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Wireless crack detection and analysis system for nuclear power plant

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ABSTRACT

After the Fukushima nuclear accident, attention has been paid toward the construction and maintenance of nuclear power plants. A nuclear material spill originating from cracks in the nuclear plant's concrete structure due to natural disasters such as earthquakes or inappropriate planning and construction will have harmful consequences. There are ongoing studies for developing technologies to predict cracking in a structure when said structure is harmed by unexpected damages. This paper deals with studies on a ubiquitous crack detection and analysis system that is a combination of the extended finite element method (X-FEM) and ubiquitous sensor network (USN) technologies and can respond quickly when a nuclear plant is damaged. Because X-FEM is a considerably developed analysis technology, its use allows for relatively accurate crack analysis. Thus, the combined ability of real-time damage reporting using USN and data-based estimation of the scale of damage through crack analysis is expected to be useful for reducing damages due to unpredicted calamities.

Keywords: USN; Crack; X-FEM; Smart concrete; U-City

1. Introduction

Nuclear power generation has been popular since the first oil crisis, and to date, many countries are using it. However, after the destruction of four nuclear power plants due to the 2011 tsunami in Fukushima, there have been increasing concerns regarding nuclear power generation. Therefore, attention toward the safety of currently operating nuclear power plants is increasing.

Cracks have a major effect on nuclear power plant safety because radiation could leak from cracks. That is why crack inspection is conducted regularly at nuclear power plants. However, there are many cases where cracks cannot be determined from the outside. The cracks that occur inside the framework are especially difficult to find. Therefore, many researchers are working on methods for easing crack detection.

Although direct researches on the constant detection and monitoring of cracks in nuclear power plant concrete structures are in the nascent stage, both domestically and abroad, damage detection monitoring technology is being actively researched in

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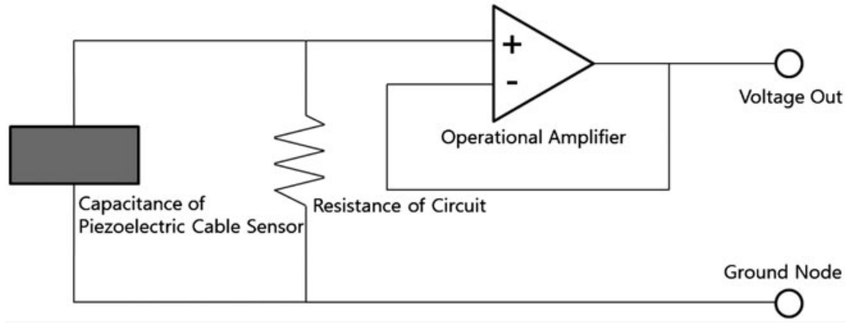

Fig. 1. Circuit of piezoelectric cable sensor [16].

developed foreign countries. In this field, the technology that estimates damage by verifying the relationship between changes in the natural vibration characteristics and structural characteristics comprise the majority of the research. In addition, methods for measuring and analyzing structural conditions of a structure using various sensors are being researched.

This study attempted to develop a crack detection technology for nuclear power plant structures by combining a ubiquitous sensor network (USN) [1], smart concrete, and a crack analysis method. The detection of structural damages using smart concrete with built-in piezoelectric cable sensors. These sensors send the location of damage to the central control center through the USN. Then, crack analysis is performed on the collected information using the selected method. In this system, crack size and direction are analyzed with extended finite element method (X-FEM). Because this method is an extension of the regular finite element method (FEM), relatively accurate analysis is possible. Because programs that use X-FEM are being widely used in the research community and said analysis method has been verified, it is believed to be suitable for detecting cracks in nuclear power plant structures.

If the system is universalized, it could help to achieve effective structural safety maintenance because the system could replace periodic crack inspection as a constant detection system. Furthermore, we can use the most current wastewater treatment techniques [2,3] to clean the wastewater instead of special treatment for nuclear hazarded water by preventing nuclear power plant disasters using our system.

2. Foundation technologies

2.1. Health monitoring using sensors

Because sensor technology and technologies that process information from sensors are being developed, many industries are attempting to increase task effectiveness by introducing such technology. Structural health monitoring is an industry where sensor technology is in high demand. Although bridges, skyscrapers, and construction sites are required to be structurally sound at all times, it is difficult to constantly monitor structural safety. Therefore, studies have attempted to use technologies based on sensors, such as USN and other systems that employ other remote networks, for understanding structural safety.

Among all structures, sensors are frequently used for understanding the condition of bridges. Chae et al. [4] were able to inspect bridge conditions using USN technology, which transmits information through the zigbee technology based on the sensor that combines a temperature sensor, a strain gage, an accelerometer, and an anemometer. Frager et al. [5] suggested bridge health monitoring system based on an accelerometer, temperature sensor, and strain gage. Furthermore, other researchers have introduced sensors for ensuring bridge safety [6–11].

Fig. 2. Piezoelectric cable sensor mounted in concrete beam [16].

The use of sensors for determining the building condition is frequently researched as well. Jang et al. [12] monitored a building environment using a wireless sensor node. In addition, many other studies for applications such as checking the condition of ancient buildings using sensors [13] and constructing a sensor-based system that could check the structural stability of under-construction buildings with a sensor [1,14] are being conducted.

2.2. Smart concrete

2.2.1. Overview of smart concrete

Given that continuous economic development is enhancing the social and cultural standards of living, consciousness regarding the destruction of the earth's environment as well as its safety has heightened, and there have been demands for improvements to the quality of life.

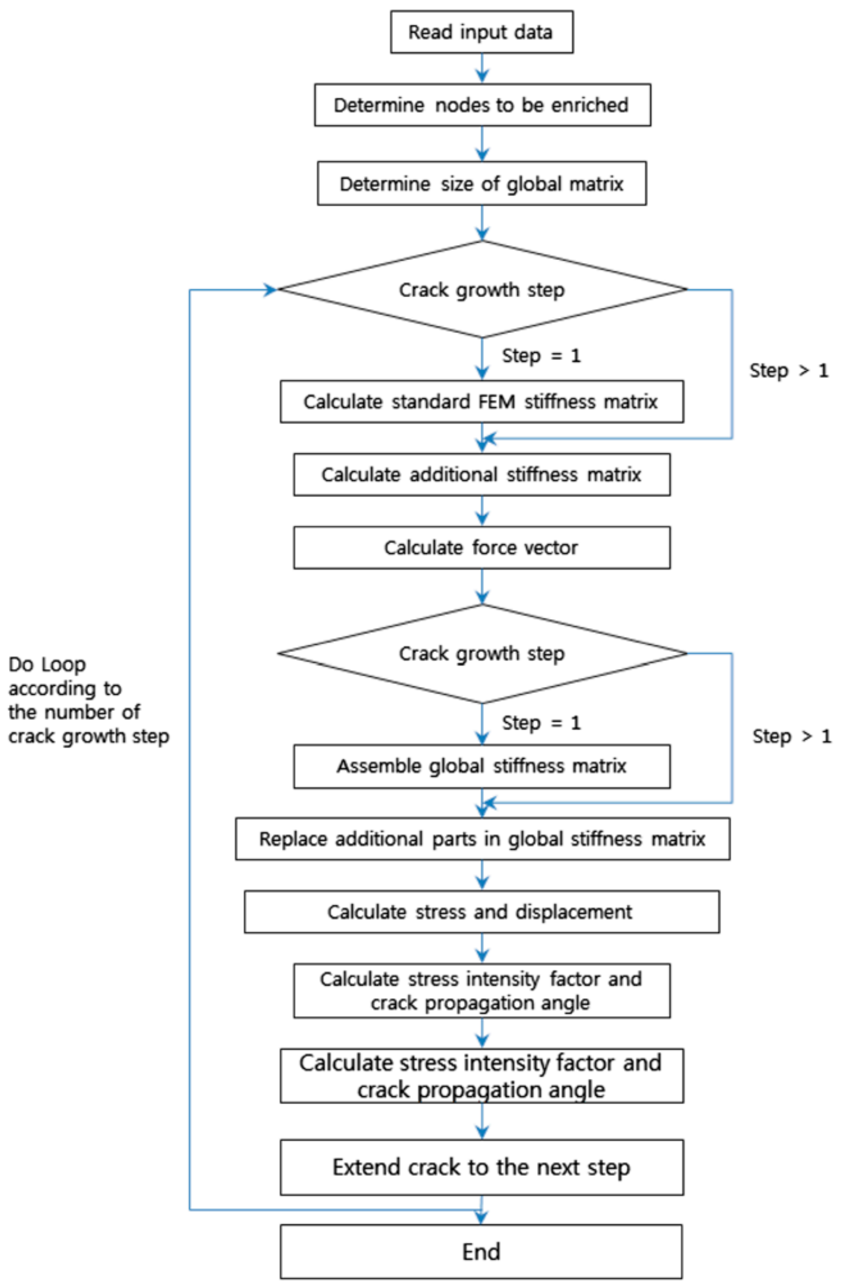

Fig. 3. X-FEM process.

It is necessary to develop smart concrete that adds high functionality such as self-diagnosis, air purification, and humidification or concrete that allows for the health monitoring of structures through in-built sensors.

In this paper, we report a combination of the concept of smart concrete with sensors. We use smart concrete combined with piezoelectric cable sensors, a combination that is being researched widely.

2.2.2. Piezoelectric cable sensor

A piezoelectric material is a typical example of smart materials [15,16]. This research suggests a basic system for crack inspection in concrete structures using piezoelectric cable sensors which were developed recently. The piezoelectric cable sensor converts physical quantities/magnitudes into electric signals. This sensor offers both sensing and actuation capabilities. The electric signals from a piezoelectric cable are proportionate to the stress on that cable. On the basis of this characteristic, piezoelectric cable sensors installed in concrete can detect cracks in concrete structures. The circuit of a piezoelectric cable sensor is shown in Fig. 1.

In piezoelectric cables, a piezoelectric film, which generally functions as a sensor, lies between the inner conductor and the outer copper braid. The shape of piezoelectric cable sensor, which is mounted into a concrete beam, is shown in Fig. 2.

The optimal location for inserting piezoelectric cable sensors is determined by locating the points where stress could be focused easily FEM. Many studies have proved that the output of piezoelectric cable sensors is proportionate to the external stress. Furthermore, recently, studies were conducted by mounting this sensor with other sensors.

2.3. X-FEM analysis method

Cracks distributed over a structure decrease structural stability and serviceability during the performance period. Although cracks are minuscule in the beginning, they slowly grow owing to the load and after expanding to a certain point, rapid growth from momentary excessive loads act as a major factor in decreasing structural stability and service life.

Although the FEM grew with the rapid development of computers in the 1970s and contributed to the development of optimal design techniques, there remain issues regarding the method's effectiveness and accuracy in the optimization process, which includes grid regeneration and the grid distortion phenomenon. Especially, in optimization, changes to the planning variables require grid regeneration, and grid crushing was unavoidable during that time. When the scale of the problem is large, grid regeneration requires considerably long analysis time.

The modeling of geometric discontinuities such as cracks using the FEM is a bothersome process. If such discontinuous parts move with crack growth, grid distortion occurs. Furthermore, simple repetitive works related to updates of the finite element model are required in every process. To overcome this, Belytschko suggested X-FEM. This method includes an enrichment function and separates the discontinuities into the grid and function parts. This means that because the grid is independent, it is fixed during the optimization process. Only alteration of the function's parameter as a planning variable will make possible the optimization of discontinuity surface formation without grid regeneration. A numerical analysis algorithm for crack growth analysis by applying the X-FEM concept is shown in Fig. 3.

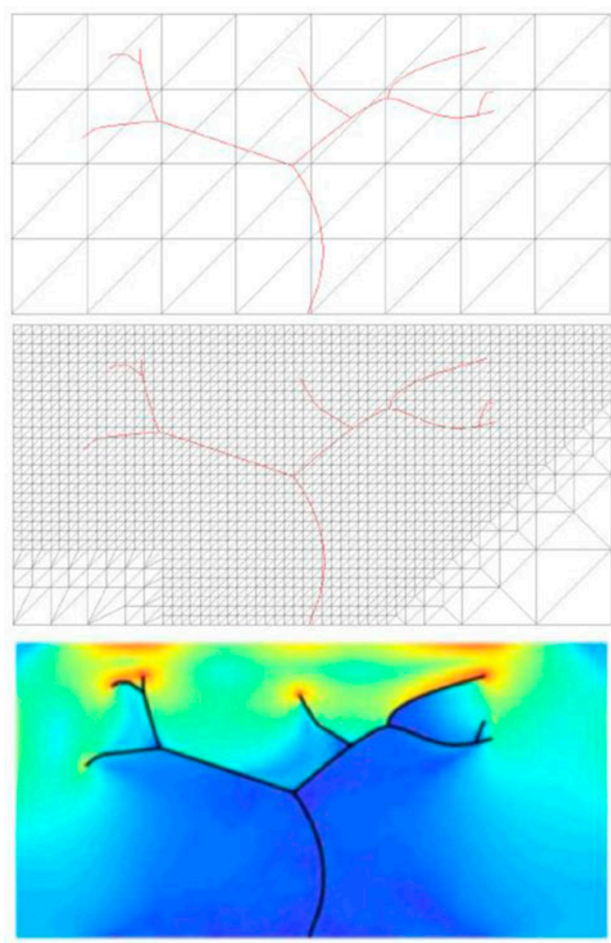

Fig. 4. Analysis using X-FEM.

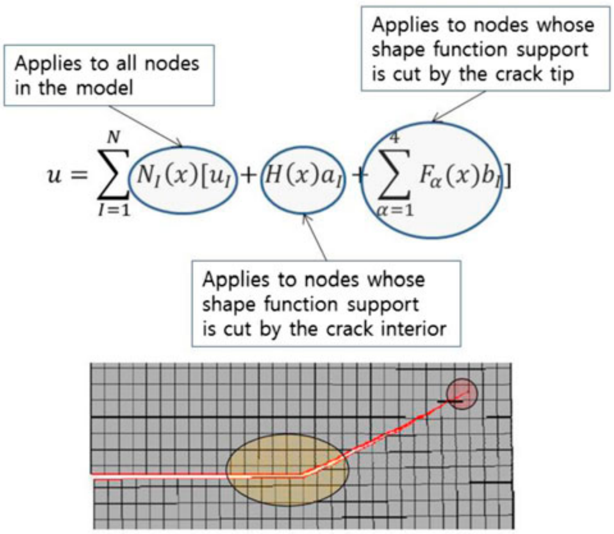

Fig. 5. Basic X-FEM concept in ABAQUS.

This algorithm could automate the process for calculating fracture mechanics' coefficients from the analysis results. Based on this information, cracks could be propagated, and then joints that require additional shape function extension for reflecting local special behaviors could be searched for. Additionally, the algorithm extends them into an appropriate additional extension function form.

Fig. 4 shows an example of crack growth analysis using X-FEM.

Since the development of X-FEM, many researchers have been applying it, and it is used in commercialized analysis programs such as ABAQUS with the added functionality of crack analysis. Fig. 5 shows an example of X-FEM analysis with ABAQUS [17].

3. Ubiquitous crack detection and analysis system

3.1. Current crack detection method for nuclear plant structure

Currently, in nuclear power plants, concrete structures are inspected periodically for cracks as opposed to being inspected constantly. Because nuclear power plants deal with radioactive materials, cracks in the concrete structures of nuclear power plants should be prevented at all costs. Given that cracks could appear whenever, wherever, and however, constant preparation is necessary. Consequently, attempts are being made to introduce a health monitoring system that has intelligent ubiquitous technology grafted into it. Our study attempts to suggest a ubiquitous crack detection/analysis system that combines the use of sensors with a crack analysis method. Table 1 presents a comparison of the current crack detection method with the proposed crack detection/analysis system.

In the current crack detection method, human inspectors check for external cracks with naked eyes, whereas internal cracks are detected using ultrasonic waves, etc. Because a system that monitors constantly does not exist, there is no way of understanding the progress direction, size, etc., of cracks. Given that various directions of crack progress have different effects on a structure, an accurate analysis method is necessary. In addition, considerably labor is required because the method relies on periodic inspection.

The characteristics of the proposed ubiquitous crack detection/analysis system are as follows. Constant inspection is possible because the sensor detects damages, and crack progress direction, size, and its effects on the structure can be understood by conducting a crack growth analysis with detected damages. Furthermore, because the proposed system performs constant automated inspections, it does not require labor for reasons other than system maintenance.

3.2. System concept

The proposed ubiquitous crack detection/analysis system is based on the USN technology, and it monitors a building's condition, judges the location and progress of cracks through crack analysis when the building is unexpectedly damaged, and responds instantaneously.

Ubiquitous refers to an environment where various information and communications services could be

Table 1
Comparison of current and proposed crack detection and analysis methods

	Current crack detection method	Ubiquitous crack detection and analysis system
Detection method	Naked eye, ultrasonic waves, etc.	Sensor
Inspection period	Periodic inspection	Constant inspection
Analysis of inside crack condition	Unsatisfactory	Can be predicted (by X-FEM analysis)
Manpower	Necessary	Only necessary for system maintenance

used by accessing an information network system regardless of time and place. This technology allows for constant communications and monitoring by combining various devices and objects with information and communications technology. This concept was established with the idea that if applied, it will be useful for monitoring the condition of structures such as nuclear power plants where safety is paramount. An effective system was conceived that introduces smart concrete to nuclear plant structures for constant sensing and combines various ubiquitous technologies with analysis technologies such as X-FEM.

Recently, cases where structural behavior, especially that of bridges, is monitored by inserting sensors in concrete have been increasing. Similarly, piezoelectric cable sensors are inserted in the concrete of a nuclear plant's structure, and the system constantly monitors the building's conditions with wireless AP. Recently, piezoelectric cable sensors have found widespread use for crack detection. The central point of a system based on these sensors is when the building is damaged unexpectedly, and the results are sent to the system for determining crack severity and implementing potential response measures.

As mentioned in the previous paragraph, because this system allows constant monitoring of nuclear power plant structures, responses to danger factors are quicker, and it could check areas that are difficult to check manually. Therefore, constant research and development of this system is necessary.

3.3. System process

A flowchart of the system is shown in Fig. 6. The data acquired using the piezoelectric cable sensor inserted into the concrete are classified as normal and higher than normal, and organized as a database; the system then begins crack analysis. Programs that use the X-FEM method are used for crack growth analysis. Through this, expected crack size, direction, and scale of damage are judged. The system control center can implement appropriate measures according to the results.

Because the sensor should be inserted, it is decided carefully through close analysis during structural design. Sensors are first inserted in areas suggested to be vulnerable to cracking by structural analysis. In addition, because the inserted sensor cannot be fixed later, it has to be designed in the net form so that the system can operate even if some components do not. To compensate for non-functional sensors inside the concrete, sensors are installed outside the concrete for assisting the sensors inside. Especially, sensor batteries are controlled externally.

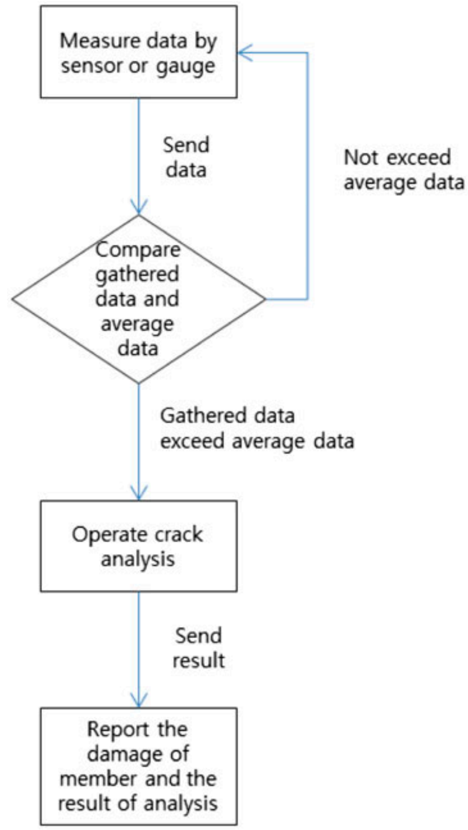

Fig. 6. System process outline.

When the sensor detects an external impact or damage due to internal stress, the system conducts a crack analysis of the structural framework. Because an analysis of the entire structure would require a lot of time, it is very important to set analysis units such that the structure can be analyzed in sectors. The analysis units are set, and then sector's structural members are modeled and saved. When the sensor detects above-average stress levels, crack analysis begins based on the stress location. Because of using X-FEM allows unlimited crack growth analysis as opposed to the various constraints on doing so in existing methods, it is possible to predict crack direction, size, etc., analytically.

Fig. 7 shows a flowchart of the USN's monitoring algorithm. Monitoring is performed by sensing, transmission control protocol (TCP) data gathering, and so on. The functions of network setting, operational control, system control, sensor node setting, and DB management performed by the system control software. In addition, the system software performs event sensing, channel scan, file saving, and sensor node management. Lastly, the monitoring software drives TCP gathering events. Situations are judged by comparing

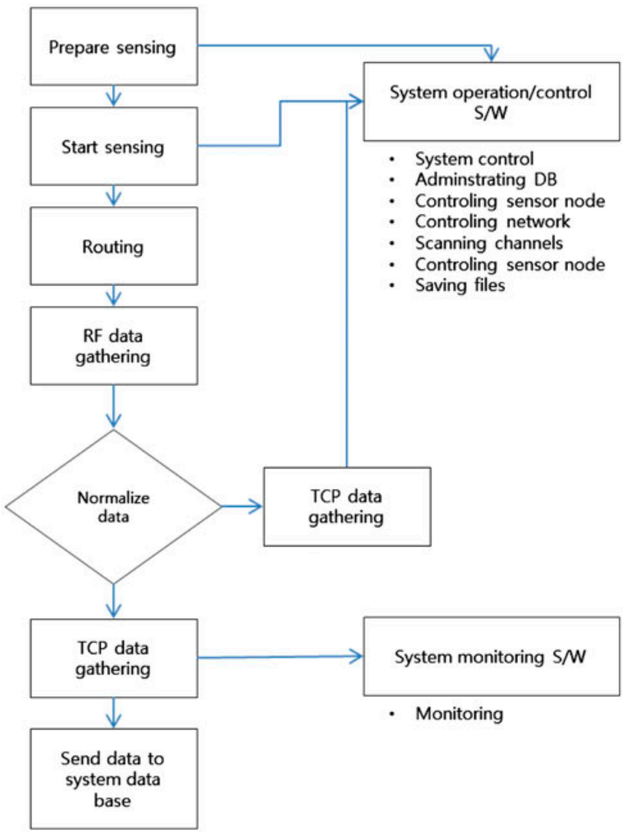

Fig. 7. System monitoring process.

the database and current responses obtained through the monitoring software.

When the sensor node, composed of the piezoelectric cable sensor, detects internal stress and is ready to send information, the router extracts the packet's location and sets the optimal route for the location. After the route is set, the data packet is controlled with TCP gathering technology. TCP is the central technology of the Internet protocol suite. TCP receives data from a data stream, divides said data into chunks, and adds TCP headers for creating TCP segments. These TCP segments are encapsulated in an IP datagram for ensuring exchange with others. The use of this method will make possible error-free data exchange in all sending stages. Using TCP gathering technology, sensing data is constantly backed up and the stored information can be used for generalized purposes.

4. Conclusion

Cracks in nuclear power plant structures could originate from many factors including earthquakes. If there are damages to the framework due to bad design or if the framework is weakened owing to unintended impacts such as weak earthquakes, instant checks and response measures can limit the damage.

This study suggests a method for instantly converting such damage into data and analyzing cracks based on said data with a USN as the base. Using a USN as the base allows for the detection of areas that cannot be observed with the naked eye, thus allowing more effective responses to situations. In other words, using the proposed USN-based crack analysis system will prevent unexpected damages, and when multiple members of a framework are damaged simultaneously, the system could also prioritize reinforcement order based on the scale of damage.

Given that many studies on crack detection are in progress, the developments of this study can be applied to make possible for the deduction of accurate results through more effective analyses.

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