Structural Behavior Monitoring System Using Scalable Carbon Nanotube Patch Sensors

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Abstract— **In this study, a scalable Carbon NanoTube (CNT) patch sensor-based system is introduced to monitor the abnormal behavior of bridge structures. The CNT sensor is a composite of carbon nanotubes and polyurethane, and it functions as a sensor that could detect the behavior of a structure using the electrical resistance change characteristics of the CNT. The size and shape of the scalable CNT patch sensor are adjustable depending on the type and surface condition of the structure, making the sensor attachable in locations where existing sensors, such as strain gauges, could not be installed. Therefore, the scalable CNT patch sensor could accurately detect abnormal behaviors occurring at any locations of the structure. The observed data is transmitted to the Internet of Things (IoT) based behavior detection and monitoring system for analysis, allowing us to proactively identify structural problems that may arise. The abnormal behavior monitoring system using scalable CNT patch sensors was field tested on a steel tied arch bridge in the United States. This confirms that the proposed system could effectively monitor the abnormal behavior of bridge structures and detect potential problems. It is expected that the structural abnormal behavior detection technology using scalable CNT patch sensors would be effectively utilized in various fields in the near future.**

Keywords- Carbon nanotube sensor; Scalable; Abnormal behavior detection; IoT sensing system; Monitoring system.

I. INTRODUCTION

Long-term monitoring of civil infrastructures, such as bridges, is essential for ensuring public safety and prolonging structural longevity. The conventional method of monitoring using strain gauges has limitations, such as small detecting area and low durability. Additionally, strain gauges could not be installed or attached to non-flat surfaces, such as layered or stepped surfaces. To overcome these limitations, sensors that use carbon nanomaterials, such as Carbon NanoTubes (CNTs), graphene and carbon fibers, are being continuously developed. The characteristics of carbon nanomaterial composites, such as electrical resistance and flexibility, depend on the type or concentration of carbon material and matrix used. These characteristics could be adjusted to meet specific measurement or installation requirements and were developed to overcome the limitations of strain gauges. The advancement of sensor technology, particularly utilizing carbon nanomaterials, not only addresses the limits of traditional strain gauges but also enhances structural monitoring capabilities in diverse environmental conditions and geometric complexities.

The strain sensor based on CNTs is designed for structural health monitoring applications. The sensor platform integrates carbon nanotubes that are known for their exceptional electrical properties to provide high sensitivity and reliability in detecting structural deformations [1].

In addition, scalable and multifunctional textile based on carbon nanotubes, which serves as distributed sensors for flow and cure monitoring not only demonstrates the versatility of carbon nanotube-based sensors but also highlights the potential applicability in various monitoring scenarios, including structural health monitoring [2].

The research for fabrication and characterization of CNT-based sensors for strain sensing applications provides valuable insights into the development of high-performance sensors capable of accurately detecting structural deformations, which are essential for ensuring the safety of civil infrastructure [3].

This research proposes a new approach to structural behavior monitoring using a composite of CNT as a patch sensor. The CNT patch sensor can be divided into small pieces from the original patch sensor, and this size-adjustable sensor is called scalable CNT patch sensor. Our methodology aims to overcome the limitations of conventional monitoring systems. Specifically, we have developed a scalable CNT patch sensor that could be adjusted to fit non-flat surfaces, including layered or stepped surfaces. We demonstrate the efficacy and practicality of our proposed monitoring system in real-world scenarios through empirical validation and field testing.

The paper is structured as follows: Section II presents the development and characteristics of CNT patch sensors. Section III outlines the implementation of a monitoring system utilizing Internet of Things (IoT) technologies. Section IV specifies the experimental procedures and findings regarding the performance evaluation of CNT patch sensors through tensile, bending, and field tests. Finally, in Section V, we present our conclusions and ideas for future work.

II. CARBON NANOTUBE-BASED SENSORS

This section introduces CNT patch and scalable CNT patch sensors utilized in structural monitoring technologies, which are both composites of CNTs and PolyUrethane (PU). The CNT patch sensors measure strain in a structure by detecting changes in resistance with deformation. The scalable CNT patch sensors aim to overcome the limitations of conventional strain gauges by providing flexibility and ease of installation. These sensors can be divided into small pieces and sized according to the attachment location and monitoring purpose.

A. CNT patch sensor

The CNT patch sensors are composed of a composite of CNTs and PU. The CNT/PU composite patch sensors are produced through a complex process, as illustrated in Figure 1. The most crucial process that affects the sensor quality is the dispersion of CNTs in the PU. Therefore, ultrasonication is used to disperse the CNTs in the PU [4][5]. The CNT patch sensor consists of the CNT/PU patch as a primary component and electrodes for wiring to the measurement device. The results of the resistance test of the CNT/PU patch indicate that the performance of the CNT patch is significantly improved with a 5 wt% CNT concentration (Figure 2). As such, using 5 wt% CNT patches is recommended for the CNT patch sensor.

The strain using a CNT patch sensor is measured by: 1) obtaining the sensitivity, S, of the specific type of CNT patch sensor through pretesting; 2) attaching the CNT patch sensors to the structure and measuring the initial resistance, R_0; 3) measuring the resistance at the required point in time to measure the deformation of the structure, R; 4) calculating the strain, ε, using (1).

$$\varepsilon = S\,(R - R_0)\,/\,R_0 = S\,\Delta R\,/\,R_0 \qquad (1)$$

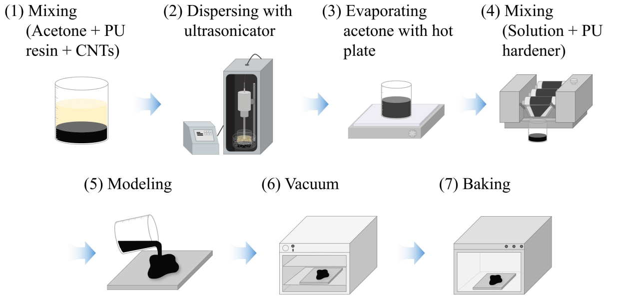


Figure 1. Fabrication of CNT patch sensors [5].

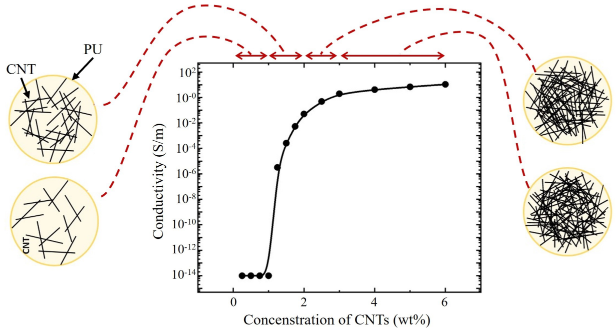


Figure 2. Degree of CNTs dispersion in polyurethane [5].

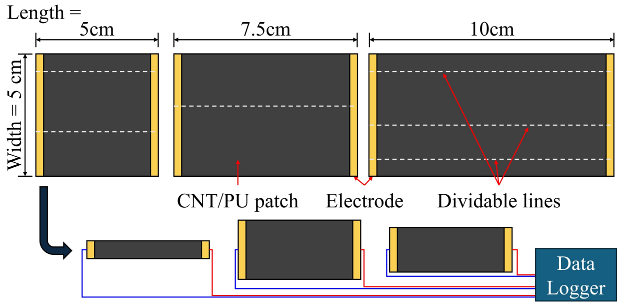


Figure 3. Shape and componants of CNT patch sensors.

B. Scalable CNT patch sensor

The aim of this research is to develop a flexible and scalable sensor that detects abnormal structural behavior, which makes it easier to install in places where conventional strain gauges are difficult to apply. Figure 3 shows examples of the geometries and components of a scalable CNT patch sensor. The sensor could be cut into multiple pieces lengthwise, with each piece having two electrodes on both ends depending on its installation location or purpose. Based on our previous study [5], the CNT patch sensor used 5 wt% CNT concentration.

The purpose of scalable CNT patch sensors is to detect any abnormal behavior in structures, such as the occurrence or development of cracks. To do so, the scalable CNT patch sensors are connected to a data logger to measure resistance. Abnormalities in the structure are detected through changes in electrical resistance trends, based on the collected time series of electrical resistance data.

III. MONITORING SYSTEM

Reliable and continuous measurement is necessary for long-term monitoring of a structure. IoT-based measurement technologies could increase maintenance and monitoring efficiency through wireless communication. The CNT patch sensor is incompatible with conventional data loggers due to its higher electrical resistance compared to typical strain gauges.

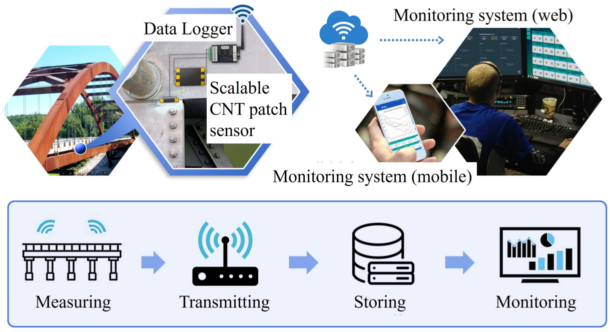


Figure 4. Overview of monitoring system using CNT patch sensors.

(a) (b)

Figure 5. Data logger prototype: (a) Inside circuit, (b) External geometry.

A dedicated data logger has been developed to measure the resistance of CNT patch sensors, including a Wi-Fi module for data communication. Figure 4 shows an overview of monitoring system using CNT patch sensors.

A. Prototype Data Logger

The prototype data logger was designed to meet specific requirements, including measurable resistance up to 10 MΩ, up to 16 simultaneous channels, a sampling rate of 0.5 Hz for each channel, and the ability to transmit measured data to the server. It was able to receive commands from the server for control of the data logger and could be directly controlled by a touchscreen on the device. Figure 5 displays the data logger prototype. The data logger was created using a Printed Circuit Board (PCB) that includes a Wheatstone bridge to measure resistance for 16 channels. Additionally, an embedded MicroController Unit (MCU) was used for circuit control. The data logger also included a Raspberry Pi module for seamless wireless communication and connection to a touchscreen LCD display, as well as a 3.5 mm jack for sensor connectivity. Various features of the prototype were tested, and the results were evaluated using the LCD screen and jack. Despite the high-power consumption of the LCD screen and the susceptibility of the jack to noise generation, we chose them for their availability and ease of use.

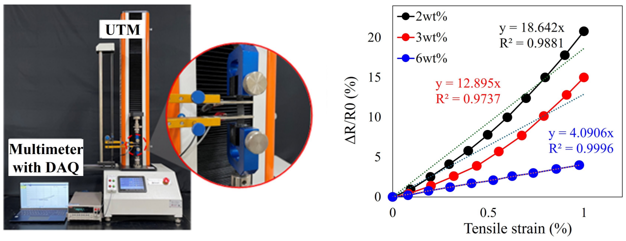
The software on the device could measure the strains of 16 CNT patch sensors, including the input sensitivity of each sensor, and control the data logger to start and stop measurements.

B. Monitoring Software

Once the resistance of the CNT patch sensor is measured and the strain is calculated, the data is transmitted to the server and stored in the database. The monitoring software then visualizes the data stored on the server in various forms for the user and includes the function to remotely control the data logger. The monitoring software can display sensor data from 16 channels and can also be expanded. The measured resistance and the calculated strain for each channel are displayed, and strain data are also displayed as a time series graph. If the strain exceeds set value, an alarm notifying the event is triggered, and the data from 30 seconds before and after occurrence of the event are stored. Figure 6 shows the monitoring software display that visualizes the measurement results in data and graphs.

CNT #01 14 07
CNT #02 22 13
CNT #03 28 11
CNT #04 05 21
CNT #05 37 11
CNT #06 03 06
CNT #07 19 45
CNT #08 40 12
CNT #09 23 14
CNT #10 10 21
CNT #11 02 06
CNT #12 52 34
CNT #13 27 33
CNT #14 36 14
CNT #15 18 05
CNT #16 40 11

Figure 6. Monitoring software prototype.



(a) (b)

Figure 7. Tensile test of CNT patch sensors: (a) Test settup, (b)strain vs. rate of resistance change ($\Delta R/R_0$).

IV. EXPERIMENTAL SETUP AND RESULTS

A. Tensile Test of CNT Patch Sensor

The CNT patch sensors were mixed with 2, 3, and 6 wt% CNT concentration and dispersed in acetone using ultrasonic waves. The sensors were installed on a Universal Testing Machine (UTM), and both electrodes of a multimeter were connected (Figure 7(a)). The UTM applied displacement to the CNT patch sensor in tensile up to 1% strain, and the resistance of the sensor was measured at each stage of strain. The results are presented in Figure 7(b). The relationship between strain and resistance change rate became more linear as the CNT concentration increases. The sensor's sensitivity was determined by the slope of its linear regression curve. An excellent fit was indicated by the coefficient of determination, R^2, of the 6 wt% sensor, which was 99.96%. As the CNT concentration increased, the sensitivity decreased. However, the sensor with 6 wt% CNT has a higher sensitivity of 4.0 compared to the conventional strain gauge, which has a sensitivity of about 2.0.

B. Bending Test of CNT Patch Sensor

Tensile tests were conducted on the CNT patch to evaluate the stability and sensitivity of patch sensors containing 6 wt% CNTs. Subsequently, the sensors were attached to a scale model of a concrete bending test specimen to verify their sensitivity to cracks during bending tests. Figure 8(a) shows the results of a four-point bending test conducted until the test specimen cracked and failed. CNT patch sensors were attached to the lower part of the test specimen to monitor its response during cracking and evaluate the performance of abnormal behavior detection, as shown in Figure 8(b). The UTM data and test results of the CNT patch sensors are presented in Figures 8(d) and 8(e), respectively. The CNT patch sensors rapidly detected cracks by exhibiting a significant change in $\Delta R/R_0$ at approximately 550, 650, and 900 seconds after the test started. The CNT patch sensors, as shown in Figure 8(c), were able to detect cracks at 550 and 650 seconds that were not visible to the

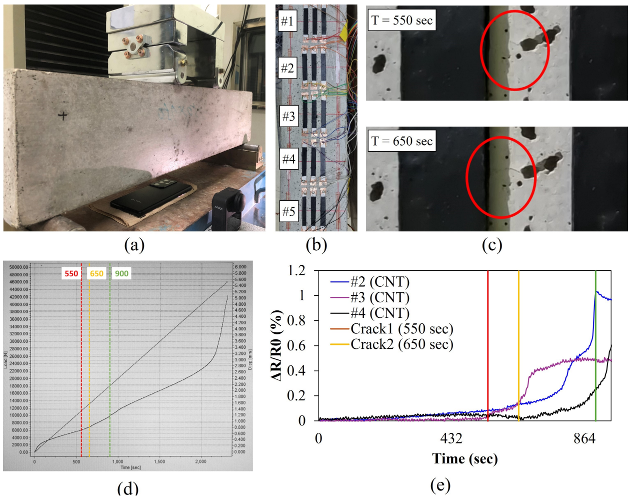


Figure 8. Bending test for detecting cracks: (a) Test settup, (b) Bottom surface of test specimen, (c) Cracks detected time, (d) Time vs. load & disp.(UTM), (e) Time vs. $\Delta R/R_0$ (CNT patch sensors).

naked eye. Figure 8(d) presents the time-series data of load and displacement from UTM and each time of cracks, but it does not unambiguously indicate whether a crack has occurred. The test demonstrated that the CNT patch sensor developed is highly sensitive to strain, making it suitable for detecting cracks and structural abnormalities.

C. *Field Test on the Bridge*

The scalable CNT patch sensors were installed on a steel tied arch road bridge (main span 158m) in the US to assess their response during loading test. The scalable CNT patch sensors and strain gauges were installed on the joint of the floor beam and girder during the loading test for safety diagnosis of the bridge, as shown in Figure 9(a). The electrical response of the CNT patch sensor was monitored using the prototype data logger, and the electrical changes of the CNT patch sensor in response to load changes were used to detect abnormal behavior of the structure. Additionally, the response of the sensor on a mobile phone with LTE communication was also monitored, as shown in Figure 9(b).

The loading tests were performed using two 31,750 kgf (70,000 lbf) trucks travelling in one or two lanes at speeds of 16.1 km/h and 72.4 km/h (10 mph and 45 mph) to measure changes in bridge behavior. Table 1 shows the loading test schedule. The sampling rate of the data logger was set to 0.5 Hz.

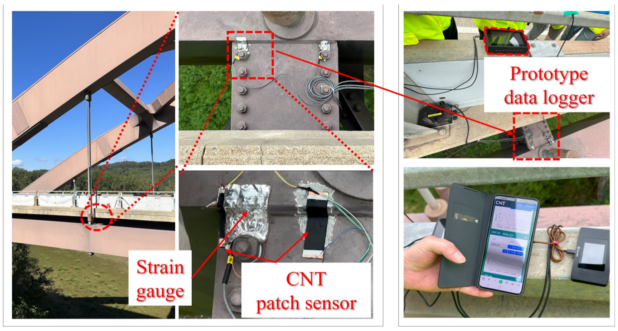


Figure 9. Field test: (a) Installation of sensors, (b) Setup of data logger and monitoring software on mobile phone.

Table 1. Field Test Schedule

Test no.	Test condition		Test no.	Test condition	
	Lane	***Speed***		***Lane***	***Speed***
#1	Left	16.1 km/h (10 mph)	#3	Left	72.4 km/h (45 mph)
#2	Right		#4	Right	

Figure 10 displays the test results. The upper plot shows the change in resistance rate from the initial resistance, $\Delta R/R_0$, over time. The lower plot displays the change in resistance rate over time from the previous resistance. The CNT patch sensors detect changes in electrical resistance during the loading test. The test results indicate that scalable CNT patch sensors are versatile and can be used in narrow or wide areas, as well as on welds with height differences on both sides, due to their flexible and scalable characteristics. Tests #3 and #4 were expected to elicit greater $\Delta R/R_0$ since the trucks were travelling at 4.5 times the speed of tests #1 and #2. However, the responses of tests #3 and #4 were inaccurate, and this is assumed to be because the sampling rate of 0.5 Hz may not have been sufficient to capture resistance changes caused by a fast-moving truck. To monitor both short-term dynamics and long-term static behavior of the structure, the monitoring system should be updated to allow for sampling rate adjustments.

V. CONCLUSION AND FUTURE WORK

This study presents a method for detecting abnormal behavior in structures using scalable CNT patch sensors. A review of prior research was conducted to understand the manufacturing and quality aspects of CNT/PU composite patch sensors. The authors found that the sensor with a 5 wt% CNT concentration exhibited the best performance and proposed a method for measuring the sensitivity of CNT patch sensors based on this finding.

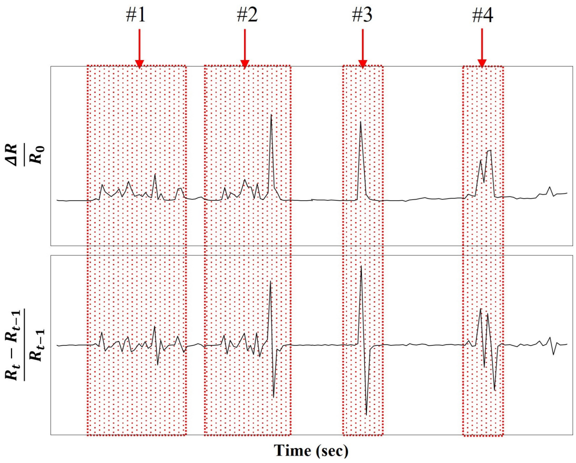


Figure 10. Field test results.

The study investigated the potential of scalable CNT patch sensors to detect abnormal behavior in structures, including superficial cracks and structural deformations. Experimental tests have demonstrated the effectiveness of these sensors in detecting such behaviors. The study demonstrates that the sensors are efficient in detecting abnormal behavior in structures. Additionally, field experimentation has confirmed the practicality of scalable CNT patch sensors. The CNT patch sensors installed on a road bridge accurately detected changes in load induced by vehicle movements.

The results of this study demonstrate the potential of CNT patch sensors as a useful tool for long-term structural health monitoring and maintenance. However, there are still challenges to be addressed before CNT patch sensors could be applied in the field, such as the development of mass production techniques for CNT patch sensors or the ability to adjust the system sampling rate for static and dynamic measurement purposes. We also plan to conduct research on sensors with integrated data loggers. Continued research is expected to address these challenges and contribute significantly to the development of safer and more efficient structural maintenance and monitoring systems in the future.

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