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NON-DESTRUCTIVE WAYS OF CORROSION MONITORING IN REINFORCED CONCRETE MEMBERS: REVIEW

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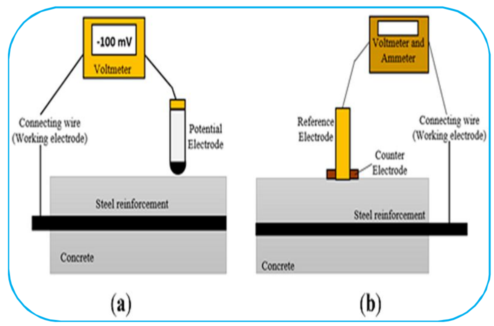
ABSTRACT

Steel reinforcement corrosion has a major impact on the longevity and structural soundness of reinforced concrete (RC) constructions. For in-situ corrosion monitoring, non-destructive techniques (NDT) are commonly applied for both short and long-term performance and safety measurements. This paper offers a thorough analysis of the current physical, optical, and electrochemical sensing methods for identifying and evaluating corrosion in RC components. Common electrochemical techniques like Half-Cell Potential (HCP), Concrete Resistivity (CR), and Linear Polarization Resistance (LPR) are highlighted, as are cutting-edge technologies like Galvanostatic Pulse Technique (GPT), macro/microcell sensors, and chloride/pH sensors. Also examined are the accuracy, range, and appropriateness in hostile conditions of sophisticated fiber optic sensors (FOS), such as Fibre Bragg Grating (FBG), Long-Period Fibre Grating (LPFG), Brillouin Optical Time Domain Reflectometry (BOTDR), and Optical Time Domain Reflectometry (OTDR). The study outlines the benefits, drawbacks, and possible applications of these techniques for thorough corrosion evaluation. It concludes that operational efficiency and prediction capability are improved by integrating several NDT approaches. This analysis will help industry experts and researchers choose the best techniques for measuring the structural health and proactive corrosion monitoring of RC infrastructure.



KEYWORDS: *Steel reinforcement corrosion , Galvanostatic Pulse Technique (GPT), Half-Cell Potential (HCP), Concrete Resistivity (CR).*

1. INTRODUCTION

Structural health monitoring is an interdisciplinary engineering field that deals with new ways to monitor structural safety, integrity, and performance without causing damage to the structure or compromising its function. Structural health monitoring is the process of adopting a damage identification approach for aerospace, civil, and mechanical engineering infrastructure (SHM). The relevance and hierarchy of SHM development are illustrated through a range of research methodologies in describe in *Farrar et al., 2007* [1]. From basic structural components (e.g., beams and plates) to sophisticated structural systems, a wide range of methodologies, algorithms, and procedures are created to handle diverse challenges faced in different structures e.g. bridges and buildings. The vibration based methods are described in a review paper, *Fan & Qiao, 2011* [2] which includes natural frequency-based approaches, mode shape-based methods, curvature mode shape-based methods, and methods that use both mode shapes and frequencies are examined for beam and plate structures. The location of damage is studied in beam structure by, *Gupta & Das, 2023* [3], and for large civil infrastructure, *Zar et al., 2024* [4].

Damage identification from SHM is divided into four different levels described below;
Level 1: Evaluating the damage present in the system
Level 2: Finding out the position of the damage
Level 3: Evaluating the amount and severity of damage in the system
Level 4: Predict the remaining lifespan of the system

SHM entails tracking the health of a structure throughout its performance, utilizing periodically sampled response readings from multiple sensors, finding out damage-sensitive information from these data, and statistically analyzing these features to establish the current status of the system. The output of this procedure is frequently updated for long-term SHM, to offer information about the structure's capacity and to execute its intended function for the sake of its inevitable aging and degradation caused by operational settings, *Worden et al.,* 2015 [5].

In concrete members, monitoring corrosion of the reinforcing steel primary task due to the major deterioration decreasing the life span of the reinforced concrete structures. Corrosion is the electrochemical process continuously and rapidly increases with the passage of time. Thus, electrochemical technique to monitor the corrosion are frequently utilized to determine the reinforcement's status i.e. passivity or the rate of active corrosion. Electrochemical techniques are some of the common techniques to measure corrosion since they may be used to evaluate the progression of the corrosive environment depending on indirect characteristics such as permeability variation, decreased adhesion at the steel/concrete interface, and cracking brought on by oxide layer (corrosion) buildup, *Thapa & Sharma, 2021 [6], Thapa & Sharma, 2023 [7]*.

This study focused on reviewing different types of non-destructive testing type sensors to monitor the corrosion in the reinforced concrete members. The study discusses working principles, methodologies and limitations of each type sensors developed by different researchers to monitor reinforcement corrosion and related parameters. This review will be providing the researchers and industries to select the appropriate type of monitoring technique based on the requirements.

1.1 Importance of SHM

Appropriate maintenance prolongs a structure's life cycle and can help to prevent catastrophic failure. The importance of monitoring the health of civil infrastructures is becoming increasingly vital due to operating loads, design complexity, and longer lifetime periods are depends on them. The economy of a country is reliant on transportation infrastructures such as bridges, railways, and roadways. Any structural failure of these causes significant damage to the nation's life and economy. Every year, millions of dollars are spent on the rehabilitation and upkeep of civil engineering structures across the globe. Failure of civil infrastructure to work at its best may have an impact on the country's gross domestic product and its development, *Frangopol et al., (2019)* [8].

From continual external loadings and the impact of the environment, the structural strength inevitably deteriorates with time. As a result, after such deterioration, it should be assessed whether the structure's performance is satisfactory. If structural strength falls below a specific threshold, the structure may break suddenly, resulting in an accident and affecting the structure's serviceability. Civil constructions have a particular need for the early detection of damage. If damage is not detected quickly, it might have major ramifications for the occupants' safety. Several natural phenomena can wreak havoc on a structure's structural integrity. After such natural disasters, it is important to guarantee that the structure is safe. The behavior of structures can be better understood if they are observed on a regular or continuous basis. It will be quite beneficial in terms of design and future health monitoring predictions, *Sabouni, 2023* [9].

1.2 Non-destructive testing (NDT)

The first kind of testing of materials could be non-destructive testing (NDT). Methods such as oil and flour are used to find tiny fissures in marble slabs as early as the Roman era. A similar technique, known as the "Oil and Whiting Method," was used later to find train wheel flaws more than a thousand years later. Blacksmiths have been known to employ a form of sonic non-destructive evaluation throughout history by merely hearing the ring of the sound produced as metal components are hammered into different shapes. Advanced Ultrasonic methods, which can identify subsurface flaws in material properties at a wavelength above the range of human hearing, have replaced advancements in this method. The modern X-Ray method, invented by German physicist Wilhelm C. Röntgen in 1895, deserves credit for being the first non-destructive application. Cathode ray research by Röntgen resulted in the development of the X-Ray for a variety of uses, including potential fault identification. Because of the groundbreaking nature of his work, he received the very first Nobel Prize. This ground-breaking invention is initially used in the medical field, and the industrial uses that its creator envisioned aren't been fulfilled for many years, *Thomas & Banerjee, (2013)* [10].

To evaluate the strength and quantify how it varies over time, non-destructive techniques are typically applied. This type of testing often uses samples extracted from the structure, though it can also involve testing entire members or structures. Non-destructive evaluation (NDE) refers to a broad range of methodologies applied in different industries to assess a material's, components, or system's characteristics without causing any damage. This method is also frequently referred to as nondestructive inspection (NDI), or nondestructive testing (NDT). NDE is an extremely advantageous approach that will save money and time in research, product evaluation, and troubleshooting since it does not alter the material properties during the inspection. NDE is frequently employed in different engineering areas such as civil, electrical, mechanical, aeronautical, petroleum, etc. *Wang et al., (2020) [11].*

2. ELECTROCHEMICAL METHODS

Based on changes in the properties of the concrete cover, electrochemical evaluation methods enable direct or indirect identification of the corrosion of steel reinforcing bars in concrete. The underlying principles of these techniques are derived from the quantitative relationships obtained from the assessed characteristics such as, for example, the relationship between the voltage change in the circuit and the intensity or interaction of specific chemical elements, or the existence of ions due to corrosive environments, etc., *Taheri, 2019 [12]*.

2.1 Half-Cell Potential (HCP) sensors

One of the pioneering techniques for determining the corrosion status of reinforced concrete (RC) was to measure the free oxidation potential (corrosion) of steel reinforcements (E_{cor}) on the concrete surface. In the 1970s first research study related to this method are published by *Page et al. (1985)*. In general, half-cell potential measurements offer a trustworthy qualitative approach, as demonstrated by several laboratory studies, *Thapa & Sharma, 2021 [6], Bhowmik & Pal, 2023 [13],* and field experiments, *Satish, 2020 [14], Makode et al., 2024 [15]*. This technique is frequently employed and the code to follow this methods has been describe in the following code *ASTM C-876, 2015 [16]*. The absence of a specified range for the observed potential, the dependency on the moisture content and temperature of the concrete, the impact of water-repellent films, and the coating on the testing specimen are some of the major disadvantages of the HCP technique.

The most common sensors right now are portable ones. They are made up of a voltmeter with a high impedance input and a reference electrode, which ensures the accuracy of the measurements made during in situ research. Electrodes filled with copper sulfate or calomel solutions are the most often used reference electrodes. The instruments are sold under various brand names in multiple countries, including Canin+ or Profometer Corrosion, made by Proceq in Switzerland, Elcometer 331T, made by Elcometer in the UK, Giatech iCOR, made by Giatec Scientific Inc. in Ottawa, ON, Canada and Armkor-1, made by InterPribor in Russia, among others. The devices' purposes vary, ranging from merely detecting and presenting the circuit voltage to tracing potentials and identifying the site's most vulnerable locations to deterioration (corrosion), [6], *[7]*.

Several studies have been conducted on sensors made from electrodes implanted in concrete that are made of silver chloride or copper sulfate solutions, *Muralidhara et al., 2006 [17]*. The efficiency based on manganese oxide electrodes as sensing devices for concrete specimens was proven by *Muralidharan et al., 2008 [18]*. A solid manganese oxide-based reference electrode has been proposed by *Jin et al., 2018* [19] which enables polarisation observations applying the HCP technique, spectroscopy of electrochemical impedance, and linear polarization. Later, *Karthick et al., 2019 [20]* proposed a modified reference electrode composed of graphene and manganese oxide (GO-MnO_2), which proved to be capable of operating steadily for a minimum of two years inside the concrete. A new technique of measuring HCP was proposed by *Chand et al., 2019 [21]* using two coils that operated following the electromagnetic induction principle based on Faraday's. Although this method is unlikely to be adopted widely due to complicity, it shows that researchers have a variety of devices today to address the issue.

Sensors that can be placed within the concrete in places particularly susceptible to corrosion are much more feasible ways for remotely measuring the values uninterruptedly. But the issue of keeping such reference electrodes stable when used with liquid electrolyte solutions has not yet been resolved; consistency can be lost and some components could even be damaged by the alkaline environment of concrete, resulting in the contamination of concrete specimen with the solution ingredients, *Colozza et al., 2021 [22]*. Figure 1 shows the working principle of HCP for reinforced concrete members.

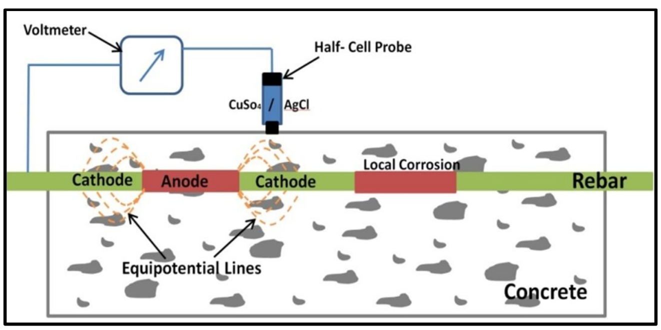


Fig. 1 Working principle of Half-cell potentiometer

2.2 Concrete Resistivity (CR) sensors

Another widely used technique for keeping tabs on the corrosion state of reinforcing bars is to evaluate the electrical resistance of concrete. The level of solvable salts (especially chlorides), electrical resistivity, and moisture content (porosity) in a concrete specimen, all depend linearly on one another, *Thapa and Sharma, 2021 [6], Thapa and Sharma, 2023 [7]*. It is well established that low resistivity is associated with fast electrochemical reactions when other circumstances are equal. However, the interpretation of the findings derived during the measurement of resistivity is greatly hampered by the reliance of CR readings on a variety of variables, such as humidity levels, the quantity of atmospheric precipitation, temperature, etc., *Azarsa and Gupta, 2017 [23]*. Therefore, the likelihood of corrosion can only be estimated from this test.

For on-site CR investigations, the Wenner probe is a popular instrument. The probe is composed of four metal electrodes that are spaced apart at a specified distance along a single line. The first and final electrodes receive an electric current (either direct or alternating) and the other electrodes' potential differences are monitored. As a result, for several pairings, a relationship between the current values and the potential difference is discovered and the concrete resistivity is estimated using the cell constant, *Ghosh et. al., 2015 [24], Lyassi et. al., 2015 [25]*. Figure 2 shows the working principle of concrete resistivity test using Wenner Resistivity instrument.

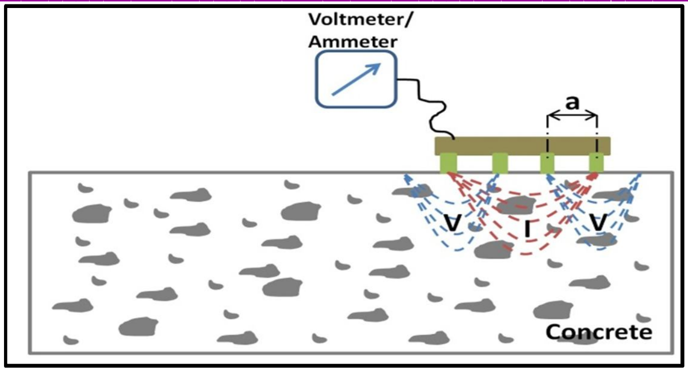


Fig. 2 Working principle of Wenner resistivity

2.3 Linear Polarization Resistance (LPR)

The LPR method is based on the inverse relationship between corrosion current density (I_{cor}) and electrochemical reaction conductivity. This method has been widely used to evaluate the extent of corrosion in steel or reinforcement since the mid of 20th century, according to *Grantham, 199*7 [26]. If the I_{cor} plot with time can be obtained, the weight loss of the metallic element or the cross-section area reduction may be computed using Faraday's law. Since the 1970s, lab and in-situ studies have made substantial use of the LPR technique, the most widely utilized form of this strategy used for monitoring corrosion in reinforced concrete members, *Pagadala et. al., 2022* [27].

A three-electrode cell is utilized for the method; the reinforcing bar act as an active electrode, the additional electrode is usually made with stainless steel, and the third reference electrode is similar as the one used in the HCP technique. During the LPR testing process, the reinforcing bars potential deviated slightly from it stable potential intentionally. The resistance against polarization (R_p) of the reinforcing bars can be computed by changing their potential by a given amount (ΔE) and monitoring the current deterioration (ΔI) for a predetermined length of time. A alternative technique called galvanostatic can also be used, which entails giving the reinforcing bars a modest, continuous current (ΔI) and monitoring the potential shift (ΔE) over a certain amount of time. According to *Pagadala et al. (2022)* [27], the parameters are changed for each repeat to ensure that the potential shift (ΔE) remains within the linear Stern-Geary area of 10–30 mV, *Hu et. al., 2022* [28].

Equations (1) and (2) can be used to calculate the corrosion current density (I_{cor}) and reinforcement polarization resistance (R_p), respectively.

$$R_p = \Delta E/\Delta I \quad (1)$$

$$I_{cor} = B/R_p \quad (2)$$

Where B represents the Stern-Geary constant, for active steel, a quantity of 25 mV, and for passive steel, a quantity of 50 mV should be selected, *Poursaee, 2010* [29]. The range of corrosion rate values that represent the risk associated with using RC structure was presented in Table 1

Table 1 Corrosion current density (I_{cor}) range from *Berke and Steven, 1990* [30]

Range		Rate of corrosion
I_{cor}, μm/cm^2	ΔL, μm/year	
Less than 0.1	Less than 1.16	Passive
0.1 to 0.5	1.16 to 5.8	Low
0.5 to 1	5.8 to 11.6	Moderate
Greater than 1	Greater than 11.6	High

Compared to HCP and CR, LPR takes much longer to perform. As a result, all three techniques can be utilized to save time and expenses. Descriptive HCP and CR assessments aid in identifying the areas where corrosion risk levels. After that, the rate of degradation of steel reinforcements is calculated using the LPR technique. It should be emphasized that the LPR approach has a measuring inaccuracy that results from a simplified calculating process (the calculated corrosion rate varies from the real one by 2-4 fold), *Andrade and Alonso, 2004 [31]*. Thus combination of monitoring different technique will results greater prediction strength and consumption of time for analysis of obtained data will also reduce.

To determine the rate of corrosion, *Pereira et al., 2008 [32]* recommended combining an available commercial GEOCOR 06 device with an embedded electrode-based sensor. The test for estimating corrosion rate was achieved on control samples rather than on the actual structures on site. This indicates that the metal deployed with the detector must have the same composition as the metal in the structure being examined. To assess the rate of corrosion, *Jin et al., 2018 [33],* and *Karthick et al., 2019 [34]* recommended combining HCP readings with an embedded LPR sensor. *Brown et al., 2018* [35] developed the corrosion sensing device based on an elastic substrate wire. The actual sensing device was combination three-electrode cell. Each electrodes were constructed from corrosion-resistant materials, such as copper that was gold-plated.

2.4 Macro and Microcell sensors:

Galvanic macro and microcell-based sensors are frequently employed to measure the depth of concrete cover and the severity of corrosion on steel reinforcing. Corrosion intensity is described as a parameter that can be used to approximate how much quicker the corrosion process is happening, but cannot be applied to accurately gauge the rate at which the steel deteriorates. After the calibration with control specimens in the laboratory, the findings may be recalculated using the proportionality constant to provide approximations of the reinforcement corrosion rate onsite, *Andrade, 2019 [36]*.

Multi-ring sensors are sensor based on microcells for measuring corrosion intensity. The sensors are composed of a measurement circuit and small circular electrodes that are remotely placed from one another. Low-carbon steel was used for making the ring electrodes. This sensor can gauge the current flowing through the galvanic cell when placed close to a higher noble metal (cathode). It can also calculate the depth and expansion of the area of corrosion based on how far they are from the surface of the concrete, *Shevtsov et. al., 2022 [37]*. A few centimetres length of metal bars is used to make up microcell-based corrosion sensors. Low-carbon steel with constituents comparable to reinforcing steel is used as the material for anodes. Copper, titanium, stainless steel, and other materials can be used to make cathodes, *Yoo et al., 2003 [38]*; *Park et al., 2005 [39]*. A single cathode is placed close to several anodes. Sometimes additional reference electrodes may also be used for such as half cells' HCP monitoring (see Section 1.1). The so-called anode-ladder system is the first and most widely used variant of these sensors, *Xu et al., 2013 [40]*. To determine the extent of corrosion in concrete, the steel bars are positioned on a "ladder" with respect to the reference electrode. Fig. 3 presents the macrocell ladder-based sensors taken from *He and Li, 2021 [41]*.

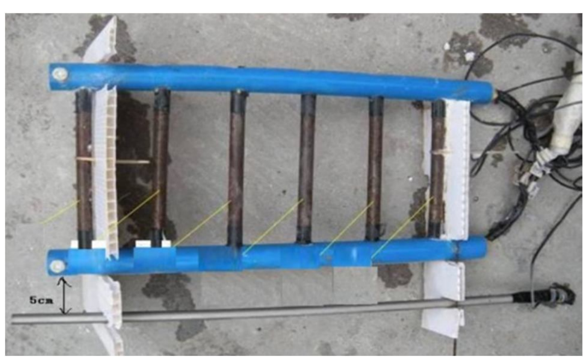


Fig. 3 Ladder type macro cell sensor taken from He and Li (2021)

Microcell-based sensors are contained in a series of various metals with a varying range of thickness in millimeters. This system is arranged in anodes and cathodes metals in an alternating pattern. The system can also be built of the same metal for every anode and cathode element by artificially arranging the potential difference between 20 to 100 millivolts *Shevtsov et al., 2018 [42]*.

2.5 Galvanostatic Pulse Technique (GPT) Sensors

When performing the GPT, the electrode potential must be continuously recorded when a weak galvanostatic pulse (less than 50 microamperes) is applied, or after the pulse has been turned off, *Vedalakshmi et al., 2010 [43]*. The process of the electrochemical reaction on concrete reinforcement bars is assumed to be explained by a straight forward Randles equivalent circuit in the analysis of the generated potential transient, *Song and Saraswathy, 2007* [44]. The following equation (3) can be used to describe the variation in potential.

$$P(t) = I_{imp}\left[1 - \exp^{\frac{T_{1/2}}{R_p X_{dx}}}\right] + M_{\Omega} \qquad (3)$$

Where *P(t)* is the observed potential, I_{imp} is the induced current, $T_{1/2}$ is the transition time, R_p is the polarization resistance, X_{dx} is the double-layer capacitance and M_{Ω} is the medium resistance. The method examines the corrosion status of steel reinforcing bars in concrete by measuring the transition time (passive state or active state). The following requirements were proposed in the study by *Glass et al., 1997 [45]*, where $T_{1/2} > 40$ sec in the passive condition, and $T_{1/2} < 25$ sec in the active state. Since the late 1980s, GPT had been employed to evaluate the reinforcing bar corrosion in concrete, *Newton and Sykes et al., 1988 [46]*, *Glass et al., 1993 [47]*. Presently, available commercial equipment relied on the Gecor 8 and Galva Pulse detector with a protective ring, such as those discussed in *Poursaee et al. (2010)*. The instrument is used to calculate the corrosion variables for equation 3. The corrosion expert can perform the examinations on-site using this instrument. It is unable to locate any information about remote measurements using GPT. However, studies demonstrate that GPT measures are more reliable and precise than LPR evaluations under bad situations when no previous data about the studied region is available. *Qiao et al., 2012 [48]* used simulated alkali solutions to evaluate Mg/graphite and Zn/graphite microcell-based sensors. Their benefit is that they can create electric current, which functions both as the monitoring signal and the power supply needed to send this signal across a wireless network. Because it does not require multiple meters of connecting cables to be installed into concrete buildings to transport the information from the recorder to the detectors, it is believed that such a system will make monitoring considerably easier.

3. CHLORIDE MONITORING SENSOR

Before starting the degradation process of RC elements, sensors for pH or chloride level might serve to monitor the onset of the corrosion state for the RC member. All researchers suggest that there is a threshold level of chloride ions that leads to the oxidation of steel reinforcements, even though varied opinions exist on the subject, *Shi et al., 2012, [49].* Thus, regular monitoring for chloride ions penetration in the member's cover and predicting ion concentration on the steel reinforcement level should be a vital process for a comprehensive monitoring technique. According to their mode of operation, chloride sensors based on non-destructive may be split into three main categories, one that measures the concrete resistivity against the current, one that uses chloride-sensitive electrodes, and last use an optical fiber sensing system. The first type is already covered in Section 1.2 (Wenner Probe). The other two categories are described in more depth in the coming section.

Initially, silver or silver chloride electrodes were embedded into concrete *as a corrosion monitoring sensors, Zhang et. al, 2022 [50]*. Later, ion-selective electrodes were applied due to simplicity and chemical robustness in harsh conditions. However, a variety of variables, including variations in temperature and pH as well as the existence of the electromagnetic field, might result in erroneous results. These embedded-type sensors also degrade quite quickly due to the depletion of the liquid electrolyte, *Muralidharan et al., 2006 [17]*.

To detect the level of chloride and establish the threshold value, *Leung et al., 2008 [51]* created fiber optic sensing depending on a Nufern single mode 780-nanometer optical fiber wrapped with an iron coating with a thickness ranging from 25 to 350 nm. The sensor's measurements are compared with the outcomes from the galvanic and macrocells results, which show a satisfactory correlation. However, the authors did not include any details about the validation of the detectors concerning the real concentration of free chlorides obtained by any widely used technique (potentiometric or titration method). As a result, the study did not disclose any data on the sensors' sensitivity levels. Detection based on thin iron plates (1.5 mm) mounted in parallel and spaced 1 mm apart on a polyester substrate was proposed by *Im et al., 2017 [52]*. To increase the sensitivity of iron in contact with chloride ions anion-exchange film was coated. The study showed that it is possible to estimate the concentration of chlorides up to 1.2 Moles. Despite the sensor's sensitivity and accurate calibration, it has a weak mechanical strength and degrades fast at high chloride concentrations. As a result, such devices cannot be inserted into masonry or concrete.

4. PH MONITORING SENSORS

The pH range for ordinary Portland cement is 12.45 to 13.5 (at 20 °C). The development of uniform steel reinforcement corrosion can be caused by a drop in concrete's pH as a result of the carbonation process, which is the interaction of carbon dioxide with calcium hydroxide, a component of cement or brick, *Melchers and Richardson, 2023 [53]*. There is a critical proportion between the hydroxide and chloride ion concentrations, to induce the localized corrosion in a reinforcement subjected to chloride ingression. Since steel reinforcements must be thoroughly monitored, it is crucial to managing the pH level of the concrete, *Tahri et al., 2021 [54]*.

Behnood et al., 2016 [55] described several techniques for regulating the concrete pH level, categorized them, and thought about the benefits and drawbacks of each approach. Thus some of the best-known sensor designs for detecting the pH level of a concrete specimen are the solid-state pH detector, ion-sensitive field-effect transistor, and optical fiber sensing based on hydrogel film. A reduction in pH is anticipated in aged concrete as a result of sulfate assaults, alkali leaching, and carbonation described in *Tariq et al., 2021 [56]*.

Deposition, electrochemical deposition, and oxidation are some common methods used to manufacture different types of pH-based electrodes for the concrete specimen, *Du et al., 2006 [57]*. Metal oxide-based substances, such as rhenium oxides, palladium, titanium, platinum, tin, rhodium, aluminum, and iridium, are frequently utilized as ion-selective substrates to ensure that sensors in concrete operate steadily and consistently. A bendable pH sensor made with iridium oxide has been proposed by *Huang et al., 2011 [58]*.

In particular, HCP, CR and LPR electrochemical techniques are the only ones employed commonly to assess the corrosion status of steel reinforcing bars in concrete, *Fan and Shi, 2022 [59]*. As a result, they are described by several standards, and a wide range of available commercial devices are based on them. There are currently no regulatory papers that specify the design and evaluation standards for the remaining other techniques for the continuously evaluating of RC members.

5. FIBER OPTIC SENSORS (FOS)

Change in the characteristic of optics (light) moving through the optical core is monitored by the FOS system. Deformations or temperature variation on the fiber significantly changes the properties of the traveling optics. As a consequence, it can evaluate the changes inside the concrete specimen that arise from the buildup of rust on the concrete/steel reinforcement interface. To monitor deformations at the concrete/steel border, FOS is often mounted on the reinforcement or nearby locations. Due to their resistance against different chemical and corrosion products, tolerance to interference from other sources, precision, simplicity, and accessibility. FOS particularly shows promising results for evaluating the rusting of reinforcing bars in concrete, *Luo et al., 2019 [60]; Alwis et al., 2021 [61]*.

Some of the most common optical fiber sensing systems available in the markets and for academic researchers for application in civil infrastructures are fiber Bragg grating strain sensor (quasi-distributed), Brillouin and Rayleigh optical time domain reflectometry (distributed), and interferometry sensor (point).

5.1 Fibre Bragg Grating (FBG) strain sensor

Due to deformations (displacement) in a fiber under test (FUT), the change in the artificial grating period inscribed along the sensing length of the fiber axis occurs, this changes the wavelength signal at the receiving end of the acquisition unit. This technique is feasible to monitor the increase of corrosion products by tracking variations in the reflected wavelength signal coming from the change in the grating period. Since the last decade, there has been a lot of discussion on using the FBG system to evaluate the rust development around the reinforcing bars inside the concrete. This method convinces us to provide valuable support for corrosion analysis. At the moment, the majority of research concentrates on the materials of the fiber and the implementation of the sensing element in the concrete specimen. Double-layer coated sensors are employed by *Hu et al., 2016 [62]*, the interior of the sensor was coated with silver and the exterior are coated with iron carbide. The research showed that corrosion rates differed depending on the origin of the chloride ion. However, calibration of the outcomes wasn't provided by the authors. Moreover, corrosion caused a portion of the layer that has been deposited on the sensor's surface to deteriorate. The developed sensors are installed surrounding reinforcing bars in this study. The FBG sensors are mounted transversely to the axis of the reinforcement steel by *Gao et al., 2011 [63]*. They were able to determine a link between the change in the reflected wavelength due to a change in the grating period from deformation and the reduction in reinforcement weight due to corrosion using the gravimetric weight loss method. Additionally, the authors identified the moment when corrosion began to occur (when the readings from the device remain unchanged) and the period during which corrosion developed (the signal start altering continuously). *Chen and Dong, 2012 [64]* outlined how the sensors worked using the ANSYS program and provided a conversion relationship between change in wavelength and displacement, although they did not define the kind of sensors properties they employed. They noted that if the thickness of concrete is five times more than the diameter of the reinforcing bar, the correlation is near 0.829 and validate that the coefficient of correlation between two parameters depends on the cover thickness. *Mao et al., 2015 [65]* recommended employing Bragg grating sensing type fiber wrapped in epoxy resin for proper protection from an aggressive environment. The sensor demonstrated mechanical resistance and crack-sensing abilities. The researchers, unfortunately, did not include any calibrated information about the relationship between the change in wavelength and deformation in concrete specimens.

***Bremer et al., 2016* [66]** applied polyimide-coated FBG sensors for measuring the moisture variation inside concrete members. The polyimide-coated FBG detector functions as a hygroscopic layer that expands due to a reaction with water molecules from the surrounding environment. The FBG is put under strain by this effect, and the degree of that strain is linearly correlated with the applied RH. As a result, by examining the returned Bragg wavelength, it is easier to determine the RH value on the specimen. This type of system indirectly assists in locating an area with a higher corrosion risk in a concrete environment.

The prevention of embedded FBG detecting fiber from mechanical stress happening during construction activity and from the dead load of the concrete specimen itself is another significant issue to be addressed, *Zhou et al., 2003 [67]*. According to *Almubaied et al., 2017 [68]*, expanded polystyrene lining should be inserted between the concrete specimen and steel bars. Although it served to shield the sensing portion, the researchers failed to account for the decrease in bonding between concrete and the reinforcing bars and its impact on the structure's ability to support external loading. A temperature sensor, an acoustic emission sensor, and FBG detectors with an epoxy protective coating are evaluated together by *Li et al., 2017 [69]*. The acoustic emission technique was used to record the spreading of cracks in concrete and the FBG technique was applied to track surface strain by noting an increase in the number of corrosion products. This technology shows promising methods for evaluating corrosion in reinforced concrete as study shows the favorable agreement with the outcomes. The sensors are still operational after the trial. So, the study concludes with the reason that any coating on FBG sensors that can withstand the alkaline conditions of concrete and concrete inherent pressure will be able to secure from deterioration and corrosion. Photronix Technologies (M) Sdn. Bhd. optical fiber was used by *Jaafar et al., 2018 [70]*, which was coated with a silicon gel safety layer over various types kinds of concrete. The authors established a correlation between the variations in HCP readings and the shift in Bragg wavelength, which are employed as a benchmark. The recommended approach guaranteed that the sensors would continue to work under accelerated corrosion for at least a year.

According to *Luo et al., 2018 [71]* research, the FBG detectors could only detect the beginning of the corrosion process when the quantity of rust (corrosion products) was 3–4 times more abundant than they are in the initial state. In other words, the level of rusting can only be estimated once the process has begun. Since the shift from the passive to active (corrosion) state cannot be measured, no preventative steps can be taken to return the system to its passive state. It should also be mindful that the range of FBG sensors inside any monitoring structures is constrained due to cost and servicing. To monitor the complete health of the massive structures a huge number of sensors are needed. These sensors are currently somewhat costly to manufacture. Figure 4 shows the working principle of fibre bragg grating sensor.

5.2 Long Period Fibre Grating (LPFG) refractive index sensor

Due to their excellent sensitivity, performance and low weight, long-period fiber grating refractive index sensing devices have drawn a lot of attention recently. LPFG in specific has drawn a lot of consideration, especially the manner the LPFG sensor combines guided modes into cladding modes at resonant wavelength, which ultimately resulted in energy loss (refraction/ higher mode) based on the relative difference in the refractive index between the guided mode and cladding mode, *Chen et al., 2024* [72]. Due to corrosion activity in the reinforcement, the reflection value of an attached LPFG sensor changes from deformation due to hoop stress generation. This finally results in a change in the resonant wavelength of the light traveling in the core. This principle helps to measure the rate of corrosion in the reinforcement.

A sensor covered with a lean coating of polymer and microscopic iron/silica granules was deposited on Corning SMFG28e single-mode optical fiber as suggested by *Huang et al., 2015* [73]. The authors conduct the correlation between the accumulations of rust (corrosion) with enhancement in the resonant wavelength caused by the corroded iron particles on the sensor, using quick laboratory tests. In other terms, the microscopic granular coating served as sacrificing materials for detection. For the pitting type corrosion of reinforcing bars in concrete members, the estimation error almost reached 26%, which is a satisfying result for future application.

Chen et al., 2016 [74] proposed a detector with a dual coating (an exterior layer depending on iron chloride and an interior layer depending on silver), with the depth of the coatings varied between very few to several tens μm. The laboratory tests with a chloride aqueous solution found that, in some ranges, the weight reduction on the exterior iron chloride layer was linearly related to resonant wavelength variations. In their subsequent investigation, *Tang et al., 2020* [75]. The researchers examined iron bars in a mortar using the recommended sensors and achieved encouraging findings for the early diagnosis of corrosion. The agreement between sensor data and gravimetric measures of corrosion rate will be the subject of future research. But because of the sensor's limited-service life (24 hours in a wet environment and 14 days in mortar), it cannot be employed for long-term monitoring of actual constructions. However, until the issue of corrosion protection against erosion of nanoparticles film is resolved, it isn't possible to use LPFG sensor signals in systems for the long-term surveillance of RC structures, despite showing quite a good correlation between both the corrosion rate and change in the resonant wavelength. Since the usage of such coatings was required, one option would be to utilize more corrosion-resistant nanoparticles or extra anti-corrosive protective films, *Tang et al., 2022* [76]. Even though the considered detectors were much mechanically strong than FBG sensing devices, they were still unable to detect the exact instant when corrosion begins since they merely record the buildup of corrosion products on reinforcing bar surfaces.

5.3 Brillouin Optical Time Domain Reflectometry (BOTDR) sensor

By determining how probing light intensity varies with time and how the Brillouin frequency shift is distributed throughout the optical fiber, it is possible to determine the distributed deformation and temperature. To track the expansion stress generated from rusting of steel, *Lv et al., 2017* [77] employed optical fiber time domain analysis based on Brillouin scattering (BOTDA) Ditest SAT200 detector. Instead of mounting the sensor directly on the steel, the researchers take a novel approach and fastened it to a 5 mm thick mortar layer that covered the reinforcing bar. The next step was to add another coat of mortar to the entire structure. The sensor seems to be long-lasting, extremely sensitive, and had a broad measuring range. As a consequence of their research, the authors created a damage coefficient that can be used to evaluate qualitatively anything from the early phases of corrosion product distribution to the breaking of the innermost concrete layer.

Three distinct types of BOTDA detectors were examined by *Jagtap and Nayak, 2019* [78]. The sensors' techniques for shielding themselves from metal corrosion products and how the fibre was attached to the reinforcing bars varied (with a permeable material sheet serving as protection). The researchers concluded that the stated sensors could be applied to lengthy measurements. They did not, however, define the best sort of sensors to be used for applications.

A distributed optical fiber sensing system placed in a helix configuration on a steel reinforcement was proposed by *Fan et al., 2019* [79]. The researchers observed relationship between Brillouin shifts can be employed to predict the loss of reinforcing bar dia. due to corrosion. The primary issues prohibiting it's in situ implementation were the requirement to install the detector across the entire reinforcing bar surface and the high likelihood of distortion or damage on a building site. Detectors with minimum cost that could be used to take measurements on the outside of RC members or inside the specimen were proposed by *Scott et al., 2019* [80]. The authors employed two detectors at once (one detector for monitoring the deformation and monitoring temperature change using another detector). A coating of polymer glue covered both sensors to provide protection. In a lab setting, the detectors were successfully tested.

The BOTDA sensors mentioned above were among the earliest technological innovations based on physical principles and were used for monitoring systems of rusting of reinforcement in actual constructions. Since they offer entire spatially distributed scanning and collecting at intervals less than 1 mm, they are widely popular for monitoring purposes. However, the application of such detectors is limited due to looping wires around reinforcing bars, the significant influence of temperature variation, and the high risk of damage during concrete cracking, *Luo et al., 2018* [81].

5.4 Optical Time Domain Reflectometry (OTDR) sensor

Bennet and Mclaughlin, 1995 [82] show the initial application of high-resolution OTDR in bridge structures for corrosion monitoring using multimode optical fiber. They artificially bend the sensing fiber using a “corrosion fuse”, when the element gets corroded the fiber straightened and the difference in the readings indicates the location of corrosion. Bending experimental results demonstrated that a considerable amount of optical intensity losses were observed when a multimode fiber was bent and established within a useful bending diameter, *Martins-Filho et al., 2007* [83] proposed a multipoint detector for corrosion monitoring in aluminum metal. The end of the cleaved fiber (detectors) was coated with an aluminum layer resulting in the reflection of light into an OTDR. When the aluminum-coated layer was etched due to artificial corrosion, the reflection of light from the detector decreases due to intensity loss. This technique helps to indirectly predict the corrosion level and location by placing multiple such detectors in the same sensing fiber with the help of applying a coupler. *Nascimento et al., 2012* [84] developed the OTDR corrosion multipoint monitoring system using Erbium Doped Fiber Amplifier (EDFA) as a booster device. Two different configurations of EDFA booster one with a remotely placed booster device away from the OTDR instrument and the other placed near the instrument were used for monitoring corrosion. The laboratory-controlled experiment outcomes demonstrate the benefits of using the amplifying device for longer structure monitoring and with greater spatial resolution.

The distributed humidity recording sensor based on an expandable polymeric optical fiber sensing detector for concrete members was developed by *Bremer et al., 2016* [85]. This sensor enables the spatial detection of the breakdown site and, consequently, the location of the moisture infiltration by analyzing the attenuation using an OTDR instrument as an interrogator. Micro bend sensing principles are applied in a single-mode optical fiber for measuring the moisture ingress inside a concrete member. The sensor provides a very optimistic result for applying in real-life structures, *Thapa & Sharma*, *2022* [86], *Thapa & Sharma, 2023* [87]. This type of sensor indirectly assists to locate the higher corrosion risk area in the concrete members. Figure 6 (a) shows the working principle of OTDR and 6(b) shows the trace plot of intensity loss using OTDR as an interrogator.

6 . CONCLUSION

Various non-destructive methods with their working principle, limitations, and applicability in the concrete members have been discussed in details in this study. Due to aging infrastructures in developed countries and to mitigate future problems in developing nations robust health monitoring methods and techniques should be applied for the betterment of the citizens and economy. Non-destructive applications in concrete structures normally started in European countries after the end of the Second World War. Many different methods and modifications have been developed by many researchers to properly understand or predict the location and number of damages or damaging factors for assessing early condition monitoring. This study shows the in-depth studies of all commonly available non-destructive techniques applicable to monitor corrosion in reinforced concrete structures. This study will be beneficial for both researchers and industries to select the appropriate techniques and sensors for corrosion monitoring in reinforced concrete members. From studying different previous non-destructive methods, the proper and effective ways to predict the corrosion in reinforced concrete based on pitting type (non-uniform) are very limited. More efficient ways to apply NDT methods are needed for measuring the mechanical and durability properties of concrete in normal as well as aggressive environments. The studies also suggest measuring the corrosion in members using various non-destructive approaches, if possible, to mitigate the limitations from one single approach.

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