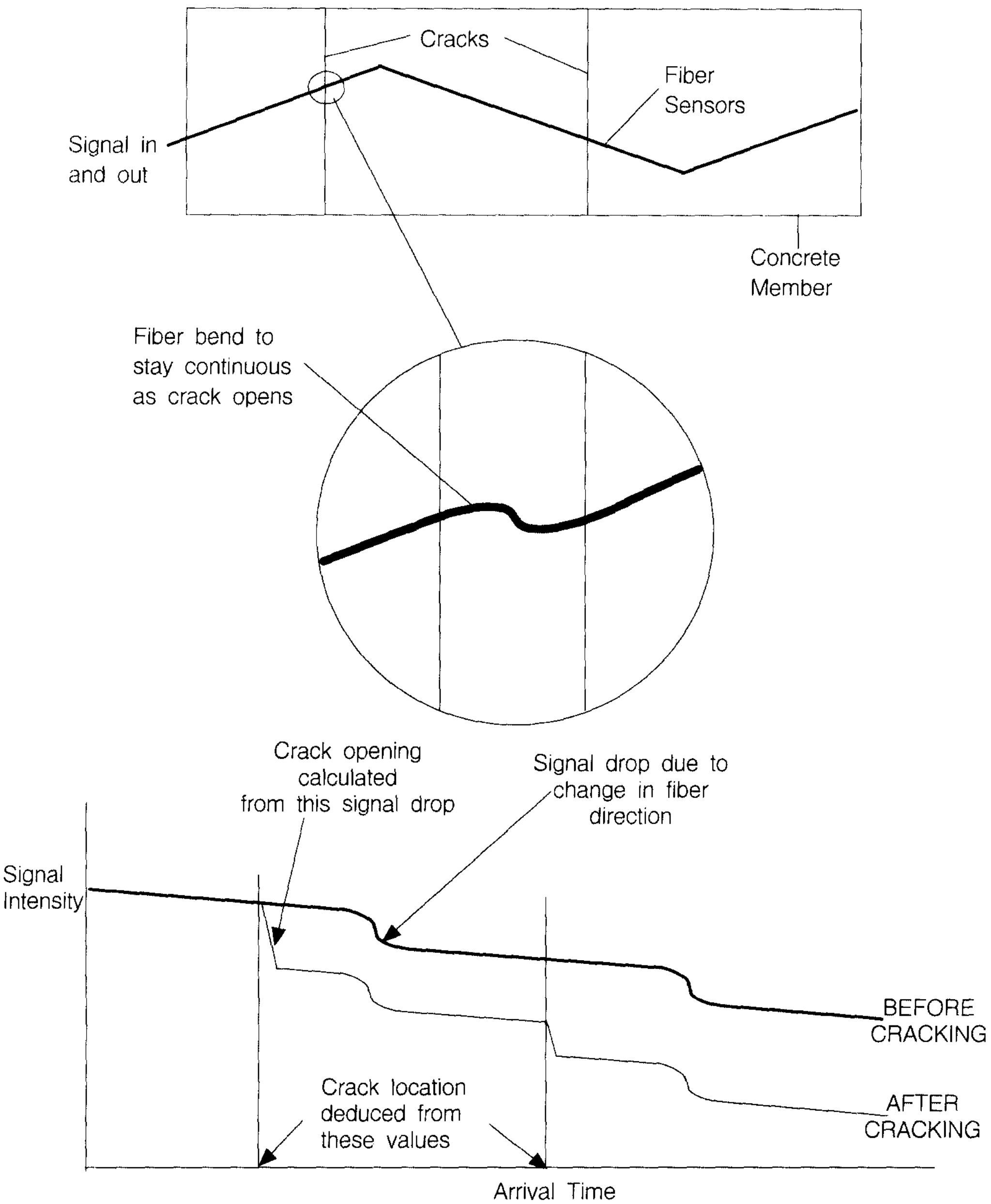


Fig. 3 A Novel concept for crack sensing (Leung, et. al.[9])

sample radar measurement result is given.

Monitoring of concrete structures using optical fiber sensor requires understanding of both electromagnetic phenomena and mechanical behavior of the device. The concept is introduced in this paper for further development of the method.

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