# Damage Detection in FRP-Reinforced Concrete Elements

Subjects: Engineering, Civil

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Fiber-Reinforced Polymer (FRP) composites have emerged as a promising alternative to conventional steel reinforcements in concrete structures owing to their benefits of corrosion resistance, higher strength-to-weight ratio, reduced maintenance cost, extended service life, and superior durability.

Keywords: Fiber-Reinforced Polymer (FRP) ; ground-penetrating radar (GPR) ; ultrasonic testing (UT)

## 1. Introduction

The construction industry predominantly utilizes two structural materials: steel and concrete [1]. However, with the increasing demand for extended service life, reduced maintenance, enhanced resilience, and sustainability, the limitations of traditional construction materials (e.g., steel reinforced/prestressed concrete, structural steel, and timber) have become more evident. In response to these demands, Fiber-Reinforced Polymer (FRP) composites have emerged as a promising alternative, offering improved durability and performance and providing the potential for extended service life and reduced maintenance costs [2]. FRPs are composite materials composed of reinforcing fibers impregnated in a polymeric resin. The reinforcing fibers in the composite are the main load-carrying (reinforcing) elements, while the polymeric matrix or resin helps to form the desired geometry and transfers forces to and between the fibers. In general, the types of FRPs used in the construction industry based on the type of fibers are GFRP (glass-FRP), CFRP (carbon-FRP), BFRP (basalt-FRP), and AFRP (aramid-FRP) composites.

## 2. FRP-Reinforced Concrete (FRP-RC) Elements

Over the past three decades, FRP composites have gained significant popularity in civil engineering, attributed to mainly their increased durability, corrosion resistance, and higher strength-to-weight ratio [3]. They have been used as reinforcement for constructing new structures as well as rehabilitating existing ones. FRPs can be used either in conjunction with concrete elements or as stand-alone structural or non-structural elements in buildings as well as bridge structures. When used in conjunction with concrete elements, FRP application can be divided into two categories: (1) internal application with FRP bars/rods and strands/tendons for new FRP-reinforced/prestressed constructions and (2) external application with FRP laminates/plates/jackets, sheets/fabrics/wraps, and near-surface mounted (NSM) bars for the strengthening, retrofitting, and repair of existing structures.

## 3. Advantages of FRP-RC Elements

Corrosion is one of the main issues that can compromise the serviceability and safety of conventional steel-reinforced/prestressed concrete structures. A 2002 Federal Highway Administration (FHWA) study conducted in partnership with the National Association of Corrosion Engineers (NACE) International, now known as the Association for Materials Protection and Performance (AMPP), estimated the average annual direct cost of corrosion for US highway bridges to be $8.29 billion [4]. A decade later, in 2013, NACE International estimated an increase in this cost to $13.6 billion per year [5]. Despite these estimates being decades old, the issue of corrosion persists, and it remains a primary cause of bridge deterioration in the US. The latest 2021 American Society of Civil Engineers (ASCE) infrastructure report card scored America's bridges a low grade of C and emphasized the use of innovative materials such as ultra-high-performance concrete (UHPC), corrosion-resistant reinforcement, high-performance steel, composites, and improved coatings to increase the lifespan of the nation's bridges [6].

FRP composites are one of such relatively new construction materials that are resistant to all the factors causing corrosion in steel-reinforced concrete (RC) structures, such as a decrease in concrete pH due to carbonation, chloride penetration, and the diffusion of halides and chemicals [7][8][9][10]. Further, FRP composites are not affected by electromagnetic disturbances from sources such as railroads with DC or AC traction, overhead power lines, and unbalanced currents from three-phase power systems, which contribute to the corrosion of metal structures and the deterioration of reinforced concrete [11]. Hence, the use of FRPs as reinforcement in concrete elements is strongly justified for locations where the corrosion of conventional steel reinforcement poses significant economic and safety risks [12].

Additionally, better mechanical performance, superior durability, and the environmental implications of the FRP composites [13][14] offer more flexibility for engineers to build structures that last longer. When compared to steel bars, FRP bars have significantly higher tensile strength [15], about one-fourth of the density of steel, and can achieve a longer service life [16]. Nevertheless, the application of FRP composites is associated with a higher initial cost, which is often quoted as one of the major drawbacks to its implementation. However, in recent years, the initial cost of GFRP bars has benefitted due to price fluctuation in the metal market worldwide since the mid-2020s and has even dropped due to the growth of the GFRP bar industry [17]. Further, despite the fact that FRP bars initially cost more than traditional steel bars, a life cycle cost study shows that they can rather be cost-effective in the long run [18]. Because of these factors, FRP bars are progressively becoming a reliable material in civil engineering. This is evident from a recent example of a coastal bridge fully reinforced with GFRP bars built in 2021 at the 23rd Avenue over Ibis Waterway located in Florida, USA, which is the second of its kind [3][19].

## 4. Damage in FRP-RC Elements

Although FRP bars offer improved durability and performance compared to steel in certain aspects, there are concerns about potential damage and defects in both FRP bars and FRP-reinforced concrete (FRP-RC) elements. Many of the serviceability issues related to conventional RC elements such as cracking, permeability, carbonation, chloride content, and concrete cover may not pose the same concern for FRP-RC elements. FRP bars and FRP-RC elements are prone to a unique set of defects as compared to their steel counterparts. For instance, the bond behavior of the FRP bar–concrete interface differs from that of the steel bar–concrete interface [20]. The bond failure of FRP bars not only occurs in the concrete but also inside the bars, unlike a steel bar [21][22]. Similarly, in a study conducted by Valentine [23], it was found that cracks are the predominant defect reported by the bridge inspectors in the inspection of FRP-reinforced bridge decks, which can be attributed to the low modulus of elasticity of the FRP bars. In this paper, the detectability of three different types of potential damage that might occur in the FRP reinforcements—rupture, debonding, and loss of cross-sectional properties—will be investigated. It should be noted that the term “potential damage” has been used due to the fact that, unlike steel bars, where corrosion is the obvious damage to be expected, there is very limited information on the damage that is possible in FRP bars, a relatively new, corrosion-resistant construction material.

## 5. Inspection of FRP-RC Elements

The literature on the application of non-destructive testing (NDT) methods for the internal application of FRP is limited and scarce. There is no standard guide available for the inspection of FRP-RC elements [24][25][26]. This represents a knowledge gap that this research study attempts to address. Hence, although the use of FRP in highway infrastructures has been on the rise [27][28][29][30], the absence of reliable condition assessment methods for FRP-RC elements has significantly hindered its extensive application. Bridge engineers are hesitant to use materials that are difficult to detect and assess for maintenance. Therefore, there’s a pressing need for research into effective condition assessment techniques for FRP-RC elements, which could greatly encourage the adoption of FRP in future construction projects.

The inspection of FRP-RC elements is limited to detecting the initiation of FRP bars–concrete debonding [31][32] or the initiation of fractures in the FRP [33][34] rather than detecting the damage in the bars themselves. This is in most part because it was believed that FRP bars are undetectable or have low detectability, making it impossible to spot them effectively during an inspection. NDT techniques used for inspecting steel-reinforced concrete rely on identifying differences in specific properties, such as the dielectric constant and acoustic impedance, between steel and concrete. However, FRP reinforcements, unlike steel, exhibit properties similar to concrete that include non-conductivity and comparable density. These similarities introduce complexities in detecting/inspecting FRP, making it a more challenging task.

However, Ékes [35] demonstrated for the first time that ground-penetrating radar (GPR) can detect both CFRP and GFRP bars embedded in concrete and therefore concluded that it is a suitable tool for locating FRP bars on bridge decks. Another study conducted by the authors of this research showed that the detectability of FRP bars/strands increased with the rise in the antenna center frequency of the GPR device and further showed that phased array ultrasonic (PAU) testing is also effective in detecting GFRP and CFRP strands [36]. PAU is sensitive in detecting air voids and hence it was effective only for FRP strands because of the air voids present within the twisted wires of strands and the uneven surface of the strands, unlike the smooth surfaces of bars. However, these studies do not give any information about the detectability of damage in FRP reinforcements using GPR and PAU.

This research explores the feasibility of employing commercially available GPR and PAU devices to identify damage in FRP bars embedded in concrete. These methods are selected among various NDTs because they are widely used in inspecting steel RC elements [24]. Further, this research also aims to determine the detection of damage in the concrete elements reinforced with FRP using GPR and PAU devices. Three small-scale slabs were fabricated with damage simulated in bars and concrete to evaluate the feasibility of the chosen NDT method. The results of this study show that GPR devices can detect damage in FRP bars/strands and concrete. However, it was observed that PAU devices are effective only for detecting damage in CFRP strands along with steel bars and concrete.

The results of this study can be utilized to drive further research on the non-destructive testing of FRP-RC elements and embedded FRP bars. One such prospective field of study in the future could be the use of NDT damage detection methods in conjunction with diagnostic load testing for bridges. Diagnostic load tests are performed to evaluate the integrity and performance of bridges and identify local damage areas based on the variations in measurements of deflections, strains, and vibration responses [19]. Once local damage areas are identified, NDT can be employed to perform a more thorough and refined damage assessment within those areas. When used together, NDT and diagnostic load testing can achieve efficient, comprehensive, and dependable damage detection and assessment of FRP bars embedded in concrete. These will provide owners with inspection options and help them in decision-making regarding necessary countermeasures for ensuring the bridge’s safety and longer service life.

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