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Structure health monitoring using wireless sensor networks on structural elements

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ABSTRACT

This paper presents a system that monitors the health of structural elements in Reinforced Concrete (RC), concrete elements and/or masonry buildings and warn the authorities in case of physical damage formation. Such rapid and reliable detection of impairments enables the development of better risk management strategies to prevent casualties in case of earthquake and floods. Piezoelectric (PZT) sensors with lead zirconate titanate material are the preferred sensor type for fracture detection. The developed sensor mote hardware triggers the PZT sensors and collects the responses they gather from the structural elements. It also sends the collected data to a data center for further processing and analysis in an energy-efficient manner utilizing low-power wireless communication technologies. The access and the analysis of the collected data can be remotely performed via a web interface. Performance results show that the fractures serious enough to cause structural problems can be successfully detected with the developed system.

1. Introduction

DETECTION of structural deficiencies poses a great importance on the prevention of casualties caused by unforeseen structure collapse. Structural deficiencies causing collapses may occur because of earthquakes, dead loads, live loads, floods or ageing. These factors exert external forces on structural elements causing fracture generation. Two of the most influential external effects are bending moments and shear forces that provoke bending cracks and shear cracks, respectively [1]. In a concrete building, bending cracks signal an ongoing deficiency progression within the element. Therefore, monitoring the visible crack over time enables taking precautions. However, such process cannot be applied on shear cracks since they are formed abruptly [2]. Shear cracks are capable of causing building collapse solely although they are usually formed besides bending cracks. To prevent casualties resulting from abrupt building collapse, utilization of systems that enable forecasting bending and shear cracks are vital [3]. Recently, Structural Health Monitoring (SHM) systems have been designed to detect and classify these impacts. In general, SHM systems are used to monitor the physical status of critical structural elements, structure integrity and usually consist of multiple sensors placed on these locations, and microcontroller(s) responsible for environmental parameter measurement and data processing tasks. Statistical analysis of the measurement data gathered from sensors enables the assessment of current physical status of the structure. This way, structural problems can be detected earlier and thus, this provides better risk assessment. In addition, after a catastrophe, health evaluation of the structures in the catastrophe area takes a long time using traditional Non-Destructive Evaluation (NDE) methods [4]. Considering the absolute necessity of performing such analysis in a short time due to the need of shelter of the people affected, the SHM systems support timely actions in crisis management thanks to their capability of providing rapid results. For monitoring tasks, the SHM systems may use various types of sensors depending on the parameters desired to be monitored. Moreover, the same kind of data may be measured using various types of sensors to increase reliability or availability. The performance within the target environment and the price of the sensor are the main criteria for sensor type evaluation.

In addition to regular hardware components, radio hardware to relay the gathered information may also be preferred. Integration of Wireless Sensor Network (WSN) technology into SHM applications provides many benefits in terms of cost, scalability, ease of deployment, and reliability [3]. Besides these benefits, the migration from tethered to wireless systems require detailed con-

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sideration of battery lifetime [5]. Therefore, the microcontroller to which sensor(s) attached are desired to have low power consumption. Moreover, the lifetime of the system also depends on the way measurements are handled. While some applications require measurements with predefined intervals, others may desire data measurements to be performed based on external trigger. For example, earthquake focused SHM applications may remotely initiate measurements only after an earthquake occurs. Similar to remote command reception, the data gathered via measurements can be processed and the extracted useful information can be transmitted to responsible authorities.

There are two possible ways to realize WSN-based SHM applications. Wireless communication may be used to either transfer the data from microcontroller to a data center directly or through a gateway [6]. The former method requires sensor node to be directly connected to the data center, which is usually provided via cellular networks. The latter method requires the microcontroller to have only short distance communication with a gateway device responsible for forwarding data towards data center. This method decreases the operational costs due to less number of SIM cards required. It also provides longer mote lifetime due to its low-power communication capability. While each microcontroller is usually provided with its own transceiver, the number of sensors interfaced to the microcontroller may vary. Finally, using any type of wireless connection, future expansions to the available systems can be made easily.

In this paper, we focus on the implementation of a reliable and low-cost solution to structure health monitoring. In our approach, multiple sensors monitoring the structure at different locations can be attached to a single mote communicating with a local gateway to relay their data to the data center. The sensors are made of piezoelectric material that allows measurement of the structural elements' impedance level which hints about the presence of fractures within the element. The collected data is then analyzed to detect physical impairments within the structure and to warn authorities. Moreover, a scalable user interface provided on a website allows multiple users to evaluate the readings.

The paper is organized as follows. Section 2 provides a brief overview of the recently reported SHM applications and their implementations. In Section 3, the hardware and the software used in this implementation are presented. Section 4 explains the methods used in this work. Section 5 discusses the experimental results. Sections 6 provides the concluding points.

2. Current applications

In the literature, various types of sensors and methods have been utilized for SHM applications in civil structures [5]. The methods can be grouped into two main categories, namely global and local structural health monitoring methods [7]. The first approach uses vibrational characteristics of the building to detect the presence of a structural problem while the other uses propagation characteristics of a penetrating ultrasonic wave to locate the location of deficiency [7]. The former is not capable of measuring small deficiencies, since it focuses on global vibrational characteristics while the latter requires an extended network of sensors in large buildings [7].

Sensor type is another important aspect of SHM implementations. For example, fractures within a concrete structural element can be detected using ultrasonic waves or acoustic emission methods [8]. However, such an approach requires trained personnel and takes a long time. Alternatively, embedding strain gauge sensors into concrete while the building is being constructed is another traditional method for SHM. Nevertheless, this method requires sensor data to be carried to expensive data logging devices via cables. Such implementation is costly and not desired [5]. Also, it is impossible to repair a sensor that may be broken after years of operation.

Mal et al. uses both vibrational and wave propagation approaches to evaluate the severity of the physical deficiencies in different scenarios [7]. Using vibrational approach, the effects of physical damages on physical behavior of the structure are exploited. In the study, the altered physical behavior is monitored using Frequency Response Function (FRF). Comparing the current FRF result with the result of the structure's intact state provides effective results. Unlike the vibrational approach, wave propagation approach targets small sized deficiencies. In this approach, multiple control points at various locations are used to measure the magnitude of the elastic waves generated at an impact point. Performance results show that the response in frequency domain show differences compared to initial undamaged case. Although this study provides valuable outcomes, the usage of expensive equipment during experiments prevents the methods from becoming widespread. Also, wired structure is usually not preferred in consumer grade applications.

In [9], a vibration characteristic based method for structure health monitoring using piezoelectric patches embedded in concrete is used. In the study, while a single patch is excited with sweep sinusoidal signals, other patches are used to measure the responses. The initial reference measurements are performed while the concrete block is intact. Following measurements are taken while bending forces at various magnitudes are applied via hydraulic presses. The study uses Root Mean Square Deviation (RMSD) as damage index. Although this study requires sensors being embedded into concrete during the construction, it provides effective results in detecting the structural problems.

Wave propagation applications is not limited to ultrasonic waves. Fiber optic sensors, which provide a proper environment for the propagation of the light is another method [10]. In this method, optical fibers are either embedded or surface bonded onto the building structure. Under stress, the fibers are either expanded or contracted altering the physical characteristics of the channel. A measurement of the originally scarce back scattered light signals provides valuable insight on the structure health including the location of the deflection using time of flight information. In a long-term monitoring application conducted by Roussel et al., both surface mounted and embedded fiber optic sensors are utilized to monitor global and local health status of a high-rise building [11]. According to the study, local and global behaviors of the building were successfully monitored. However, the study does not evaluate the detection reliability of the utilized method in case of an extreme situation since the experiments are performed on actual buildings with residents. Also, the authors state that the method they utilized is not to replace current methods and systems but to be combined.

In addition to wave propagation, acceleration data may also be adopted to determine the modes of a structure via model of the building calculated using finite element analysis methods. Jang et al. uses a wide network of wireless sensor nodes to monitor vibration and wind levels [12]. In the study, the measurements have been relayed to a base station for further analysis. To initiate a transmission, measured parameters are required to be above a certain threshold. Moreover, the study also analyzes the lifetime improvement solar harvesters provide. Although this study mainly shows the capabilities of using wirelessly tethered systems for different network sizes, the system is considered as a research project instead of a commercial product. Furthermore, the study focuses on data collection and does not inform how the data will be processed.

In [13], the authors test the feasibility of fiber optic sensor usage for SHM applications using a testbed that exerts variable levels of stress on a concrete block. As opposed to [12], the sensors are surface mounted. Results of the study show valuable findings including the validation of the capability of fiber optic sensor to successfully detect the cracks formed within the block.

In another study, Magalhães et al. focus on a specific bridge in Portugal to study damage detection [14]. They use accelerometers to identify modal parameters using three different methods. The methods are a parametric and a non-parametric method in frequency domain as well as a parametric method in time domain. A model established using the data gathered for 2 years via another monitoring system installed during the construction of the bridge. As a result, the developed system is proven capable of detecting the physical deficiencies that affect natural frequencies of the structure.

Using accelerometers, foil strain gauges and temperature sensors Hu et al. utilize a Wireless Sensor Network (WSN) structure to monitor highway bridges [15]. In the study, the data gathered via sensors are forwarded to a base station for data processing. Structure inherent frequency is determined via Power Spectral Density (PSD) algorithm and the displacement is calculated taking the integral of acceleration data twice with additional processes. In addition, strain data gathered from strain sensors are used for continuous health monitoring. Although the study manages to provide useful information on the physical state of the bridge, it requires external vibration sources, such as bridge traffic. Therefore, such implementation is not feasible for residential SHM applications for end users.

Utilizing computer vision is another method for SHM applications. Song et al. utilizes virtual visual sensors data with image processing algorithms to detect modal shapes and frequencies of an oscillating structure [16]. Moreover, physical damage detection and location estimation is performed using wavelet based analysis. The application has been tested on a metal beam and requires explicit indications of damage. Therefore, the performance of the applied method on concrete civil structures is unknown.

Although the above-mentioned studies provide great efforts into the field of SHM, most of them require trained personnel and/or expensive data logging devices via cables. The usage of expensive equipment for SHM prevents the methods from becoming widespread. Also, the wired structure is usually not preferred in consumer grade applications due its deployment costs. Hence, the widespread public usage of SHM systems requires cost-effective solutions based on reliable wireless communications. To address this need, this study aims to provide a low cost and wireless SHM system that is capable of detecting the deficiencies that may cause structural failures before they are visible to inspectors.

3. System overview

The SHM system developed in this work consists of PZT sensors for impedance measurement, a sensor mote for reading the sensor outputs, a gateway device to forward the data provided by the sensor mote to the data center, and a web server to analyze the data collected and to visualize the results. The diagram illustrating node components is shown in Fig. 1. While using multiple sensors on a single mote decreases the cost, using a gateway eliminates the requirement of the motes having a SIM card module to connect to the Internet. The cost breakout is also provided in Table 1.

3.1. Sensor

In impedance-based SHM implementations, the impedance values of the structure are monitored after stimulating the structure at high frequencies using piezoelectric sensors. The presence of fractures in host structure alters the mechanical impedance of the structure which is shown to be directly related to the electrical impedance of the PZT sensor [8].

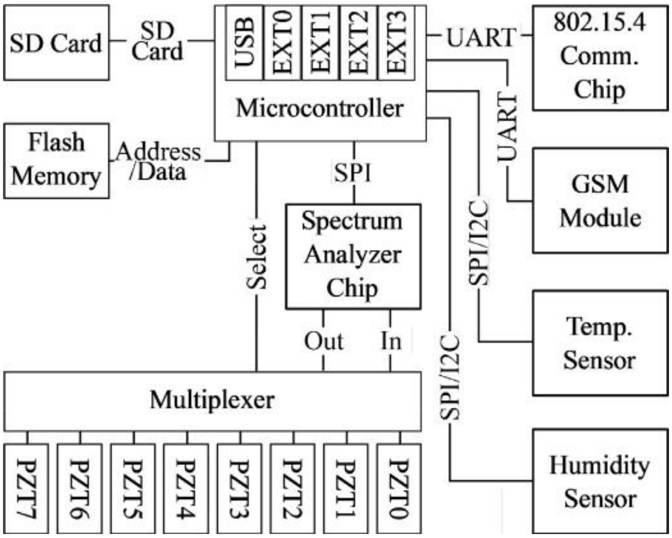

Fig. 1. Mote architecture.

Table 1
Cost breakout.

Component	Part	Cost
Mote	MCU (CC1310)	$7
	RF Module (SE2435L)	$3
	Impedance converter (AD5934)	$20
	Multiplexer (ADG707)	$7
	Flash Memory (MX25R1035F)	$1
	Temperature & Humidity Sensor (SHT21)	$8
	PZT patch (single) (LDT1-028 K)	$11
	Antenna (PRO-OB-471)	$2
	PCB	$10
	Plastic enclosure	$5
	Total	$74
Gateway		
	Raspberry Pi	$30
	Mote (without enclosure)	$69
	Plastic enclosure	$5
	Total	$104

The piezoelectric sensor utilized in this study is made of laminated piezoelectric material that enables vibration sensing [17]. A detailed explanation on the methods used for impedance measurement is provided in Section 4.

3.2. Mote

The newly designed mote used in the application is responsible for the sensor measurements and the relay of the measured data to the gateway device. The data is then forwarded to the data center. Up to eight PZT sensors can be attached into a single mote thanks to the integrated multiplexer IC [18]. In applications that require measurements from more than eight locations, multiple motes can be used.

To stimulate the sensors, an on-chip spectrum analyzer is used. The analyzer's frequency range goes up to 100 kHz and enables impedance measurements at different frequencies [19]. Since the sensitivity of the PZT sensor shows variations based on ambient temperature and humidity levels, sensors to measure these levels are also integrated [20].

The utilized CC1310 wireless MCU possesses a 48 MHz Cortex-M3 microcontroller as well as a dedicated radio controller with Cortex-M0, 20kB of SRAM, UART, I^2C and SPI ports [21]. For additional sensors such as strain gauge or accelerometer, the mote has 4 expansion ports. To store the measured data, 1 Mb of flash

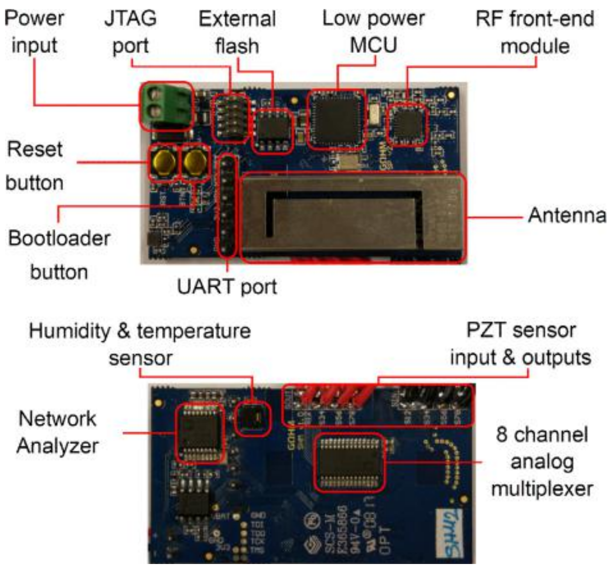

Fig. 2. Mote front and rear views.

memory [22] is also available. Communication with the gateway is provided using CC1310 device working at 2.4 GHz band adopting 802.15.4 protocol. The RF front-end module is used to increase RF power output [23]. The power to the mote is supplied using batteries.

The software on the mote written in C language provides:

- Calibration of the hardware components and sensors
- Self-testing
- Signal generation at various frequencies and reading the sensor measurements in real-time
- Activation of the transducer
- Processing and storage of the collected data
- Forwarding the stored data to the gateway

Pictures of the front and rear views of the mote with component information are provided in Fig. 2.

3.3. Gateway

The gateway used in the application consists of the same mote hardware attached to a Raspberry Pi [24]. The Raspberry Pi runs on Linux and relays the data collected from sensor mote(s) to data center. The wireless connections from the mote and towards the Internet use 802.15.4 and 802.11 protocols, respectively. For mote connection, the same transceiver as the motes is used.

3.4. Web server

The software on the web server is responsible for providing a scalable user interface for multiple device types (PC, tablet, mobile phone, etc.) with a list of the measurements. The software running on the web server is capable of:

- Monitoring and remote management of the inventory
- Collecting the measurements from various locations
- Performing various analyses thanks to flexible libraries
- Enabling multiple queries from different devices
- Reporting selected parameters within certain intervals

The tasks performed in the SHM system can be listed as:

- The PZT sensor(s) to be used for measurement is selected via web user interface

Table 2
Technical specifications.

Component	Feature	Specifications
Mote	Supply voltage	1.8 to 3.8 V
	Piezo-sensor inputs	8
	Data rate	50 kbps
	TX power	10 dB
	RF frequency	867 MHz
	RF range	500 m
MCU	CPU	ARM Cortex-M3
	Clock speed	48 MHz
	Memory	8 kB of cache 20 kB of SRAM
	Flash	128 kB
	Current consumption	Active: 2.5 mA Standby: 0.7 µA
Temperature & humidity sensor	Temp. range	−40 to 125 °C
	Temp. tolerance	±0.3 °C
	Hum. range	0 to 100% RH
	Hum. tolerance	±2% RH
Network analyzer	Impedance range	1 kΩ to 10 MΩ
	Frequency resolution	27 bits (<0.1 Hz)
	Programmable voltage freq.	1 to 100 kHz
Antenna	Return loss	<−10 dB
	Frequency	860–870 MHz
	Impedance	50 Ω
	Total efficiency	>65% (−1.8 dB)

- Input voltage with a frequency of 1 Hz to 100 kHz is supplied to the sensor
- Spectrum analyzer IC calculates the real and imaginary parts of admittance value for each frequency level and sends the result to the microcontroller
- Temperature and humidity sensor values are read and stored in the microcontroller unit
- The admittance values previously sent to the microcontroller are used to calculate the RMSD values on the microcontroller
- The RMSD measurements are named using a tag including date, time, temperature and humidity levels
- The steps taken are repeated for other sensors attached to the same mote
- The data is forwarded to the gateway
- The gateway sends the data to the data center

Fig. 3 illustrates the steps taken in different hardware modules. Initial execution of the system is triggered via the webpage user interface by providing frequency, channels (sensors to be used), sampling interval and sample number parameters. The parameters are then forwarded to sensor node. In return, the sensor node sends the temperature and humidity readings followed by the impedance measurements to the gateway using RF. Finally, recorded results are relayed to data center. Table 2 shows hardware technical specifications.

4. Applied methods

This section explains how data is gathered from the sensors and how it is converted into useful information.

The concrete column used in the tests incorporate Carbon Fiber Reinforced Polymer (CFRP) with 150 mm separation to increase the column performance and decrease the number of areas that are prone to fracture generation. This way, positioning of the sensors is made easier. Since the focus of this study is to evaluate the performance of the proposed method, using CFRP is crucial to diminish the time tests take enabling fracture generation close to the sensors.

Fig. 4 shows the model of the sensor and the structure it is attached [25]. Using the model, the relation between the inverse of the PZT sensor impedance ($Y(\omega)$), mechanical impedance of the

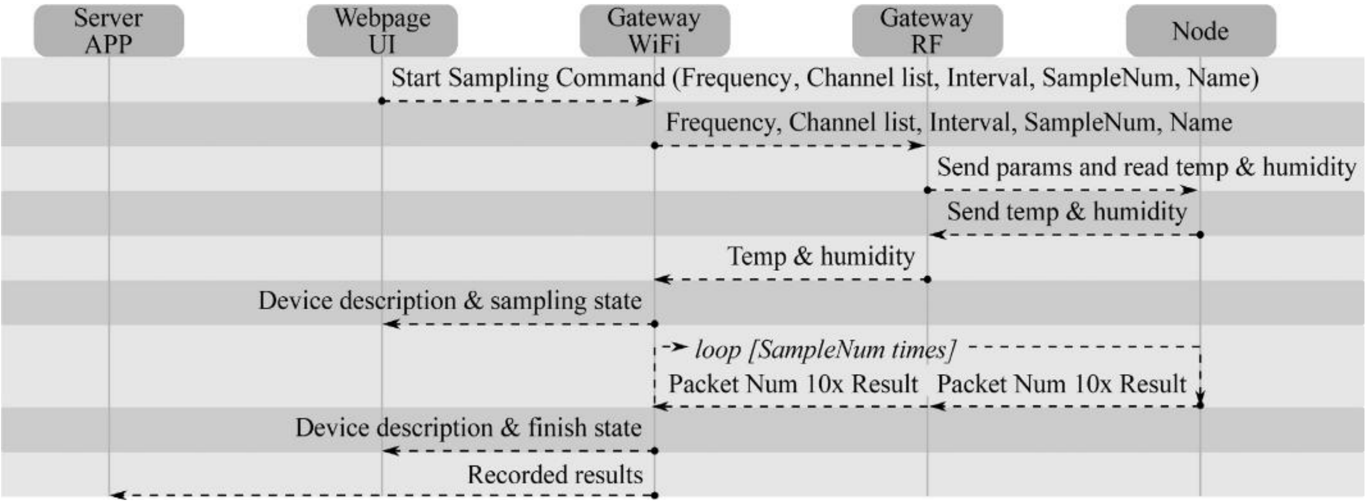

Fig. 3. Data flow overview.

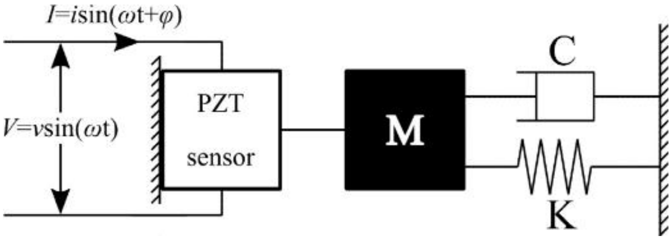

Fig. 4. Sensor model.

PZT sensor ($Z_a(\omega)$) and the mechanical impedance of the structure ($Z_s(\omega)$) is formulated as:

$$Y(\omega)=\frac{I_0}{V_i}=j\omega a\left(\bar{\varepsilon}_{33}^T-\frac{Z_s(\omega)}{Z_s(\omega)+Z_a(\omega)}d_{3x}^2\hat{Y}_{xx}^E\right) \tag{1}$$

where, V_i and I_0 represent sensor input voltage and output current, respectively. Other parameters a, $\bar{\varepsilon}_{33}^T$, d_{3x}^2, and Y_{xx}^E represent geometry constant, complex dielectric constant of the PZT at zero stress, piezoelectric coupling constant, and Young's modulus. Assuming the electrical and mechanical behavior of the sensor do not vary, the variations in sensor admittance is caused only by the variations in the mechanical impedance of the building. To get a meaningful result, the measurement of the building impedance should be repeated over time and the differences should be analyzed. Peairs et al. suggest using RMSD calculation shown in (2) [26].

$$RMSD(\%)=\sqrt{\frac{\sum_{i=1}^{i=N}(Z(\omega_i)-Z_0(\omega_i))^2}{\sum_{i=1}^{i=N}(Z_0(\omega_i))^2}}\times 100 \tag{2}$$

In (2), Z_0, Z_1 and ω_i represent the reference impedance measurements taken in healthy state of the building, the current impedance measurement and the frequency value, respectively. The higher the RMSD value the more crucial the level of damage within the structure.

5. Experiments and performance results

The back and forth movement of a Reinforced Concrete (RC) building during an earthquake may cause generation of fractures within its carrier elements. The fractures that do not result a collapse may still pose vital risks and should be detected and analyzed to decide the building's residual lifespan.

Fig. 5. Experiment setup.

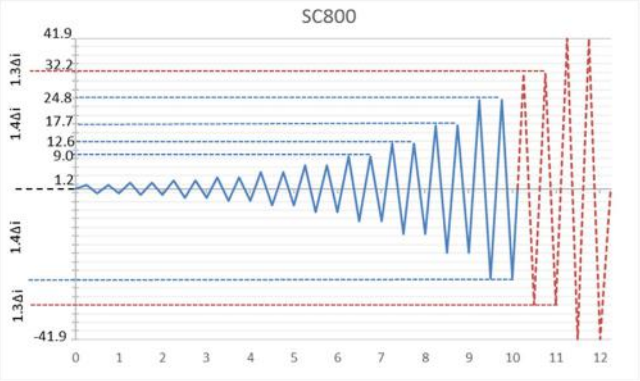

Fig. 6. Loading procedure.

To test the validity of the methods for fracture detection, a special test environment with hydraulic presses that exert vertical and horizontal forces on a RC short column to create fractures has been used. This way, comparing the system's output with that of visual inspection, one can determine if the system provides accurate output in terms of fracture presence.

Short columns are usually prone to shear effects due to having shorter effective length than that of regular columns. Although they are considered vulnerable, they are frequently used due to architectural or geographical requirements. These columns cannot endure to dynamic stresses (e.g., earthquake) as much as regular

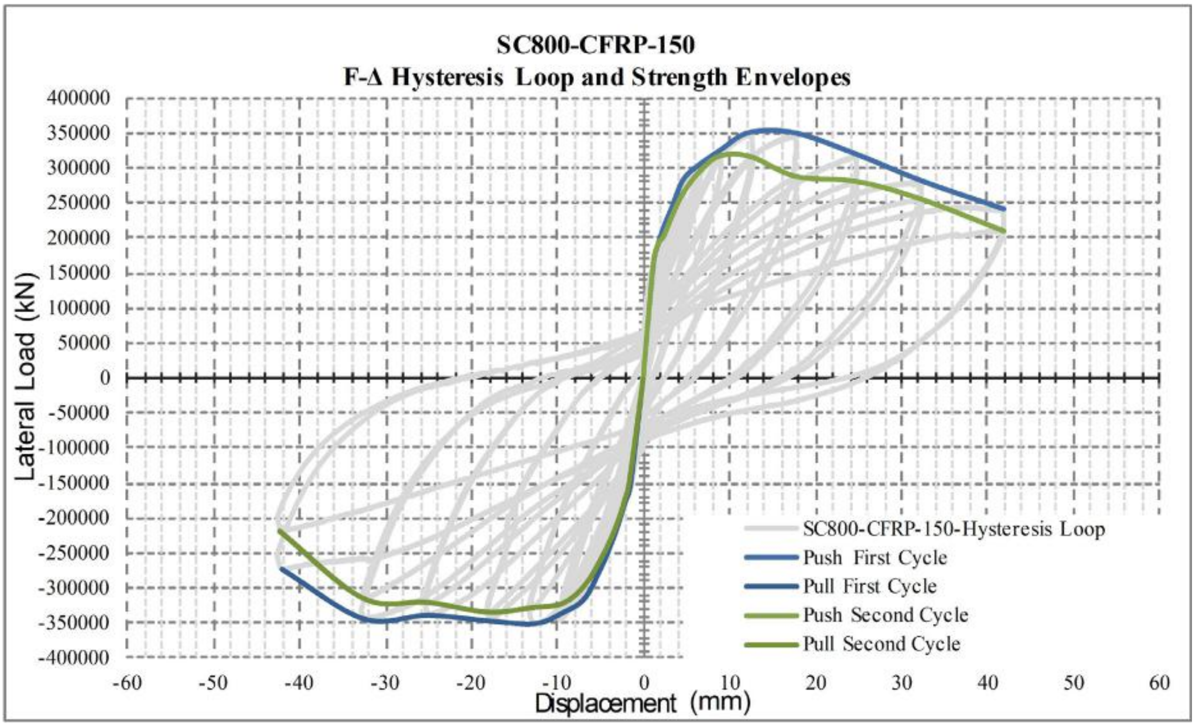

Fig. 7. Hysteresis loop and strength envelopes of RC short column.

Fig. 8. A view of crack development measured with PZT.

columns do. However, they possess a rigid behavior by causing less lateral displacement. Since the displacement is not a flexible behavior, shearing is inevitable.

In this study, a cyclic static force is applied to the short columns. To evaluate the detection results, PZT sensors are placed on positions both with and without fracture formation expectation. This way, sensors' detection capability at different distances to fractures is also evaluated.

Applying forces on two directions for fracture generation is meant to simulate a column of a RC structure in case of an earthquake scenario. While the constant axial load represents the weight of the higher sections of the building, the varying horizontal force represents the loads created due to the bending of the physical structure when an earthquake wave goes through the building's location. The experiment environment is shown in Fig. 5.

For measurements, 8 sensors attached to a single mote have been used. The sensors have been attached to the surface of the concrete block using a quick adhesive. The locations of the sensors have been selected near the areas that visible fractures would occur. While 4 of the sensors (#3, #4, #5, and #8) are attached to the front of the block that is compressed during pushing action, the rest is attached to the side of the block. After the placement of the sensors, the required reference measurements for RMSD calculations are taken. Following this step, the push and pull displacement of the RC short column is started. During these cycles, the displacement of the column is measured using linear variable displacement transducers. For impedance measurements at the end of the motion in each direction, the column has been kept at fixed displacement values by varying the horizontal force applied to it. To prevent generating new fractures or expanding existing fractures, displacement values are kept fixed instead of applied force.

Since short columns are more prone to shear cracks, the cyclic lateral load values are applied according to FEMA-461, the protocol for determining seismic performance characteristics [27]. The values are applied as push and pull forces as depicted in Fig. 6. A single cycle is defined as the duration until the column goes into

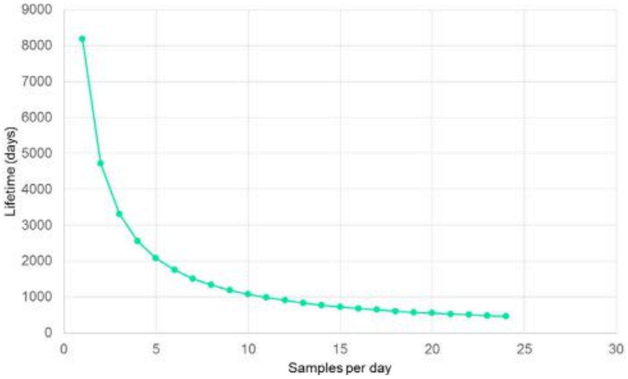

Fig. 9. Lifetime with different sample numbers.

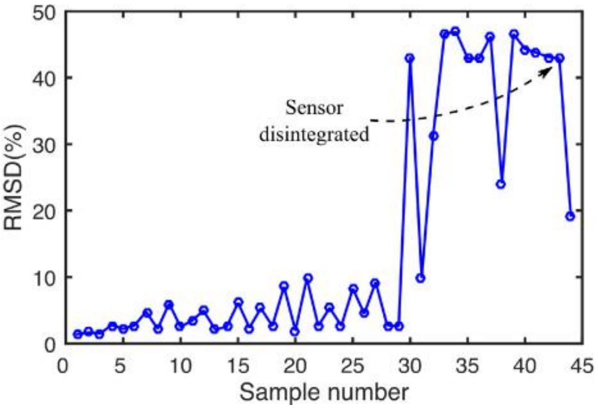

Fig. 10. RMSD results for sensor 1.

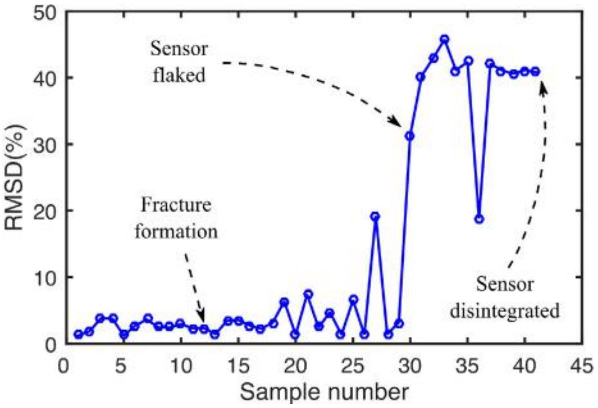

Fig. 11. RMSD results for sensor 2.

its initial state after a push and pull force is applied. Following the protocol, each cycle is repeated twice and two cycles is defined as a step. Throughout the experiment, 12 steps (24 cycles) of continuous load is applied.

The hysteresis loops and strength envelopes of the experiment are shown in Fig. 7. The figure shows the displacement versus lateral load values that provide insights about strength, ductility, rigidity and toughness of the column. PZT sensor measurements are conducted until the 10th step (20th cycle). This is the last step following the loading procedure. If the procedure is further followed, the columns start to collapse.

Using the methods and the hardware explained in the previous sections, the simulations are conducted. A view of the crack development is provided in Fig. 8.

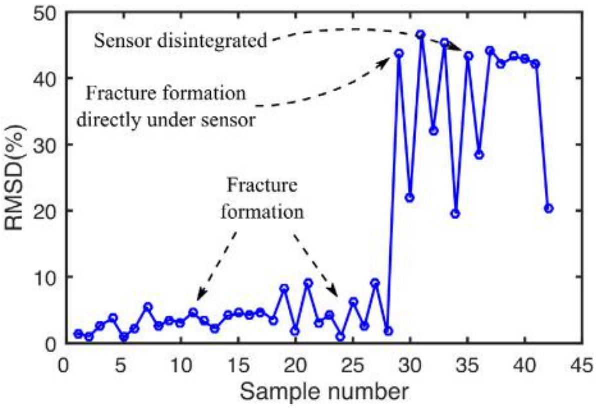

Fig. 12. RMSD results for sensor 3.

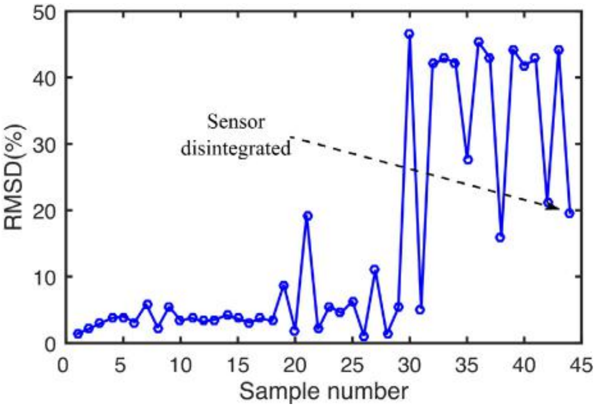

Fig. 13. RMSD results for sensor 4.

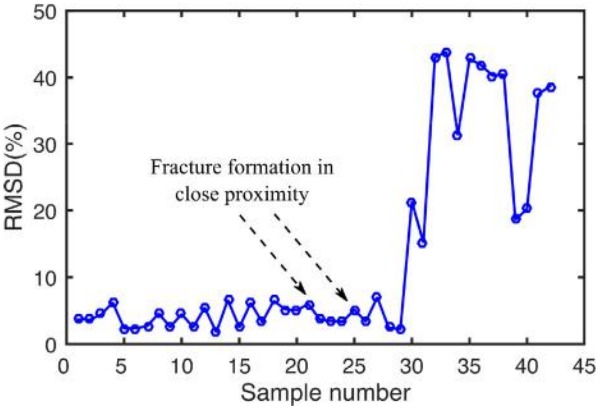

Fig. 14. RMSD results for sensor 5.

Furthermore, Fig. 9 shows the mote lifetime at different number of samples taken within a day. It is shown that lifetime can go up to 8000 days when single sample is taken daily. The lifetime is decreased to around a year when up to 25 daily samples are taken.

The results are shown in Fig 10 to Fig 17 for each sensor respectively. The main trend in all the resulting graphs shows fluctuations until 25th to 30th sample while the RMSD value increases abruptly beyond this point. The initial fluctuations are considered the result of back and forth movement of the RC column caused by push and pull forces from the pressure cylinder. The measurements taken from the front of the test column are focused on the fractures that are compressed during push forces. The compression causes fracture size to shrink thus lower RMSD values. Similarly, the pull force causes an opposite reaction. Besides, shear cracks

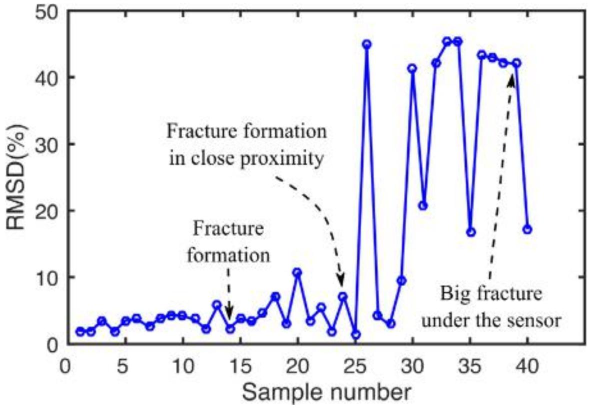

Fig. 15. RMSD results for sensor 6.

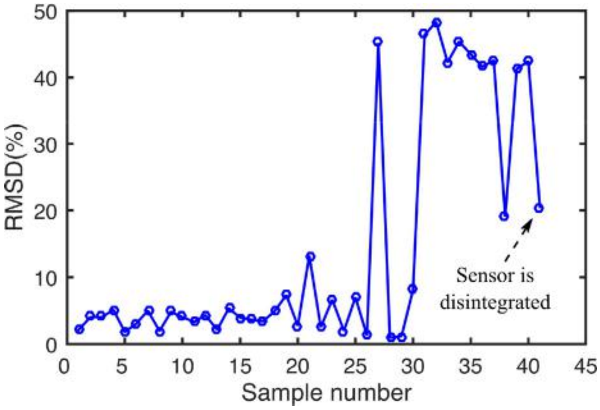

Fig. 16. RMSD results for sensor 7 .

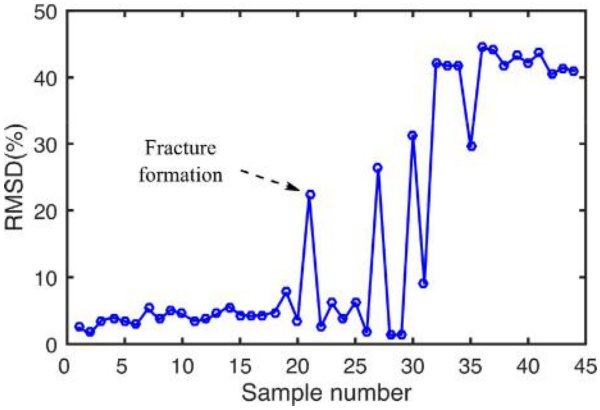

Fig. 17. RMSD results for sensor 8 .

have occurred on each sides of column. Therefore, until a fracture with considerable size is formed, the RMSD value fluctuates at low values. After a significant fracture is formed under the sensor, the RMSD value shows an abrupt increase. In the experiment, these high values are observed at the time of big visible fractures' formation. The fluctuations observed beyond this point are also caused by the shrinkage of the fracture size during push movement. Despite these fluctuations, using an RMSD threshold of around 20%, the first time the RMSD value goes above this level can be considered as the time visible fractures are detected. After the detection, the authorities can be informed on the risks. This way, energy efficiency is improved not sending periodical measurements.

The provided cost of the system is quite low considering how promising the results are. Moreover, the costs listed in Table 1 are single item prices. In case of a bulk production (over 1000), part prices go below half the current prices.

6. Conclusions

It has been shown that impedance measurement via PZT sensors provides an effective and cheap solution for fracture detection on RC buildings. To validate the method, forces have been applied on RC column to trigger fracture formation while taking impedance measurements via PZT sensors. Applying RMSD calculations on the collected data, the results show significant difference after the formation of visible fractures. The fractures formed in initial cycles and developed in the following cycles are detected before they are visible to human eye. This is extremely important since it allows warning authorities while the fracture is small.

Periodical measurements using PZT sensors can be achieved by attaching the sensors to a data logger system. This way, the fractures formed due to vertical loads, durability problems, and natural disasters are easily monitored. The possibility of attaching PZT sensors on existing concrete structural elements, masses and masonry structures is a vital advantage over strain gauge sensor-based SHM solutions.

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