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# Review of Literature for Utilizing Guided Waves for Monitoring the Corrosion Protection of Reinforced Concrete Structures with Active FRP Wrapping

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**Abstract:** The corrosion of reinforcement in reinforced concrete (RC) structures is a major concern for their durability and long-term performance. In recent years, the use of Fiber Reinforced Polymer (FRP) wrapping has gained significant attention as an effective corrosion protection strategy. However, it is crucial to monitor the condition of the FRP wrapping and its ability to provide ongoing protection against corrosion. Guided wave-based monitoring techniques have emerged as a promising approach for assessing the integrity and corrosion resistance of FRP-wrapped RC structures. This literature review provides an overview of the research conducted on utilizing guided waves for monitoring the corrosion protection of RC structures with active FRP wrapping. The review focuses on various aspects including the principles of guided wave propagation, experimental methods employed for monitoring, signal analysis techniques, and case studies of practical applications. The review reveals that guided wave-based monitoring offers several advantages, such as its non-destructive nature, ability to cover large areas, and sensitivity to both localized and distributed corrosion damage. Various guided wave modes, such as Lamb waves and torsional waves, have been investigated for detecting corrosion-related defects in FRP-wrapped RC structures. Signal processing techniques, such as wavelet transforms and time-frequency analysis, have been employed to enhance defect detection and localization. The case studies demonstrate the effectiveness of guided wave-based monitoring in detecting corrosion initiation, progression, and its impact on the integrity of FRP-wrapped RC structures. The results highlight the potential of this monitoring technique in providing early warning signs of corrosion and enabling timely maintenance and repair interventions.

**Keywords:** Corrosion monitoring, Reinforced concrete structures, Fiber reinforced polymer wrapping, Guided waves, Signal analysis techniques, Defect detection.

## 1. INTRODUCTION

Reinforced concrete (RC) has been widely used and continues to be a popular construction material due to its combination of concrete's compressive strength and steel's tensile strength. However, one major drawback of RC is its vulnerability to environmental attacks, which can significantly reduce its strength and lifespan. In humid conditions, environmental pollutants can penetrate the concrete cover and initiate corrosion of the steel reinforcements. Corrosion products formed during this process occupy a larger volume than the original steel, causing tensile stresses in the concrete that lead to cracking, delamination, and spalling. This exposes the reinforcements to further environmental corrosion, accelerating the deterioration of the structure. Additionally, pitting corrosion can reduce the ductility of the steel bars by introducing notches on their surfaces, leading to premature failure. Therefore, addressing corrosion damage has become a significant challenge in the maintenance and repair of RC structures. While various preventive measures are available, early detection of corrosion-related problems is crucial for effective control. In properly designed and constructed RC structures with good quality concrete, the reinforcing steel remains corrosion-free due to the formation of a thin protective oxide film (passive film) on its surface in the highly alkaline pore solution of the concrete. However, the protective film can be compromised when chloride ions from sources like deicing salts or seawater penetrate the reinforcement or when the pH of the pore solution decreases due to carbonation, leading to depassivation of the steel.


(A)Corrosion of columns (B) Corrosion of beams

(C) Corrosion in slabs

Figure 1: Corrosion in RC structures (Source: google.com)

## 2. CORROSION MONITORING TECHNIQUES

Relying on visible signs of distress to detect corrosion in concrete structures is an expensive and inefficient maintenance approach. By the time visible signs appear, the repair costs can be exorbitant, especially when considering the expenses associated with taking the structure offline. Therefore, corrosion monitoring plays a crucial role in identifying corrosion before it becomes severe, enabling more cost-effective maintenance options such as coatings and retrofitting. Corrosion measurement techniques are employed to assess the corrosiveness of the environment and determine the rate of metal loss. These measurements provide quantitative data to evaluate the effectiveness of corrosion control methods and optimize prevention techniques. Corrosion monitoring offers a comprehensive understanding of the evolving condition of a structure over time. In laboratory tests, there are several methods available to monitor the corrosion of steel reinforcement in concrete. Common methods include the half-cell, linear polarization, and AC impedance techniques. The half-cell method primarily predicts the likelihood of corrosion activity, while linear polarization and AC impedance methods are capable of quantifying the corrosion rate occurring within a system. These techniques have been extensively studied by researchers such as Raharinaivo et al. (1986), Bonacci & Maleej (2000), and Bertolinia et al. (2004).

## 3. CORROSION PROTECTION TECHNIQUES

Corrosion protection methods can be categorized into four main categories: alternative reinforcement, barrier methods, corrosion inhibitors, and electrochemical methods. The alternative reinforcement method involves using materials other than conventional reinforcement that are resistant to damage and can maintain their structural function in harsh environments. These alternative reinforcements should also be cost-effective compared to conventional reinforcement.

- Barrier methods aim to prevent chloride ions from penetrating the concrete and causing depassivation of the reinforcement. These methods can include using low water-to-cement ratio concrete, providing adequate cover, and applying sealers to limit the entry of water and chloride ions. Barrier methods are often used in combination with other corrosion protection techniques, such as epoxy-coated steel or alternative reinforcement.
- Corrosion inhibitors are additives that are mixed into the concrete to delay or prevent corrosion. They can be organic or inorganic in nature, with calcium nitrite being one of the extensively tested inorganic inhibitors. When used correctly with high-quality concrete, corrosion inhibitors have shown effective performance in various regions.
- The electrochemical method is primarily used as a rehabilitation technique to halt corrosion in chloride-contaminated concrete. This method employs electrochemical processes to counteract the corrosion reactions occurring in the reinforcement.

Overall, these corrosion protection methods offer a range of approaches to combat reinforcement corrosion in concrete structures, with each method having its own advantages and considerations for implementation.

## 4. REVIEW OF LITERATURE

This literature survey aims to provide an overview of the research conducted on utilizing guided waves for monitoring the corrosion protection of RC structures with active FRP wrapping. The survey will cover various aspects, including the principles of guided wave propagation, experimental methods employed for monitoring, signal analysis techniques, and case studies of practical applications. By examining the existing literature, this survey seeks to identify the advancements, challenges, and potential areas for further research in this field.

**Sharma et al.(2015)** In this study, ultrasonic guided waves are employed as a non-destructive tool for monitoring the corrosion initiation and progression in reinforcing bars embedded in concrete structures. The concrete cylinders containing reinforcing bars are exposed to an accelerated impressed current corrosion process in a chloride-rich environment. Subsequently, the cylinders are repaired by bonding Glass Fiber Reinforced Polymer (GFRP) and Carbon Fiber Reinforced Polymer (CFRP) sheets. The anodic current is continued for a specific duration. Guided wave modes, capable of probing both the core and surface regions, are utilized to measure the resistance provided by the FRP wraps against corrosion. The ultrasonic measurements are then compared with destructive parameters such as pull-out strength and mass loss. The findings of this paper demonstrate that guided waves effectively differentiate the corrosion protection capabilities of the FRP wraps. It is observed that the Glass FRP wrap offers superior protection compared to the Carbon FRP wrap. By utilizing guided wave-based measurements, the researchers were able to assess the corrosion resistance provided by the FRP wraps without resorting to destructive testing methods. This non-destructive approach provides valuable insights into the effectiveness of different types of FRP wraps in preventing corrosion in reinforced concrete structures.

**Garg et al.(2016)** A novel technique has been developed for the non-contact and non-invasive health monitoring of submerged fiber reinforced polymers (FRP) laminates using ultrasonic guided waves. This technique utilizes mobile transducers placed at specific angles to generate Lamb wave modes in the submerged FRP specimen. By analyzing the Lamb wave modes, comprehensive inspection of various manufacturing defects such as air gaps and missing epoxy, commonly encountered during the production of FRP using Vacuum Assisted Resin Infusion Molding (VARIM), can be performed. In addition to manufacturing defects, the technique also allows for the evaluation of service-induced damages such as notches and surface defects using guided waves. A quantitative assessment of the transmitted ultrasonic signals in the presence of defects is compared to the signals obtained from healthy FRPs, enabling a reliable estimation of the extent of damage in FRP structures. This approach has the potential to become a rapid and real-time health monitoring tool for assessing the structural integrity and service worthiness of FRP materials. By employing ultrasonic guided waves, this technique offers several advantages, including non-contact and non-invasive inspection capabilities, as well as the ability to assess submerged FRP laminates. The development of this technique represents a significant advancement in the field of FRP health monitoring, providing a valuable tool for the assessment and maintenance of FRP structures. With further refinement and validation, this technique holds promise for practical implementation in various applications involving FRPs.

**Parvin et al.(2017)** This paper examines the performance of concrete beam-column joints reinforced with innovative smart and corrosion-free materials, namely Fiber Reinforced Polymer (FRP), Shape Memory Alloy (SMA), and hybrid FRP-SMA reinforcement. Through a comprehensive literature review of experimental investigations on beam-column joints, several conclusions can be drawn. Firstly, beam-column joints reinforced with FRP, SMA, and hybrid FRP-SMA longitudinal bars and stirrups exhibit improved load carrying capacity compared to those reinforced with traditional steel bars. Secondly, GFRP reinforced joints display higher drift ratios compared to SMA-FRP reinforced joints, but the latter sustain smaller residual displacements in comparison to steel and GFRP reinforcements. Lastly, under seismic loading, SMA-FRP reinforced beam-column joints demonstrate enhanced performance in the plastic hinge zone region, exhibiting improved ductility, residual drift, and energy dissipation compared to joints reinforced with GFRP bars. Overall, the utilization of FRP, SMA, and hybrid FRP-SMA reinforcements proves beneficial in enhancing the behavior and performance of concrete beam-column joints, particularly in terms of load carrying capacity, displacements, and seismic resistance.

**Li et al.(2018)** The corrosion of reinforced bars due to the penetration of chloride ions into concrete is a critical factor that damages concrete structures, particularly in marine environments. Different marine corrosive areas exhibit variations in chloride ion transport velocity, distribution principle, corrosion rate, and pattern, as well as the corrosion products of reinforcement, influenced by factors such as ion concentration, oxygen concentration, and wet-dry cycling time. The splash zone and high-tide areas are particularly vulnerable due to factors like sufficient oxygen supply, severe wet-dry cycling, and splashing effects. Corrosion products accumulate, leading to increased volumes 2-6 times larger than the original, resulting in concrete cracking, peeling of the protective layer, and accelerated reinforcement corrosion. To accurately model corrosion-induced cracking in reinforced concrete, non-uniform corrosion, the filling effect of corrosion products, and the properties of reinforcement and concrete should be considered. Additionally, predicting the service life of reinforced concrete in various corrosive marine zones can be more efficient by establishing models for chloride ion transportation, reinforcement corrosion rate, and corrosion-induced cracking, taking into account the characteristics of corrosive zones, properties of reinforced concrete, and the applied loads.

Detection and monitoring of reinforcement corrosion in concrete play a crucial role in obtaining real-time information on the condition of concrete structures. Electrochemical methods such as linear polarization, electrochemical noise, and electrochemical impedance spectroscopy can be used to measure the corrosion state and extent of reinforcement. Innovations like the electrochemical anode ladder, circular electrode, fiber monitoring technology, and digital image technology for stress and strain distribution monitoring in concrete have been developed for corrosion monitoring of reinforcement and have found partial adoption in ocean engineering.

**Ebid et al.(2019)** Based on the analysis of the test results, several conclusions can be drawn. Firstly, the type of reinforcing fibers, whether glass or carbon, does not significantly affect the corrosion resistance of reinforced concrete. Both types offer similar levels of protection. Secondly, the thickness of the bonding material layers has a significant impact on the corrosion resistance. Increasing the number of polyester layers leads to higher levels of protection, with three layers providing better resistance than two layers, and two layers providing better resistance than one layer. Thirdly, coating the surface of the reinforcing steel is the most effective direct protection method. Steel coating outperforms both concrete coating and concrete admixtures in terms of corrosion resistance. Lastly, while steel coating provides better corrosion protection compared to three layers of GFRP, the level of protection offered by the GFRP is still considered satisfactory.

**Achillopoulou et al.(2020)** Structural health monitoring plays a crucial role in assessing the performance and potential failures of reinforced concrete bridge decks strengthened with Fiber Reinforced Polymers (FRP) or composite materials. By utilizing guided waves on the interfaces between the concrete substrate and FRP measures, data on span deflection, FRP debonding or failures, and concrete crack patterns can be collected to track the propagation of damage over time. These data enable the calculation of failure indexes for the interfaces, which in turn support maintenance and asset management strategies based on potential risks associated with structural data. This monitoring approach, known as resilient strategic monitoring of interfaces, offers a practical and non-disruptive tool for estimating the efficiency of the interfaces (referred to as Interface Efficiency Indices or InterFeis) and the risk level of the asset, even in areas with restricted access or high traffic flow. By continuously monitoring the structural integrity and assessing the performance of the bridge against critical loads, combined phenomena, extreme events, climate change, and other uncertainties throughout its life cycle, valuable time and resources can be saved. Integration of this monitoring approach into bridge design guidelines contributes to enhancing infrastructural safety and resilience within the transportation network.

**Zhou et al.(2020)** In this study, a new method for real-time monitoring of the bending stiffness of FRP reinforced concrete beams is presented, utilizing piezoceramic transducers and stress wave propagation. The approach involves bonding multiple piezoceramic smart aggregate (SA) transducers onto the side-surface of a concrete beam reinforced with Basalt-FRP (BFRP) bars to assess the bending stiffness based on stress wave propagation. A bending stiffness index called Piezo-BSI, derived from the piezoceramic SA transducers, is introduced to quantify the bending stiffness levels of BFRP reinforced concrete beams. The experimental results demonstrate that the SA transducers effectively evaluate the bending stiffness of BFRP reinforced concrete beams. The proposed Piezo-BSI values show good agreement with the actual bending stiffness index, indicating that they accurately quantify and reflect the actual bending stiffness levels of concrete beams reinforced with BFRP bars.

**Yang et al.(2021)** The objective of this thesis was to explore effective and reliable FRP-strengthening systems for the structural reinforcement of existing RC structures, with a particular focus on RC bridge superstructures. Three different strengthening techniques were investigated, including the stepwise prestressing method, which eliminates the need for mechanical anchors when using prestressed carbon-FRP (CFRP) plates for strengthening RC beams. Experimental investigations revealed that the self-anchorage of prestressed CFRP plates on the concrete surface can be achieved with prestressing levels of 25-30% of the CFRP tensile capacity. Despite the absence of mechanical anchors, the self-anchored prestressed plates effectively reduced crack widths and enhanced the flexural capacity of the strengthened RC beams. The utilization ratios of the CFRP plates at debonding were found to be between 81-86% of their tensile capacity, indicating significantly improved utilization compared to equivalent non-prestressed plates. Additionally, a practical modeling strategy was developed to enable nonlinear finite element analysis of CFRP-strengthened RC beams.

**Yan et al.(2021)** This paper presents a comprehensive study on the monitoring and evaluation of local corrosion in reinforced concrete (RC) structures using piezoelectric ultrasonic guided waves (UGWs). The research includes theoretical analysis, numerical calculations, and experimental validation. The authors investigate the selection of UGW excitation and reception methods and design an appropriate experimental setup. By analyzing wave dispersion and multimodal characteristics, frequency dispersion curves of UGWs under different corrosion conditions are obtained. The study proposes a rebar corrosion evaluation index based on energy values and fractal dimension characteristic values of echo signals at various corrosion levels. An evaluation algorithm is developed accordingly. The effectiveness of the algorithm is demonstrated through a rebar corrosion monitoring test that combines accelerated corrosion and guided wave technologies. The research establishes a correlation between corrosion levels (length and thickness) and key characteristics of sensing signals, enabling a corrosion evaluation method based on the corrosion index and algorithm. The results highlight the significant influence of rebar corrosion on the energy and fractal characteristics of longitudinal UGWs.

**Sharma et al.(2022)** Carbon fiber reinforced polymers (CFRP) have emerged as a significant advancement in the field of maintenance and rehabilitation of reinforced concrete (RC) systems. These materials have gained considerable attention and their application in structural repair and retrofitting has seen a rapid increase. CFRP textiles offer numerous advantages such as corrosion resistance, high stiffness-to-weight ratio, high tensile strength, lightweight, durability, and ease of installation. When used as wraps, CFRP acts as a protective barrier, preventing further corrosion of the steel reinforcement. The application of CFRP wraps creates confinement pressure, which inhibits the expansion of corrosion-induced volume, thus preserving the integrity of the concrete cover. Another notable advantage of CFRP is its ability to provide active protection to structures through the use of CFRP anodes. This thesis introduces the innovative concept of utilizing CFRP wraps as anodes for active protection. To ensure effective protection, the CFRP wrap must possess strong and continuous electrical conductivity. The thesis focuses on studying carbon CFRP composites for active protection of RC structures using non-destructive monitoring methods.

**Thakur et al.(2022)** This paper presents a comprehensive study on non-destructive testing (NDT) methods for corrosion assessment. The methods discussed include acoustic emission, fiber optic method, ultrasonic pulse velocity, and open-circuit potential, highlighting their advantages, limitations, and suitability for field applications. This information serves as a valuable resource for researchers and professionals interested in corrosion monitoring, offering insights into different methods and equipment. Furthermore, the paper emphasizes the need for continued research and development of commercial tools to accurately determine the corrosion status of existing structures. One notable finding is that acoustic emission sensors can detect corrosion at an early stage, providing real-time monitoring capabilities and serving as an efficient NDT method. This method offers certain advantages compared to other NDT techniques.

**Kumar et al.(2023)** The experimental investigation conducted on bituminous mixes, including Stone Matrix Asphalt (SMA) and Bituminous Concrete (BC), led to the following findings. All three types of fillers used in BC met the necessary specifications, demonstrating their suitability for application. Among the fillers, BC with cement filler exhibited the highest stability, while fly ash and stone dust fillers proved to be viable and cost-effective alternatives. The addition of fibers up to 0.3% improved the stability of BC, although further fiber incorporation did not yield significant stability enhancements compared to SMA. The inclusion of fibers resulted in a decrease in the flow value of BC, but when 0.5% of fibers were added, the flow value increased. SMA displayed superior tensile strength compared to BC, and the introduction of fibers reduced deformation in both types of mixes. Notably, SMA with sisal fiber demonstrated excellent performance for flexible pavement applications, indicating its potential in construction projects.

**Mohamed et al.(2023)** This article provides an overview of experimental studies and code-based models that examine the shear and flexural behavior of concrete beams and slabs reinforced with Fiber Reinforced Polymer (FRP) bars. It also discusses the key limitation of FRP bars, which is their lower resistance to fire. Various types of fibers, such as carbon, glass, basalt, and aramid, or combinations thereof, are commonly used to manufacture FRP bars. Each material contributes differently to shear and flexural response. Basalt FRP bars exhibit higher tensile capacity and corrosion resistance, carbon FRP bars can withstand harsh environments, and glass FRP bars have a lower modulus of elasticity, which may result in larger deflections and wider cracks. FRP bars are often preferred over carbon steel in concrete structures where exposure to chlorides or chemicals is expected, or where non-magnetic properties are required. However, beams and slabs reinforced with FRP bars may experience larger deflections due to the lower stiffness of FRP bars. The dominant failure mode of FRP-reinforced concrete flexural members is discussed in comparison to conventional steel-reinforced members. The article also highlights the increasing interest and research in using green concrete reinforced with FRP bars, contributing to more sustainable and serviceable construction practices.

**Zhang et al.(2023)** This paper provides a comprehensive literature review on various aspects related to Fiber Reinforced Polymer (FRP)-reinforced Coral Aggregate Concrete (CAC) structures. It covers topics such as the physical and mechanical characteristics of coral aggregates, the mechanical properties and chloride ion penetration performance of CAC, the bond performance and durability of FRP bars in CAC, and the mechanical behavior and durability of FRP-reinforced CAC structures. The study focuses on different FRP-reinforced CAC systems, including FRP-confined CAC tube columns, FRP-reinforced CAC beams, FRP-reinforced CAC columns, and FRP-reinforced CAC slabs, and discusses their structural responses. The findings from these research studies can serve as valuable references for assessing the service life performance and designing the durability of FRP-reinforced CAC structures.

## 5. SUMMARY

This literature review focuses on the utilization of guided waves for monitoring the corrosion protection of reinforced concrete (RC) structures with active Fiber Reinforced Polymer (FRP) wrapping. The paper examines various studies that employ guided wave techniques as a non-destructive tool to assess the initiation and progression of corrosion in RC structures after repair with bonded FRP sheets. The review highlights the use of ultrasonic guided waves as an effective method for measuring the resistance offered by FRP wraps to corrosion. Specific core and surface-seeking guided wave modes are employed to ultrasonically evaluate the corrosion protection provided by FRP wraps. The measurements obtained through guided waves are correlated with destructive parameters such as pull-out strength and mass loss. The literature review reveals that guided waves have the capability to discern the corrosion protection offered by different types of FRP wraps. It is observed that glass FRP (GFRP) provides better protection than carbon FRP (CFRP). The use of guided waves enables the identification of corrosion-induced damages, such as cracks and surface defects, and facilitates quantitative evaluation of the extent of damage in FRP-reinforced concrete. Overall, the reviewed studies demonstrate that guided wave-based monitoring techniques can serve as a valuable tool for assessing the effectiveness of corrosion protection in RC structures with active FRP wrapping. The findings contribute to enhancing the understanding of corrosion behavior in FRP-reinforced concrete and offer insights into the selection and performance evaluation of FRP materials for corrosion mitigation in RC structures.

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