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Review of monitoring methods for chloride-induced reinforcement corrosion on reinforced concrete bridges

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Abstract

Reinforcement corrosion is a serious durability problem that has been overlooked in the management of structures, as most Bridge Management Systems (BMS) primarily rely on visual inspection to determine the condition of bridges. The study aimed to identify monitoring methods for Reinforced Concrete (RC) bridges affected by chloride-induced reinforcement corrosion that can be included in the overall assessment jointly with visual inspections in the Struman BMS. The reviewed monitoring methods were categorised into visual inspections, Non-Destructive Testing (NDT), and remote monitoring. Monitoring technologies have the potential to allow for the early diagnosis of problems, resulting in better maintenance and damage prevention. They could also improve the speed and scope of condition assessments, offer reliable and comprehensive data, and eliminate traffic disruptions while taking measurements.

Keywords: chloride-induced reinforcement corrosion, Bridge Management System, Reinforced Concrete bridges, monitoring methods, condition assessment

1. INTRODUCTION

Reinforcement corrosion is a major cause of deterioration in Reinforced Concrete (RC) bridges, mainly caused by the ingress of chloride ions. This problem leads to a loss of structural capacity, concrete degradation, and increased maintenance costs. To manage and optimize allocated financial resources for bridge maintenance, repair, and rehabilitation, Bridge Management Systems (BMS) have been developed and implemented in different countries [1]. However, visual inspection remains the predominant method used in BMS to assess and monitor the condition of structures, despite the serious impact of corrosion.

2. CURRENT CORROSION MONITORING IN SOUTH AFRICA

The Struman BMS is commonly used in Southern African Development Community (SADC) countries. It was developed in South Africa to manage the maintenance of deteriorating bridges with limited budgets. The system uses visual inspections to rate defects on a scale of 1 to 4, based on their Degree, Extent, Relevance, and Urgency (DERU) [2]. The DERU rating data is used to prioritize bridges for repair and maintenance, and assessments are done every five years. However, there is a need for the use of appropriate monitoring systems, particularly for reinforcement corrosion, which is a significant cause of deterioration in RC structures.

3. MONITORING OF REINFORCEMENT CORROSION

Chloride-induced reinforcement corrosion happens in three stages namely: initiation, propagation, and acceleration. Detecting corrosion at early stages through monitoring methods is important to prevent severe damage and reduce repair costs. Research on technologies for the early detection of corrosion has been increasing since the 1990s, with most publications on corrosion monitoring published in the last decade. The review focused on visual inspection, Non-Destructive Testing (NDT), and remote corrosion monitoring methods to evaluate reinforcement corrosion damage in RC structures, particularly bridges.

3.1 Visual Inspection

Visual inspection is a common and cost-effective method to identify corrosion on RC bridges, but it has limitations when it comes to assessing reinforcement corrosion. This is because defects only manifest on the surface of concrete when significant damage has already occurred. Visual inspections do not quantify the damage or identify the effect, making it difficult to establish effective maintenance practices to prevent advanced corrosion damage. Additionally, visual inspections are subjective, relying on the experience and judgement of the inspector [3]. While visual inspections still provide useful information about the condition of bridges, they need to be complemented by other methods to address their shortcomings.

3.2 Non-destructive Corrosion Monitoring

NDT methods assess the degree, extent, and severity of deterioration in a structure without affecting its integrity. Several types of NDT methods include electrochemical, elastic wave, electromagnetic, and thermal methods.

3.2.1 Electrochemical methods

Electrochemical methods measure parameters such as corrosion potential, concrete resistivity, and polarization resistance. These parameters can be measured periodically using surface electrodes or sensors or continuously using embedded sensors. By monitoring these parameters, the extent and severity of corrosion can be assessed, and appropriate interventions can be taken to prevent further damage.

Half-Cell Potential (HCP) measurement involves measuring the potential difference between two half-cells, usually a metal in its solution, and an external Reference Electrode (RE). HCP measurements are done using surface or embedded REs, and new methods involving climbing robots and flying drones have also been developed [4]. HCP measurements can identify high corrosion risk before visible damage appears on the surface of the structure, allowing for appropriate interventions to be taken at the right time. However, HCP measurements are affected by factors, such as the availability of oxygen, cover depth, and the composition of the pore solution, which should be considered during interpretation [4].

Electrical Resistivity (ER) affects the flow of ions and the rate of corrosion in the concrete. ER measurements have been used to indirectly assess the quality of the concrete, chloride ion diffusion and degree of saturation. The Wenner Four probe is the most used device for measuring ER [5]. ER measurements can identify high corrosion risk areas but must be used in conjunction with other parameters such as HCP. However, ER measurements are influenced by various factors such as moisture content, temperature, concrete composition, curing conditions, cover depth, and probe contact during testing [4, 6]. Even though this method is fast, non-intrusive, and does not require connection to embedded steel, it does not indicate whether corrosion has occurred or to what extent active corrosion has occurred.

Linear Polarization Resistance (LPR) is a technique used to measure the corrosion rate of steel by monitoring corrosion activity over time. It works by correlating the HCP of corroding steel to the externally applied current. New technologies such as Gecor 8™ and CorroMap simplify the measurement process by automatically evaluating and displaying data [7, 8]. These technologies are considered non-intrusive as they only require a connection to the reinforcement without damaging the structure. The Giatec iCOR is a wireless device that can measure corrosion rate, corrosion potential, and electrical resistivity without needing a connection to the steel in concrete [9]. Using one device for all three parameters saves time and reduces costs. This device also allows easy reporting, exporting, and sharing of results, enabling fast and efficient condition assessment. However, temperature, concrete resistivity, and relative humidity can affect the accuracy of measurements and should be considered.

3.2.2 Elastic wave methods

Elastic wave methods are used to estimate the mechanical properties and heterogeneous characteristics of concrete. They can detect damages caused by reinforcement corrosion, such as internal cracks, voids, delamination, and corrosion products. Examples of these methods include Impact Echo (IE), Ultrasonic Pulse Velocity (UPV), and Acoustic Emission (AE).

The IE method is based on the propagation and reflection of elastic waves in concrete. It works by inducing a low-frequency stress wave using a mechanical impact into the concrete, which reflects off internal cracks, voids, or changes in material characteristics. The resulting displacement-time curves are analysed in the frequency domain to detect anomalies. IE has been used in several studies to detect flaws such as internal cracks, voids, and delamination, as well as to determine the thickness of concrete elements and measure crack depth [10, 11].

The UPV method measures the propagation time of an ultrasonic pulse through concrete to determine its properties and detect internal flaws such as cracks, voids, and delamination caused by reinforcement corrosion [12]. Laboratory-based studies have attempted to relate UPV measurements to reinforcement corrosion. Amplitude attenuations correlate well with corrosion damages, while internal cracking results in wave attenuations and a decrease in UPV. UPV measured by the first wave peak describes the reinforcement corrosion process from the formation of corrosion products to the visibility of corrosion damage indicators on the concrete surface [13]. Even though UPV is less reliable in detecting shallow defects, it can estimate concrete strength, determine member thickness, and measure crack depth. Its results are influenced by pulse attenuation, concrete composition, and aggregate sizes.

The AE method is a technique that detects elastic waves generated from localised sources in concrete, such as internal crack growth and corrosion product generation [5]. The emitted elastic waves are detected using AE sensors. Detecting active cracks at an early stage makes it suitable for long-term monitoring. AE analysis can also identify different stages of corrosion, including corrosion onset and nucleation of corrosion-induced cracking [13, 14]. However, there are currently no critical standards for its procedures, installation, or interpretation of results in terms of corrosion, and it has mainly been used in laboratory settings.

3.2.3 Electromagnetic methods

The cover meter and Ground-Penetrating Radar (GPR) are electromagnetic methods used to locate reinforcement and cover thickness. They are used to mark out the measurement grid which is essential to other monitoring methods such as ER, HCP, and LPR. Cover meters have been used for cover measurements because they are portable, lightweight, and easy to use. They are also established and standardised. The ACI 357 specifies a minimal cover of at least 50 mm for RC members subjected to seawater, which applies to submerged and atmospheric-exposed structural elements. SANS 10100-2, however, recommends a cover of 65 mm for members in contact with seawater [15].

GPR works by emitting and receiving high-frequency electromagnetic waves that can penetrate concrete and reflect when they encounter changes in material properties. GPR is also used to detect other subsurface features, such as voids and delamination, which can provide additional information about the condition of the structure [16]. This method is usually preferred because it can cover large areas of measurement in a short time. However, it can only be used on horizontal structural elements such as decks and slabs. Its use in corrosion evaluation is still in progress. GPR was found useful in providing bridge condition ratings in the BMS [16]. It can detect early reinforcement corrosion during the propagation period; larger wave transit times and lower amplitude zones were associated with increased chloride content and the presence of corrosion products [17, 18]. The GPR signal can thus be associated with changes within the concrete during the corrosion process, particularly from the formation of corrosion products to internal crack formation and propagation.

3.2.4 Thermal methods

Infrared Thermography (IRT) is a method used to detect radiation emitted from materials, including concrete. IRT can be passive or active. Passive IRT is commonly used, where specimens are artificially heated before testing to induce temperature differences. Defects disrupt heat transfer, causing localised differences in surface temperature [19]. IRT is preferred for bridge inspection and evaluation due to its high speed, reliability, accuracy, and cost-effectiveness [20]. It can detect sub-surface defects without requiring direct access to the element being inspected, which eliminates the need for traffic disruption and lane closures. Its application in detecting early reinforcement corrosion is still in the development stage. IRT has been used to detect reinforcement corrosion and delamination in RC bridges, but surface-related and environmental factors can affect the test results [16, 21].

3.3 Remote Monitoring

Remote monitoring systems for bridges use sensors connected to a data acquisition system and can be installed in new or existing structures. They are particularly useful for bridges that are difficult to access for regular inspections. These systems provide data that can help with planning and implementing required interventions to prevent premature deterioration. Six different remote monitoring systems are discussed, including their application, principle, and parameters measured, as shown in Table 1.

Table 1: Summarized comparison of the remote monitoring systems

System characteristics	ALS*	ERS*	MRE*	CW*	CR*	ISE* sensors
Application						
Used in new structures	X	-	X	X	-	-
Used in existing structures	-	X	X	-	X	X
Principle						
Anodes placed at various depths in the	X	X	X	X	X	-
HCP technique (measurement of anode vs cathode)	X	X	-	X	-	X
Measured corrosion parameters						
Potential voltage (V)	X	X	-	X	X	X
Electrical current (µA)	X	X	-	X	X	-
Concrete resistance (kΩ)	X	X	X	-	-	-
Temperature (◦C)	X	X	-	-	-	-
Moisture content	-	-	X	-	-	-
Chloride concentrations	-	-	-	-	-	X

*ALS – Anode Ladder System
ERS – Expansion Ring System
MRE – Multi-ring Electrode
CW – CorroWatch
CR – CorroRisk
ISE sensors –Ion Selective Electrode sensor

3.3.1 Time to corrosion monitoring systems

Time to corrosion monitoring systems measures the time to corrosion initiation by monitoring the ingress of aggressive agents, such as chlorides. These systems use a macrocell reinforcement corrosion approach and involve the measurement of current flow between separate anode and cathode areas [22]. Several anodes are placed at different depths within the concrete cover to determine the time to corrosion initiation continuously. The anodes are the same composition as the reinforcing steel to ensure they corrode at the same time. The onset of corrosion of the anodes is determined at any time, provided the cover to reinforcement is known. The depassivation of the anodes is related to an increase in electrical current and a decrease in potential using the specified thresholds [23]. Four methods (Anode-Ladder System, Expansion-Ring System, CorroWatch, and CorroRisk) use this principle.

The Anode-Ladder System (ALS) is used for long-term chloride-induced corrosion monitoring, typically embedded in new RC structures between the reinforcement cage and the concrete surface. The ALS determines the critical depth of chloride content when the six steel anodes that form up the anode ladder depassivates sequentially. The system has been used successfully in various countries to monitor corrosion in new structures [24, 25] The ALS is durable and typically designed for a service life of more than 100 years [23]. However, it cannot be used in submerged structures because it needs to be installed near the concrete surface where sufficient oxygen is available.

The Expansion Ring System (ERS) developed by Sensortec [26] is used in existing structures before corrosion initiation. In structures where the propagation period has begun (when the critical depth of chloride content is reached), the corrosion potential and resistance indicate corrosion risk. The ERS comprises an expansion-ring anode (with six circular steel anodes), a titanium oxide cathode bar and a temperature sensor drilled into the concrete. This system has been tested in the laboratory and on-site, and it was found unsuitable for submerged elements [27].

CorroWatch (CW) and Corrorisk (CR) sensors were developed by Force Technology to provide early warning on corrosion initiation in RC structures. CW sensors are used in new structures, while CR sensors are installed in existing structures that are exposed to aggressive environments or are inaccessible for inspection. Measurements of potential and current in these systems are carried out continuously using a remote monitoring modem or automatic data logger attached to the system. Though these systems have been used in some projects [28], their research is very limited.

3.3.2 Moisture content monitoring systems

Monitoring moisture content in concrete is important for controlling reinforcement corrosion, as a significant drop in electrical resistivity indicates the vulnerability of the concrete to corrosion. The Multi-Ring Electrode (MRE) system is a new technology that can be used to monitor moisture content, and it measures electrical resistance and provides a profile across the sensor depth. The resistivity readings are converted to moisture profiles using concrete-specific calibrated curves [29, 30]. This technology is installed before concrete placement in new structures and drilled and anchored with mortar in existing structures. The sensors need to be connected to a measuring device which records data automatically. Moisture content governs the initiation and progression of reinforcement corrosion, and reducing it to below 40% can stifle corrosion. The MRE is beneficial because it provides electrical resistance measurements in case NDT methods are not used.

3.3.3 Chloride content monitoring systems

New non-destructive methods have been developed to continuously monitor chloride concentration in concrete. One of these methods is using potentiometric sensors or Ion Selective Electrodes (ISE), which can determine free chlorides in RC. The system consists of an ISE sensor and a reference electrode that measures the change in potential between the two, allowing for the estimation of chloride activities and subsequently, the determination of chloride concentration using the chloride activity coefficient. This method can be used in existing structures, especially in inaccessible areas. The ISE sensors are commercially available and have been used in various studies to detect chlorides non-destructively in concrete [27, 31]. They have also been tested in laboratories, in which they were found to successfully measure chloride activity [32]. Some of the sensors include but are not limited to Ag/AgCl-ISE and the ERE 20 reference electrodes.

4. CONCLUSIONS, REMARKS AND FUTURE TRENDS

Reinforcement corrosion poses a significant challenge to the durability of RC structures, often going unnoticed in visual inspections and leading to costly repairs. To address this issue, monitoring technologies are needed to detect corrosion damage throughout the lifespan of RC bridges and enable proactive maintenance. The Struman BMS currently relies mainly on visual inspection, but it needs to incorporate corrosion monitoring methods to detect damage earlier. While progress has been made in developing NDT and remote monitoring methods, further refinement is necessary to effectively incorporate them into the BMS for condition assessments. By incorporating various monitoring methods, including cover depth and chloride measurements, HCP measurement, LPR, and other corrosion onset sensors, the Struman BMS can provide a comprehensive condition assessment, reduce maintenance and repair costs, and improve the speed and scope of condition assessment. It is recommended to use multiple monitoring methods in conjunction to effectively detect and quantify relevant defects in reinforcement corrosion damage.

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