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Nondestructive Testing (NDT) for Damage Detection in Concrete Elements with Externally Bonded Fiber-Reinforced Polymer

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Abstract: Fiber-reinforced polymer (FRP) composites offer a corrosion-resistant, lightweight, and durable alternative to traditional steel material in concrete structures. However, the lack of established inspection methods for assessing reinforced concrete elements with externally bonded FRP (EB-FRP) composites hinders industry-wide confidence in their adoption. This study addresses this gap by investigating non-destructive testing (NDT) techniques for detecting damage and defects in EB-FRP concrete elements. As such, this study first identified and categorized potential damage in EB-FRP concrete elements considering where and why they occur. The most promising NDT methods for detecting this damage were then analyzed. And lastly, experiments were carried out to assess the feasibility of the selected NDT methods for detecting these defects. The result of this study introduces infrared thermography (IR) as a proper method for identifying defects underneath the FRP system (wet lay-up). The IR was capable of highlighting defects as small as 625 mm^2 (1 $in.^2$) whether between layers (debonding) or between the substrate and FRP (delamination). It also indicates the inability of GPR to detect damage below the FRP laminates, while indicating the capability of PAU to detect concrete delamination and qualitatively identify bond damage in the FRP system. The outcome of this research can be used to provide guidance for choosing effective on-site NDT techniques, saving considerable time and cost for inspection. Importantly, this study also paves the way for further innovation in damage detection techniques addressing the current limitations.

Keywords: CFRP laminates; externally bonded FRP; NDT methods; inspection; damage detection

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1. Introduction

1.1. FRP Composites

In steel-reinforced concrete (RC) structures, corrosion poses a significant problem, causing the loss of cross-sectional area, deterioration of the rebar-to-concrete bond, and deterioration of the concrete cover [1,2]. Various methods exist to prevent or mitigate corrosion, along with techniques for strengthening, repairing, and retrofitting deteriorated structures. Fiber-reinforced polymer (FRP) composites offer an alternative to steel for strengthening purposes due to their mechanical properties and chemical resistance [3–5]. They are favored for their strength-to-weight ratio, ease of installation, and adaptability to curved surfaces. FRP composites can be produced using various types of fibers, such as glass, carbon, basalt, and aramid [6–9]. Thermosetting resins, such as polyester, epoxy, and vinyl ester, are commonly employed with fibers in the production of FRP composites.

Extensive research efforts have been dedicated to examining the long-term durability of FRP materials. The findings indicate that FRP materials exhibit minimal degradation over extended periods [10]. Additionally, when compared to traditional materials, FRP composites display superior resistance to salt, water, and various chemicals. Notably, substances like oil and other heavy hydrocarbons have a comparatively reduced impact on FRP composites in comparison to their effects on conventional materials [11–14]. The aging process typically results in the need of repairs in conventional steel-RC structures. Furthermore, structural elements often require strengthening and retrofitting due to design and construction errors, damage from exceptional events or accidental impacts, natural disasters, and functional modifications [15,16].

FRP laminates (i.e., wraps/fabrics, strips, and plates) are the most common externally bonded FRP (EB-FRP) systems for strengthening existing structures. The application techniques can be categorized into 'wet lay-up', 'prepreg', and 'precured' systems. In a 'wet lay-up' system, the resin impregnation occurs on site, while in a 'prepreg' system, it takes place at the manufacturer's facility, with the resin matrix being partially cured beforehand. Conversely, 'precured' FRP systems, which are manufactured off site, are available in multiple forms [17]. Commonly, the same polymer resin is also employed to act as an adhesive in plates or as a primer, putty coat, and saturant in 'wet lay-up' systems [18].

1.2. Application of EB-FRP Systems

The utilization of FRP composites in concrete bridges has experienced substantial growth in recent decades. EB-FRP systems are generally applied to the tension side of the concrete girders, beams, and slabs to enhance their flexural strength. They can also be used to provide additional shear strength when applied on the sides of beams and girders. In seismic zones, FRP wraps can be used for columns to increase pseudo-ductility due to the induced confinement of the concrete [19]. Although, research studies have indicated substantial increases in flexural ultimate strength, often ranging from 40% to 95%, and stiffness, typically showing improvements of 17% to 95% [20–22], design guidelines impose strengthening limits to guard against collapse of the structure. The effectiveness of these applications depends on factors like proper anchorage systems, reinforcement configuration, and FRP type. Due to its ease of installation, the wet-layup system is preferred over other systems when used as an externally bonded strengthening material. Figure 1 shows a typical application procedure for EB-FRP systems. Before strengthening, the extent of deficiency and suitability of FRP strengthening should be evaluated. Surface preparation, which removes contamination and weak surface layers, is one of the most important steps in adhesive bonding of composite laminates to the concrete elements [23–25]. Improper surface preparation can lead to premature failure of bonded FRP sheets due to rupture/debonding [26]. It is crucial to ensure that fibers are thoroughly wetted, and the amount of resin is maintained at the minimum level as per the manufacturer's recommendations.

While a wide variety of fiber and resin combinations exist, carbon FRP (CFRP) with epoxy resin stands out as the most employed type for external applications (strengthening) in RC elements within the US market. It has been extensively studied in the available literature and it has consistently demonstrated superior performance in aggressive environments (typically, there is less than a 10% reduction in tensile strength when subjected to harsh environmental conditions), and its higher stiffness, compare to other types of FRPs [27], makes it more suitable for strengthening applications.

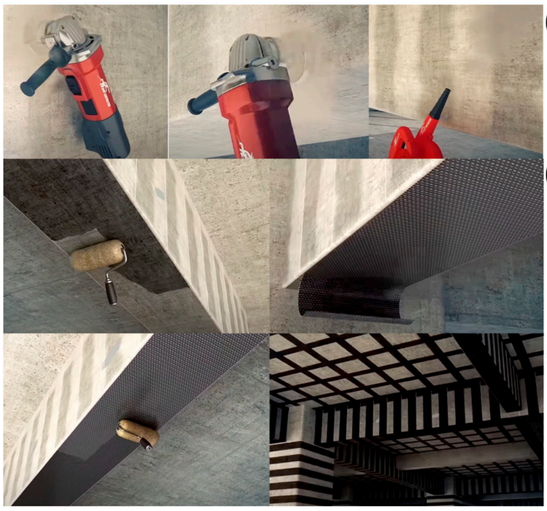


Figure 1. Application of an Externally Bonded FRP system [28]; (**a**) surface preparation; (**b**) application of resin and FRP sheets; (**c**) coating and finishes.

Several organizations have developed guidelines for the design of reinforced concrete structures externally bonded with FRP composites [29–31]. For external application, different systems can be used for strengthening, retrofitting, or repairing of RC elements that are normally reinforced with conventional steel. However, there are currently no established inspection protocols for evaluation and maintaining structures exposed to demanding environments or dealing with potential issues in the FRP system. These issues in FRP applications can be traced back to various causes, encompassing mechanical, environmental, and design considerations, as well as fabrication and workmanship [27].

1.3. Inspection of EB-FRP Concrete Elements

Nondestructive testing (NDT), in general, is defined as "an examination, test, or evaluation performed on any type of test object without changing or altering that object in any way, in order to determine the absence or presence of conditions or discontinuities that may have an effect on the usefulness or serviceability of that object." [32]. NDT methods have been increasingly used for quality control, quality assurance and quality assessment of both new and old structures [33–35]. Many NDT techniques, such as visual inspection (**VT**) [36,37], tap testing (**TT**) [38–42], impact echo testing (**IE**) [43–47], microwave testing (MW) [48–53], ground penetrating radar (**GPR**) [54–58], ultrasonic testing (**UT**) or phased array ultrasonic testing (**PAU**) [59–64], infrared thermography testing (**IR**) [56–64], acoustic emission testing (**AE**) [65–68], laser testing (**LT**) [69–74], radiographic testing (**RT**) [75], etc., have been studied for detecting damage in the externally applied FRP composites.

The external application of FRP composites to strengthen/repair RC structures involves three materials: internal reinforcement (typically steel rebars, with the potential for future adoption of FRP rebars), and concrete and FRP composites (wet lay-up system), along with the different interfaces. Defects associated with the external application of FRP composites can occur within either of the three materials or at the interface between them [15].

The present study was divided in the following tasks: The initial step involved identifying and classifying the location of potential damage and defects in externally bonded FRP (EB-FRP) concrete elements. This included determining where the damage occurs on the element (i.e., rebar, concrete, or interface, as seen in Figure 2). Understanding "where" the potential defects can occur was crucial to further investigation, as it facilitated precise targeting of the specific location. Along with the "where", it was essential to address the timing and reasons behind the occurrence of damage. This involved investigating the factors that contribute to defects/damage in FRP external applications and when they manifest (i.e., during fabrication or service life). Understanding the "why" and "when" helped uncover the root causes of the potential defects/damage. Building upon the understanding of the location, timing, and causes, the subsequent step was to conduct a literature review focusing on the damage and defects of EB-FRP concrete elements. The objective was to identify and classify observed and potential damage comprehensively. This step aimed to answer the question of "what" potential defects/damage exist. Finally, an experimental phase was carried out to assess the selected NDTs. Two small-scale slabs were fabricated with different rebars and internal/external defects to evaluate the feasibility of the chosen NDT method. The findings of this research offer a reference for inspectors in choosing the most suitable on-site NDT techniques, with the prospect of saving both time and cost significantly.

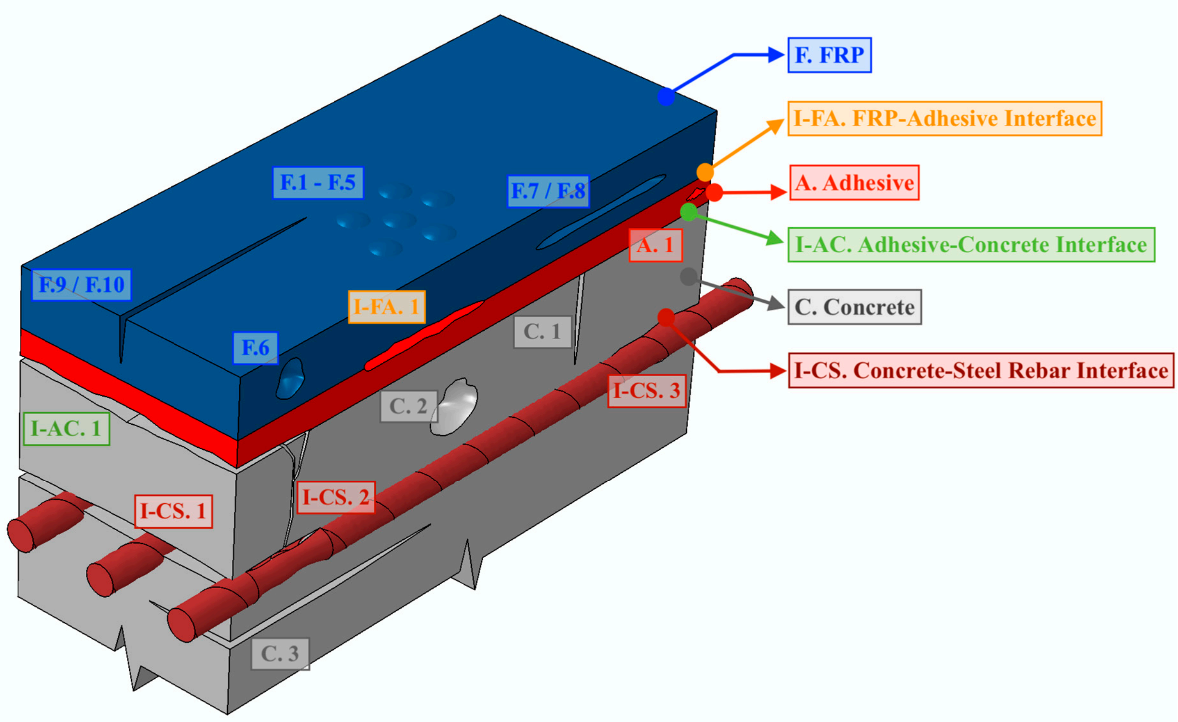


Figure 2. Defects in EB-FRP concrete elements [15].

2. Location of Potential Defects or Damage

The term "defect" can be defined as "discontinuity whose size, shape, orientation or location (1) makes it detrimental to the useful service of its host object or (2) exceeds an accept/reject criterion of an applicable specification" [76], while damage can be defined as "changes introduced into a system that adversely affect its current or future performance" [77]. Defects denote material-level anomalies, while damage encompasses the combination of these material-level imperfections, ultimately evolving into system-level deterioration. Breaking down the EB-FRP concrete element into its distinct components enables a focused approach to examine the potential defects and damage that may arise during its service life. Initially, potential damage and defects in EB-FRP concrete elements were categorized based on their likely locations, i.e., where they occur, typically falling into three distinct groups: (1) defects in FRP composites (i.e., FRP composites (F)); (2) bond defects (i.e., FRP–adhesive interface (I-FA), adhesive (A), and adhesive–concrete interface (I-AC); and (3) defects in concrete (i.e., concrete (C) and concrete–steel rebar interface (I-CS)) [15]. In a prior study, the authors classified damage based on its location and initiation time, while also identifying its sources. Figure 2 illustrates the location of the most likely defects in EB-FRP concrete elements [15].

3. Damage and Defects in EB-FRP Concrete Elements

Once the locations of potential defects have been determined and the question "where do they occur?" has been answered, it is important to establish "what" damage and defects exist that affect the performance of the EB-FRP concrete element. Tables 1–3 present the defects shown in Figure 2 with brief descriptions. These defects were identified based on the available literature [6,33,78–87] and can be further explored in Malla et al. (2023) [15] for more in-depth information.

Table 1. Defects in FRP composites (F—FRP composites).

Defects	Description
F.1 Surface Defects—Blisters	Blisters are observed as bubble-like formations on the surfaces of the EB-FRP system because of the combined action of freeze–thaw cycles and entrapped moisture. However, since their effects are primarily limited to the surface, this imperfection have minimal impact on the structural performance of the structure.
F.2 Surface Defects—Wrinkling	Wrinkling appears as creases or folds on the surface of the FRP composites, often occurring at corners and curves of the structure. It is caused by improper installation practices. The safety of the structure is compromised only if they result in insufficient surface contact of the FRP composites with the substrate.
F.3 Surface Defects—Scratches	Scratches represent marks or wounds on the surface of the FRPs and can occur at any point during the installation and service life of the structure. They become detrimental when they evolve into full-depth cracks.
F.4 Surface Defects—Discoloration	Discoloration manifests as stains on the FRP composites and is primarily induced by exposure to UV rays, heat, chemicals, fire, excessive strain, subsurface defects, voids, and moisture penetration. These stains serve as indicators of composite degradation, frequently preceding the occurrence of cracks and embrittlement.
F.5 Surface Defects—Fiber Exposure	Improper handling and installation of FRP composites results in exposed fibers of FRP composites. These exposed fibers serve as entry points for moisture and contamination into the composite, leading to the deterioration of its properties.
F.6 Voids in FRP	Voids are cavities that exist at the fiber–matrix interface, formed as a result of entrapped air within the layers of the composites. They can also occur due to the overlapping of fabrics during fabrication or installation. They cand lead to a reduction in their laminar shear strength.
F.7 Debonding	Debonding within FRP composites refers to the separation at the interface between the two components of the composite: the fiber and the matrix. This separation is primarily triggered by the presence of surface moisture on the fibers. The consequences of debonding encompass a loss of composite action.
F.8 Delamination in FRP Layers	Delamination in FRP involves the separation at the interface between the layers. It is frequently induced by factors such as moisture, foreign object contamination, and trapped air between the FRP layers. The repercussions are significant and can result in a substantial reduction in the material's shear transfer capacity.
F.9 Cracks	Cracks in FRP composites primarily occur parallel to fiber layers due to factors like trapped air, uneven resin distribution, and exposure to impact and service loads. Failure risk increases as cracks deepen and widen under sustained or dynamic loading.
F.10 Impact Damage in FRP	Impact damage can happen from both slow-moving and fast-moving objects. Slow-moving objects may harm the internal structure, while fast-moving ones cause severe surface damage. Regardless, impact damage harms the system's structural integrity.

Table 2. Bond defects (**I-FA:** FRP–adhesive interface; **A:** adhesive; **I-AC:** adhesive–concrete interface).

Defects	Description
I-FA.1 FRP–Adhesive Debonding	FRP–adhesive debonding between laminates can occur due to factors such as the use of an inappropriate adhesive, improper mixing, poor adhesive application, or insufficient curing of the adhesive. These factors can lead to a weakened bond between the FRP layers, reducing the effectiveness of the composite material.
A.1 Voids in Adhesive	Voids are areas where FRP composites lack contact with the concrete substrate. They result from trapped air, contaminants in the resin, or substrate irregularities, and can sometimes resemble "bubbles." Voids create stress concentrations, weakening the bond strength of the FRP application.
I-AC.1 Adhesive–Concrete Debonding	Debonding is the separation of externally applied FRP from the concrete substrate, often due to factors like high loads, improper installation, inadequate resin curing, or surface moisture. Excessive debonding can lead to brittle concrete fracture, as the composite loses its ability to transfer stresses to the substrate.

Table 3. Defects in concrete (C: concrete; **I-CS:** concrete–steel rebar interface).

Defects	Description
C.1 Cracks in Concrete	Obscured cracks in the concrete substrate, hidden beneath the externally applied FRP, result from various factors such as shrinkage, thermal stresses, chemical exposure, and more. They can lead to structural failure by allowing corrosive chemicals to attack steel reinforcement and weaken the bond between FRP and concrete.
C.2 Voids in Concrete	Concrete voids, unrelated to external FRP application, stem from inadequate design and construction practices during casting. Causes include improper vibration, concrete quality issues, rebar congestion, consolidation problems, and irregular aggregates. These voids lead to gradual structural deterioration.
C.3 Delamination/Spalling in Concrete	Delamination is caused by the relatively weaker nature of concrete compared to the adhesive and FRP materials. It occurs when high stresses in the FRP material pull the concrete apart, typically near cracks or the ends of the FRP system where stress buildup is significant. Delamination failures are sudden and brittle, posing a serious structural risk.
I-CS.1 Cover Separation	Cover separation differs from delamination and occurs deeper within the concrete, extending to the cover distance of internal reinforcement. This separation happens as cracks near the internal reinforcement propagate horizontally due to high stresses from external FRP. Like delamination, it is a sudden, brittle failure.
I-CS.2 Corrosion in Steel Reinforcement	External FRP strengthening is typically applied to steel-reinforced concrete elements. Although it can reduce the corrosion rate of steel reinforcement, it does not completely stop it. As a result, corrosion continues over time, and it is essential to monitor corrosion activity in concrete elements even after applying strengthening measures.
I-CS.3 Concrete Reinforcement Debonding	Due to environmental and load factors, the bond may gradually weaken over time, resulting in bond failure of the steel-reinforced concrete element. Debonding might compromise the structure integrity and tensile resistance, making it susceptible to more damage.

4. Source of Damage

After locations and potential defects ("where" and "what") have been determined, it is important to establish the possible sources of these defects/damage ("why") as well as the timing during the service life when they occur ("when"). Based on the existing literature reports on similar studies [88], the causes of defects in FRP application can be categorized into four main sources. These sources include fabrication and workmanship, design factors, mechanical factors, and environmental factors, as presented in Table 4. The initial two sources are associated with the construction process of the EB-FRP concrete element, encompassing the manufacturing of the FRP composite, the design of the RC element, and its subsequent construction. The latter two occur during the in-service stage.

Table 4. Source of damage and defects in FRP applications [15].

Fabrication and Workmanship	Design Factors	Environmental Factors	Mechanical Factors
• Manufacturing • Transportation • Storage • Handling • Installation	• Unreasonable Design/Lack of Specification and Code • Calculation/Design Errors • Inadequate Installation/Construction Details (Constructability) • Improper Composite Choice	• Water Exposure • Saline Exposure • Alkaline Exposure • UV Exposure • Elevated Temperature Exposure • Freeze–thaw Cycles Exposure	• Fatigue • Creep Rupture • Shrinkage • Impact • Service Loads

The classification of damage/defects in EB-FRP concrete elements and their sources are depicted in Figure 3. The damage is classified based on "when" they could occur. Malla et al. (2023) [15] and Ortiz et al. (2023) [27] provide more in-depth information about the source of the damage. Each defect is rationally related to its possible cause.

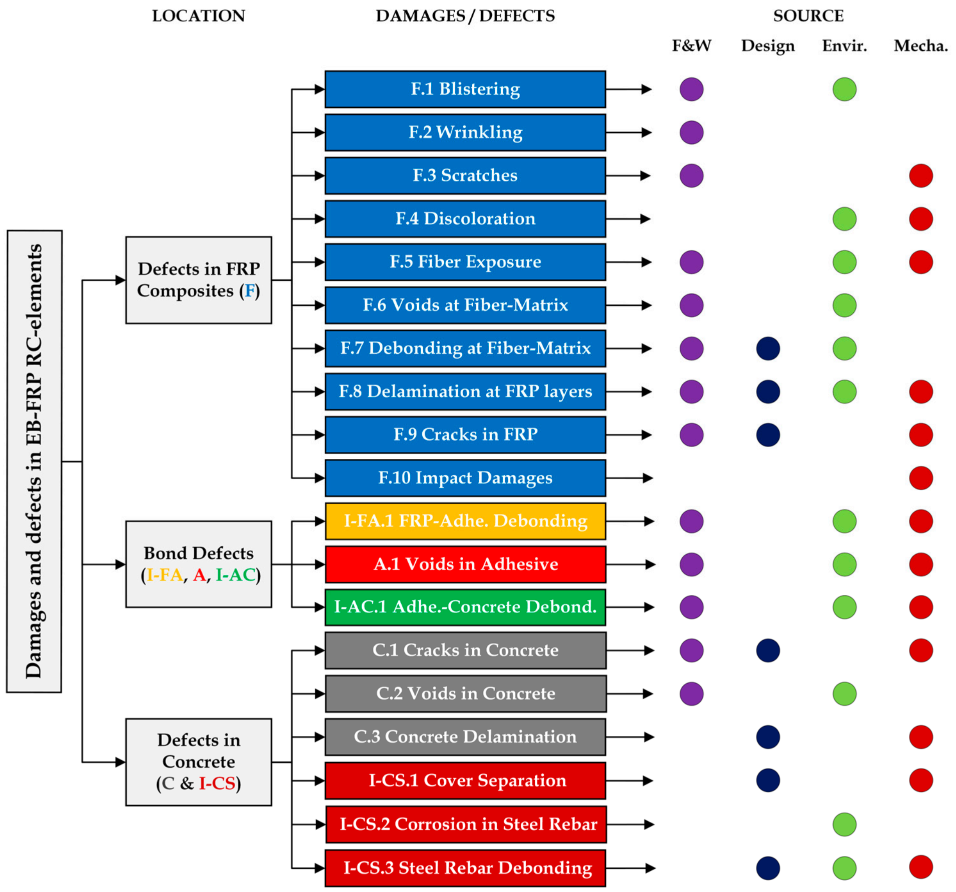


Figure 3. Source of damage in EB-FRP concrete elements. Note: colors are related to location given in Figure 1 and source given in Table 4.

5. NDT Methods Applicable to EB-FRP Concrete Elements

A previous study by the authors reviewed the applicability of available non-destructive testing (NDT) methods for detecting damage in structural elements reinforced or strengthened with FRP [89]. An extensive literature survey was conducted, encompassing over 100 past studies on the application of NDT methods in detecting damage in FRP for external applications. The damage detectability was divided into seven groups: **i.** surface Anomalies (F.1–F.5), **ii.** defects within FRP composite layers (F.6–F.10), **iii.** bond defects (I-FA, A, I-AC), **iv.** cracks in concrete (C.1), **v.** voids in concrete (C.2), **vi.** delamination in concrete (C.3), **vii.** steel reinforcement defects (I-CS). The most promising methods were selected and are summarized in Table 5, along with the percentage of applicability in the available literature for detecting each of the seven groups of damage. Khedmatgozar Dolati et al. (2023) [89] can be consulted for a deeper explanation on each NDT method. The following is a brief description of the most used NDT methods found in the available literature.

Table 5. Applicability of NDT methods for EB-FRP concrete elements in the available literature [89].

NDT Method	i. Surface Anomalies *	ii. FRP Composite	iii. Bond Defects	iv. Cracks in Concrete	v. Voids in Concrete	vi. Concrete Delamination	vii. Rebar Defects
Tap testing (**TT**)	-	**12%**	6%	0%	0%	0%	0%
Impact echo testing (**IE**)	-	5%	5%	**15%**	**20%**	**20%**	10%
Ground-penetrating radar (**GPR**) and microwave testing (MW)	-	7%	17%	12%	**30%**	**42%**	**70%**
Ultrasonic testing (**UT**) and phased array ultrasonic testing (**PAU**)	-	**27%**	**16%**	**37%**	15%	9%	10%
Infrared thermography testing (**IR**)	-	**26%**	**38%**	8%	9%	5%	0%
Acoustic emission testing (**AE**)	-	4%	5%	0%	0%	0%	0%
Laser testing method (**LT**)	-	7%	11%	0%	0%	0%	0%
Radiography testing (**RT**)	-	**12%**	2%	5%	9%	1%	0%
Impulse response testing (**IRT**)	-	0%	0%	**20%**	**17%**	**23%**	5%
Magnetic flux leakage (**MFL**)	-	0%	0%	3%	0%	0%	5%

* Visual inspection (**VT**) can be used for qualitative and quantitative detection of almost all surface anomalies.

- **Visual Inspection (VT):** A common, versatile, and straightforward NDT method, is used to identify surface defects in EB-FRP concrete elements. Although some researchers do not consider VT as an NDT method, it completely fits the definition of NDT method as described earlier in this paper. In any case, it is a fast and cost-effective method, and provides real-time results, serving as a baseline for other NDT techniques. Based on its findings, decisions can be made about further inspection. However, it can only detect surface defects and may be subjective, depending on individual perception.
- **Tap Testing (TT):** This method detects defects by analyzing changes in stiffness and sound frequency upon impact. It is a quick, cost-effective, and user-friendly approach for inspecting large areas in real-time, but its results are subjective and can vary due to differences in applied force, angle, and equipment. Misinterpretations may occur due to ambient noise and geometric changes.
- **Impact Echo Testing (IE):** This method relies on stress waves from an impact to identify subsurface defects in materials, particularly in concrete. It is effective for evaluating issues like cracks and delamination. By using lower frequencies, it can penetrate deeper and requires access to only one surface for testing. However, its applicability is limited to materials up to 40 inches thick. Skilled operators are needed, and it may have difficulty detecting smaller cracks and discontinuities.
- **Ground-Penetrating Radar (GPR):** This method uses radio waves to pass through a material and detects reflections from any interfaces between materials or subsurface defects like voids, cracks, debonding, and delamination. It can go beyond concrete–air interfaces, inspecting features below, and identifying defects at greater depths than some other NDT methods. It is not effective for detecting air-filled defects.

- **Ultrasonic Testing (UT) and Phased Array Ultrasonic Testing (PAU):** This method uses the reflection of ultrasonic waves at material interfaces with differing acoustic impedances to locate defects. It excels in identifying defects in concrete and composites due to the strong reflection caused by these flaws. It offers fast and field-friendly testing with good resolution, capable of penetrating materials and detecting various defects. It necessitates highly trained personnel for conducting and interpreting tests and is primarily suitable for materials of limited thickness. **PAU** uses multiple transducer elements in a phased array probe to enable precise control.
- **Infrared Thermography Testing (IR):** This method relies on differences in thermal properties between anomalies and sound areas within the material. By measuring surface temperature, it can detect subsurface defects to some extent. It is particularly suitable for inspecting larger surface areas quickly and cost-effectively, with real-time data interpretation. However, it is not reliable for detecting water-filled defects, has limitations in identifying deep-seated defects in concrete, and necessitates specific environmental conditions for optimal results.

The results from their literature review indicated that **IR**, **GPR**, and **UT** can be considered the most applicable methods for detecting bond defects [89]. For damage detection within FRP composites (e.g., debonding, voids, delamination at layers), **UT**, **IR**, and **TT** have been recognized as the most suitable ones. For concrete damage detection, **UT**, **IRT**, **GPR**, and **IE** have emerged as the most promising approaches. For all FRP surface anomalies, visual testing (**VT**) is proposed. Overall, **GPR** has been selected as the most effective NDT method for detecting different types of damage in FRP strengthened concrete elements followed by **UT**, as shown in Table 5.

GPR with high frequency antennas of about 2 GHz was able to easily detect debonding and delamination. A 1.5 GHz ground-coupled GPR antenna was effective for water-filled voids (as small as $50 \times 50 \times 1.5$ mm^3). Air-filled voids could not be detected because of CFRP's higher electrical conductivity that leads to higher attenuation and smaller echoes [90]. However, it exhibits limitations in accuracy and frequency dependencies when assessing various structural defects. **UT** was able to detect debonding of 6.3 mm in diameter and qualitatively detect debonding and voids. Studies confirmed its efficacy in detecting and locating typical FRP defects. It was able to detect flaws as small as 0.8 mm with a penetration depth of 25 mm. **IR** detected air-filled debonding of sizes 75 mm $\times$ 75 mm, 50 mm $\times$ 50 mm, and 35 mm $\times$ 35 mm along with water-filled debonding. It also detected near-surface voids (<10 cm from surface). Furthermore, it provided qualitative detection of delamination.

6. Experimental Verification—Inspection of EB-FRP Concrete Elements

6.1. Materials and Constrcution

In order to assess the most promising NDT methods for damage detection in EB-FRP concrete elements (i.e., **VT**, **TT**, **GRP**, **UT**, **IR**), two small-scale slab specimens were fabricated (as shown in Figures 4–6). Slab M′ was 760 mm (30 in.) wide by 760 mm (30 in.) long and 178 mm (7 in.) deep, and Slab Q′ was 904 mm (36 in.) wide by 904 mm (36 in.) long and 178 mm (7 in.) deep. The concrete mix used to cast the slab specimens was 'Class II 4500 Bridgedeck' concrete, as per the Florida Department of Transportation (FDOT). This class specified a guaranteed compressive strength of 31 MPa (4500 psi). Type II Cement was used with a water to a cementitious material ratio (w/m) of 0.44, and #57 stone and silica sand were used as coarse and fine aggregate, respectively. To obtain the actual strength value, concrete cylinders were fabricated and tested according to ASTM C39 [91]. An average compressive strength of 31.7 MPa (4600 psi) was obtained with a standard deviation of 0.69 MPa (100 MPa).

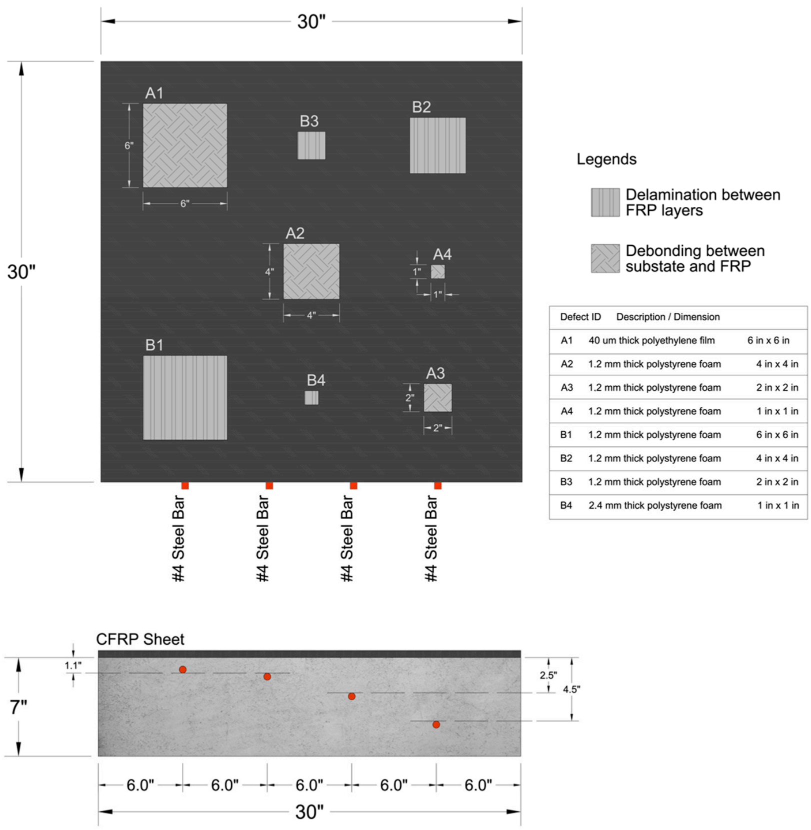


Figure 4. Slab M′, specimen with steel rebars and damage in the EB-FRP system. 1 in. = 25.4 mm.

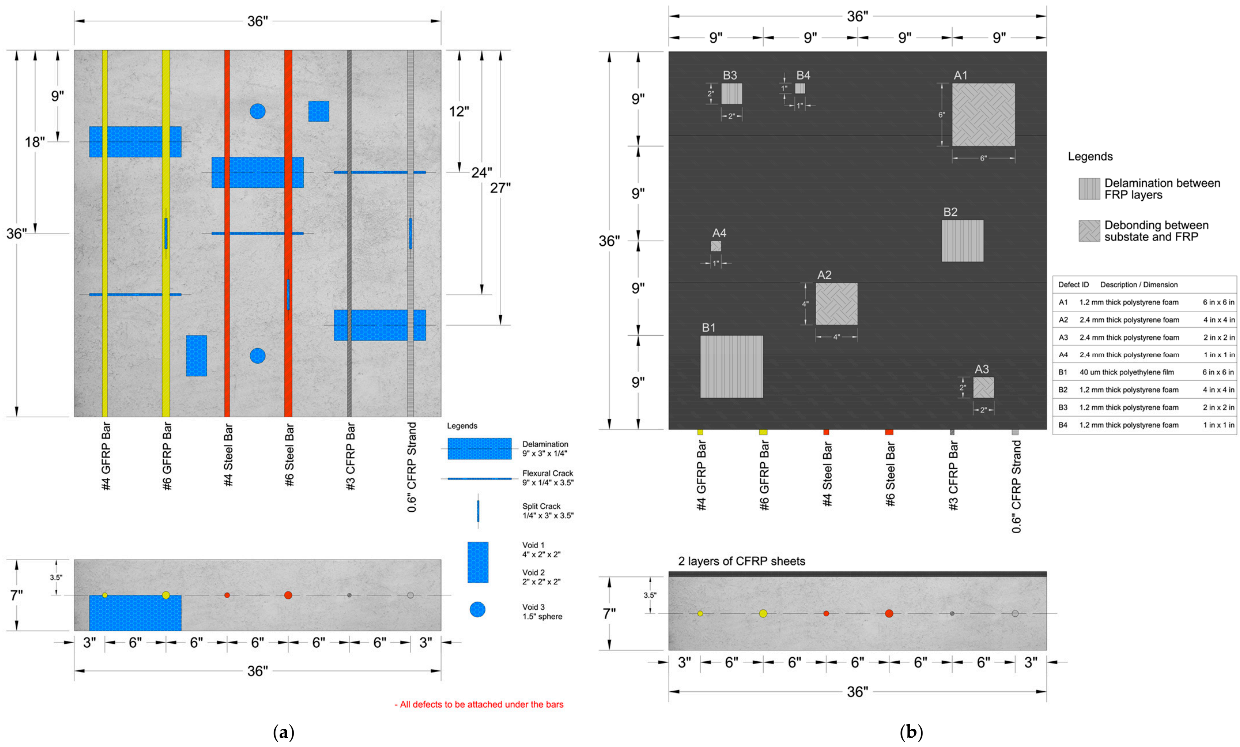


Figure 5. Slab Q′, specimen defects within concrete and in the EB-FRP system. 1 in. = 25.4 mm. (**a**) Before EB-FRP system installation. (**b**) After EB-FRP system installation.

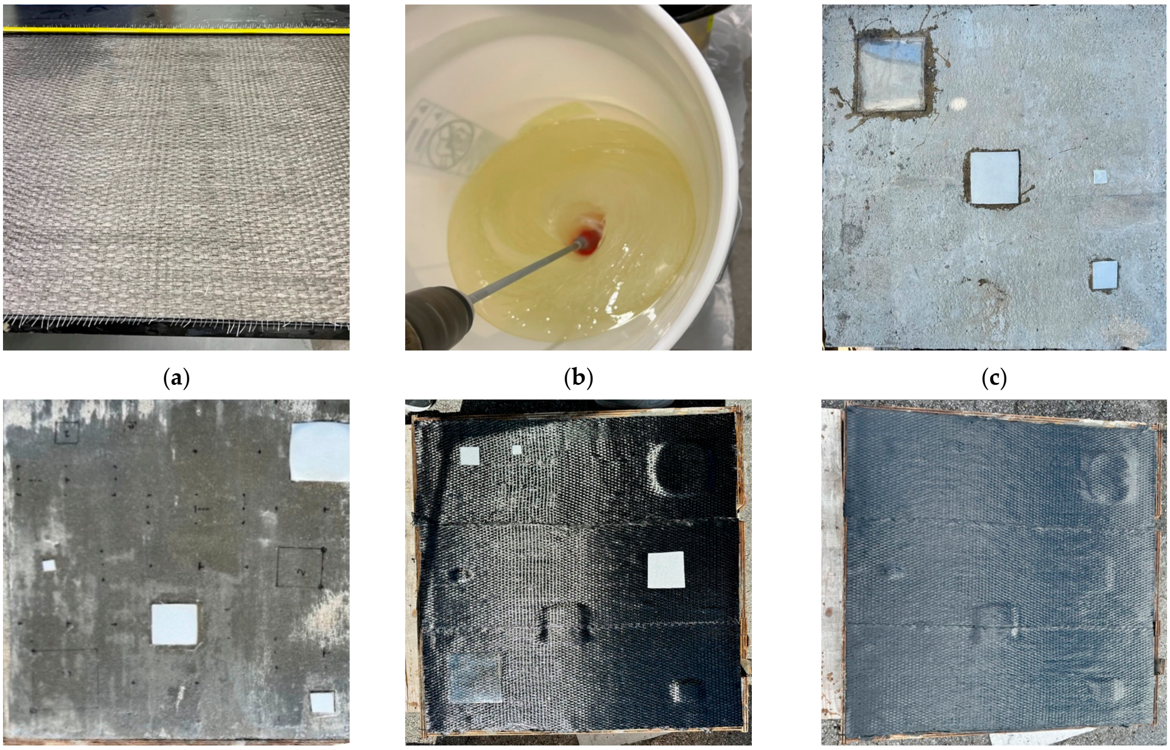


Figure 6. Defects generation in EB-FRP concrete elements. (**a**) Unidirectional CFRP sheet, (**b**) mixing of the resin, (**c**) adhesive–concrete debonding, (**d**) surface impregnation, (**e**) first layer of CFRP, (**f**) strengthened slab.

To eliminate the need for plastic chairs/spacers or internal supports for the rebars, openings were made in the sides of the formwork and the rebars were inserted through them for support. In Slab M′, the internal steel reinforcement was located in different depths in order to target different possible concrete covers (see Figure 4). Additionally, as in a future FRP-RC elements will become more available and they could also require strengthening and retrofitting, Slab Q′ was constructed using different internal reinforcement types (i.e., glass-, carbon-FRP, and steel rebars). In this case, they were all located at the same depth since this slab had defects and damage within the concrete, as shown in Figure 5. The reason to incorporate different reinforcement types was also to evaluate the detectability of these materials when an EB-FRP system is used.

Four types of defects in concrete were simulated to evaluate the feasibility of different NDT methods when an EB-FRP system is applied on the surface of the element. These defects were selected based on the literature review of prior phase (i.e., C1 to C3 in Table 3). Delamination, flexural and split cracks, as well as voids in the concrete, were simulated in Slab Q′ using thin architectural polystyrene foam (thickness of 6.35 mm or 1/4″) held in place with the use of epoxy as shown in Figure 5a.

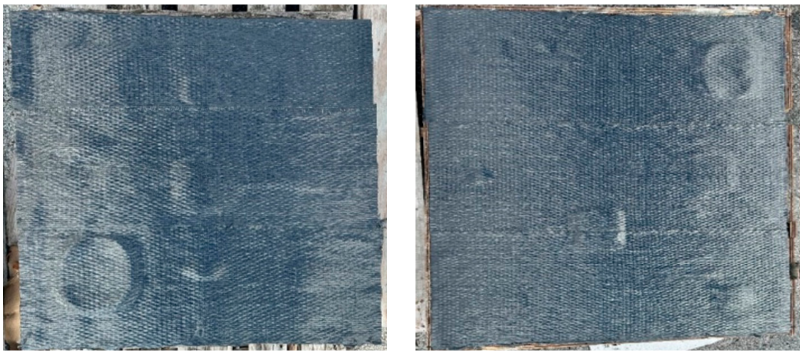
6.2. Defects Generation for EB-FRP Concrete Elements

External application commonly refers to the installation of an FRP system, typically a wet-layup system where an FRP fabric/sheet is impregnated with resin in situ to facilitate the strengthening process. To simulate the common/potential defects of external FRP applications, two layers of an CFRP unidirectional system was applied on one face of the slab. Two different types of defects were generated to evaluate the feasibility of application of the selected NDT methods. The first, “adhesive–concrete debonding” (or FRP composite–concrete debonding in general) was generated by placing a thin film of 1.2 mm expanded polystyrene foam (EPS) on the surface of the concrete before impregnating it with resin. Figure 6a shows the first layer of defects also with a 40 µm thin film of polyethylene; however, this material was more difficult to bond to the concrete surface and prevent movement during installation. The second defect, FRP–adhesive debonding or delamination between layers of FRP sheets in a composite, was simulated by applying the same thin film (polystyrene foam) between the CFRP layers, thus creating a discontinuity between the layers. Figure 5 shows the strengthening application process.

7. Results and Discussion

7.1. Visual Inspection (VT)

Visual inspections were conducted on the EB-FRP slab specimens to identify various defects and damage such as fiber kinks, waviness, swelling, bubbles, voids, debonding, delamination, peeling, cracking, and fiber breakage (Figure 7), with further tap testing to confirm defects in areas suspected of having air pockets. Inspectors should also watch for signs of internal steel reinforcement damage, like corrosion, indicating potential concrete deterioration beneath the FRP layer. Visual inspection is limited to determining the location and quantity of defects/damage that appear on the surface, while additional NDT like UT, GPR, and IR may be needed to accurately size defects or locate those not visible on the surface, such as voids. The visual inspection on Slab M′ and Q′ successfully detected defects simulated with polystyrene foam but struggled to identify those created using thinner and denser polyethylene cutouts, suggesting that delamination without bulging of the laminate could be challenging to perceive.



(**a**) (**b**)

Figure 7. Visual inspection of slabs: (**a**) Slab M′, (**b**) Slab Q′.

7.2. Tap Testing (TT)

Tap testing (TT) was conducted over the suspected areas determined from visual inspection and over remaining areas with at least one strike per 0.1 m^2 (1 sq. ft), as shown in Figure 8. The procedure was executed on the external FRP application to discern variations in sound between bonded and unbonded laminate. It is similar to the one performed over concrete elements by bridge inspectors trained to hear the difference between concrete with and without delamination. The tap testing conducted successfully detected all simulated defects and damage in Slab M′ and Q′. Small areas of 625 mm^2 (1 $in.^2$) were detected with TT. Typically, delamination less than 1300 mm^2 (2 $in.^2$) is permissible as long as the delaminated area is less than 5% of the total laminate area and there are no more than 10 such delaminations per 1 m^2 (10 ft^2) [30].

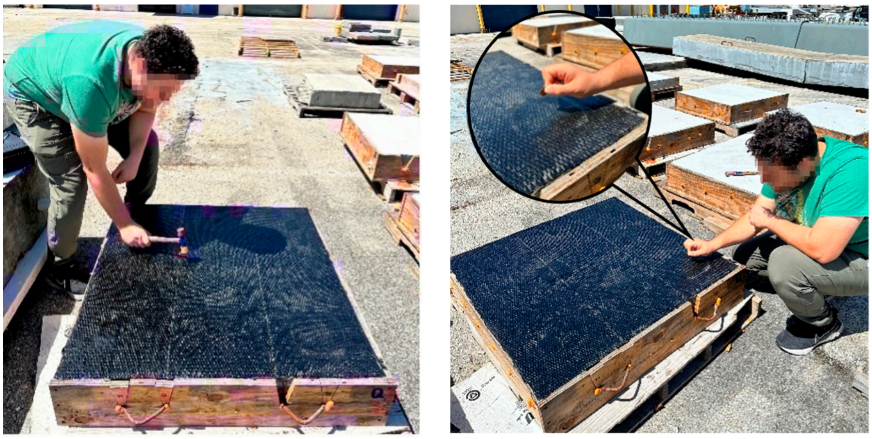
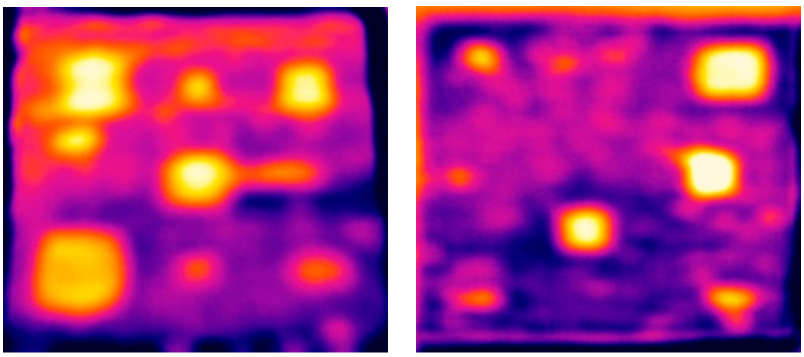


Figure 8. Tap Testing on Slab Q′.

7.3. Infrared Thermography (IR)

Infrared thermography was conducted on the slab specimens to identify minor defects and damage beneath the laminate, which may not have been detected through visual inspection and tap testing. The test relied on solar heating to establish a thermal gradient between the defective and intact areas. In cases where the slabs had maintained a uniform temperature across the top surface due to prolonged sun exposure prior to testing, a canopy was employed to induce the necessary thermal gradient. All defects and damage appeared as thermal anomalies or hot spots in the infrared images of the slabs (Figure 9). These anomalies recorded temperatures of about 49 °C (120 °F) in contrast to approximate 40 °C (105 °F) registered in the sound element. The IR was capable of highlighting defects as small as 625 mm^2 (1 $in.^2$), but the most favorable results were observed in the 2500 mm^2 (4 $in.^2$), whether between layers (delamination) or between the substrate and FRP (debonding). The B1 defect (delamination between layers) in Slab Q′ was created using a 40 µm polyethylene film, making it harder to identify the defect. However, this demonstrates that IR could detect delamination without bulging with the adequate expertise of the inspector.



(**a**) (**b**)

Figure 9. Infrared image of slabs: (**a**) Slab M′, (**b**) Slab Q′.

7.4. Ground-Penetrating Radar (GPR)

The externally applied CFRP sheets on Slabs M′ and Q′ acted as a reflective surface for GPR devices due to their conductivity. GPR line scans (Figure 10) indicated significant interference, with multiple hyperbolas and reflections, making it challenging to discern any targets beneath the CFRP layer. The distinctive hyperbolas representing the four steel rebars embedded in Slab M′ before the application of the EB-FRP system, were no longer discernible in the line scan conducted over the slab with the EB-CFRP layer, as displayed in Figure 10 (perpendicular to the direction of the rebars). No information about external defects could be detected. No tests were conducted for the external application of GFRP sheets in this study, primarily because the vast majority of external FRP applications utilize CFRP due to its higher strength and stiffness. Therefore, it remains a possibility that GPR could detect anomalies in the concrete substrate if GFRP sheets were employed.

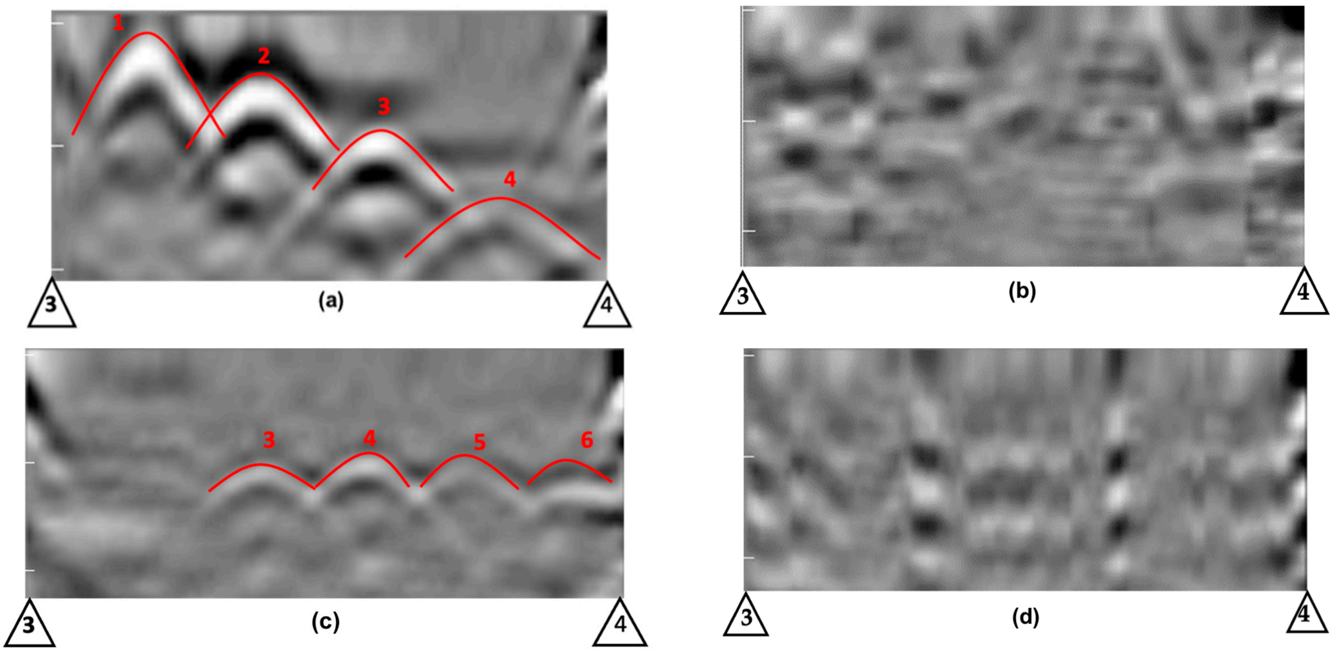


Figure 10. GPR line scans of Slab M′ and Q′. (**a**) Slab M′ before strengthening, (**b**) Slab M′ after strengthening, (**c**) Slab Q′ before strengthening, (**d**) Slab Q′ after strengthening.

7.5. Phased Array Ultrasonic Testing (PAU)

The advantage of employing PAU instead of a GPR device for inspecting externally applied FRP systems is its ability to penetrate conductive FRP layers, such as CFRP layers. The individual B-scan (line scan) of Slab Q′ with externally applied CFRP sheets, obtained during a PAU stripe scan, revealed the detectability of internal features like a 230 mm × 76 mm (9 in. × 3 in.) concrete delamination (Figure 11i) and steel rebars (Figure 11iii), which was not achievable using GPR. Although, in Figure 11ii, it is evident that a debonding introduced between the first layer of CFRP and the concrete substrate is clearly detectable, the size of this defect cannot be clearly established (in this case, it was a 100 mm × 100 mm (4 in. × 4 in.) debonding). However, this defect also acts as a strong reflector for nearly all ultrasonic waves, which explains why Figure 11ii appears uniformly red beneath the top surface. This implies that it is not possible to detect internal features immediately beneath the defects or damage on the top surface using PAU. Furthermore, other simulated defects such as voids and cracks could not be detected using PAU.

The effectiveness of the evaluated NDT methods (i.e., GPR, PAU, VT, TT, and IR) for inspection of EB-FRP concrete elements is presented in Table 6. They were classified into three different categories based on the detectability of the introduce defect: D (Detectable) if the defect was detectable either quantitative or qualitative; LD (Limited Detectability) is based on size of defect/damage; and ND (Not Detectable) if the defect cannot be either quantitatively or qualitatively detected by the technique evaluated.

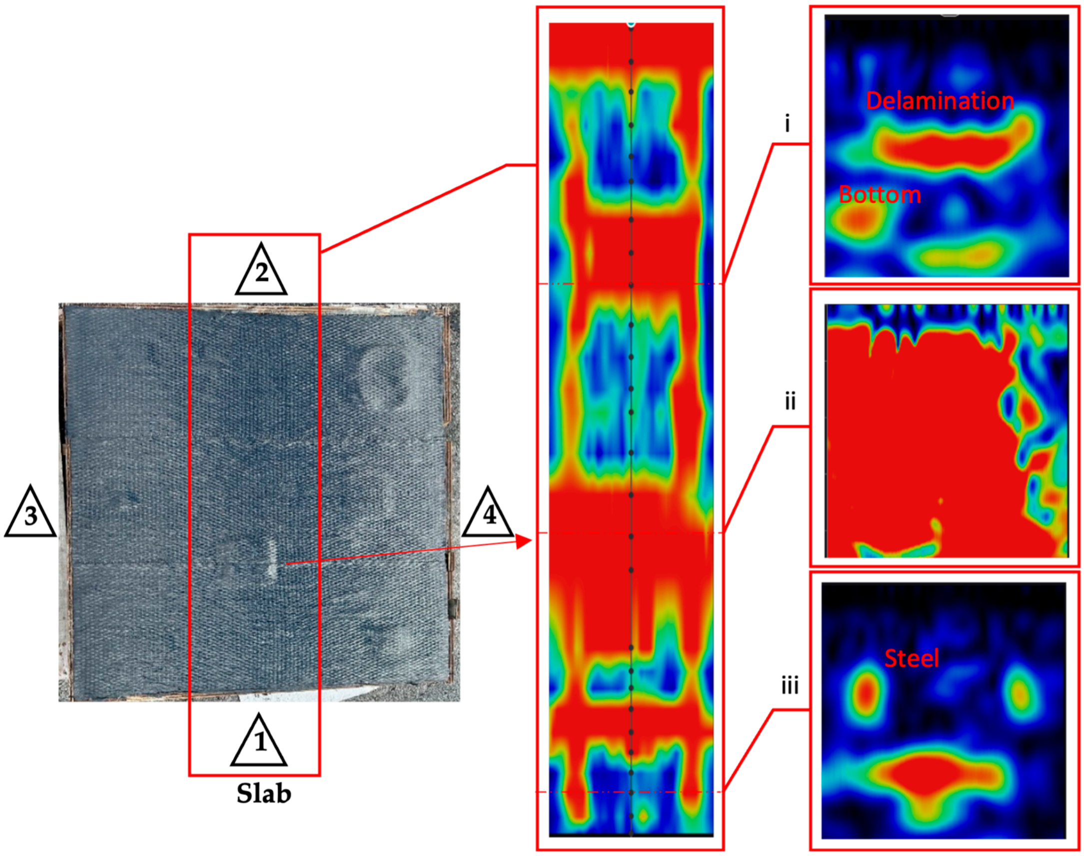


Figure 11. PAU stripe scan of Slab Q′. (**i**) 300 mm, (**ii**) 570 mm and (**iii**) 800 mm from face 2.

Table 6. Effectiveness of selective NDT methods for inspection of EB-FRP concrete elements.

Slab	Parameters [1]		Selected NDTs				
			GPR	PAU	VT	TT	IR
M′	Internal Targets		ND	D [2]	-	-	-
	External defects/damage	Debonding or Delamination	ND	LD [3]	LD [1]	D	D
Q′	Internal Targets		ND	D [2]	-	-	-
	External defects/damage	Debonding or Delamination	ND	LD [3]	LD [1]	D	D

Note: D = Detectable; LD = Limited Detectability; ND = Not Detectable. [1] Limited detection (LD) is based on the size of defect/damage. [2] Concrete delamination is detectable as long as the external applied fabric is sound. [3] Qualitatively detectable.

8. Conclusions

This study examined the types, characteristics, and identification of damage and defects that were either observed or expected in EB-FRP concrete elements. The defects and damage were categorized based on their location, time of initiation, and sources. The inspection of FRP-EB concrete elements can be categorized into three main groups. The first category focuses on visible surface damage and defects within the FRP composite. The second category involves inspecting damage within the FRP composite and at the bond layer between the FRP and concrete. The third category concentrates on identifying damage and defects in the concrete substrate itself. The most promising non-destructive testing (NDT) methods were reviewed and subsequently evaluated in small-scale EB-FRP concrete slabs. By offering a structured framework for inspecting structures utilizing wet lay-up carbon FRP systems, the findings of this study can serve as the foundation for the development of a guide and training materials for the inspection of structures employing wet lay-up carbon FRP systems.

- The externally applied FRP system should be visually examined thoroughly to identify surface anomalies, including blister-like formations, exposed fibers, surface scratches, and cracks. Signs of moisture and water stains near joints or lower areas underneath the structure. Surface anomalies observed in the externally applied FRP may indicate defects within the FRP composite or bonding issues between the FRP and concrete.
- Inspecting FRP composite defects and bond issues may necessitate NDT methods beyond visual inspection (VT). Tap testing (TT) is suitable for detecting bond defects to prevent the separation of externally applied FRP system from the concrete substrate. Additionally, IR can be employed for quantitative defect assessment within the FRP composite or between the FRP and concrete, capable of detecting areas as small as 625 mm^2. PAU can be employed for qualitative assessment of the EB-FRP.
- Inspecting hidden concrete under external FRP is challenging but achievable by noting evidence of internal defects (e.g., detecting FRP tearing due to concrete spalling), observing anomalies deviating from sound FRP (e.g., CFRP bulging indicating underlying cracks), and checking for rust stains (e.g., a sign of embedded steel corrosion). Employment of NDT devices capable of penetrating FRP (e.g., PAU) is desirable for an in-depth investigation. The coupling of these defects potentially adds complexity to accurate defect identification. However, the effectiveness of the device and the technician's expertise play a crucial role in detecting and distinguishing such complex defects. Nevertheless, the presence of damage regardless of the type and complexity should trigger further examination and potentially corrective action.
- In a contrast to the results of a previous literature review, it was determined that GPR could not detect defects or damage introduced into the externally applied CFRP and the internal targets beneath the CFRP layer due to its conductive nature. PAU exhibited relatively better performance in inspecting the external application of FRP, being able to qualitatively detect introduced debonding/delamination in the external FRP and delamination within the concrete. Other NDT techniques, including visual inspection (VT), tap testing (TT), and infrared thermography (IR), were also found to be quite effective in detecting primarily surface anomalies and some bond defects, such as voids.

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