# Novel Wireless Sensing Design for Composite Durability Study

Chang Liu[1*], Qichen Fang[1], and Khalid Lafdi[1,2]

[1] Department of Chemical and Materials Engineering, University of Dayton, Dayton, OH 45469, USA.

[2] Department of Mechanical Engineering, Northumbria University, Newcastle upon Tyne, UK.

Abstract

Structural health monitoring (SHM) of chemical penetration in composites is a critical issue for their durability as composite storage. Current methods are either complicated or expensive. Besides, the wired sensing system introduces defects in the composite structure. Herein, we present a novel wireless sensing design for detecting aggressive chemicals in composite reservoirs. Remarkably, the sensing system used in this work is cost-effective and easy to be configured. In this study, we used Radio Frequency Identification (RFID) as wireless sensing technology. A sensor embedded composite panel was prepared and tested in a harsh environment, 30wt% $H_2SO_4$. Additionally, we modified an RFID tag with conductive nanocomposite for the aim of selective sensing. We found that the RFID tags are working well as sensors for detecting the chemical penetration in composites. Compared with conventional color-based methods, the presented novel wireless sensing method provides a much earlier warning signal for chemical penetration.

[*] Corresponding to Chang Liu: xiandaihanyucidian@gmail.com

## 1. Introduction

Composite materials are used in various infrastructures due to their excellent weight/strength ratio, durability, and feasibility of manufacturing[1]. However, with the use of composite material, structural health monitoring (SHM) of the composite structures becomes an emerging issue[2]. Additionally, many composite structures are designed for storing aggressive chemicals, such as concentrated acid solutions. In order to maintain a healthy structure, many SHM methods were studied, such as electromagnetic impedance spectroscopy/tomography (EIS/EIT)[3-5], acoustic emission[6, 7], and fiber optics-based spectroscopic methods (modified optical fiber[8, 9], Bragg fiber grating[10, 11]). However, the complexity of mathematics, time costs, and instrumentation costs have delayed the deployment of these new technologies. In practice, a more convenient and cheaper method is to be developed. For which several characteristics need to be satisfied: easy use, affordable, and reliable in the long-term[2, 12].

Previously, we have explored the use of carbon nanomaterials and conjugated polymer in detecting the acid penetration in the polymer nanocomposites [13-16]. Based on our experimental and modeling results, we have confirmed that the change in conductivity of the polymeric matrix can be used as a primary indicator to monitor the acid penetration in the composite. This change of conductivity comes from the penetration of ions. Additionally, we have proposed the idea of using wireless technology in SHM of chemical penetration[15]. In practice, a wired sensor is not suitable for the manufacturing of large infrastructures. Radio-frequency identification (RFID) technology is one of the best solutions.

The RFID technology uses a magnetic wave to transmit signals in the radio frequency range[17], respectively, 120 kHz to 10 GHz. Multiple bands are regulated in this regime, and the different

bands have various ranges (functional distance). For example, 13.56 MHz band (high frequency, HF) is used for smart cards in a range (maximum) of 10 cm to1 m, 2450-5800 MHz (microwave) is used for Bluetooth applications in a range of 1 to 2 meters. The HF range RFID is the most deployed and available is most smart-phones. By using an appropriate app, one can read the information in the RFID tag easily. However, in order to study and use the RFID tag as a sensor, the signal strength has to be examined. The composite material interferes with the transmission of electromagnetic waves, especially conductive material. For example, the carbon fiber based composite[18, 19] has a strong electromagnetic wave shielding effect in 100 MHz range and up to x-band (10GHz) range[20, 21]. In this case, the use of RFID technology has to be carefully chosen based on real conditions. Another advantage of RFID technology is the information carried tag can be passive. The passive RFID works without a power supply. The transmitted electromagnetic wave from the RFID reader is the power source for the RFID tag. In other words, the RFID tag works without a battery and which reduces the cost and increases its feasibility.

Passive RFID based wireless sensing has been used for sensing of gaseous chemicals[22-25]. Timothy et al. modified commercial passive RFID tag for sensing of oxygen and nerve gases[23-25]. A demonstration of using a smartphone for quick identification and monitoring was shown as well. The passive RFID technique has also been used for SHM subjects[17]. Merilampi et al. designed a modified RFID tag sensor using silver ink as a strain sensor[26]. Thus a sensor was based on the geometry change of the structure and failure of the silver connections. Overall, the use of RFID for SHM is not a new idea. However, embedding the RFID tag inside a composite structure for the detection of liquid chemical penetration has not been explored yet.

This paper presents a first study on wireless sensing of the penetration of aggressive chemicals in composite materials. A commercially available and cost-effective RFID tag was embedded into

composite penal, and an aggressive test was carried out to explore its SHM property. Besides, we also tried to modify the RFID tag using CNT based nanocomposite aiming at transferring the sensor from a failure sensor to an active sensor and endowing selectivity. The embedded sensor could be either printed[27, 28] or formed by self-assembly methods. In this case, the sensor could be integrated into composite structure. For example, modified conductive nanoparticles could be used for selective sensing. By designing the matrix system, the nanoparticles could form unique patterns inside the matrix[29-32]. As a result, the pattern nanoparticles respond to designed electromagnetic characteristics.

## 2. Materials and Methods

### 2.1 RFID tag and its modification

The RFID tag (VM2R1703, MIFARE Classic 1K Chip, 13.56MHz, adhesive back, blank paper finished, $\phi$25mm) was used as a primary sensor, and it was purchased from the Amazon. The tag consists of a polyethylene terephthalate (PET) substrate, a MIFARE chip, and an aluminum base coil on both sides of the plastic substrate. The thickness of this tag is 0.06 mm in the coil area and 0.17 mm with the chip. The geometry of this tag is also shown in figure 1.

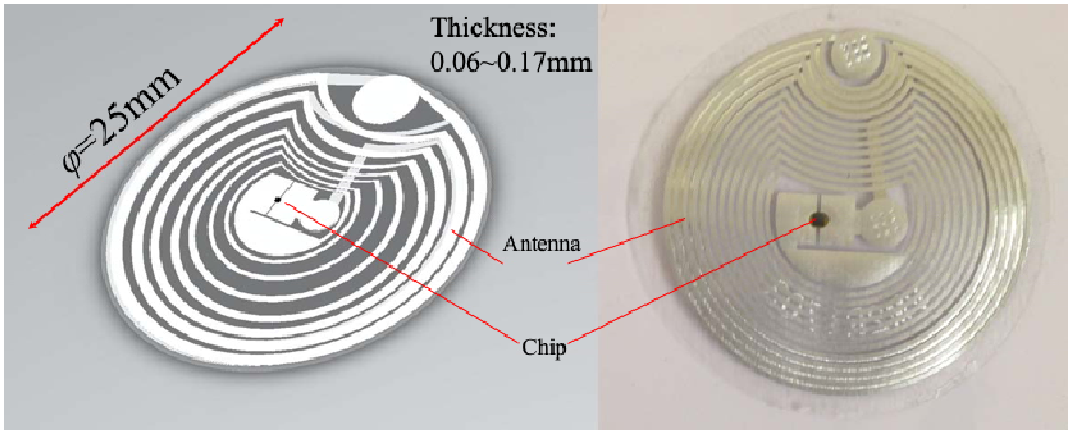



Figure 1. Dimension of the RFID tag and an image of the tag.

Modification of this sensor was carried out by cutting a small piece of coil section and filling the space with CNT based nanocomposite. The CNT based nanocomposite consists of 1wt% of polyurethane (PU) and 99wt% of CNT. Acetone was used as the solvent to disperse the CNT and dissolve the PU. As shown in figure 2a, the tag was modified by cutting the coil for 1 mm in length. After filling the space with CNT/PU nanocomposite with a tweezer and drying in air, the nanocomposite sticks onto the substrate. A reproducibility test with formic acid was performed for all modified sensors. This test was proceeded by drop 0.2 μL formic acid and read the signal strength of the sensor with an Arduino-RC522 setup. The tag reader system consists of an Arduino motherboard, an LCD display, and an RC522 reader, as shown in figure 2b. This set up is powered by a common computer-based USB port. The signal strength data were collected and recorded by the Arduino software (version 1.85).

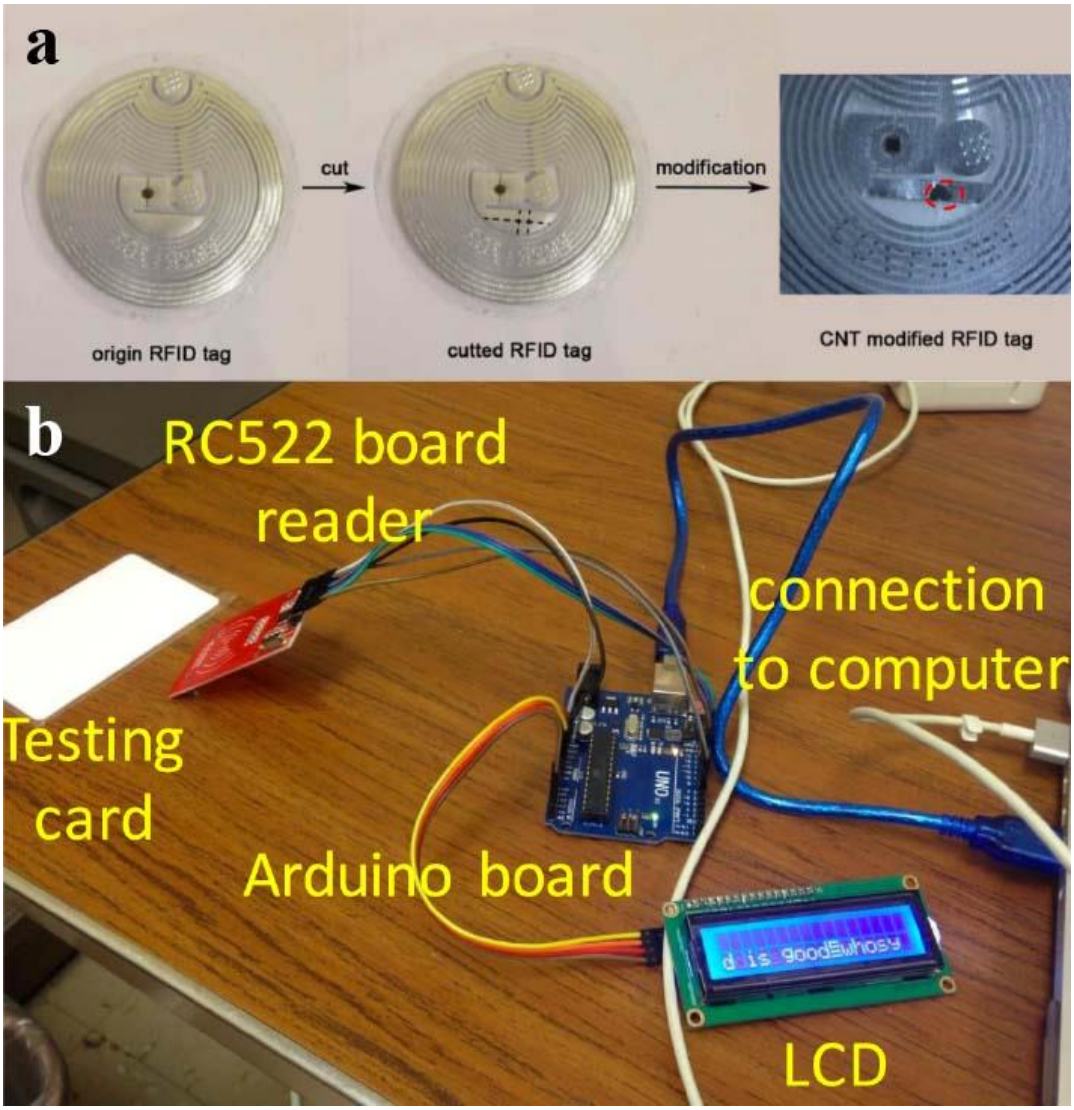
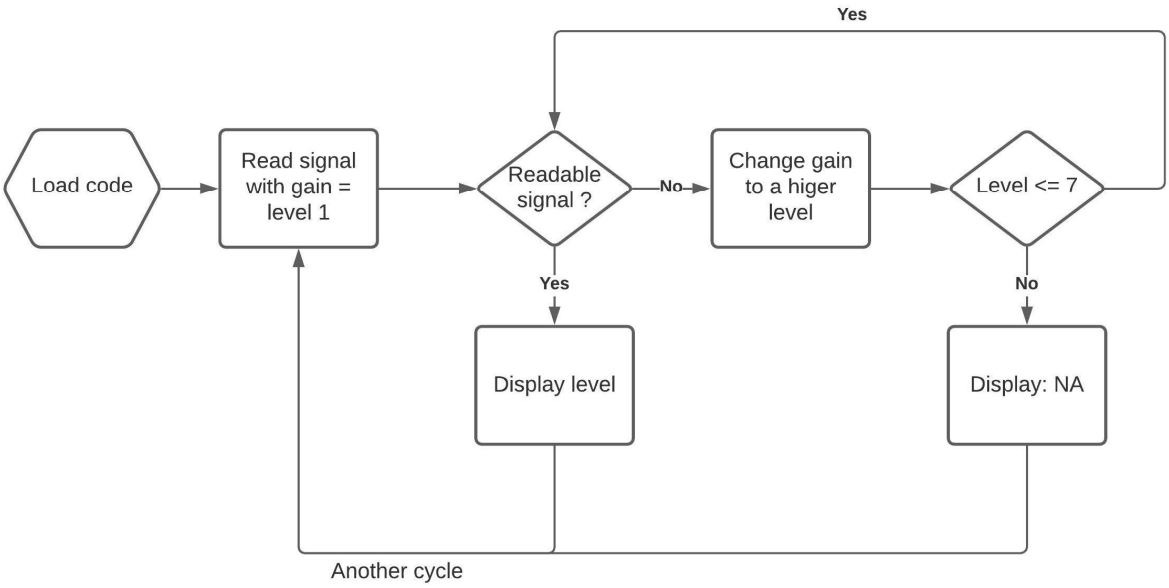



Figure 2. (a) CNT modification of the RFID tag. (b) Assembly of the wireless sensing system.

## 2.2 Mechanism of Arduino code

The Arduino based RFID system does not have the capability to detect the signal strength of the RFID tag. The gain strength of the RC522 reader antenna is changeable. In this case, we developed a coarse signal strength detecting code [33]. By changing the gain to a higher level, the reader can sense the stronger signal and ignore the weaker one, as illustrated in the following

flow chart (scheme 1). In practice, after running the code, the RC522 scans signal with the highest sensitivity (gain). Once a signal is detected, the value of signal strength is recorded and displayed. The defaulted gains for RC522 were in 7 levels: 102 dB, 96 dB, 80 dB, 64 dB, 48 dB, 32 dB and 16 dB. In practice, when choosing 32 dB gain, the reader can sense a feedback signal as low as 32 dB. And which means the feedback signal is fairly strong compared to the 64 dB one. However, not all levels can be read due to the hardware limitation, the highest signal strength that can be detected is 32 dB rather than the 16 dB level. The program has been verified simply by checking the signal strength through moving the RFID tag toward and far from the RC522 reader. The results were consistent, reproducible, and stable.




Scheme 1. Flowchart of the Arduino code.

2.3 Fabrication of tag embedded composite panel

A non-woven glass fiber based epoxy composite panel was prepared, and RFID tags were embedded (figure 3). The panel was prepared using a vacuum assist lay-up method [13]. Twelve layers of non-woven glass fiber mats and a modified epoxy resin formulation (Epon 862/Jeffamine D230/PVP) were used. The #1 RFID tag is in the middle layer of the panel, and the #4 RFID tag is on the surface of the panel. An image of the fabricated panel is illustrated in figure 3c.

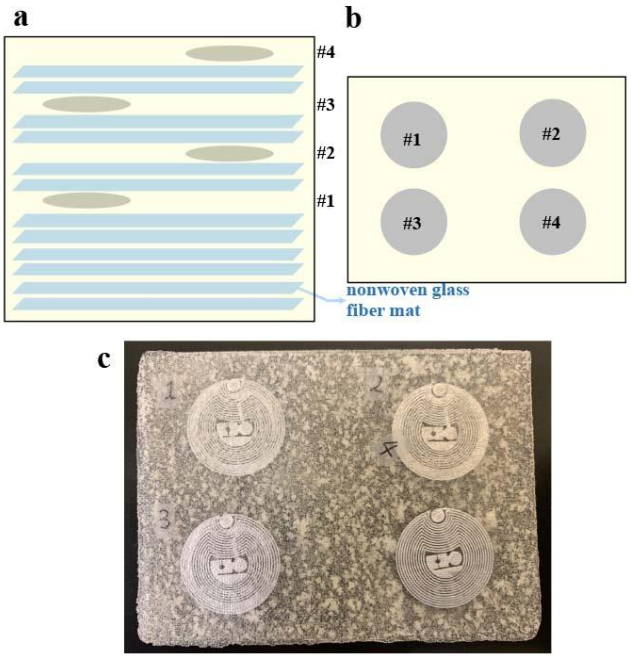



Figure 3. (a) Lay-up and side view of the composite panel and the embedded RFID tags. The RFID tags are labeled as shown. (b) Top view and label of the composite panel. (c) An image of the finished composite penal after curing. Here the label of #4 moved from its original position due to resin flow during making the sample.

2.4 Testing of the composite panel

After curing, the panel was immersed into a 30wt% $H_2SO_4$ solution. The solution was stirred continuously. Each time at each test, the panel was washed with water and dried with tissue paper. When testing with the RFID reading system, the function-ability of the tag was firstly verified by reading its ID. After this verification, the signal strength of the tag was read by attaching the panel and the RC522 reader. A stable reader was finally recorded.

## 3. Results and discussion

### 3.1 Signal decay

By recording the signal strength of the composite panel each day, the failure process of each RFID tag is shown in figure 4a. The color chart shows the failure of tags in a 20-days period. Obviously, and as expected, the out-most RFID tag failed first. Figure 4b-e shows the first 20 daysô image of the panel. At Day 1, the aluminum antenna of tag #4 started to detach to the substrate. At Day 2, the aluminum antenna of tag #4 had failed. At day 11, one side of the tag #4 was fully corroded and tag #3 was started to be corroded. The other tags remained unchanged. However, as shown in figure 4a, the signal strength of tag #2 was altered. This phenomenon shows that the penetration of the acid changed the electromagnetic characteristics of the RFID tag, such as, the impedance, resistance, and inductance of the RFID tag. The same behavior could be found for tag #1 as well.

The slow change of these characteristics allow us to establish an evaluation method for the penetration of aggressive chemicals, and a standard to maintain the safety of composite structures. Additionally, this change on the RFID signal is regarded as an early-warning compare to conventional SHM methods. As shown in figure 4f and 4g, the images of Day 41 and 60, the polymer matrix colored into orange/brown due to the attacking of the aggressive sulfuric acid.

Also, tag #3 was corroded on Day 41 and fully dissolved by Day 60. On Day 60, blistering and deforming of the composite panel is clearly shown in figure 4g. Tag #1 and tag #2 show pitted corrosion pattern. As a conclusion, the RFID signalôs decay comes much early than the color change.

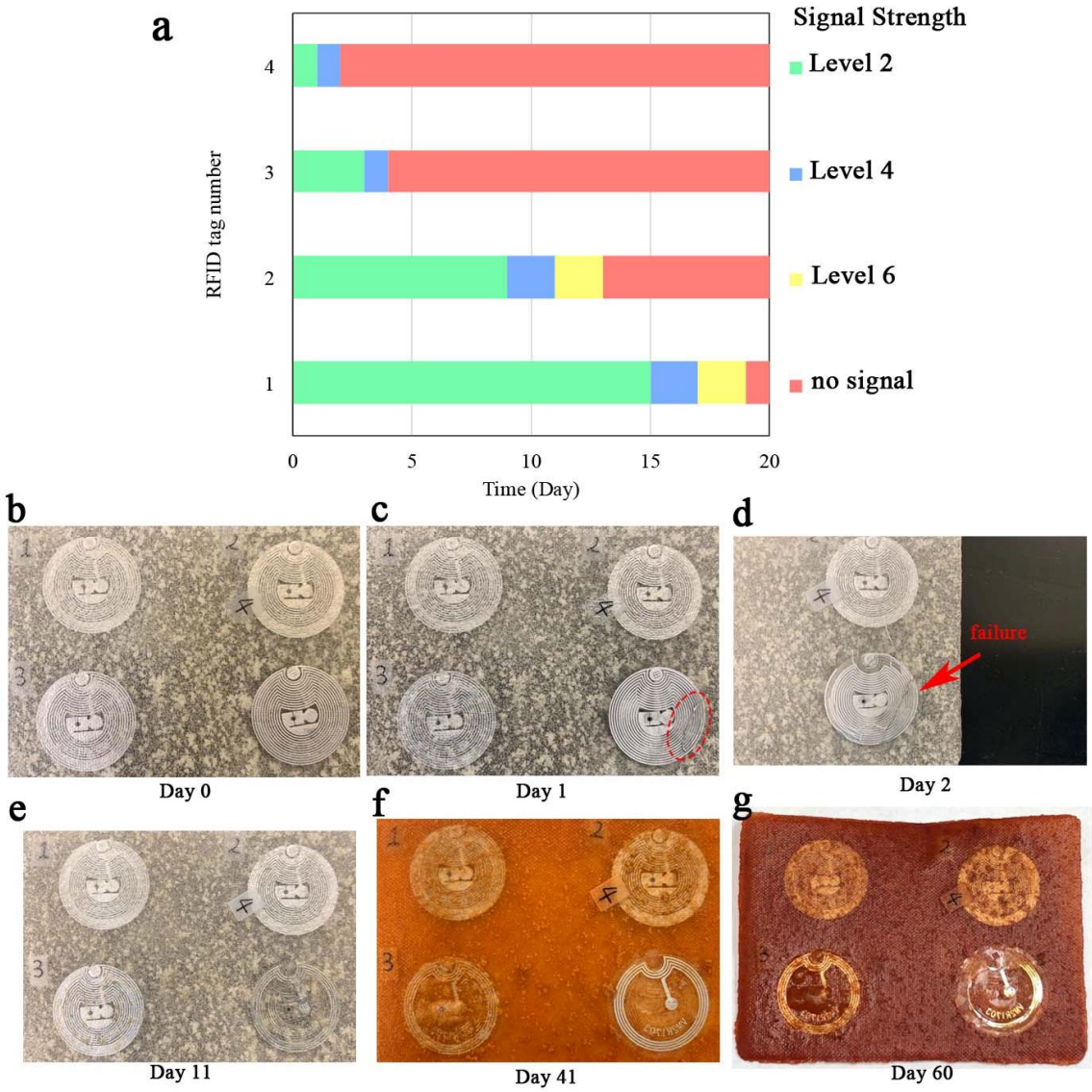



Figure 4. (a) The signal strength of the RFID tags changes over time. Photo images of the composite penal over time: (b) Day 0: the origin panel; (c) Day1: Initial failure of the tag #4; (d)

Day2: Failure of the tag #4; (e) Day 11: Total corrosion of the tag #3 and #4; (f) Day 41: Corrosion of the tag #2, #3 and #4; (g) Day 60: Corrosion of the Tag #1, #2, #3 and #4.

3.2 The modified RFID tag

Figure 5 shows the signal profile change upon a drop of formic acid was added onto the modified RFID tag. The formic acid was dropped at the red arrows, and the signal was increased by multiple levels. As a preliminary experiment, it demonstrates that the sensor was functioning well upon the adding of chemicals. Theoretically, the chemicals change only the electrical characteristics, such as impedance and inductance. In this case, it is possible to detect different chemicals by analyzing the responding signal profiles. However, due to the accuracy issue of this instrument setup, the selective sensing property could not be studied. Timothy et al. have explored using a modified RFID tag as a gas type chemical sensor with high selectivity and sensitivity [23-25]. In this case, our proposed sensing device could achieve similar functions such as detecting the chemical penetration species in composite structure for targeted infrastructure protection.

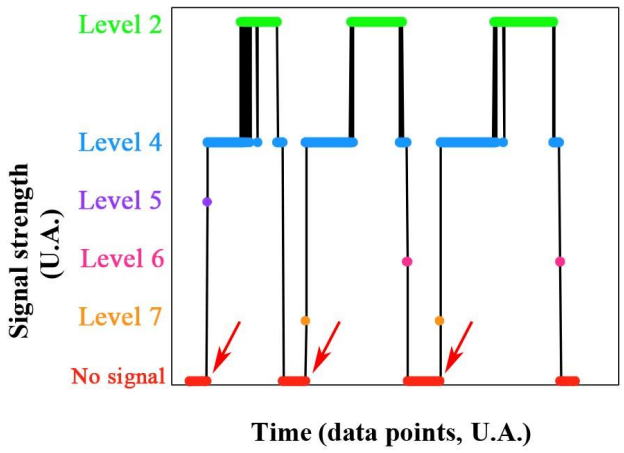


Figure 5. The signal strength of CNT modified RFID tag upon attacking of formic acid. The formic acid was dropped on the sensor at the red arrow.

## 4. Sensing Mechanism

The sensing of chemical penetration is fundamentally based on the characterization of the effect of ionsô diffusion in composite material, include matrix and matrix-reinforcement interface. Previously, we have explored the diffusion of acid aqueous in epoxy based carbon nanocomposite [13,16]. We find that the diffusion of some ions is much faster than the others. This phenomenon leads to a step-wise conductivity change of the composite. Such a behavior could be used for the early detection of chemical penetration. Kun et al. also studied the diffusion difference between segregated matrix and well-dispersed structure [32]. The segregated conductive matrix shows a better sensing property. These fundamental studies show the diffusion of ions in composite material could alternate its electrical properties progressively, such as impedance and conductivity. These concepts enable us to combine nanocomposite systems with electronics into a sensing device.

Passive RFID tag is a typical source/powerless device used widely in various industries. The basics of this kind of RFID tag rely on well designed and tested antenna, chip and substrate. A small mismatch of the impedance of each component induces a detectable signal frequency or intensity change. These changes could be expressed either by a simple RFID reader with signal strength decay or a sophisticated network analyzer with oscillograph change. The signal strength is defined by the reader signal strength, antenna parameters, chip impedance, and the impedance of the medium. There are two stages for the sensing functional mechanism: chemical penetration stage (early stage) and chemical erosion stage (late stage). In the first stage, the chemical

penetration stage, the diffusion of chemical ions changes the dielectric and electromagnetic properties of the composite material. Basically, the impedance of composite material. However, the sensing signal is not only depending on the impedance of composite material, the matching of medium (composite matrix), antenna, chip are the key factors for understanding the signal. The second stage is a simple failure sensor design. The RFID tag deactivates while erosion processes. Such a mechanism has been approved by depth wise penetration test and repeatable chemical test introduced previously.

## 5. Conclusion

In this work, we have embedded RFID tags in a composite panel at different layers. The environmental test shows the RFID tags functions well as a sensor for detecting the penetration of the sulfuric acid. It also showed that the decay of RFID tag signal strength occurs much early than the composite color change. In this case, the RFID tag could be used as an early warning sensor for the SHM of composite storage in contact with aggressive chemicals. At the same time, the modified RFID tag is a promising sensor with high sensitivity and selectivity.

[1] Liao Y, Liu C, Coppola B, Barra G, Di Maio L, Incarnato L, et al. Effect of Porosity and Crystallinity on 3D Printed PLA Properties. Polymers. 2019;11(9):1487.

[2] Song G, Wang C, Wang B. Structural Health Monitoring (SHM) of Civil Structures. Applied Sciences. 2017;7(8):789.

[3] Tallman TN, Hassan H. A network-centric perspective on the microscale mechanisms of complex impedance in carbon nanofiber-modified epoxy. Composites Science and Technology. 2019;181:107669.

[4] Thomas AJ, Kim JJ, Tallman TN, Bakis CE. Damage detection in self-sensing composite tubes via electrical impedance tomography. Composites Part B: Engineering. 2019;177:107276.

[5] Zhu J, Wang Y, Qing X. A real-time electromechanical impedance-based active monitoring for composite patch bonded repair structure. Composite Structures. 2019;212:513-23.

[6] Wirtz SF, Beganovic N, Söffker D. Investigation of damage detectability in composites using frequency-based classification of acoustic emission measurements. Structural Health Monitoring. 2018;18(4):1207-18.

[7] Baran IJ, Nowak MB, Chłopek JP, Konsztowicz KJ. Acoustic Emission from Microcrack Initiation in Polymer Matrix Composites in Short Beam Shear Test. Journal of Nondestructive Evaluation. 2018;37(1):7.

[8] Gotou T, Noda M, Tomiyama T, Sembokuya H, Kubouchi M, Tsuda K. In situ health monitoring of corrosion resistant polymers exposed to alkaline solutions using pH indicators. Sensors and Actuators B: Chemical. 2006;119(1):27-32.

[9] Gotou T, Katagiri N, Sakai T, Kubouchi M, Tsuda K. Detection of environmental acid penetrated in FRP using optical fiber. In: Proceedings of 16TH International Conference on Composite Materials. Kyoto, Japan, Conference, Conference 2007. p. 8-13.

[10] Ciminello M, Boffa ND, Concilio A, Memmolo V, Monaco E, Ricci F. Stringer debonding edge detection employing fiber optics by combined distributed strain profile and wave scattering approaches for non-model based SHM. Composite Structures. 2019;216:58-66.

[11] Shrestha P, Kim J-H, Park Y, Kim C-G. Impact localization on composite wing using 1D array FBG sensor and RMS/correlation based reference database algorithm. Composite Structures. 2015;125:159-69.

[12] Spencer BF, Ruiz-Sandoval ME, Kurata N. Smart sensing technology: opportunities and challenges. Structural Control and Health Monitoring. 2004;11(4):349-68.

[13] Liu C, Sergeichev I, Akhatov I, Lafdi K. CNT and polyaniline based sensors for the detection of acid penetration in polymer composite. Composites Science and Technology. 2018;159:111-8.

[14] Liu C, Lafdi K. Self-Assembly and Surface Tension Induced Fractal Conductive Network in Ternary Polymer System. Acs Appl Polym Mater. 2019;1(3):493-9.

[15] Liu C, Lafdi K. Environmental Monitoring of Composite Durability Use Multiple Sensing Technologies. In: Proceedings of CAMX 2018 – The Composites and Advanced Materials Expo. Dallas, Conference, Conference 2018. p. TP18-0586.

[16] Liu C, Lafdi K. Chinesta F. Durability Sensor Using Low Concentration Cabron Nano Additives. Composite Science and Technology. 108200

[17] Zhang J, Tian G, Marindra A, Sunny A, Zhao A. A Review of Passive RFID Tag Antenna-Based Sensors and Systems for Structural Health Monitoring Applications. Sensors. 2017;17(2):265.

[18] Liu C, Lafdi K. Fabrication and characterization of carbon nanofibers from polyacrylonitrile/pitch blends. J Appl Polym Sci. 2017;134(42):45388.

[19] Al Habis N, Liu C, Dumuids JB, Lafdi K. Intelligent design of conducting network in polymers using numerical and experimental approaches. Rsc Adv. 2016;6(97):95010-20.

[20] Munalli D, Dimitrakis G, Chronopoulos D, Greedy S, Long A. Electromagnetic shielding effectiveness of carbon fibre reinforced composites. Composites Part B: Engineering. 2019;173:106906.

[21] Gong S, Zhu ZH, Arjmand M, Sundararaj U, Yeow JTW, Zheng W. Effect of carbon nanotubes on electromagnetic interference shielding of carbon fiber reinforced polymer composites. Polymer Composites. 2018;39(S2):E655-E63.

[22] Hillier AJR, Makarovaite V, Gourlay CW, Holder SJ, Batchelor JC. A Passive UHF RFID Dielectric Sensor for Aqueous Electrolytes. IEEE Sensors Journal. 2019;19(14):5389-95.

[23] Zhu R, Desroches M, Yoon B, Swager TM. Wireless Oxygen Sensors Enabled by Fe(II)-Polymer Wrapped Carbon Nanotubes. ACS Sensors. 2017;2(7):1044-50.

[24] Zhu R, Azzarelli JM, Swager TM. Wireless Hazard Badges to Detect Nerve-Agent Simulants. Angewandte Chemie International Edition. 2016;55(33):9662-6.

[25] Azzarelli JM, Mirica KA, Ravnsbæk JB, Swager TM. Wireless gas detection with a smartphone via rf communication. Proceedings of the National Academy of Sciences. 2014;111(51):18162-6.

[26] Merilampi S, Björninen T, Ukkonen L, Ruuskanen P, Sydänheimo L. Embedded wireless strain sensors based on printed RFID tag. Sensor Review. 2011;31(1):32-40.

[27] Kim S, Georgiadis A, Tentzeris M. Design of Inkjet-Printed RFID-Based Sensor on Paper: Single- and Dual-Tag Sensor Topologies. Sensors. 2018;18(6):1958.

[28] Singh R, Singh E, Nalwa HS. Inkjet printed nanomaterial based flexible radio frequency identification (RFID) tag sensors for the internet of nano things. RSC Adv. 2017;7(77):48597-630.

[29] Chen H, Ruckenstein E. Nanoparticle aggregation in the presence of a block copolymer. The Journal of Chemical Physics. 2009;131(24):244904.

[30] Chen H, Ruckenstein E. Structure and particle aggregation in block copolymer-binary nanoparticle composites. Polymer. 2010;51(24):5869-82.

[31] Chen H, Ruckenstein E. Micellar Structures in Nanoparticle-Multiblock Copolymer Complexes. Langmuir. 2014;30(13):3723-8.

[32] Dai K, Zhao S, Zhai W, Zheng G, Liu C, Chen J, Shen C. Tuning of liquid sensing performance of conductive carbon black (CB)/polypropylene (PP) composite utilizing a segregated structure. Composite Part A: Applied Science and Manufacturing. 2013; 55: 11-18.

[33] Liu C. RFID (RC522) simple signal strength detection via changing antenna gain. In: Liu C, editor. Mendeley Datasets. 1 ed2018.