Structural Crack Detection System using Internet of Things (IoT) for Structural Health Monitoring (SHM): A Review

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ABSTRACT

Monitoring the state of civil engineering infrastructure is critical for a country's economic development since structures with long service life and timely maintenance have lower reconstruction costs. Crack occurrence is the most important element that influences the performance and lifespan of civil infrastructures like bridges and pipelines. As a result, several fracture detection and characterization approaches have been explored and developed in the domains of Structural Health Monitoring (SHM) throughout the last few decades. The major goal of implementing the Internet of Things (IoT) paradigm is to enable the Internet-based connectivity extension of various typical SHM devices. As a result, connected devices can communicate and process data, opening new possibilities in the design of acquisition systems in various disciplines of research and engineering. The researchers have extended the application of the IoT paradigm to the SHM crack detection because of the advances, ensuring that the tests done in this framework can produce good results with promising future improvements. Thus, this paper reviews structural crack detection based IoT for SHM as reported by previous research in the literature. The strengths and limitations of current systems are discussed. This paper is aimed to serve as a reference for crack detection and characterisation researchers as well as others who are interested in SHM in general. In addition, several case studies on real structures, as well as laboratory experiments for monitoring structural crack health of civil engineering structures, are also presented.

Keywords: Structural crack; structural health monitoring; sensors; internet of things

INTRODUCTION

Structural health monitoring has become an essential aspect of civil engineering. This scenario is because all human-made structures are not perfect and have many flaws that will, at one time or another fails whether due to normal wear and tear, natural disasters, or not following proper regulations and testing during construction. The degree of failures might vary from one structure to another, but the most catastrophic failures are when it involves the loss of human life. For example, a disaster that happened recently is the Charles de Gaulle Airport Collapse in Paris in 2004. Six modules which consist of ready-built concrete and external metal structures of the roof structure of the boarding area in Terminal 2E at the airport collapsed, killing six persons while injuring three others (Torres 2004). Investigators found that the roof was not strong enough to hold the heavy metal modules although there are external reinforcements added to them. However, the external reinforcements did not pass the optimum location needed to support the roof and rendering them ineffective (Kaljas 2017).

The need for structural health monitoring comes from the initiatives of engineers around the globe to monitor the conditions of erected buildings and structures. Although during the design phase of the building construction, all the safety regulations and requirements are followed to the letter, real-world experience for the building is still considered the actual test of performance and integrity for said building. Nevertheless, in some cases, the worst-case scenarios controlling the design do not occur. Therefore, the true structural design is never fully verified (Collins et al. 2014). To remedy the problem, in-situ monitoring is needed to verify and assess the condition of the structure. Bischoff et al. proposed a monitoring application using a wireless sensor network that was performed on a 95-year-old riveted steel railway bridge, and its operation is in the event-based mode for energy efficiency (Bischoff et al. 2009). After processing the raw data acquired and eliminating the noises and unwanted readings, the result obtained by the system is sufficiently good for fatigue assessment. Another approach by Wang et al is by designing a wireless system for detecting vibrations from a distance (Wang 2014). The system is implemented in a multi-storey building to predict the initial stage of an earthquake. The results obtained are satisfactory because of the use of multiple sensors across each level of the building, providing a precise data acquisition.

Most individuals are curious about the causes behind concrete cracks. Cracks of concrete only can be minimized with the correct foundation at the first stage of the job site, and they cannot be avoided as almost of homes or buildings based on concrete happen to have cracks. The major issue of this project is cracks, which arise because of foundation difficulties and result in a range of crack forms. Vertical, horizontal, and diagonal cracks are the three types of cracks that may occur on a structure, with the horizontal crack being the most hazardous. This is due to it can reduce the cross-section of a structure as well as lower its structural capability (Yao et al. 2014). Concrete cracks are caused by a variety of factors, which can be described as concrete shrinking and expanding due to the heavy load applied, due to temperature differences, the improper cover provided during concreting and some cause due to corrosion of reinforcement steel (Rahman 2016)

Conversely, inspections are carried out in accordance with construction specifications, and it is a responsibility to determine when a project is ready for inspection. All type of foundation cracks is serious and should be inspected continuously and remotely (Lifetech 2021) However, humans are prone to forgetfulness and do not run away from committing errors or making mistakes. Some of the time, human does not act fast as they should to prevent major home or building damage due to unnoticeable type of cracks. Visual inspections that are usually done by structural engineers are difficult and risky, especially after an earthquake, because the building may collapse, or the structures may be inaccessible due to rubble. (Donelli & Viani 2017) Therefore, it is preferable if the inspection is carried out by a system instead of the human itself.

Contrariwise, the embedded system may have created a detailed wireframe and a mock-up for a more detailed exploration, but neither of these methods allows the design to be thoroughly tested in the real world. There is no standard testing protocol to test an SHM IoT based system. The testing can be beneficial in the process, but if the concepts bring to life, they can fail. Failure is an important element of success since it allows you to learn from your mistakes. Developers may detect the design's flaws and solve them quickly by testing them with a functional prototype that connects with IoT (Suroso 2022)(Salis 2021)(Singh 2020). If these flaws are discovered later, they become significantly more costly blunders, and any cost saved during the testing process will be wasted anyway (Nexus 2017) Eventually, in the end, everyone must agree that monitoring the width of foundation cracks is ultimately the best way to avoid costly foundation repairs as well as can extend the life of the structure.

Thus, we could conclude that SHM will be a major technological advancement in civil engineering structures to assist civil engineers to monitor significant structural information continuously and remotely. Hence this paper is aimed to serve as a reference for crack detection and characterisation researchers as well as others who are interested in SHM in general. In addition, several case studies on real structures, as well as laboratory experiments for monitoring cracks and structural health of civil engineering structures, are also presented.

The paper is divided into six sections. Section 2 presents the different structural health monitoring parameters. The review methodology will be discussed in Section 3. Section 4 will describe and review the IoT based structural health monitoring for crack detection in detail. Section 5 documents the detailed discussion on the advantages and disadvantages of the available IoT based structural health monitoring for crack detection in the literature. Finally, Section 8 concludes the article.

STRUCTURAL HEALTH MONITORING PARAMETERS

Structural health monitoring, or SHM, is known as the process of implementing a damage identification strategy for aerospace, civil, and mechanical engineering infrastructure (Farrar and Worden 2007). The process involves the observation of the structure material and its behaviours throughout the monitoring period. From there, an assessment is made to determine the current structure performance and predict its future behaviour. Furthermore, Manson, Worden, and Allman believe that the information system for structural health monitoring includes a sensor, data acquisition devices, computers, software, and a database (Manson 2003). Moreover, the structural health monitoring process has been defined as a four-step statistical pattern recognition paradigm for a general guideline, that includes operational evaluation, data acquisition, normalization and cleansing, feature selection and information condensation, and statistical model development for feature discrimination (Farrar et al. 2001). However, it should be noted that the process of structural health monitoring data acquisition is application-specific, and maybe the stated paradigm needed some adjustment in its process. In structural health monitoring, the assessment of the infrastructure is usually done by damage identification. According to the Oxford Dictionary, the damage is defined as physical harm that impairs the value, usefulness, or normal function of something. Therefore, damage in this context means any physical changes, either inside or outside the structure, that deteriorates its durability in the long run, while also may harm the occupants inside the structure. Every material used in a building structure has predetermined boundary conditions. For example, for reinforced concrete, crack formation on its surface is an indication that its structural integrity is deteriorating, usually due to excessive load on certain points on the concrete. Therefore, by definition, it can be said that the concrete structure is damaged. The structural health monitoring objective is to find this damage automatically and predicts it before it is happening. In this way, countermeasures can be taken swiftly to avoid more structural deformities from happening that can render the building inhabitable by humans.

Structural Health Monitoring can be divided into three main parameters: Corrosion, Strength, and Cracking. However, recently these parameters have extended into more detailed boundaries. This paper will focus on the 3 main parameters.

CORROSION

Corrosion in the context of structural concrete is when the steel rebars in the reinforced concrete are exposed to elements that are harmful to them such as carbon dioxide (CO2), chloride from salt, which are commonly used to de-icing a structure typically during the winter season, and the surrounding humidity. The exposure from said elements will result in a formation of rust around the steel rebar, which in turn will increase the volume of the steel by two or four times its original volume while owning none of the beneficial mechanical properties. Steel rebar is fundamental in structural concrete as it provides the tensile properties that are needed to prevent the failure of concrete structures, which are subjected to tensile and flexural stresses due to traffic, winds, dead loads, and thermal cycling (Vavpetic 2008).

STRENGTH

Another parameter in structural health monitoring is strength. The strength of concrete is very important as it is mainly judged for its quality. Although other properties to improve concrete durability are not necessarily dependent on strength, concrete strength remains one of the considered aspects. Certain building designers have specified that the concrete strengths of 5000 to 6000 psi, or even higher are needed for certain structural elements. However, strengths in the range from 15,000 to 20,000 psi have also been produced for lower-floor columns in high-rise buildings (Neville 2015). Concrete that fails to develop the strength as expected is probably deficient in other respects as well. Two kinds of strength are considered for structural concrete, which is compressive and flexural. Compressive strength is usually the maximum stress or load that concrete can withstand before it is starting to crack or breaks in half. Flexural strength is a bit similar, in that it is the maximum degree of bending of concrete when there are loads exerted onto them before they are starting to break. Bending occurred when the bottom part of the concrete experienced tensions while the upper part experienced compressions.

CRACKING

Cracking, as defined by Committee 201 of the American Concrete Institute is a complete or incomplete separation, of either concrete or masonry, into two or more parts produced by breaking or fracturing (ACI Committee 1997). In structural concrete, one of the common causes of cracking is the expansion due to the internal stress of the concrete from the results of the corrosion of the steel rebar. When there are visible cracks on the concrete, it is usually the result of months or years of interior micro-crack formation. If left unattended, the cracks will grow larger and larger every day which will result in a catastrophic failure of the integrity of a structure, which in turn will increase the probability of the structure collapsing.

METHODOLOGY

The literature search was carried out via academic search engines as follows; SpringerLink, ScienceDirect, Emerald Insight, and Google Scholar. The literature search was conducted with terms relevant to the subject area keywords; "Structural Crack", "Structural Health Monitoring (SHM)", and "Internet of Things (IoT). In achieving a more accurate search specific to the structural crack detection system, a manual filtration is conducted to comb through the search results achieved from the academic search engines. The result was analysed based on the crack sensing method. From the review the crack sensing method can be divided into 8 methods; Distributed Optical Fiber Sensor (DOFS), MEMS Sensors, Wire-based Triboelectric Resonator (WTER), Digital Sampling Moire (DSM), RF Power Detector, Crack Tip Opening Displacement (CTOD), Fiber Optic Sensors, Plastic Optical Fiber Sensors, and Fiber Bragg Grating (FBG).

STRUCTURAL HEALTH MONITORING: IOT BASED CRACK DETECTION

Structural Health Monitoring (SHM) aims to provide sensing and diagnostic capability of the state of the component materials of the various parts, as well as the whole assembly of these elements that make up the structure, at any time during its life. Although normal ageing due to usage, environmental action, and unintentional events can all affect the structure's state, it must remain within the domain defined in the design (Balageas 2010). SHMs are most used in civil engineering to monitor the state of concrete. They are, however, manually employing equipment to monitor the condition of a structure. They must use a tape measure to determine the length of a crack. However, the crack continues to expand, and there is no way that an engineer or those in charge of the operation will keep track of the information distance of a concrete crack. People nowadays choose simple methods of monitoring, thus there has been an improvement in the measurement of crack distance in civil engineering, which will include electrical engineering workers. To keep up with technological advancements, automatic structural health monitoring is being researched and developed to make their jobs easier.

A new sort of monitoring can be done in structural health monitoring. For example, crack detection, corrosion detection, score, and seismic damage detection (Hui &

Jinping 2011). A crack can be discovered both on and in concrete. There have also been a few studies that show that cracks can occur in aluminium, aircraft, and bridges for a variety of reasons. Aside from that, the cracks themselves are divided into three types: vertical cracks, diagonal cracks, and horizontal cracks (Lifetech 2021). All these patterns are useful for the life of a structure in structural health monitoring if cracks are detected. The next point is to search for corrosion. This sort of structural health monitoring is most associated with the oil and natural gas industries. Due to specific obstacles, such as stability and durability in extreme and hard conditions such as high pressure inside subsurface wellbores and high temperature (Wright et al. 2019) only a few papers were discovered to do this project.

CRACK SENSING METHOD: DISTRIBUTED OPTICAL FIBER SENSOR (DOFS)

Every project that has been developed to assess structural health has used a different type of sensor. This can be seen in the fact that the papers that were examined used a distributed optical fiber sensor (DOFS), MEMS sensor, WTER sensor, ADNS-3080 sensor, RF power detector sensor, fiber optic sensor, Plastic Optical Fiber sensor, FBG sensor, the sensor that detect COD or CTOD, and RFID sensor. The article Embedded Distributed Optical Fiber Sensors in Reinforced Concrete Structures (Barrias et al. 2018) uses DOFS sensors as in Figure 1 to achieve the protection need, the robustness of the sensor formation, and measurement accuracy both in the uncracked and cracked stages, as well as during loading, unloading, and reloading process. Using the DOFS method and the technique Rayleigh Optical Frequency Domain Reflectometry (OFDR) approach, the optical fiber is bonded crossing the cracks and to the rebar delivered good results even in the case of unloading and loading of the specimen.

CRACK SENSING METHOD: MEMS SENSORS

Apart from DOFS, Asfana et al. utilized MEMS sensors to do a Wireless Sensor Network based Crack Detection on Concrete Bridges or Buildings (Asfana et al. 2018) They discuss highway bridges that connect roadways in both urban areas and rural, and how to monitor the structural health of highway bridges using an autonomous wireless sensor network system to check for deterioration due to external and internal variables. As the operator, they can view the bridge's data in real-time via a smartphone. The bridge crack detection is identified based on angle altering and the crack is detected with the position in the vibration of the bridge utilising MEMS sensor, vibration sensor, and GSM as an input to the microcontroller. When the bridge is cracked, the values are delivered through a GSM modem and monitored via web pages on the internet. The bridge crack identification and angle position are traced using a Raspberry Pi microcontroller as in Figure 2.

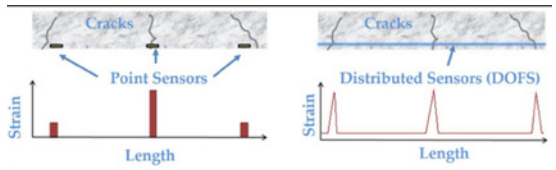

FIGURE 1. Distributed Optical Fiber Sensors (DOFS) (Barrias et al. 2018)

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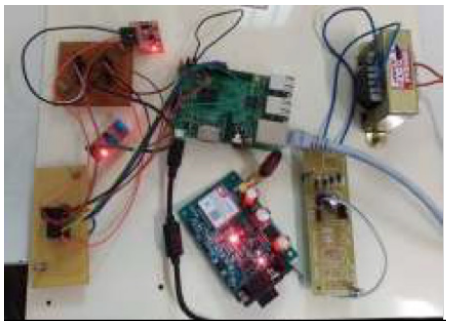

FIGURE 2. Interfacing GSM and Raspberry Pi (Asfana et al. 2018)

CRACK SENSING METHOD: WIRE-BASED TRIBOELECTRIC RESONATOR (WTER)

Next, Yeonseok Jung, Hee Jae Hwang, Jiseop Yu, Divij Bhatia, and Kwun Bum Chung used a wire-based triboelectric resonator (WTER) for the self-powered crack monitoring system (Jung et al. 2020) The WTER sensor detects a crack by vibrating on a dielectric film of metal wire, which produces a resonant frequency. By combining a WTER with an Arduino board, a self-powered crack monitoring device was created as in Figure 3. This setup successfully observed 100 Um elongation with resonant frequency change of around 30Hz, with monitored frequency values errors of less than 1%.

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CRACK SENSING METHOD: DIGITAL SAMPLING MOIRE (DSM)

Chen et al. present an Optical Crack Growth Sensor Using the Digital Sampling Moire (DSM) Method. This study (Chen et al. 2018) used an ADNS-3080 sensor to monitor two-dimensional (2D) crack propagation as in Figure 4. To achieve accurate 2D displacement and improved sensitivity at a lower computing cost, the DSM requires no prior calibration. It is also more resistant to changes in imaging distance, which is determined by the difference in height between the two sides of cracks' concrete.

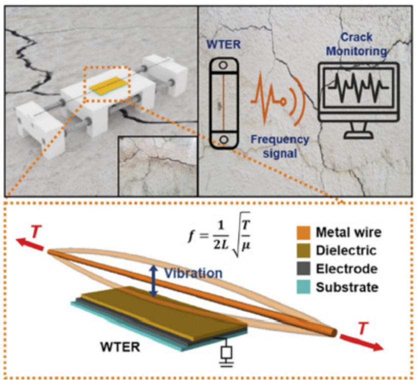

FIGURE 3. Concept of WTER used to crack monitoring (Jung et al. 2020)

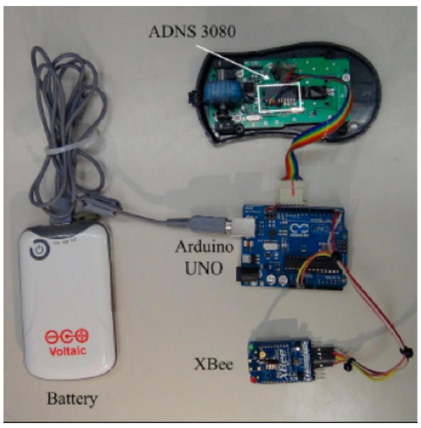

FIGURE 4. Digital Sampling Moire (DSM) (Chen et al. 2018)

CRACK SENSING METHOD: RF POWER DETECTOR

RF Power Detector, which used a four-channel complementary split-ring resonator (CSRR) loaded array has three CSRRs per channel (Salim et al. 2020). A voltage-controlled oscillator (VCO) that three frequencies were generated successively for each channel using a single-pole four-throw (SP4T) switch. A microcontroller interprets the transmitted RF signal as in Figure 5, which is transformed to a DC voltage level. Aluminium sheets that have cracks embedded in the surface are used to demonstrate the detection of cracks of various shapes, locations, and sizes.

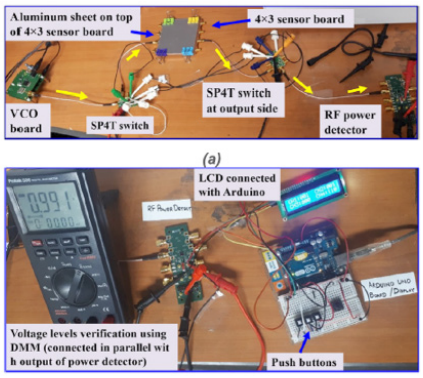

FIGURE 5. Complete system design to detect multiple cracks, positions, and sizes (Salim et al. 2020)

CRACK SENSING METHOD: CRACK TIP OPENING DISPLACEMENT (CTOD)

A guide for recommended practices to perform crack tip opening displacement (CTOD) tests in high strength low alloy steels were presented (Ávila et al. 2016). The purpose of this work as in Figure 6 is guidance for fracture toughness in metallic materials that feature cracks. It not only improves the structure's architecture but also its service life. This research focuses on several practical concerns surrounding the use of the CTOD parameter to assess crack toughness in high strength low alloy steels (HSLA), specifically pipeline steels for oil and gas transportation.

CRACK SENSING METHOD: FIBER OPTIC SENSORS

As previously stated, the SHM makes extensive use of fiber optic sensors in their work, including optical fiber sensors, plastic optic fiber, and FBG. Therefore, the papers on optical fiber sensors are explained in this section.

There are several papers reported about optical fiber sensors that have been reviewed. Lin Cheng et al state presents the sensing principle that has a linear macro-bending loss for optical fiber' new type of crack sensor and its experimental research (Cheng et al. 2018) This research discussed the relationship between COD and the fiber's macro-bending loss, which poses a number of challenges. To tackle this difficulty, this study establishes a linear relationship between the COD and the fiber's macro-bending loss by regulating the fiber winding shaft to keep the bending radius constant. A crack sensing principle for optical fiber is developed based on this linear connection. A validation experiment was carried out as in Figure 7 using three groups of fiber winding shafts with varying diameters and three groups of working light sources with different wavelengths to evaluate the feasibility of this crack-sensing principle. The macro-bending loss is linearly related to the COD, according to the experimental results. A unique type of optical fiber crack sensor is built based on the suggested crack sensing technique to monitor the COD of pre-existing fractures and contraction joints of structures.

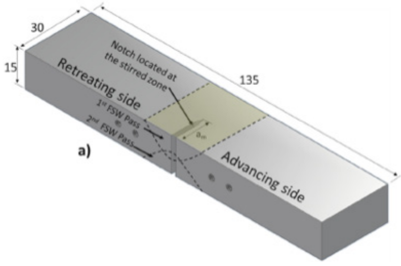

FIGURE 6. CTOD Test (Ávila et al. 2016)

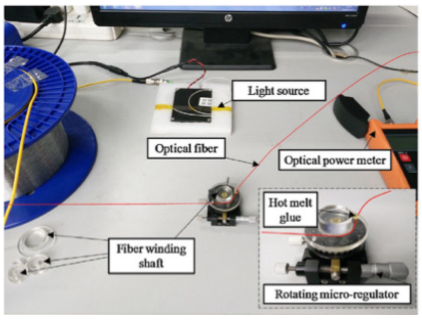

FIGURE 7. Experimental device diagram of the sensor size parameter (Cheng et al. 2018)

Fiber optic sensors for the SHM of building structures (Bremera et al. 2016) discussed detection of the moisture ingress into the concrete use two types of fiber which are fiber optic humidity sensors and a fiber optic crack sensor as in Figure 8. Furthermore, the properties of mechanical's optical glass fiber sensors degrade, and thus their long-term reliability and stability, due to the chemical and mechanical impact of the concrete environment, as well as the benefit of using a fiber optic sensor system for SHM of sewerage tunnels are discussed. As a result, the fiber optic sensor can detect a crack with a dimension of 1.4mm in this paper.

Karolina Bednarska, and et al review Hybrid Fiber Optic Sensor Systems in Structural Health Monitoring in Aircraft Structures (Bednarska et al. 2020). In this paper, the modern aircraft structure is said to use a material with high strength as it reduces the weight of structural elements. In addition, aircraft structure is exposed to numerous damages and failures. Complex construction causes difficulty to monitor during impacts. Therefore, it is made to perform strain measurement on large scale for ultrafast strain measurement or potential operational load monitoring on a small scale for potential damage detection as in Figure 9. The method used in this paper is using a hybrid fiber optic system embedded in composite materials and it is necessary to monitor the structural health of the most vulnerable structures as it has the possibility of barely visible damage occurring on their outer surfaces. The monitoring techniques using optical fibers are used to monitor the structure from the inside. Thus, hybrid optical fiber sensors embedded in composite materials show the ability to discriminate between temperature, strain, stress, vibration and mechanical defects.

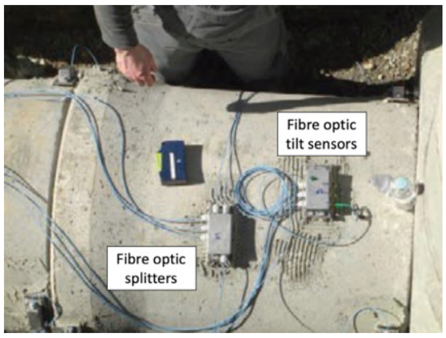

FIGURE 8. Fiber optic splitters and fiber optic tilt sensors on the top of the sewerage pipe (Bremera et al. 2016)

CRACK SENSING METHOD: PLASTIC OPTICAL FIBER SENSORS

Aside from fiber optical sensors, plastic optical fiber sensors are also used on SHM. A Plastic Optical Fiber Sensing System for Bridge Deflection Measurement (Zhang et al. 2020). In this study, a sensing system based on variations in optical fiber intensity is suggested to assess bridge deflection in various positions using connected pipes as in Figure 10. The suggested system is made up of three components: connected pipes that connect the measurement spots along with the structure, the liquid that fills the connected pipes, and a sensing unit that detects level changes. The designed system's sensing element is a plastic optical fiber sensor based on intensity change. The results reveal that this system has a precise linear response and a high level of reliability in a variety of environments. The sensor's measurement of the test beam deflection coincides with the linear variable differential transformer (LVDT) within a 2.1 percent error margin. The proposed technology has a lot of potential for long-span bridge health monitoring in the future.

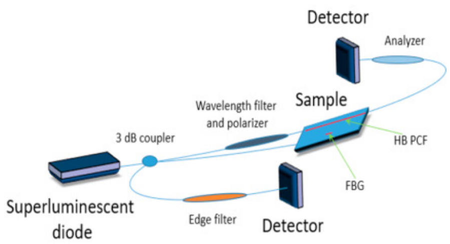

FIGURE 9. Hybrid fiber optic sensor system in aircraft structure (Bednarska et al. 2020)

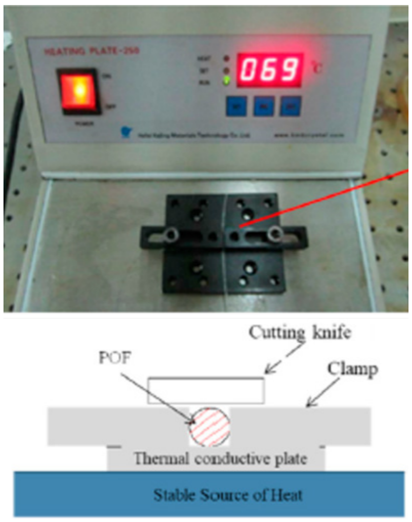

FIGURE 10. Equipment used for POF sensing (Zhang et al. 2020)

Fatigue crack monitoring in train track steel structures using plastic optical fiber sensor (Yang et al. 2017) that practicality of utilizing POF sensors in conjunction with a signal-processing method to identify and monitor fatigue-induced cracks in rail track steel structures in real-time. The POF sensor system is made up of low-cost components (LED light sources, photodetectors, and data collecting units) that are simple to mount on the host structure. The results reveal that all three types of sensors demonstrate remarkable similarities in terms of fracture initiation and propagation identification, demonstrating the potential of the proposed sensor for crack initiation detection and subsequent fracture propagation monitoring. Track steel structures using a POF sensor is depicted in Figure 11.

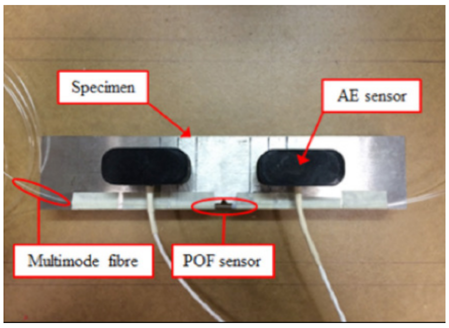

FIGURE 11. Track steel structures using POF sensor (Yang et al. 2017)

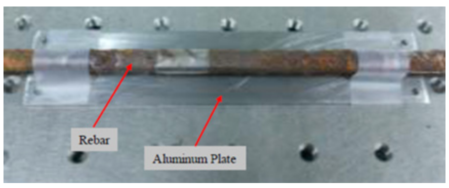

FIGURE 12. Corrosion on rebar (Tan et al. 2016)

CRACK SENSING METHOD: FIBER BRAGG GRATING (FBG)

Fiber Bragg Grating (FBG) is used more on SHM. Three papers have been revised as well. One of them is Fiber Bragg Grating (FBG) Based Sensing System: Early Corrosion Detection for Structural Health Monitoring (SHM) (Tan et al. 2016). Most construction structures are supported by rebar, which leads to damage or collapses due to corrosion and during the concrete casting on the rebar surface, the formation of a passive film from the alkaline cement is pasted to protect the layer against corrosion. However, corrosion will still take place at the rebar surface due to the penetration of Chloride (Cl-) ions. Rebar corrosion within concrete structures as in Figure 12 is one of the primary reasons which make an entire construction weakened. Therefore, this paper studied using the method of FBG sensor with and without coating to fulfil the objective of this paper which is to detect early corrosion on rebar. The protection of the FBG sensor is believed very important for the long-term monitoring of a composite structure in SHM.

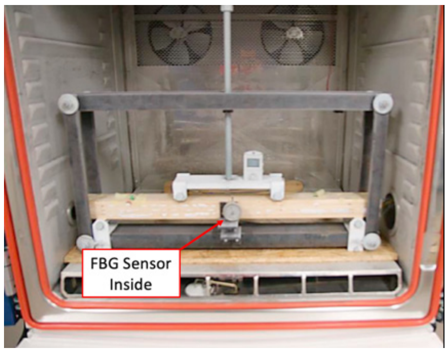

FIGURE 13. Environmental Testing of a FBG Sensor System (Čápová et al. 2019)

Environmental Testing of an FBG Sensor System for Structural Health Monitoring of Building and Transport Structures (Čápová et al. 2019) is about standard strain gauges that are commonly used to monitor the mechanical stresses of wooden or concrete structures placed on a beam surface in Figure 13. However, mechanical damage, electromagnetic interference, or unfavourable influences on the recorded data during the measurement, such as temperature changes or probable data loss due to an explosive environment, make these sensors vulnerable. The paper by Kristýna Čápováa et al. has a fiber optic sensor system that provides a more suitable and reliable solution since the sensor may be integrated into the load-bearing structure during its construction and therefore protected from ambient environmental conditions by the construction material.

Matveenko et al. published a work titled Measurement of stresses using optical fiber Bragg grating sensors integrated into polymer composite material (Matveenko et al. 2018). The experimental results of strain measurements made using fiber Bragg grating sensors embedded in polymer composite materials are presented in this work (PCMs). The capabilities of fiber optic sensors to measure strains in the situation of prominent gradient distribution inside the material, under compression and tension, during cyclic variation of strains with time, and at different temperatures is demonstrated through a series of tests. The findings of strain measurements taken during the preparation of PCM, as well as residual process-induced strain measurements, are discussed. The findings of strain measurements using fiber optic strain sensors (FOSS) are compared to numerical modelling results using the finite element approach and independent measurement data collected using a digital optical system Vic3D and other experimental instruments. This study derives an interrelation model between Bragg wavelength peak shift and optical fiber strain in the fiber Bragg grating region for a sensor that is not impacted by the environment. The Various specimens used based on the FBG sensor are depicted in Figure 14.

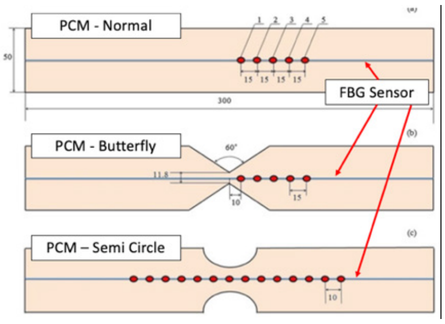

FIGURE 14. Various specimens were used based on the FBG sensor (Matveenko et al. 2018)

CRACK SENSING METHOD: RFID SENSORS

There are three types of RFID sensors. Low-frequency passive RFID, ultra-high RFID, and the RFID sensor itself are all used. This is a paper regarding passive low-frequency RFID. In the paper Feature Extraction for Robust Crack Monitoring Using Passive Wireless RFID Antenna Sensors (Zhang et al. 2018) the problem statement that robustness to measurement variation, including environmental variables, is a practical concern for permanently fixed monitoring to achieve. The objective of this project is to enhance the robustness of the low-cost RFID sensing system as the purposed method is validated by a case study in open crack detection and characterization under varied measurement conditions as in Figure 15. As result, the crack growth decreases the resonant frequency of the tag coil and the coupling between the reader and tag coils is improved which means the crack develops, the tag coil's self-inductance and mutual inductance between the reader and tag coils both rises.

Omer et al discussed passive Ultra-high frequency (UHF) RFID tags as a tag sensor to detect crack depths (Omer et al. 2018) The problem identified in this paper is due to a small crack on the metal material surface that affects the performance of the mechanical structure. Therefore, the solution for this problem using a method of a new technique for crack depth sensing by using a passive UHF RFID tag as a sensor which is interrogated by the Thingmagic M6e platform in Figure 16 as the objective of this paper is to detect the crack range accuracy at stainless steel and ferromagnetic materials. As the result, the stainless steel has high accuracy which detects crack depth range between 0.5 to 1.3mm meanwhile ferromagnetic detected crack depth range between 8 to 8.55mm.

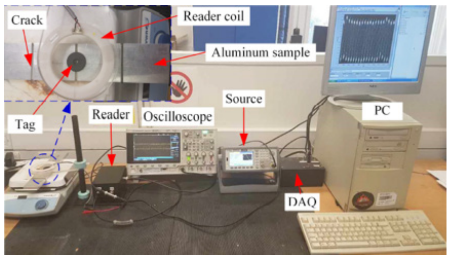

FIGURE 15. Setup for characterization and crack detection based on LF RFID sensing system (Zhang et al. 2018)

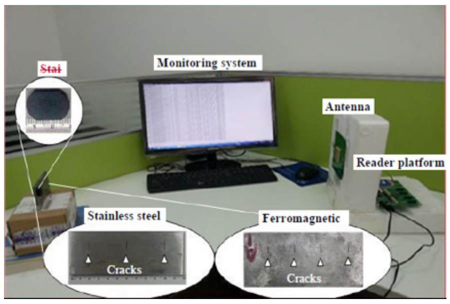

FIGURE 16. The sample under test and reader measurement platform (Omer et al. 2018)

Jun Zhang et al addressed wireless passive ultra-high frequency RFID antenna sensors for surface crack monitoring and quantitative analysis (Zhang et al. 2018) about the problem crack detection sensitivity and reliability are highly dependent on crack position in relation to antenna mode and the size of metal to be installed. The goal of this

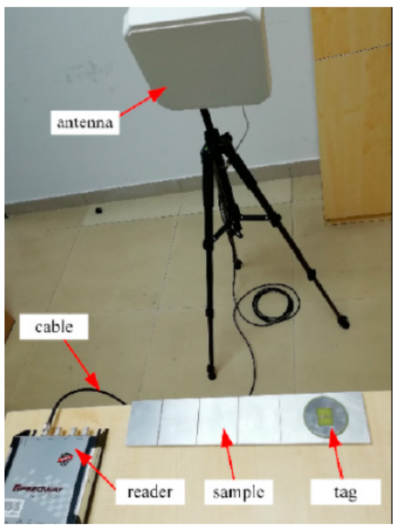

FIGURE 17. The UHF RFID sensing system test setup (Zhang et al. 2018)

paper is to investigate the reliability of fracture detection and characterization using an antenna's mode analysis by using the method in Figure 17 using an antenna sensor that can monitor the evaluation of already existing cracks or junctions prone to cracks. The result of this research is that crack growth reduces the quality factor with time, increasing the antenna's realized gain, where the profile is a significant factor in determining the trade-off between sensing and communication.

Wireless Passive RFID Crack Width Sensor for Structural Health Monitoring (Caizzone & DiGiampaolo 2015) focuses on reducing maintenance costs by avoiding needless inspections. For this goal, a variety of technologies and systems can be utilized; among them, those proposing the use of wireless passive crack meters have a high impact potential in terms of ease of installation and measurement in Figure 18, as well as low cost. As a result, the current study presents a crack width wireless radio frequency identification (RFID) sensor, which has been designed for use on a variety of materials (including concrete and metal) and can detect sub-millimeter deformations on the item on which it is installed. This paper uses a design strategy based on high sensitivity phase detection.

Improved Metal Surface Defect Detection Sensor Research based on a 3D RFID Tag Antenna (Li et al. 2020) discussed the foregoing issues are solved using a mix of wireless sensor technology and intelligent detection technologies. As a result, the tag antenna smart sensor is investigated in this study, which is used to characterize the extension of metal flaws in SHM. The antenna is then shown as a wireless passive three-dimensional sensing antenna in Figure 19, with simulations proving its viability. The antenna can characterize the two extension directions of depth and width of the metal surface structure smooth imperfection, according to the simulation findings. Simultaneously, the antenna may determine the position of smooth flaws on the surface of metal structures in relation to the antenna and then implement the smooth defect positioning.

FIGURE 18. RFID reader wirelessly interrogates a couplet of RFID tags that were placed on the cracked wall (Caizzone & DiGiampaolo 2015)

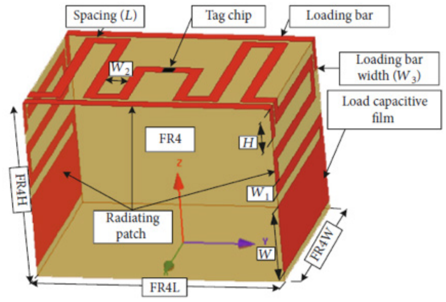

FIGURE 19. Simulation of surface defects on the metal surface (Li et al. 2020)

S.G.N. Murthy's paper Batteryless Wireless RFID based Embedded Sensors for Long-Term Monitoring of Reinforced Concrete Structures. This paper (Murthy 2015) presented Embedded RFID based sensors that can measure and store temperature, humidity, and corrosion rate in reinforced concrete structures with minimal power supply. These tiny, embedded sensors run on a few microwatts of electricity extracted from an interrogating RF signal and use an inductive link to receive power and data converted from their attached sensors, making them wireless in Figure 20. As a result, they can stay inside the structure for the duration of their life cycle, requiring no maintenance and posing no risk of damage. The RFID-based embedded sensors, hand-held reader, and data gathering software are all discussed in depth in this study.

A new wireless sensor network module for health monitoring of civil structures (Carosso et al. 2017) The prototypal implementation of an innovative low-cost module for SHM that would allow the measurement of internal displacements inside civil structures was discussed in this work. These sensors could be part of a larger Wireless Sensor Network (WSN) and placed as in Figure 21. The Hall Effect is the sensor's basic functioning mechanism. This effect occurs when a magnetic field is applied to a conductor, causing electrons to migrate toward one of the conductor's extremes, resulting in an electric signal. The Hall Effect sensor detects voltage variations caused by differences in

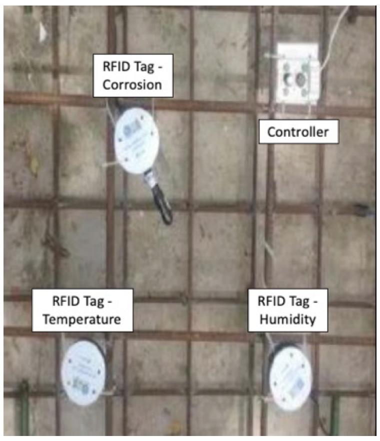

FIGURE 20. RFID Reader and sensors on steel (Murthy 2015)

the distance between two equal sensors put in a deforming structure. The sensor is described, along with an explanation of the sensor's possible installation style. The findings of the tests are presented, along with a discussion of how sensors might be used in the real world.

Finally, the literature review is a significant element of this project because it reveals a lot of commonly used sensors as well as many applications for each sensor, such as RFID sensors, distributed optical fiber sensors (DOFS), MEMS sensors, WTER sensors, ADNS-3080 sensor, RF power detector sensor, fiber optic sensor, Plastic Optical Fiber sensor, FBG sensor and sensor that detect COD or CTOD. A literature search was conducted to determine all the related previous research related to SHM crack detection using IoT. The search queries are to crack sensors specifically optical, FBG and RFID sensors and the search is conducted in the IEEE Explore, Web of Science, Science Direct, and Scopus databases. A detailed search is further defined as monitoring using the Internet of Things (IoT). The targeted articles are from 2015 to 2020 namely the last five years duration.

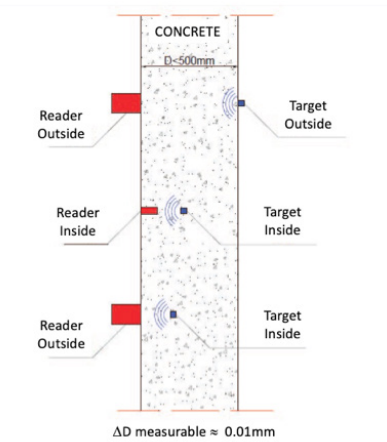

FIGURE 21. Three possible configurations (Carosso et al. 2017)

DISCUSSION

This paper has reviewed major SHM crack detection systems using IoT reported in the current literature. Firstly, it discussed the different SHM parameters usually civil structure monitor. Then, a thorough literature review was conducted to review different methods of detecting a crack in civil structures. The review focused on the strength and weaknesses of each method. Table 1 summarises the different structural crack detection system using IoT methods. It can be summarised that FBG, and RFID sensors have better compromises when the advantages outweigh the disadvantages. What the authors could suggest based on accuracy, convenience, and cost-effectiveness.

FBG sensors exhibit linear response in the measurement of strain, pressure and temperature and thus can offer more accurate crack reading compared to RFID. When FBG sensors are used with high power tuneable laser, they can perform measurements over long distances with little or no loss in signal integrity this provides reading effectiveness however with additional hardware the cost would also increase. RFID sensors are very convenient since it is available off the shelf, with mass production the cost for each module is very affordable and easily interfaces with any embedded system thus making it a more attractive option for fast prototyping. It could be concluded that for accuracy purposes and efficient sensor reading researcher is recommended to use FBG sensors, otherwise, for low-cost and fast prototyping solution it is recommended to utilise RFID sensor.

TABLE 1. Summary of Structural Crack Detection System using Internet of Things Methods Currently Reported in the Literature

Articles	Crack Sensing Method	Content	Details
Wireless Sensor Network based Crack Detection on Concrete Bridges or Buildings (Asfana 2018)	MEMS Sensors	Problem statements	As the operator, they can view the bridge's data in real-time via a smartphone
		Objectives	To monitor the structural health of highway bridges using an autonomous wireless sensor network system to check for deterioration due to external and internal variables
		Method	The bridge crack detection is identified based on angle altering and the crack is detected with the position in the vibration of the bridge utilising MEMS sensor, vibration sensor, and GSM as an input to the microcontroller
		Conclusion	Values are delivered through a GSM modem and also monitored via web pages via the internet. The bridge crack identification and angle position are traced using a Raspberry Pi microcontroller
Wire-Based Triboelectric Resonator (WTER) To Self-Powered For Crack Monitoring System (Jung 2020)	Wire-Based Triboelectric Resonator (WTER)	Problem statements	To self-powered for crack monitoring system and detect the resonant frequency
		Objectives	The WTER sensor detects a crack by vibrating on a dielectric film of metal wire, which produces a resonant frequency
		Method	Combining a WTER with an Arduino board, a self-powered crack monitoring device
		Conclusion	Observed 100 Um elongation with resonant frequency change of around 30Hz, with monitored frequency values errors of less than 1%
Optical Crack Growth Sensor Using the Digital Sampling Moire (DSM) Method (Chen 2018)	Digital Sampling Moire (DSM)	Problem statements	Accurate 2D displacement and improved sensitivity at lowa er computing cost
		Objectives	To monitor two-dimensional (2D) crack propagation
		Method	Used an ADNS-3080 sensor
		Conclusion	Resistant to changes in imaging distance, which is determined by the difference in height between the two sides of cracks' concrete
Complementary Split-Ring Resonator (CSRR) Loaded Sensor Array To Detect Multiple Cracks: Shape, Size And Position On Metallic Surface (Salim 2020)	RF Power Detector	Problem statements	To demonstrate the detection of cracks of various shapes, locations and size
		Objectives	Three frequency is generated for each channel using single-pole four-throw (SP4T) switch
		Method	A microcontroller interprets the transmitted RF signal which is transformed into a DC voltage level
		Conclusion	Aluminium sheets that have cracks embedded in the surface are used to demonstrate the detection of cracks of various shapes, locations and size
The Sensing Principle That Has Linear Macro-Bending Loss For Optical Fiber' New Type Of Crack Sensor And Its Experimental Research (Cheng 2018)	Fiber Optic Sensors	Problem statements	The relationship between COD and the fiber's macro-bending loss, poses several challenges
		Objectives	To establishes a linear relationship between the COD and the fiber's macro-bending loss
		Method	A validation experiment was carried out using three groups of fiber winding shafts with varying diameters and three groups of working light sources with different wavelengths to evaluate the feasibility of this crack-sensing principle
		Conclusion	A unique type of optical fiber crack sensor is built based on the suggested crack sensing technique to monitor the COD of pre-existing fractures and contraction joints of structures

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Fiber Optic Sensors For The SHM Of Building Structures (Bremer 2016)	Fiber Optic Sensors	Problem statements	The properties of mechanical's optical glass fiber sensors degrade, and thus their long-term reliability and stability, due to the chemical and mechanical impact of the concrete environment
		Objectives	Detection of the moisture ingress into the concrete use two types of fiber
		Method	Using a fiber optic sensor system for SHM of sewerage tunnels
		Conclusion	The fiber optic sensor can detect a crack with a dimension of 1.4mm in this paper
Embedded Distributed Optical Fiber Sensors in Reinforced Concrete Structures (Barrias 2018)	Fiber Optic Sensors	Problem statements	The uncracked and cracked stages, as well as during the loading, unloading, and reloading process
		Objectives	To achieve the protection, need, the robustness of the sensor formation, and measurement accuracy
		Method	DOFS method and the technique Rayleigh Optical Frequency Domain Reflectometry (OFDR)
		Conclusion	The optical fiber is bonded crossing the cracks and to the rebar delivered good results even in the case of unloading and loading of the specimen.
A Plastic Optical Fiber Sensing System for Bridge Deflection Measurement (Yang 2020)	Plastic Optical Fiber Sensors	Problem statements	A sensing system based on variations in optical fiber intensity
		Objectives	To assess bridge deflection in various positions using connected pipes
		Method	The designed system's sensing element is a plastic optical fiber sensor based on intensity change
		Conclusion	This system has a precise linear response and a high level of reliability in a variety of environments
Fatigue Crack Monitoring In Train Track Steel Structures Using Plastic Optical Fiber Sensor (Yang 2017)	Plastic Optical Fiber Sensors	Problem statements	Structural health monitoring when POF sensor system is made up of low-cost components in use
		Objectives	To identify and monitor fatigue-induced cracks in rail track steel structures in real-time
		Method	POF sensors in conjunction with a signal-processing method
		Conclusion	All three types of sensors demonstrate remarkable similarities in terms of fracture initiation and propagation identification, demonstrating the potential of the proposed sensor for crack initiation detection and subsequent fracture propagation monitoring
Fiber Bragg Grating (FBG) Based Sensing System: Early Corrosion Detection for Structural Health Monitoring (SHM) (Tan 2016)	Fiber Bragg Grating (FBG)	Problem statements	Most construction structures are supported by rebar, which leads to damages or collapses due to corrosion and during the concrete casting on the rebar surface
		Objectives	To protect the layer against corrosion
		Method	Method of FBG sensor with and without coating to protect the layer against corrosion
		Conclusion	The protection of FBG sensor is believed very important for the long-term monitoring of a composite structure in SHM.
Environmental Testing of a FBG Sensor System for Structural Health Monitoring of Building and Transport Structures (Čápová 2019)	Fiber Bragg Grating (FBG)	Problem statements	Mechanical damage, electromagnetic interference, or unfavourable influences on the recorded data during the measurement, such as temperature changes or probable data loss due to an explosive environment, make these sensors vulnerable
		Objectives	To monitor the mechanical stresses of wooden or concrete structures placed on a beam surface
		Method	Has fiber optic sensor system provides a more suitable and reliable solution since the sensor may be integrated into the load-bearing structure during its construction
		Conclusion	Protected from ambient environmental conditions by the construction material.

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Measurement Of Stresses Using Optical Fiber Bragg Grating Sensors Integrated Into Polymer Composite Material (Matveenko 2018)	Fiber Bragg Grating (FBG)	Problem statements	The ability of smart materials to fulfil actuation and sensing functions
		Objectives	To measure strains in the situation of prominent gradient distribution inside the material, under compression and tension, during cyclic variation of strains with time, and at different temperatures
		Method	The findings of strain measurements using fiber optic strain sensors (FOSS) are compared to numerical modelling results using the finite element approach and independent measurement data collected using a digital optical system Vic3D and other experimental instruments
		Conclusion	An interrelation model between Bragg wavelength peak shift and optical fiber strain in the fiber Bragg grating region for a sensor that is not impacted by the environment
Wireless Passive RFID Crack Width Sensor for Structural Health Monitoring (Caizzone 2015)	RFID	Problem statements	A variety of technologies and systems can be utilised
		Objectives	Reducing maintenance costs by avoiding needless inspections
		Method	The use of wireless passive crack meters has a high impact potential in terms of ease of installation and measurement
		Conclusion	The current study presents a crack width wireless radio frequency identification (RFID) sensor, which has been designed for use on a variety of materials (including concrete and metal) and is capable of detecting sub-millimetre deformations on the item on which it is installed
Improved Metal Surface Defect Detection Sensor Research based on a 3D RFID Tag Antenna (Li 2020)	RFID	Problem statements	Detection efficiency, long term monitoring and unreliable systems
		Objectives	To characterise the extension of metal flaws in SHM
		Method	Using a mix of wireless sensor technology and intelligent detection technologies
		Conclusion	The antenna may determine the position of smooth flaws on the surface of metal structures about the antenna, and then implement the smooth defect positioning
Batteryless wireless RFID based Embedded Sensors for Long-Term Monitoring of Reinforced Concrete Structures (Murthy 2015)	RFID	Problem statements	The durability of the reinforced concrete structure depends on the use but environmental conditions based on geographical location are needed.
		Objectives	Embedded RFID based sensors that can measure and store temperature, humidity, and corrosion rate in reinforced concrete structures with minimal power supply
		Method	Tiny embedded sensors run on a few microwatts of electricity extracted from an interrogating RF signal and use an inductive link to receive power and data converted from their attached sensors, making them wireless
		Conclusion	Stay inside the structure for the duration of its life cycle, requiring no maintenance and posing no risk of damage
The Prototypal Implementation Of An Innovative Low-Cost Module For SHM (Carosso 2017)	RFID	Problem statements	The prototypal implementation of an innovative low-cost module for SHM
		Objectives	To measurement of internal displacements inside civil structures
		Method	A larger Wireless Sensor Network (WSN) and placed and the Hall Effect is the sensor's basic functioning mechanism. This effect occurs when a magnetic field is applied to a conductor, causing electrons to migrate toward one of the conductor's extremes, resulting in an electric signal
		Conclusion	The Hall Effect sensor detects voltage variations caused by differences in the distance between two equal sensors put in a deforming structure.

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Passive UHF RFID tags as a tag sensor to detect crack depths (Omer 2018)	RFID	Problem statements	Due to a small crack on the metal material surface that affects the performance of the mechanical structure
		Objectives	To detect the crack range accuracy at stainless steel and ferromagnetic materials
		Method	A new technique for crack depth sensing by using a passive UHF RFID tag as a sensor which interrogated by Thingmagic M6e platform
		Conclusion	The stainless steel has high accuracy which detects crack depth range between 0.5 to 1.3mm meanwhile ferromagnetic detected crack depth range between 8 to 8.55mm.
Wireless passive ultra-high frequency RFID antenna sensor for surface crack monitoring and quantitative analysis (Zhang 2018)	RFID	Problem statements	Crack detection sensitivity and reliability are highly dependent on crack position antenna mode and the size of metal to be installed
		Objectives	To look into the reliability of fracture detection and characterisation using an antenna's mode analysis
		Method	An antenna sensor that can monitor the evaluation of already existing cracks or junctions prone to cracks
		Conclusion	The crack growth reduces the quality factor with time, increasing the antenna's realised gain
Feature Extraction for Robust Crack Monitoring Using Passive Wireless RFID Antenna Sensors (Zhang 2018)	RFID	Problem statements	That robustness to measurement variation, including environmental variables, is a practical concern for permanently fixed monitoring to achieve
		Objectives	To enhance the robustness of the low-cost RFID sensing system as the purposed method is validated by a case study in open crack detection and characterization under varied measurement conditions
		Method	The crack develops, the tag coil's self-inductance and mutual inductance between the reader and tag coils both rise using a low-cost RFID sensing system
		Conclusion	The crack growth decreases the resonant frequency of the tag coil and the coupling between the reader and tag coils is improved

CONCLUSION

In conclusion, a review of the SHM crack detection using IoT that focused on crack sensors specifically FBG and RFID sensors was conducted. It was found that using different types of sensing methods offers its strength and limitation. It can be summarized that FBG, and RFID sensors have better compromises when the advantages outweigh the disadvantages. From the literature search, it can be concluded that the selection of the sensing method depends on the preferences of the researcher. It is suggested that an experiment can be conducted to compare the two-method based on a specific type of crack whether it's concrete, or beam just to name a few. To summarise, the authors could conclude that for designers who prefer an accurate, efficient system and don't mind the hefty cost it is best to implement their system designs with FBG sensors. However, the designer who prefer fast-prototyping capabilities and low-cost system designs the authors suggested applying RFID sensors as their solution for crack detection IoT systems. The last word from the authors, it is hoped that this review article would assist designers and researchers in selecting sensors for exclusive SHM purposes.

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DECLARATION OF COMPETING INTEREST

None

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