ndt

MDPI

Review

Review of Ground Penetrating Radar Applications for Bridge Infrastructures

Paola Boldrin, Giacomo Fornasari and Enzo Rizzo *

Department of Physics and Earth Science, University of Ferrara, 44121 Ferrara, Italy; paola.boldrin@unife.it (P.B.); giacomo.fornasari@unife.it (G.F.)
* Correspondence: enzo.rizzo@unife.it

Abstract: Infrastructure bridges play a crucial role in fostering economic and social development. However, the adverse effects of natural hazard and weather degradation, coupled with escalating rates of traffic, pose a significant threat. The resultant strain on the structure can lead to undue stress, elevating the risk of a critical asset failure. Hence, non-destructive testing (NDT) has become indispensable in the surveillance of bridge infrastructure. Its primary objectives include ensuring safety, optimizing structural integrity, minimizing repair costs, and extending the lifespan of bridges. NDT techniques can be applied to both existing and newly constructed bridge structures. However, it is crucial to recognize that each NDT method comes with its own set of advantages and limitations tailored to specific tasks. No single method can provide an effective and unequivocal diagnosis on its own. Among the various NDT methods, Ground Penetrating Radar (GPR) has emerged as one of the most widely employed techniques for monitoring bridges. In fact, recent technical regulations now mandate the use of GPR for bridge monitoring and characterization, underscoring its significance in ensuring the structural health and longevity of these critical infrastructures. Ground Penetrating Radar (GPR) stands out as one of the most highly recommended non-destructive methods, offering an efficient and timely assessment of the structural conditions of infrastructure. Recognizing the pivotal role of non-destructive testing (NDT) in this context, this paper aims to elucidate recent scientific endeavors related to the application of GPR in bridge engineering structures. The exploration will commence with a focus on studies conducted both at the model level within laboratory settings and on real cases. Subsequently, the discussion will extend to encompass the characterization and monitoring of the bridge's main elements: slab, beam, and pillar. By delving into these scientific experiences, this paper intends to provide valuable insights into the efficacy and applicability of GPR in assessing and ensuring the structural integrity of bridges. This paper provides a concise survey of the existing literature on the application of Ground Penetrating Radar (GPR) in the assessment of bridges and viaducts constructed with masonry and reinforced concrete, taking into account papers of journal articles and proceedings available on open databases. Various approaches employed in both laboratory and field settings will be explored and juxtaposed. Additionally, this paper delves into discussions on novel processing and visualization approaches, shedding light on advancements in techniques for interpreting GPR data in the context of bridge and viaduct evaluations.

Keywords: GPR; bridge; slab; beam; pillar

Citation: Boldrin, P.; Fornasari, G.; Rizzo, E. Review of Ground Penetrating Radar Applications for Bridge Infrastructures. *NDT* **2024**, *2*, 53–75. https://doi.org/10.3390/ndt2010004

Academic Editor: Fabio Tosti

Received: 15 January 2024
Revised: 1 March 2024
Accepted: 14 March 2024
Published: 21 March 2024

1. Introduction

Bridges serve as crucial infrastructures, enabling connectivity between different regions and streamlining communication routes. Obtaining an exact count of bridges worldwide is challenging, but a significant proportion of the longest bridges globally are concentrated in China. In Italy, it is noteworthy that 92% of bridges exceed 40 years in age, with 38% constructed in the post-World War II era. Moreover, it has been observed that at least 50% of Italian reinforced concrete bridges exhibit signs of degradation, emphasizing the pressing need for assessments and maintenance of these aging structures. As a result, a significant number of these structures, affected by factors such as substandard materials, adverse climatic conditions, constant usage, and the application of defrosting salts, require maintenance and repair. For prestressed concrete bridges, the accurate identification of tendon ducts and conventional reinforcement is paramount in rehabilitation efforts. Furthermore, it is essential to validate the quality of the construction both during its execution and in its early stages to forestall the onset of premature deterioration, such as corrosion of the reinforcement [1]. Reinforced concrete can be subject to widespread deterioration processes, presenting detachments and cracks, thus favoring the infiltration of water with a high chloride content that triggers most steel corrosion processes [2]. The other main cause that can damage the work, creating significant structural damage, is the process of carbonation that reduces, due to the presence of carbon dioxide, the alkalinity of the concrete, thus damaging the iron cover and then triggering oxidation of the reinforcements [3]. Another phenomenon that can occur is delamination, which leads to the creation of horizontal cracks, scaling, and spalling. These phenomena lead to a loss of adhesion between the steel bars and the concrete, causing a decrease in the stability and resistance of the work. It will therefore be essential to identify non-destructive methods (NDTs) that allow us to diagnose the problem with reduced times and costs, thus leading to a timely identification of the deterioration to best act according to the work under consideration [4,5]. There are several NDT techniques, but Ground Penetrating Radar (GPR) allows us to assess the condition of the decks of a concrete bridge, allowing us to detect the probability of triggering the delamination and corrosion of the structure, with increased inspection efficiency and speed. Many researchers carry out research on the laboratory scale to observe phenomena such as the corrosion process and to analyze its impact on the recorded signal. In fact, there is a relationship between the amplitude of the measured signal and the content of chlorides present in the test medium: the greater the presence of dissolved salts, the smaller the amplitude measured by the signal [6]. Moreover, recent papers highlight the corrosion evolution along the reinforcement bar, taking into account the amplitude signals elaborated with the Hilbert Transform approach [7].

This paper presents a review of the works published within the scope of GPR in the assessment of transport infrastructure, focusing on bridges. While it has been proven that GPR has brought significant benefits to inspection practices, successfully overcoming some of the limitations of conventional methods, it also has some constraints. To optimize the application of Ground Penetrating Radar (GPR), it is imperative to acknowledge these limitations and possess the ability to tailor test procedures and interpret results based on the specific conditions of the work environment. This paper describes the various applications of Ground Penetrating Radar (GPR) in the study and characterization of masonry and reinforced concrete bridges. In masonry bridges, the key applications encompass the identification of unknown geometries like hidden arches and historical profiles, analysis of restoration and reconstruction in masonry structures, assessment of moisture content within masonry components, examination of bridge foundations, detection and characterization of gaps and cracks in the masonry, and evaluation of the condition and distribution of filling materials and thickness of the ashlars. The characterization of the work is fundamental for the optimization in the reassuming and restoration phases. This review will encompass articles focused on laboratory studies of samples, aiming to enhance both the acquisition and interpretation phases in real case studies. In the context of reinforced concrete bridges, consistent maintenance and periodic inspections are imperative for identifying indications of deterioration and averting the risk of failure or collapse. Consequently, an analysis of Ground Penetrating Radar (GPR) applications will be undertaken to detect reinforcement bars, examine geometry, assess the thickness of the iron cover, and identify potential degraded areas. Moreover, a detailed study concerning the bridge's main elements (slab, beams, and pillar) is highlighted. Given the often intricate and challenging nature of GPR data, the data processing phase assumes crucial importance. Various authors proposed novel processing approaches, employing different algorithms to streamline and enhance the localization of reinforcement bars and the resolution of the data. Finally, a novel data visualization method will be suggested, offering a substantial contribution to the examination of pylon degradation.

2. Materials and Methods

GPR is usually applied for different topics, but this review focuses on its application in the engineering field, in more detail, in the study of bridges. The GPR technique allows us to detect the thickness of the different layers, evaluate the quality of the materials, identify the presence of reinforcement structures, and identify any anomalies below the surface. The propagation speed of electromagnetic waves (EM) in a medium is absolutely contingent upon the dielectric properties of the material through which they traverse. Any change in the dielectric constant in the medium manifests itself in the recorded response signal. However, these variations can result from several different factors, such as moisture, heterogeneity of materials, the presence of chlorides, or a variation in the thickness of the concrete cover. High levels of chloride ions and humidity in concrete are also two of the key factors contributing to a greater attenuation of the EM wave and a decrease in the speed of the EM wave. Indeed, elevated levels of chloride ions and humidity in concrete are significant factors contributing to increased attenuation of electromagnetic (EM) waves and a subsequent reduction in the speed of EM wave propagation. The presence of chloride ions, often associated with exposure to marine environments or de-icing salts, can amplify the conductivity of concrete, leading to greater absorption and attenuation of EM waves. Additionally, high humidity levels can impact the dielectric properties of the material, affecting the speed of EM wave transmission through concrete structures. These considerations are crucial when interpreting data from techniques such as Ground Penetrating Radar (GPR), which is used for the subsurface inspection of concrete. Moreover, they are the key factors to the corrosion of reinforcing steel in concrete, causing serious damage to infrastructure. The ASTM D6087 standard, focusing on identifying potential corrosion phenomena within reinforced concrete structures, bases its analysis on studying variations in signal amplitudes [8]. Analyzing these amplitude variations can provide insights into potential corrosion issues, aiding in the assessment and maintenance of concrete structures. As a result, the main limitations of this technique emerge when meeting high conductivity materials and heterogeneous conditions, which lead to signal attenuation and complex scattering phenomena, respectively. The main problem is that there are several parameters and physical and environmental factors that can have a significant impact on the signal detected by the device, causing a reduction in the measured amplitude.

Changes in humidity, fluctuations in the thickness of the concrete cover, and the presence of surface defects are among the factors that can cause variations in the amplitude of the measured signal. These complexities underscore the need for a thorough understanding of the influencing factors and careful interpretation of GPR data in concrete structure assessments. One of the drawbacks of Ground Penetrating Radar (GPR) is that interpreting radargrams is not intuitive and demands considerable expertise to accurately process and understand measurements. The complexity of GPR data and the need for nuanced interpretation pose challenges, emphasizing the importance of expert practitioners in the analysis. Despite this disadvantage, the notable strengths of GPR lie in its ability to swiftly collect data at high speeds, continuously, using mobile capture units, and in a contactless mode. This efficiency is particularly advantageous for evaluating transport infrastructure areas, as it allows the continued use of the region during GPR assessments, thereby minimizing costs and inconvenience for users.

Currently on the market, there are several manufacturers of Ground Penetrating Radar (GPR) and commercial equipment available. The performance of different Ground Penetrating Radar (GPR) systems varies depending on factors such as the type of antennas utilized and their frequency. These variations have direct implications for crucial aspects of GPR applications, including operating speed, resolution, penetration depth, and sampling frequency. The choice of antennas and their frequency is a critical consideration in tailoring GPR systems to specific applications and optimizing their effectiveness in different scenarios. High-frequency antennas generally provide better resolution but have limited penetration depth, while lower-frequency antennas can penetrate deeper but might sacrifice resolution. The selection depends on the specific requirements and objectives of the GPR survey. The frequencies cover a broad spectrum, typically ranging from 10 MHz to 6 GHz. This wide frequency range allows for flexibility and adaptation to the specific needs of various GPR applications. Indeed, dual-polarization Ground Penetrating Radar (GPR) systems utilize antennas that emit and receive radar waves with different polarizations. This approach enables the acquisition of additional information about the subsurface characteristics. Dual-polarization GPR systems are typically designed for surface contact and operate with central frequencies ranging from 400 MHz to 2.5 GHz. The choice of central frequencies in the range of 1 to 2.5 GHz for detailed studies of engineering structures is common. This frequency range provides an optimal balance between data resolution and depth of investigation. The higher frequencies contribute to better resolution, making them suitable for applications where a detailed examination of subsurface features, such as in engineering structures, is crucial. This approach allows practitioners to capture fine details while still achieving adequate penetration into the material being studied. Another type is horn antennas, which have been designed for use in the assessment of transport infrastructure. These antennas are designed to operate at the speed of traffic, making them suitable for rapid data collection in dynamic environments. Horn antennas typically have frequencies ranging between 1 and 2.5 GHz, with the specific frequency chosen based on the desired depth of investigation. These antennas are commonly mounted on mobile vehicles, and they are positioned at a certain height above the survey surface. This configuration allows them to operate effectively while the vehicle is in motion. The ability to acquire data at speeds up to 80 to 120 km/h is crucial for efficient and non-disruptive assessments of transportation infrastructure. This feature enables swift data collection without causing disturbances to the normal flow of vehicular traffic [9]. Generally, GPR is connected to a global navigation satellite system to control the distance trace range and measure the distance traveled. Due to the complexity of the data obtained from the acquisitions, several authors use a combination of different programs to achieve the most optimal results. The data obtained from the acquisitions require a processing phase to improve quality and ease of interpretation. The most widely used raw data processing software products are RADAN (GSSI) and REFLEX (Sandmeier company), which allow the removal of unwanted signals, the application of filters, and the creation of maps and 3D models. For the creation of maps of the area investigated, several authors, besides using these programs, use the help of other software products such as Surfer (Golden software). Moreover, several authors make use of the personal algorithm made with MATLAB to elaborate the post-processing GPR data. Therefore, the tables that will be presented below will summarize in a schematic way the choices made by various authors during the phases of data acquisition and processing. For each case study, information will be presented on the year of publication, the software utilized for data processing, the type of GPR employed during the acquisition phase, the central frequencies utilized, and whether additional techniques were adopted as part of the study. Three overviews will be proposed, transitioning from masonry bridges to laboratory works and real cases for reinforced concrete bridges.

3. Overview on GPR in Bridges

Over the last few decades, the number of bridges has grown considerably, mainly due to the significant expansion of the road and railway network. Currently, many of these structures present a wide range of problems and defects. Nonetheless, ensuring the safety and effective operation of these bridges is crucial. This involves conducting thorough assessments of their condition and safety, followed by the implementation of necessary maintenance and rehabilitation measures. These processes require the collection of a large amount of data regarding the characteristics and conditions of bridges. In this paper, various applications of the GPR technique applied in masonry and reinforced concrete bridges for the purpose of characterization and monitoring the work will be described. Concerning reinforced concrete structures, the analysis will delve into laboratory-scale model studies before transitioning to comprehensive examinations of real-world case studies.

3.1. Overview on GPR in Masonry Bridges

Masonry bridges may belong to different historical periods, but many of the oldest masonry bridges date back to the Roman and medieval periods. Many existing masonry arch bridges are still in use within the transport network. Consequently, it is imperative to conduct regular inspections to monitor any alterations in the structural condition, facilitating the development of efficient preventive and maintenance measures. The application of GPR is crucial for assessing the conservation status of these abandoned historical structures. This is essential to preserve both historical authenticity and structural integrity in the long term. The main GPR applications include the detection of unknown geometries such as hidden arches and ancient profiles, masonry restorations and reconstructions, masonry moisture content, bridge foundation, voids and masonry cracks, distribution of the filling, and thickness of the ashlars. In fact, an accurate structural evaluation of a masonry arch bridge requires a thorough knowledge of the different materials and structural systems presented. The main aim is to characterize the bridge at different levels as follows: (i) the geometric level, (ii) the structural level, and (iii) the material level. The studied papers are scheduled in Table 1, and they describe acquisition approaches for the assessment of humidity conditions, crack distribution [10,11], and the detection and study of bridge geometry [12].

Table 1. Summary of studied articles on masonry bridges.

Paper	Data Processing	GPR Instrument	Frequency Antenna	Other Methods
Trela et al. [10]	NA	SIR-20 GSSI	500 MHz 900 MHz-1.5 GHz	No
Kalogeropoulos and Brühwiler [11]	NA	NA	900 MHz–1.5 GHz	No
M. Solla et al. [12]	Reflex, GprMax	RAMAC	250 and 500 MHz	No
M. Solla et al. [13]	GprMax v.2.0, MATLAB© software, Reflex	RAMAC	500 MHz	Yes
Pérez-Gracia et al. [14]	Ramseries software	RAMAC	800, 500, and 250 MHz	No
De Castro et al. [15]	TNO Diana	X3M GPR system	250 MHz	Yes
Diamanti et al. [16]	NA	GSSI SIR 3000	1.5 Ghz	No
Solla et al. [17]	ReflexW	RAMAC	250–500 MHz	No
Lubowiecka et al. [18]	Photomodeler Scanner software	NA	250 and 500 MHz	Yes
Stavroulaki et al. [19]	ReflexW	RAMAC	250and 500 MHz	Yes

A major problem affecting these types of structures is the detection and localization of water, because it is crucial for the stability and durability of structures. When the water content is sufficiently high, the potential for significant damage increases, including material degradation and volumetric variations that may manifest as defects such as swelling or cracking. The identification of moisture zones within masonry is fundamental for civil engineers involved in planning future conservation and consolidation measures. It serves as a crucial element, providing essential insights to optimize the restoration phases and enhance the overall preservation of the structure. Solla et al. [13] and Trela et al. [10], in both their studies, centered on assessing the moisture conditions prevalent in the bridges under investigation. Due to the heterogeneity of historical masonry arch bridges, the analysis and interpretation of GPR data can be complex. In fact, in many studies, sophisticated numerical modelling has been employed to facilitate the interpretation of data. They are intended to facilitate interpretation by simulating the propagation of GPR waves in the medium. To extend the range of possible defects present in bridges and to understand the internal geometry of the work, many authors create numerical models (Figure 1) that will allow the study of the various response signals of the medium [14,15]. In addition, Diamanti et at. [16] highlighted the complexity of the GPR data due to the heterogeneity of masonry arch bridges. Therefore, they defined a GPR numerical model to study the attributes of reflected signals from various targets. However, there are limitations of the GPR data on this kind of bridge structure. Exploiting the use of GPR in combination with different techniques (laser scanner, infrared, and others), many authors focus on the detection of flaws of the work and the study of the detailed geometry facilitating the interpretation of data through models [17–19].

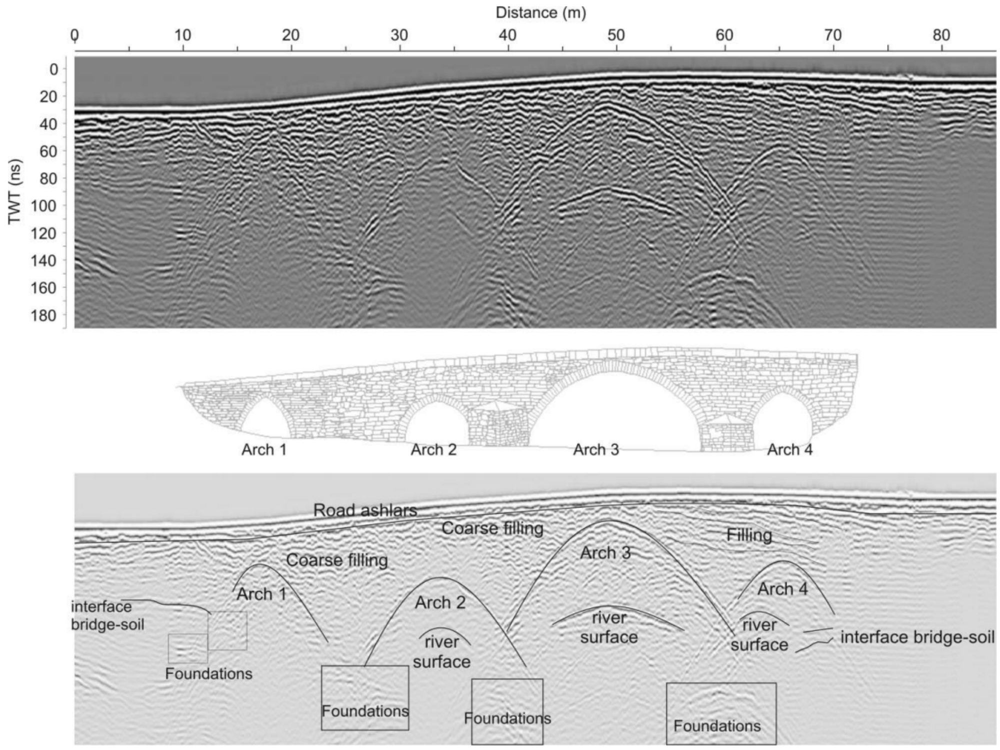

Figure 1. Data obtained from a longitudinal profile crossing a bridge and interpretations [14].

3.2. Overview of GPR in Laboratory-Scale Reinforced Concrete Model

The primary objectives of reinforced concrete bridge management are closely linked to the strategic planning of maintenance and restoration efforts. GPR systems are effective tools for obtaining information such as reinforcement depth, asphalt pavement thickness, and concrete damage under pavement. The capability of identifying issues arising in concrete bridge decks is the most important aspect. Common problems such as cracks, leaching, scaling, chipping, corrosion of rebars, poor-quality concrete, and delamination underscore the critical need for effective monitoring and inspection. For this purpose, the use of laboratory-scale models (Table 2) before conducting a field study is a common and highly important practice in the field of engineering and scientific research [20]. Such phenomena can prove challenging to study directly in the field due to uncontrollable variables. Utilizing a laboratory model (Figure 2) enables the isolation of specific aspects, facilitating a deeper understanding of the behavior of a structure or system under diverse conditions. In order to evaluate both the constraints and advantages of different tools and enhance the acquisition phase, several authors focus on the examination of laboratory-scale models. The versatility of the technique allows different authors to focus on different issues.

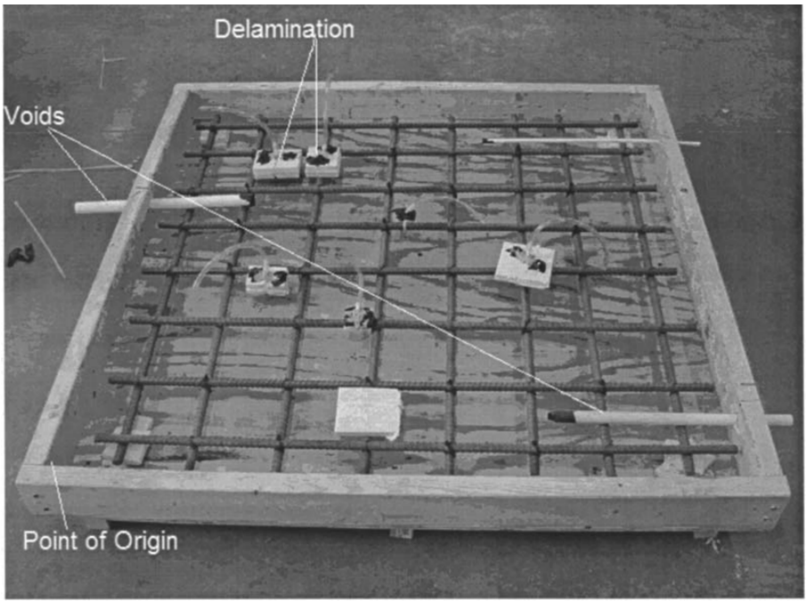

Figure 2. Slab with induced defects before casting [20].

Rathod et al. [21] describe the application of GPR on rebar detection, in order to obtain valuable information about the diameter of the rebars, the spacing, and depth of the reinforcement bars to determine the structural capacity (load factor) of the deck. In this case, GPR was applied on a reinforced concrete test plate panel available in the materials laboratory. GPR data was collected using the same 20 × 20 grid (610 mm × 610 mm). GPR was run along each of the grid lines, for a total of 26 different steps with GPR (13 vertical lines, 13 horizontal lines). The integrity of the bridge comprises mainly the delamination of the concrete and the corrosion of the built-in steel reinforcement. To detect delamination, voids, and surface cracks, Sherif Yehia et al. [22] designed and manufactured six concrete test pieces to compare GPR capabilities. Three samples were simulated to replicate internal bridge defects, while the other three samples served as control specimens without any simulated defects. The GPR device consisted of a high-resolution, high-frequency antenna with a central frequency of 1500 MHz. Moreover, Sherif Yehia et al. [22] prepared a laboratory sample with induced delamination to validate GPR's ability to measure the depth of a delamination. The slab is 122 × 122 cm and 18 cm thick. A reinforcing mesh was used. A half slab filled with cement consolidated the other with bad cement. The depth of the rebar was then identified with the aim of obtaining maps of degradation of the area investigated. The main aims of Clem et al.'s [23] paper are the depth of the reinforcements, the thickness of the sample, and delamination phenomena in the concrete, defining three reinforced concrete mock-up bridge specimens. In the laboratory, the first specimen is slightly reinforced (upper layer) with variable thickness. The second sample simulates the deck of the concrete bridge with artificial delamination and, finally, the last specimen is a beam of a bridge with varying dimensions of rebars and two empty post-tensioning ducts. To evaluate the efficacy of GPR in detecting delamination within reinforced concrete bridge decks and to refine their understanding of its capabilities, Ali A. Sultan et al. [24] undertook a laboratory experiment. The investigation encompassed an examination of GPR's reliability, employing the methodology outlined in the current ASTM standard for a comprehensive assessment. The authors made a laboratory simulation of the delamination, which represented a separation in the concrete layer without corrosion. All GPR tests were performed using commercial GPR instrumentation (SIR-3000 GSSI). One of the most important elements in bridges is the beams. This element plays the key role in transferring the weight from traffic and other loads to the superstructure. The beams are often faced with intense bending, torsion, and cutting efforts. Due to the large amount of effort that is generated, it is of paramount importance to pay special attention to the study and monitoring of these parts. In fact, P. Jaishankar et al. [25] performed measurements on sample beams using the GSSI SIR-20 system. A 1.6 GHz frequency antenna was continuously moved to the beam surface with a regular distance of 5 cm between the profiles, along the longitudinal directions.

Through these investigations, the objective was to observe the thickness of the samples and the various defects present in the beams. Deterioration mechanisms, such as rebar corrosion, often commence long before any visible damage can be detected through routine visual inspections. The gradual processes leading to structural degradation may include factors like environmental exposure, chemical reactions, and other stressors, working silently beneath the surface before manifesting as observable deterioration. Early detection and intervention mechanisms are crucial to mitigate potential structural issues and prevent further damage from progressing unnoticed. In fact, many scholars are engaged in the analysis of this phenomenon, with the aim of acquiring significant knowledge to interpret the state of deterioration of a bridge [26]. Martino et al. [27] carried out experiments using a GSSI SIR-3000 with a 2.6 GHz antenna. In order to minimize the impact of environmental variables on the investigation of reflection amplitudes, the sample reinforcements were fabricated within a controlled laboratory environment. Subsequently, these samples were allowed to undergo a drying process over a period of several months before the testing made by authors [27]. Following the drying phase, the laboratory plates were deliberately subjected to artificial corrosion processes to simulate and study the effects of deterioration on the reinforcement. This systematic approach allows for a more controlled and replicable examination of reflection amplitudes, helping to isolate and understand the impact of corrosion under controlled conditions. This controlled drying procedure helps ensure that the samples achieve a stable condition, reducing the influence of ambient moisture or humidity on the study of reflection amplitudes. Another critical component in the design of many bridges and structures is post-tensioned cables. These cables, subjected to controlled tension after the concrete has set, enhance the structural integrity and load-bearing capacity of the construction. The application of post-tensioning technology allows for more efficient use of materials and contributes to the overall durability and performance of the bridge or structure. It is often used to reduce deformation, improve load-bearing capacity, and allow the construction of bridges and structures that are slimmer and lighter. It can also be subject to corrosion phenomena, and for the monitoring of structures, it is vital to locate the latter and locate possible defects. Giannopoulos et al. [28] conducted a study in which beams with ducts were manufactured using both metal and plastic materials. The beam had a cross-section of 0.4 m $\times$ 0.45 m and a length of 2 m. The pipes had external diameters of 64 mm and internal diameters of 50 mm, and a steel curtain with a diameter of 20 mm was included inside. The main purpose of the experiment was to detect the emptied section of the duct while scanning using both 900 MHz and 1.5 GHz GSSI antennas. The purpose of these radargrams was to determine whether it was possible to detect a completely emptied conduit that represents the worst-case scenario in which cables are most vulnerable to corrosion. The same methodology was applied to detect the presence of simulated gaps within post-voltage ducts, which were filled with mortar. Slawski et al. [29] focused on the study of pre-post-tensioned concrete beams (Figure 3) and the main aim was to evaluate the rebar location and the cover depth of prefabricated “T” bridge girders with an IDS Alladin with a 2 GHz bipolar antenna.

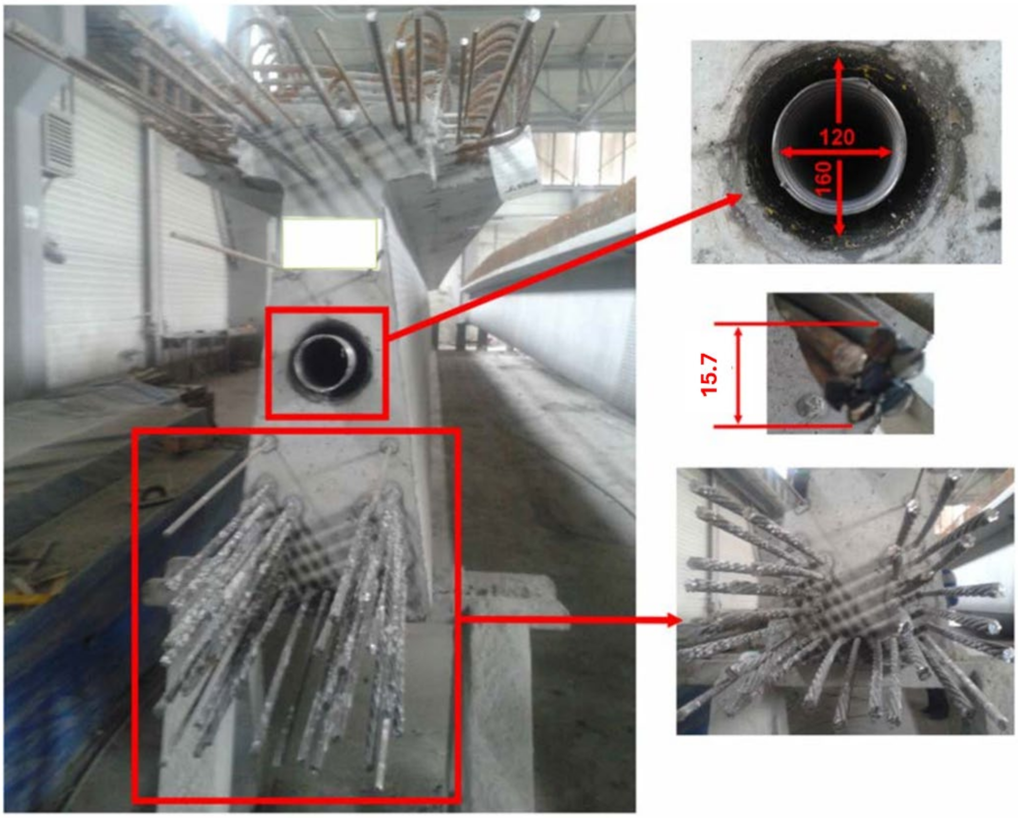

Figure 3. Study of pre-post-tensioned beam [29].

Table 2. Summary of various articles on the study of concrete-reinforced laboratory models.

Paper	Data Processing	GPR Instrument	Frequency Antenna	Other Methods
Rathoda et al. [21]	RADAN, AutoCAD	GSSI	NA	Yes
Yehia et al. [22]	NA	NA	1.5 GHz	Yes
Clem et al. [23]	NA	Handy search JRC 95B	NA	No
Sultan et al. [24]	RADAN	GSSI SIR-3000	1.6 GHz	No
Jaishankar et al. [25]	RADAN	GSSI SIR-20 system	1.6 GHz	Yes
Martino et al. [27]	NA	GSSI SIR-3000	2.6 GHz	Yes
Giannopoulos et al. [28]	GPR FDTD simulator GprMax2D/3D	GSSI SIR-1OH GPR system	1.5 GHz 900 MHz	No
Slawski et al. [29]	NA	IDS Alladdin	2 Ghz	No

3.3. Overview on GPR in Real Case Reinforced Concrete Bridges

Ground Penetrating Radar (GPR) systems are experiencing growing utilization as diagnostic and quality assurance tools for concrete structures. Prestressed concrete bridges, due to their exposure to various stresses and environmental conditions, are susceptible to factors that can affect their long-term stability and durability [30] (vehicle loads, climate changes, humidity, wear, corrosion, etc.). Regular maintenance and periodic inspection are crucial to detect signs of deterioration and prevent catastrophic failures. Therefore, the application of GPR in this context emerges as a valuable method to assess the condition of prestressed concrete structures, enabling proactive maintenance and ensuring the continuous integrity of these bridges over time. Reinforced concrete bridges are complex and crucial structures in the infrastructure landscape. They are primarily composed of three fundamental parts: slab, beam, and pillar. The slab represents the driving surface of the bridge, the part that supports the load of vehicular and pedestrian traffic. Usually constructed from concrete, it can exhibit a variety of architectural and functional solutions. Its strength and durability are essential to ensure the safety of bridge users. The beams are horizontal structural elements that connect the pillars and support the slab. Positioned perpendicular to the direction of traffic flow, the beams distribute loads and contribute to the stability of the structure. Their shape and size can vary depending on the specific design of the bridge, often reinforced with the use of steel to enhance performance. The pillars are vertical elements that support the beams and transfer loads to the ground through foundations. Placed strategically along the length of the bridge, the pillars are fundamental to ensuring the stability and structural resistance of the entire construction. They are also commonly made of reinforced concrete to withstand various loads and environmental conditions. Several studies on the use of GPR applied on bridge elements are presented and summarized in Table 3. Even if several papers highlight applications on slab, few of them focus their attention on pillars and beams. Most studies focus on the examination of the bridge slab because its lifespan is typically shorter than other parts of the bridge. Indeed, the bridge slab constitutes the section designed to bear the loads and traffic moving across the bridge, and it is susceptible to various deterioration phenomena, including cracking, leaching, encrustation, chipping, reinforcement corrosion, presence of poor-quality concrete, and delamination. Consequently, the ability to promptly identify issues manifesting in concrete bridge slabs plays a fundamental role. The structure of the bridge slab can vary depending on the specific project. Investigations conducted on the slabs to gather information about the progress of the degradation, geometry, and arrangement of metal bars involve an acquisition phase where longitudinal and transverse profiles of the lanes under examination are anticipated. These acquisitions enable the creation of maps illustrating the level of structure deterioration based on signal attenuation, allowing the identification of potential areas where corrosion processes may develop [31–37]. Figure 4 provides an example of a signal attenuation map acquired on a bridge slab. Furthermore, models describing the evolution of deterioration over time are developed [38,39]. To verify the effectiveness of the GPR method in providing a significant contribution to the assessment of a structure's deteriorated state, Christopher L. Barnes and Jean-Francois Trottier [40] focused their attention on comparing GPR data with half-cell potential data acquired on different bridges. Their study revealed a remarkable spatial correlation and an impressive quantitative alignment between predictions derived from GPR assessments and the deterioration observed on the investigated bridges. These results underscore GPR's capacity as a valuable management tool, offering reliable estimates for bridge repair quantities and aiding in the strategic prioritization of potential repair candidates at the network level.

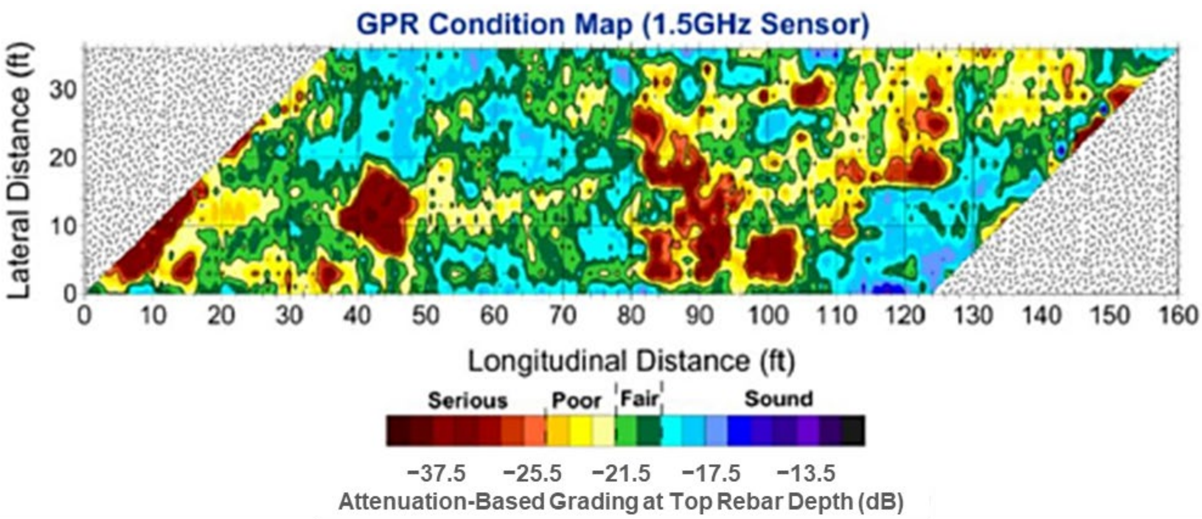

Figure 4. Example of a map of the attenuation of the acquired signal on the bridge slab [35].

Table 3. Summary of various articles on the study of concrete bridges in real cases.

Paper	Data Processing	GPR Instrument	Frequency Antenna	Bridge Element	Other Methods
Cruza et al. [1]	NA	-MALA Geoscience	1.6 GHz, 900 MHz	pillar	Yes
Rathoda et al. [21]	RADAN	GSSI	-	slab	Yes
Varnavina et al. [31]	RADAN	GSSI SIR System-3000 unit coupled	1.5 Ghz	Slab	No
Amos et al. [32]	RADAN	GSSI SIR System-3000 GPR	1.5 Ghz	slab	No
Rahman and Zayed [33]	Matlab and RADAN	GPR GSSI SIR® 3000	1.5 Ghz	slab	No
Parrillo and Roberts [34]	RADAN Bridge, Surfer	GSSI's BridgeScan system	1.5 Ghz	slab	No
Manh La et al. [35]	The NDE software is developed by utilizing Qt development kit and Cpp	NA	1.5 Ghz	slab	No
Rhee et al. [36]	RADAN	Geophysical Survey Systems, Inc. (GSSI)	1 Ghz	slab	No
Gagarin et al. [37]	NA	SFR GPR	NA	slab	No
Dinh et al. [38]	GSSI RADAN 7, Matlab, Surfer	GSSI	1.5 Ghz	slab	No
Dinh et al. [39]	NA	NA	1 GHz	slab	yes
Barnes and Trottier [40]	NA	Penetradar IRIS GPR system	100 Hz samples frequency	slab	Yes
Goulias et al. [41]	NA	NA	600 MHz and 2 Ghz	slab	No
Dinh et al. [42]	Programclusterbridges	NA	1.5 GHz	slab	Yes
Wang et al. [43]	RADAN, Surfer	NA	NA	slab	No
Carter et al. [44]	NA	NA	NA	slab	No
Barnes and Trottier [45]	NA	GSSI SIR-10	1.5 GHz	slab	Yes
Rhee et al. [46]	RADAN	Sir Series of Geophysical Survey Systems Inc. (GSSI)	1 GHz	slab	No
Diamanti et al. [47]	NA	NA	1 GHz	slab	No
Hugenschmidt et al. [48]	Et	OSSI-SIR20 radar	NA	slab	No
Pailes and Gucunski [49]	NA	NA	1.5 GHz	slab	Yes
D'Amico et al. [50]	ENVI SARscape	IDS Georadar	1 and 2 Ghz	slab	Yes
Pashoutani and Zhu [51]	GPR Max	SIR-4000	1.5 GHz	slab	Yes
Bavusi et al. [52]	Personal software	SIR 3000	900 and 1500 MHz	slab	Yes
Gagarin et al. [53]	3d Examiner	3D-Radar DXG1820	antenna array 200 MHz–3 GHz	slab	No
Owerko et al. [54]	Reflex-Win	Mala Geoscience	1 GHz	Pillar	yes

Table 3. *Cont.*

Paper	Data Processing	GPR Instrument	Frequency Antenna	Bridge Element	Other Methods
Hugenschmidt and Mastrangelo [55]	NA	System GSSI SIR-20	1.2 Ghz	beams	No
Yelf and Carse [56]	NA	Georadar Research Pty Ltd.	1.5 Ghz	beams	No
Dérobert et al. [57]	NA	NA	1.5 Ghz	beams	Yes
Beben et al. [58]	GRED 3D	NA	2 Ghz	beams	No

The iron cover is an essential part to protect the reinforcements from external agents, which can trigger and accelerate corrosive phenomena; the study of geometries and thickness of the iron cover on slab are described in some studied papers [21,24,41]. Variations in thickness have significant effects on the measurement signal amplitude study [42]. The detection of existing defects within the work leading to the identification of the presence of voids within the structure can cause a redistribution of stress and areas of moisture accumulation, and areas susceptible to delamination induced by corrosive phenomena [43,44]. In detail, Barnes and Trottier [45] focused on studying individual waveforms to identify probable areas with delamination induced by corrosion. The observation of cracks or holes through visual inspections generally precedes GPR investigations [34]. The degradation of the reinforced concrete bridge structure results in alterations in the dielectric properties of the concrete, primarily induced by the presence of chlorides and reinforcement corrosion. As chlorides infiltrate the concrete, they contribute to the corrosion of reinforcements, leading to changes in the dielectric characteristics of the material. This interaction between chemical factors and structural corrosion underscores the complex nature of concrete deterioration in reinforced bridges, emphasizing the importance of monitoring and addressing these issues for the overall integrity of the structure. Rhee et al. [46] proposed a practical approach to bridge condition assessment by investigating changes in the dielectric constant. Therefore, the presence of moisture and saltwater is the main cause of reinforcement corrosion that can cause severe structural damage, as described in the work of Diamanti et al. [47]. In fact, Hugenschmidt et al. [48] conducted an inspection of a bridge slated for demolition, aiming to comprehensively study chloride contamination through destructive tests (surveys). The goal was to compare and correlate data obtained from these destructive tests with Ground Penetrating Radar (GPR) acquisitions. This integrated approach enables a more thorough understanding of chloride distribution within the structure, providing valuable insights for assessing the bridge's condition and informing decisions related to its planned demolition. To improve the obtained results of surface and underground degradation on bridges and infrastructure, many authors integrated the GPR data with other NDT techniques [7,49] or the InSAR (Interferometric Synthetic Aperture Radar) method [50]. Pashoutani, S and Zhu [51] proposed a real depth-correction method for GPR data analysis, obtaining a reliable assessment of concrete slab conditions. To assess and contrast distinct depth-correction techniques, the authors employed the gprMax software to simulate GPR signals across some models characterized by differing dielectric constants and conductivity levels. Bavusi et al. [52] described the microwave tomographic approach on GPR data acquired on a reinforced concrete bridge. The microwave tomographic approach on GPR data involves integrating principles of tomography with GPR technology to create detailed images of subsurface structures based on variations in dielectric properties. This technique enhances the capabilities of GPR for subsurface investigations and imaging. A specific approach within the GPR technology is the Step Frequency GPR (SF-GPR) method. SF-GPR systems emit radar signals at discrete frequencies across a range, and by analyzing the reflected signals, it is possible to create subsurface images. The advantage of using step frequencies lies in the ability to gather more detailed information about the subsurface structure and properties. Gagarin et al. [53] implemented a post-processing algorithm for

SF-GPR data, to explore the development of the bridge slab condition rating methodology using fuzzy sets modeling (Figure 5).

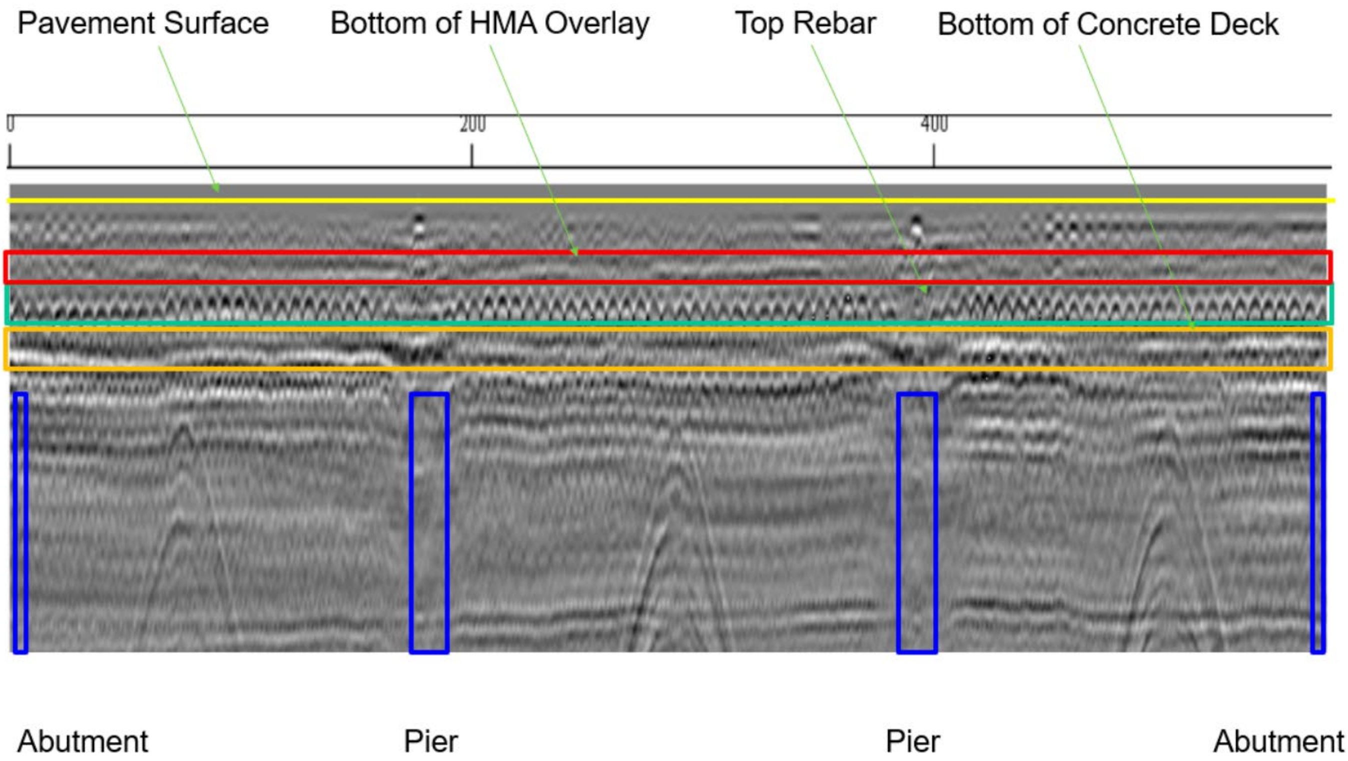

Figure 5. Examples of profile view of bridge slab. The yellow line defines the pavement surface. The red square indicates the bottom of RMA overlay. The red square defines the top rebar. The orange square the bottom of the concrete deck [53].

To obtain a more accurate and detailed assessment of the conditions of reinforced concrete bridges, some authors focus on the detailed study of the main beams, which may present certain issues [54,55]. Commonly, within these beams, pre-compressed cables or post-tensioning cables are strategically placed to enhance the strength and load-bearing capacity of the structure. The presence of voids and significant cracks could compromise stability, leaving a portion of the pre-compressed profile exposed and vulnerable to corrosion, with the risk of a gradual release of pre-compression [56,57]. Furthermore, a study conducted by Ben et al. [58] investigated two main beams of a viaduct, performing both longitudinal and transverse analyses. This allowed for the identification of the position of reinforcement bars, stirrups, and a hole within the beam (Figure 6).

A structural element that is not extensively discussed in the literature is the pillars. These elements can vary significantly based on the structural objectives, site conditions, and the type of bridge. Like other components, they are subject to significant vertical and lateral loads and can undergo severe corrosive phenomena, leading to a different distribution of forces. Indeed, Owerko et al. [54] presented the results of GPR investigations conducted on a trapezoidal-shaped railway pillar to locate defects, such as the presence of deeper voids that would result in a different distribution of stresses and affect the load-bearing capacity of the pillar.

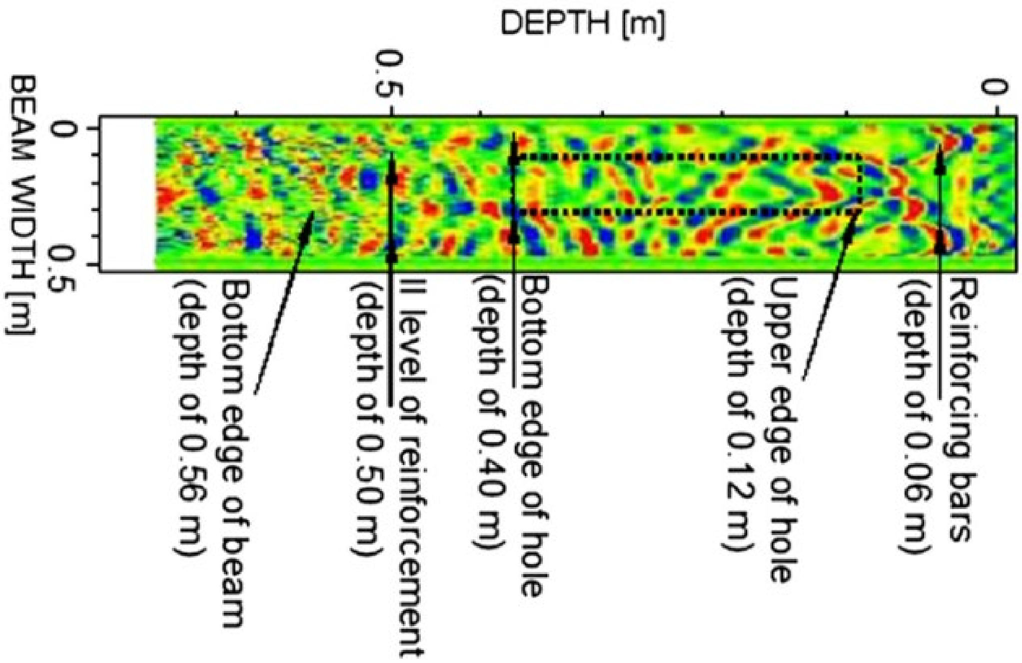

Figure 6. Processed transverse radargram with bars and hole [58].

Meanwhile, Cruz et al. [1] focused on the analysis of three case studies involving the use of GPR techniques for inspecting concrete bridges. The objective was to locate the actual position of metal reinforcements, tendon ducts, and assess the material quality in both beams and pillars. Field acquisitions mainly consist of 2D radargrams performed on the longitudinal beams of the bridges. In each position, a series of parallel and vertical lines were defined to carry out accurate GPR acquisitions. Additionally, to evaluate the degree of corrosion progression and observe the variation in the cover thickness, investigations were conducted on some columns of the viaduct. These investigations highlighted several issues. Figure 7 shows a view of the investigated pillar and a radargram where the location of rebars is well detected, highlighting how the concrete cover changes along the circumference of the column. This difference means that some of the reinforcement bars are located very close to the surface, which can cause an early occurrence of corrosion [1]. Furthermore, the discrepancy between the actual arrangement of the metal bars and the initial design necessitates further investigations to assess the real positioning of the reinforcements, as this can significantly influence the strength and durability of the pillar.

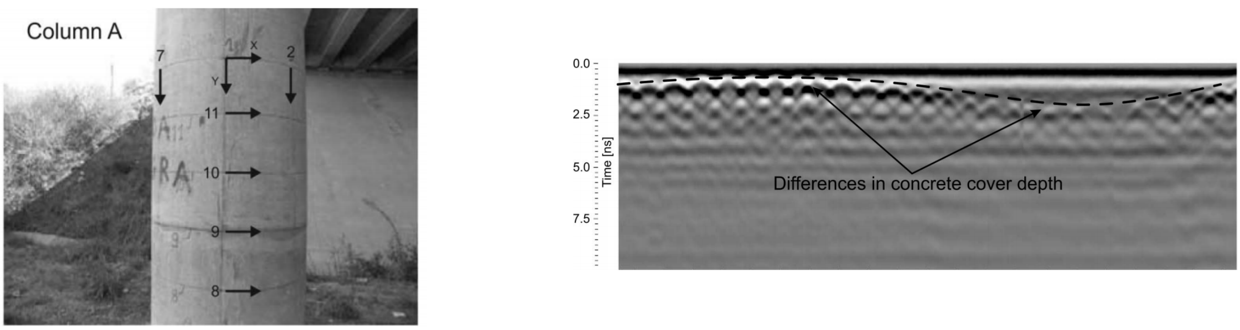

Figure 7. View of the investigated column and the radargram showing the different offset between rebars and variations in the concrete cover. The number on the pillar indicated the line profile acquired with GPR. Modified from [1].

4. Overview of GPR on Data Processing and Visualization

Ground Penetrating Radar (GPR) emerges as a standout detection technology due to its impressive efficiency in swiftly gathering data at a minimal cost. This rapid and convenient data acquisition capability positions it as a valuable tool across diverse applications. As the demand increases, there is a growing necessity to enhance the data processing and representation methodologies, aiming for substantial improvements in optimizing and simplifying the interpretation phase. Several studies on different methods of data visualization are presented and summarized in Table 4. Ground Penetrating Radar (GPR) is widely acknowledged as a highly effective and efficient technology for examining bridge decks or slabs, enabling a thorough investigation into the progression of defects and degradations. Bridges and infrastructure are susceptible to deterioration, with the primary factor leading to a decline in structural stability often attributed to the corrosion of reinforcement bars [59]. Although most of the authors use commercial software, several use their own algorithms developed on a MATLAB platform to process the GPR post-processing data faster and, above all, in larger quantities. Ghodoosia et al. [60] developed a deterioration model calibrated with GPR results to estimate the reliability of the bridge slab, in order to optimize the nonlinear finite element predicted model on real-life structures. The RADAN software was used to elaborate the GPR data, and a map of defects has been depicted using a visual approach.

Table 4. Summary of studied articles on data processing and visualization.

Paper	Data Processing and Visualization	GPR Instrument	Frequency Antenna	Other Methods
Ghodoosia et al. [60]	Radan	GSSI	1.5 Ghz	No
Dinh et at. [61]	MATLAB algorithm	NA	1.5 GHz	No
Dinh et al. [62]	MATLAB algorithm	GSSI	1.5 GHz	Yes
Zhang et al. [63]	MALÅ GroundVision software	MALÅ ProEx system	2.3 GHz	No
Tarussov et al. [64]	Software developed by authors: RADxpert	NA	NA	No
Abouhamad et al. [65]	RADxpert	GSSI SIR-3000	1.5 GHz	No
Benedetto et al. [66]	Personal Algorithm	RIS Hi Brignt	2 GHz	No
Shakibabarough et al. [67]	Personal Algorithm developed in MATLAB applied on radargram images.	GSSI	1.5 GHz	No
Dinha et al. [68]	Personal Algorithm developed in MATLAB applied on radargram images.	GSSI	1.5 GHz	No
Asadi et al. [69]	Machine Learning (ML) approach on radargram images	GSSI SIR System3000	1.6 GHz	No
Rahman et al. [70]	RADAN, MATLAB	GSSI	1.6 GHz	No

The attenuation of the GPR signal stands out as the predominant criterion for assessing potential deterioration and damage in concrete bridge decks. Nevertheless, due to the presence of numerous factors that can influence the signal, the accuracy of attenuation maps in precisely depicting the bridge's deterioration may be compromised. Kien Dinh et al. [61] proposed an attenuation bridge model based on A-scan GPR correlations by evaluating the possible deterioration and damage in concrete bridge slab. The proposed approach used a MATLAB algorithm that depicted attenuation contouring maps on the investigated zone compared with electrical conductivity and potential distribution methods. Another MATLAB algorithm approach was proposed by Dinh et al. 2019 [62]. The authors proposed a total and complete automation of the process to obtain amplitude maps of the deck of the bridge to detect rebars, deck joints, or drain grates and to pinpoint the areas of likely corrosive environments. The method was successfully implemented, and the results were validated on the decks of four bridges in the US and Canada.

Zhang et al. [63] applied a MATLAB algorithm to detect moisture damage on the asphalt pavement of a bridge deck. The algorithm analyzed the A-scan trace of the GPR signal, and with an automatic procedure recognized the moisture area.

In order to obtain potentially corroded maps, some numerical approaches have been developed. Some authors [64,65] used a specific interactive software (RADxpert) to detect maps of the damage zones. The authors proposed to develop an interactive analysis software that assists the operator in delineating and mapping damaged areas. The analyst, therefore, can assign to the zones of the area under examination the degree of the more opportune state of progress. The numerical method was not sufficient to determine with certainty the presence or absence of corrosion in the investigation area; new modes of processing are proposed by different authors, which exploit different types of algorithms to simplify and improve the resolutions given by the tool. Benedetto et al. [66] presented a new numerical approach aimed at the automatic tracking of cracks in the decks through the processing of GPR data. It would allow tracing, in a three-dimensional domain, the cracks and then evaluating their gravity by comparing the amplitudes of the reflected signals. The proposed approach tracks the geometry of the cracks in a 3D visualization; however, the critical point of this approach is fixing the proper value of the threshold of detection [66]. Even if the numerical approach is well defined, the methods based on numerical amplitude values have many limitations. In fact, the amplitude value in a B-scan ignores most of the information contained in a radar profile. Therefore, several authors considered GPR B-scans as an imaging tool rather than a numeral measuring tool. They developed novel algorithm approaches to improve the interpretation of GPR data, taking into account the radargram images. The advantages of using visual image-based analysis are several: detection of exact limit zone corrosion, and the reduction in noise using visual filtering. Azin Shakibabarough et al. [67] proposed a new method for detecting areas of deterioration rebar, taking into account a MATLAB image processing tool applied on post-processed radargram images. The same kind of approach was used by Dinha et al. [68], who proposed a MATLAB algorithm to automate picking rebars from the radargram images. The approach presented automated rebar detection to help the time-consuming and labor-intensive manual collection of reinforcements in GPR survey data from concrete bridge decks. Asadi et al. [69] exploits Machine Learning (ML) that, through an algorithm, allows the identification of the bars within the structure and an estimate of their degradation status. The threshold for determining the presence of potentially corroded areas is ASTM D6087 (2008). In detail, the proposed method is based on a combination of image processing, ML data classification, data filtering, and spatial pattern analysis for the quantification of deterioration in concrete bridge decks [69]. Moreover, Rahman et al. [70] instead developed a model to generate reliable deterioration maps using B-scan images for RC bridge and structural elements through automated hyperbola detection based on a trainer classifier Viola Jones algorithm [71].

Even if there are several papers on bridge slab and beam structures that investigated different processing and visualization tools, few articles discuss bridge abutments, piers, or pillars, and, consequently, there is a scarcity of available operational visualization methods. The GPR methodology focuses mainly on the upper surface of the bridge and the load-bearing beams. In the context of the design and safety of bridges, pillars (or bridge piers) also play an extremely important role. In fact, they are vertical or near-vertical supports that transfer the load from the bridge deck to the foundation, supporting the structure above water or other obstacles. The primary function of bridge piers is to support the bridge deck and transfer the loads from the superstructure to the substructure and ultimately to the ground or water below. Bridge piers are specifically designed to withstand dynamic loads, such as those imposed by moving vehicles, and they are engineered to ensure stability and safety in the context of a bridge structure. The degradation of bridge piers refers to the process by which these structural elements experience a decline in their condition or performance over time. Several factors can contribute to the degradation of bridge piers, leading to potential safety concerns and the need for maintenance or rehabilitation. Effective inspection, maintenance, and repair strategies are essential to address and mitigate the degradation of bridge piers. Regular assessments using non-destructive testing methods, such as Ground Penetrating Radar (GPR) or visual inspections, help identify signs of deterioration, enabling timely intervention to ensure the continued safety and functionality of the bridge structure. Additionally, rehabilitation or retrofitting measures may be implemented to extend the service life of degraded bridge piers. Owerko et al. [54] focused on the detection of voids within a trapezoidal-shaped railway pillar. These defects in fact would involve a different distribution of the loads of the structure, causing more stress in the concrete. Another case is that of Cruz et al. [1], who, to assess the possible degradation of a bridge, carried out GPR surveys in two circular columns on access viaducts. The aim was to identify areas within the elements that could potentially exhibit corrosion phenomena. To increase accuracy in the detection of structural defects and in the optimization of the layout of the internal reinforcements, a circular visualization of the GPR data was presented by Rizzo et al. [72]. The technical report is based on results obtained through analyses carried out on two series of pylons, thus bringing considerable added value to the observation and analysis of the wear of structures. The pylons being studied are part of the Moliano viaduct (Basentana highway, Basilicata Region). The data acquisitions will take place on a recently renovated pillar and another where no restoration application has been implemented (Figure 8). The viaduct was built in the 1970s and the original project drawing shows a cavity inside with an internal radius of about 1.10m, while the outer one is 1.50 m; consequently, the effective thickness of the pillar is about 40 cm. The original drawing depicts the arrangement of the internal rebars that follows two reinforcement lines (one internal and one external); each one highlights 28 rebars with an interline of about 20 cm, while in the vertical section, there are brackets with an interline of about 40 cm.

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

Figure 8. Two pillars of Moliano viaduct on the Basentana Highway, close the city of Potenza (Basilicata Region, Italy); (**a**) old pillar without restoration; (**b**) restored pillar.

In detail, the acquisition phase involved profiling with the CTrue Antenna (2 Ghz) from the IDS system. Measurements were conducted around both pillars as part of the data collection process. The profile executed around the circumference in both cases was positioned 10 cm from the ground plane, where a metric string had been placed to maintain alignment of the instrument during the dragging process.

Furthermore, only in the case of the older pillar, at a height of approximately 2 m, was a horizontal profile spanning about 3 m conducted, corresponding to an area with the presence of an iron cover. All the acquired data were elaborated using ReflexW software and the typical elaboration was used: time zero, dewow filter, background removal, and bandpass filter were applied on the data set. To establish a specific location for the acquired data, a circular reconstruction of the pillar was initiated by converting Cartesian positions into polar coordinates through a straightforward mathematical conversion. Following the coordinate conversions, the GPR data were presented in a circular visualization (Figure 9).

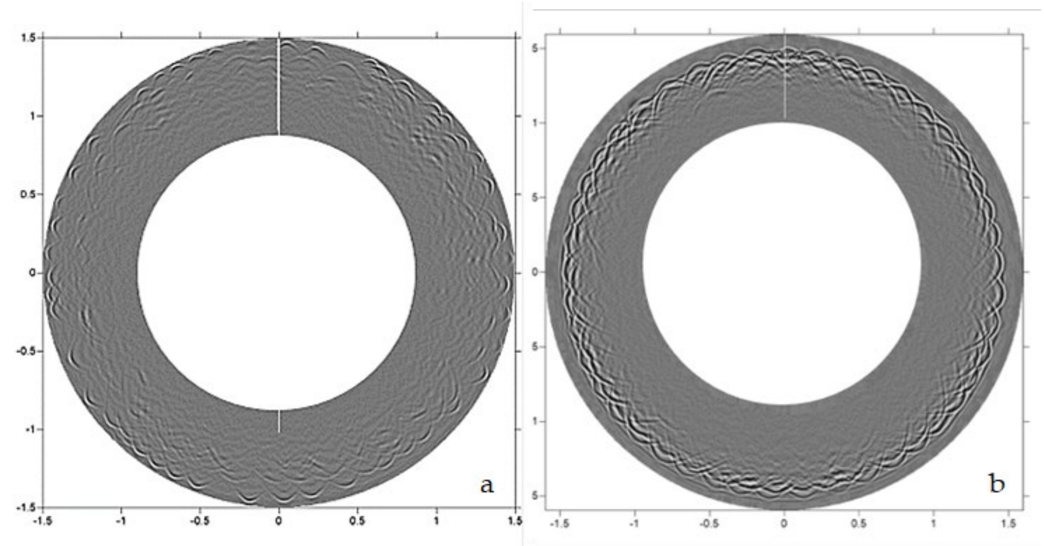

Figure 9. The circular visualization of the GPR data acquired on the circumference of a pillar; (**a**) the pilar without restoration; (**b**) the restored pillar.

The circular GPR image of the pillar without any restructuring is seen very clearly; the hyperboles of reflections caused by the presence of longitudinal irons were as planned, but you can notice a second row of irons placed at a greater depth. The hypothesis made by observing both profiles is that either they derive from the final bending of the longitudinal irons, which can also be observed in the project, or from the reinforcement of the foundation. Radargrams have allowed us to highlight the fact that the thickness of the iron cover is not constant at all points, and this could result in areas subject to degradation, which would greatly affect the structure. The characterization of the pillar also highlighted how the interline presented by the project is not kept constant at the actual site. If we observe, even in more detail, the acquisition of a part of the circumference at a height of about 2 m, we can see that every eight longitudinal rows at a depth of about 20 cm, there are reflections which are probably related to irons that are not indicated in the project. By comparing the results obtained with the initial projects, we aim to underscore the significance of characterizing structures, whether old or newly constructed. The circular reconstruction has proven crucial in achieving enhanced data visualization. It facilitates the observation of both internal geometries of the structure and the arrangement of reinforcement bars within the medium. This circular visualization of data representation seems more quickly and intuitively aware of the real discrepancies that arise between the project and reality. This is especially important if this kind of image is used for redesigning lost projects.

5. Conclusions and Discussion

This comprehensive, though not exhaustive, review of GPR applied on bridge elements has proven to be a technological and operational breakthrough. Moreover, the review essentially demonstrates that GPR applications on bridge elements are almost endless and not exhaustive, especially on the pillars. This study provided the opportunity to observe and compare several approaches to the examination and assessment of the degradation state of a bridge. It has been evident that GPR, being a non-destructive technique, is exceptionally well-suited for this purpose. This enables investigations that not only minimize time but also reduce costs associated with the assessment process. The capability of GPR to swiftly examine extensive areas, while also offering insights into depth and reinforcement spacing, positions it as a valuable tool for studying bridges and viaducts without compromising their stability. The bridge stands as the pivotal component within global road infrastructures, with numerous studies exploring GPR applications across its three primary elements: slab, beam, and pillar. This review emphasizes a range of papers examining both laboratory studies and real-world cases. Among these, many focus on applications on slabs, some on beams, and only a few on pillars. Therefore, several factors still require thorough discussion and investigation. The results of the literature review can be summarized in the following comments:

- Even though GPR has become a highly important tool in the engineering sector, particularly for bridge infrastructures, it is still necessary to conduct laboratory tests, especially to better understand all the variabilities encountered in real cases in terms of concrete deterioration, steel corrosion, moisture influence, etc.
- Current data processing GPR tools have become highly efficient, and even an inexperienced operator can achieve good results up to the visualization of radargrams. However, only an expert can understand how to utilize the results to better comprehend what is being observed.
- Currently, data processing tools allow for obtaining sufficient information to meet the required needs. However, when dealing with large datasets, only automated software operating systems can truly be useful in extracting valuable information. Therefore, artificial intelligence algorithms that analyze radar image data prove to be highly efficient tools for real-world applications. This review of the literature has identified several approaches to the improvement of the data processing phase through programs that allow automatic processing and localization of the rebars to obtain accurate information on the conditions of the bridge. The various methods, therefore, aim to improve and optimize any phase of rehabilitation and restoration of bridges that are often subjected to different external stresses and that in most cases have significant discrepancies in the arrangement of the reinforcements with respect to the actual design.
- The analysis of bridges using GPR techniques represents the perfect blend of the research world and industrial interest because it is necessary to develop tools that make GPR results easy to read and simple to handle.
- GPR has, therefore, proved to be a very valuable tool for assessing the condition of reinforced concrete structures. The various methods proposed will certainly be improved, leading to an update in the management and maintenance system of the work, to make the evaluation of bridges and viaducts faster and more reliable.
- The presence of few articles dedicated to bridge pillars highlights how there is still much to develop and enhance in an area of the bridge that often presents numerous challenges precisely because it represents the contact zone between the bridge and the supporting terrain (critical infrastructure zone).
- The GPR data carried out on the pillar in the viaduct and a circular vision are presented, allowing us to improve the interpretation in terms of the arrangement of the rebars and the variations in the iron cover, and to contribute significantly to the visualization of data.

This review highlights the cutting-edge design and functionality of GPR instruments empowering bridge inspectors with high accuracy and depth penetration, enabling the comprehensive evaluation of bridge structures and subsurface conditions, ultimately enhancing overall safety and structural integrity assessments. The utilization of GPR technology on bridges, particularly focusing on the examination of pillars, showcases its immense potential for revolutionizing infrastructure assessment and maintenance practices, promising a future of enhanced safety and efficiency in bridge management. The diverse software options available for GPR applications provide all the needs and preferences, offering flexibility and customization in data processing, visualization, and interpretation, ensuring optimal utilization across a spectrum of bridge inspection and maintenance tasks. In conclusion, the integration of advanced software solutions tailored for GPR data analysis further amplifies the efficacy of bridge inspection processes, facilitating precise interpretation and actionable insights for optimal decision-making in structural maintenance and rehabilitation efforts.

Author Contributions: Conceptualization, E.R.; data curation, P.B. and G.F.; writing—original draft preparation, P.B.; writing—review and editing, E.R.; funding acquisition, E.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the MIUR PON R&I 2014–2020 Program (Project MITIGO—"Mitigazione dei rischi naturali per la sicurezza e la mobilità nelle aree montane del Mezzogiorno", ARS01_00964).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No data were available to write this paper.

Acknowledgments: The authors thank Geol. Gregory De Martino and Ing. Vito Santarsiere for their contribution to the acquisitions in the investigated test site.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Cruz, P.J.; Topczewski, L.; Fernandes, F.M.; Trela, C.; Lourenco, P.B. Application of radar techniques to the verification of design plans and the detection of defects in concrete bridges. *Struct. Infrastruct. Eng.* **2010**, *6*, 395–407. [CrossRef]
2. Kassir, M.K.; Ghosn, M. Chloride-induced corrosion of reinforced concrete bridge decks. *Cem. Concr. Res.* **2002**, *32*, 139–143. [CrossRef]
3. Lollini, F. Corrosione da carbonatazione: Fenomeno di degrado e prevenzione. *IN CONCRETO* **2015**, *129*, 24–25.
4. Barnes, C.L.; Trottier, J.-F.; Forgeron, D. Improved concrete bridge deck evaluation using GPR by accounting for signal depth–amplitude effects. *NDT E Int.* **2008**, *41*, 427–433. [CrossRef]
5. Alani, A.M.; Aboutalebi, M.; Kilic, G. Applications of ground penetrating radar (GPR) in bridge deck monitoring and assessment. *J. Appl. Geophys.* **2013**, *97*, 45–54. [CrossRef]
6. Wong, P.T.; Lai, W.W.; Sham, J.F.; Poon, C.-S. Hybrid non-destructive evaluation methods for characterizing chloride-induced corrosion in concrete. *NDT E Int.* **2019**, *107*, 102123. [CrossRef]
7. Fornasari, G.; Capozzoli, L.; Rizzo, E. Combined GPR and Self-Potential Techniques for Monitoring Steel Rebar Corrosion in Reinforced Concrete Structures: A Laboratory Study. *Remote Sens.* **2023**, *15*, 2206. [CrossRef]
8. *ASTM D6087-08*; Standard Test Method for Evaluating Asphalt-Covered Concrete Bridge Decks Using Ground Penetrating Radar. ASTM International: West Conshohocken, PA, USA, 2008.
9. Hugenschmidt, J. Concrete bridge inspection with a mobile GPR system. *Constr. Build. Mater.* **2002**, *16*, 147–154. [CrossRef]
10. Trela, C.; Wöstmann, J.; Kruschwitz, S. Contribution of radar measurements to the inspection and condition assessment of railway. In *WIT Transactions on The Built Environment*; High Performance Structures and Materials IV; WIT Press: Billerica, MA, USA, 2008; Volume 97, p. 535. ISSN 1743-3509.
11. Kalogeropoulos, A.; Brühwiler, E. High-resolution 3D condition survey of a masonry arch bridge using Ground Penetrating Radar. In Proceedings of the First Middle East Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures, Dubai, United Arab Emirates, 8–10 February 2011; pp. 1–9.
12. Solla, M.; Lorenzo, H.; Rial, F.; Novo, A. Ground-penetrating radar for the structural evaluation of masonry bridges: Results and interpretational tools. *Constr. Build. Mater.* **2012**, *29*, 458–465. [CrossRef]

13. Solla, M.; Lagüela, S.; Riveiro, B.; Lorenzo, H. Non-destructive testing for the analysis of moisture in the masonry arch bridge of Lubians (Spain). *Struct. Control. Health Monit.* **2013**, *20*, 1366–1376. [CrossRef]
14. Pérez-Gracia, V.; Di Capua, D.; Caselles, O.; Rial, F.; Lorenzo, H.; González-Drigo, R.; Armesto, J. Characterization of a Romanesque Bridge in Galicia (Spain). *Int. J. Arch. Heritage* **2011**, *5*, 251–263. [CrossRef]
15. Bautista-De Castro, Á.; Sánchez-Aparicio, L.J.; Carrasco-García, P.; Ramos, L.F.; González-Aguilera, D. A multidisciplinary approach to calibrating advanced numerical simulations of masonry arch bridges. *Mech. Syst. Signal Process.* **2019**, *129*, 337–365. [CrossRef]
16. Diamanti, N.; Giannopoulos, A.; Forde, M.C. Numerical modelling and experimental verification of GPR to investigate ring separation in brick masonry arch bridges. *NDT E Int.* **2008**, *41*, 354–363. [CrossRef]
17. Solla, M.; Lorenzo, H.; Riveiro, B.; Rial, F. Non-destructive methodologies in the assessment of the masonry arch bridge of Traba, Spain. *Eng. Fail. Anal.* **2011**, *18*, 828–835. [CrossRef]
18. Lubowiecka, I.; Arias, P.; Riveiro, B.; Solla, M. Multidisciplinary approach to the assessment of historic structures based on the case of a masonry bridge in Galicia (Spain). *Comput. Struct.* **2011**, *89*, 1615–1627. [CrossRef]
19. Stavroulaki, M.E.; Riveiro, B.; Drosopoulos, G.A.; Solla, M.; Koutsianitis, P.; Stavroulakis, G.E. Modelling and strength evaluation of masonry bridges using terrestrial photogrammetry and finite elements. *Adv. Eng. Softw.* **2016**, *101*, 136–148. [CrossRef]
20. Sherif, Y.; Osama, A.; Saleh, N.; Ikhlas, A. Detection of Common Defects in Concrete Bridge Decks Using Nondestructive Evaluation Techniques. *J. Bridge Eng.* **2007**, *12*, 205–225. [CrossRef]
21. Rathod, H.; Debeck, S.; Gupta, R.; Chow, B. Applicability of GPR and a rebar detector to obtain rebar information of existing concrete structures. *Case Stud. Constr. Mater.* **2019**, *11*, e00240. [CrossRef]
22. Yehia, S.; Abudayyeh, O.; Abdel-Qader, I.; Zalt, A. Ground-Penetrating Radar, Chain Drag, and Ground Truth. *Transp. Res. Rec. J. Transp. Res. Board* **2008**, *2044*, 39–50. [CrossRef]
23. Clem, D.J.; Schumacher, T.; Deshon, J.P. A consistent approach for processing and interpretation of data from concrete bridge members collected with a hand-held GPR device. *Constr. Build. Mater.* **2015**, *86*, 140–148. [CrossRef]
24. Sultan, A.A.; Washer, G.A. Reliability Analysis of Ground-Penetrating Radar for the Detection of Subsurface Delamination. *J. Bridg. Eng.* **2018**, *23*, 04017131. [CrossRef]
25. Jaishankar, P.; Kanchidurai, S.; Thomas, A.C.; Mohan, K.S.R. Experimental investigation on Non-Destructive behaviour of repaired FRP concrete beams. *Mater. Today Proc.* **2022**, *64*, 990–994. [CrossRef]
26. Darmawan, M.S.; Stewart, M.G. Spatial time-dependent reliability analysis of corroding pretensioned prestressed concrete bridge girders. *Struct. Saf.* **2007**, *29*, 16–31. [CrossRef]
27. Martino, N.; Maser, K.; Birken, R.; Wang, M. Determining Ground Penetrating Radar Amplitude Thresholds for the Corrosion State of Reinforced Concrete Bridge Decks. *J. Environ. Eng. Geophys.* **2014**, *19*, 175–181. [CrossRef]
28. Giannopoulos, A.; Macintyre, P.; Rodgers, S.; Forde, M.C. GPR detection of voids in post-tensioned concrete bridge beams. In Proceedings of the 9th International Conference on Ground Penetrating Radar, Santa Barbara, CA, USA, 29 April–2 May 2002. [CrossRef]
29. Sławski, Ł.; Kosno, Ł.; Swit, G. Evaluation of Precast Pre-post-tensioned Concrete Bridge Beams with the Use of GPR Method. *Procedia Eng.* **2016**, *156*, 443–450. [CrossRef]
30. Wang, W.; Wang, L.; Xiong, H.; Luo, R. A review and perspective for research on moisture damage in asphalt pavement induced by dynamic pore water pressure. *Constr. Build. Mater.* **2019**, *204*, 631–642. [CrossRef]
31. Varnavina, A.V.; Khamzin, A.K.; Torgashov, E.V.; Sneed, L.H.; Goodwin, B.T.; Anderson, N.L. Data acquisition and processing parameters for concrete bridge deck condition assessment using ground-coupled ground penetrating radar: Some considerations. *J. Appl. Geophys.* **2015**, *114*, 123–133. [CrossRef]
32. Amos, W.; Evgeniy, T.; Anderson, N. Bridge Deck assessment using ground penetrating radar (GPR). In *Symposium on the Application of Geophysics to Engineering and Environmental Problems*; SEG Library: Houston, TX, USA, 2009. [CrossRef]
33. Rahman, M.A.; Zayed, T. Developing Corrosion Maps of RC bridge elements based on automated visual image analysis. In Proceedings of the Session of the 2016 Conference of the Transportation Association of Canada, Toronto, ON, Canada, 25–28 September 2016.
34. Parrillo, R.; Roberts, R. Bridge Deck Condition Assessment using Ground Penetrating Radar. In Proceedings of the 9th European Conference on NDT, Berlin, Germany, 25–29 September 2006.
35. La, H.M.; Gucunski, N.; Kee, S.-H.; Van Nguyen, L. Data analysis and visualization for the bridge deck inspection and evaluation robotic system. *Vis. Eng.* **2015**, *3*, 6. [CrossRef]
36. Rhee, J.-Y.; Choi, J.-J.; Kee, S.-H. Evaluation of the Depth of Deteriorations in Concrete Bridge Decks with Asphalt Overlays Using Air-Coupled GPR: A Case Study from a Pilot Bridge on Korean Expressway. *Int. J. Concr. Struct. Mater.* **2019**, *13*, 23. [CrossRef]
37. Gagarin, N.; Goulias, D.; Mekemson, J.; Cutts, R.; Andrews, J. Development of Novel Methodology for Assessing Bridge Deck Conditions Using Step Frequency Antenna Array Ground Penetrating Radar. *J. Perform. Constr. Facil.* **2020**, *34*, 04019113. [CrossRef]
38. Dinh, K.; Zayed, T.; Romero, F.; Tarussov, A. Method for Analyzing Time-Series GPR Data of Concrete Bridge Decks. *J. Bridg. Eng.* **2015**, *20*, 04014086. [CrossRef]
39. Alsharqawi, M.; Zayed, T.; Abu Dabous, S. Integrated condition rating and forecasting method for bridge decks using Visual Inspection and Ground Penetrating Radar. *Autom. Constr.* **2018**, *89*, 135–145. [CrossRef]

40. Barnes, C.L.; Trottier, J.-F. Ground-Penetrating Radar for Network-Level Concrete Deck Repair Management. *J. Transp. Eng.* **2000**, *126*, 257–262. [CrossRef]
41. Goulias, D.G.; Cafiso, S.; Di Graziano, A.; Saremi, S.G.; Currao, V. Condition Assessment of Bridge Decks through Ground-Penetrating Radar in Bridge Management Systems. *J. Perform. Constr. Facil.* **2020**, *34*, 04020100. [CrossRef]
42. Dinh, K.; Gucunski, N.; Kim, J.; Duong, T.H. Understanding depth-amplitude effects in assessment of GPR data from concrete bridge decks. *NDT E Int.* **2016**, *83*, 48–58. [CrossRef]
43. Wang, Z.W.; Zhou, M.; Slabaugh, G.G.; Zhai, J.; Fang, T. Automatic Detection of Bridge Deck Condition from Ground Penetrating Radar Images. *IEEE Trans. Autom. Sci. Eng.* **2010**, *8*, 633–640. [CrossRef]
44. Carter, C.R.; Chung, T.; Holt, F.B.; Manning, D.G. An automated signal processing system for the signature analysis of radar waveforms from bridge decks. *Can. Electr. Eng. J.* **1986**, *11*, 128–137. [CrossRef]
45. Barnes, C.L.; Trottier, J.-F. Effectiveness of Ground Penetrating Radar in Predicting Deck Repair Quantities. *J. Infrastruct. Syst.* **2004**, *10*, 69–76. [CrossRef]
46. Rhee, J.-Y.; Park, K.-E.; Lee, K.-H.; Kee, S.-H. A Practical Approach to Condition Assessment of Asphalt-Covered Concrete Bridge Decks on Korean Expressways by Dielectric Constant Measurements Using Air-Coupled GPR. *Sensors* **2020**, *20*, 2497. [CrossRef]
47. Diamanti, N.; Annan, A.P.; Redman, J.D. Concrete Bridge Deck Deterioration Assessment Using Ground Penetrating Radar (GPR). *J. Environ. Eng. Geophys.* **2017**, *22*, 121–132. [CrossRef]
48. Hugenschmidt, J.; Wenk, F.; Bruhwiler, E. GPR chloride inspection of a RC bridge deck slab followed by an examination of the results. In Proceedings of the 15th International Conference on Ground Penetrating Radar—GPR 2014, Brussels, Belgium, 30 June–4 July 2014. [CrossRef]
49. Pailes, B.M.; Gucunski, N. Understanding Multi-modal Non-destructive Testing Data Through the Evaluation of Twelve Deteriorating Reinforced Concrete Bridge Decks. *J. Nondestruct. Eval.* **2015**, *34*, 30. [CrossRef]
50. D'Amico, F.; Gagliardi, V.; Bianchini Ciampoli, L.; Tosti, F. Integration of InSAR and GPR techniques for monitoring transition areas in railway bridges. *NDT E Int.* **2020**, *115*, 102291. [CrossRef]
51. Pashoutani, S.; Zhu, J. Real Depth-Correction in Ground Penetrating RADAR Data Analysis for Bridge Deck Evaluation. *Sensors* **2023**, *23*, 1027. [CrossRef]
52. Bavusi, M.; Soldovieri, F.; Di Napoli, R.; Loperte, A.; Di Cesare, A.; Ponzo, F.C.; Lapenna, V. Ground penetrating radar and microwave tomography 3D applications for the deck evaluation of the Musmeci bridge in Potenza, Italy. *J. Geophys. Eng.* **2011**, *8*, S33–S46. [CrossRef]
53. Gagarin, N.; Goulias, D.; Mekemson, J. Condition Rating of Bridge Decks with Fuzzy Sets Modeling for SF-GPR Surveys. *Remote Sens.* **2023**, *15*, 3631. [CrossRef]
54. Owerko, P.; Ortyl, Ł.; Salamak, M. Identification of concrete voids in an untypical railway bridge pillar by Ground Penetrating Radar Method. *Meas. Autom. Monit.* **2015**, *61*, 3.
55. Hugenschmidt, J.; Mastrangelo, R. GPR inspection of concrete bridges. *Cem. Concr. Compos.* **2006**, *28*, 384–392. [CrossRef]
56. Yelf, R.; Carse, A. Audit of a road bridge superstructure usign groud penetrating radar. *Proc. SPIE* **2000**, *4084*, 249–254. [CrossRef]
57. Dérobert, X.; Berenger, B. Using ground-penetrating radar (GPR) to assess an eight-span post-tensioned viaduct: A case study. *Civ. Struct. Eng.* **2010**, *2*, 574–584. [CrossRef]
58. Beben, D.; Mordak, A.; Anigacz, W. Identification of viaduct beam parameters using the Ground Penetrating Radar (GPR) technique. *NDT E Int.* **2012**, *49*, 18–26. [CrossRef]
59. Beushausen, H.; Torrent, R.; Alexander, M.G. Performance-based approaches for concrete durability: State of the art and future research needs. *Cem. Concr. Res.* **2019**, *119*, 11–20. [CrossRef]
60. Ghodoosi, F.; Bagchi, A.; Zayed, T.; Hosseini, M.R. Method for developing and updating deterioration models for concrete bridge decks using GPR data. *Autom. Constr.* **2018**, *91*, 133–141. [CrossRef]
61. Dinh, K.; Gucunski, N.; Kim, J.; Duong, T.H. Method for attenuation assessment of GPR data from concrete bridge decks. *NDT E Int.* **2017**, *92*, 50–58. [CrossRef]
62. Dinh, K.; Gucunski, N.; Zayed, T. Automated visualization of concrete bridge deck condition from GPR data. *NDT E Int.* **2018**, *102*, 120–128. [CrossRef]
63. Zhang, J.; Zhang, C.; Lu, Y.; Zheng, T.; Dong, Z.; Tian, Y.; Jia, Y. In-situ recognition of moisture damage in bridge deck asphalt pavement with time-frequency features of GPR signal. *Constr. Build. Mater.* **2020**, *244*, 118295. [CrossRef]
64. Tarussov, A.; Vandry, M.; De La Haza, A. Condition assessment of concrete structures using a new analysis method: Ground-penetrating radar computer-assisted visual interpretation. *Constr. Build. Mater.* **2013**, *38*, 1246–1254. [CrossRef]
65. Abouhamad, M.; Dawood, T.; Jabri, A.; Alsharqawi, M.; Zayed, T. Corrosiveness mapping of bridge decks using image-based analysis of GPR data. *Autom. Constr.* **2017**, *80*, 104–117. [CrossRef]
66. Benedetto, A. A three dimensional approach for tracking cracks in bridges using GPR. *J. Appl. Geophys.* **2013**, *97*, 37–44. [CrossRef]
67. Shakibabarough, A.; Bagchi, A.; Zayad, T. Automated Detection of Areas of Deterioration in GPR Images for Bridge Condition Assessment Fourt Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures. In Proceedings of the Fourth Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures, Zürich, Switzerland, 13–15 September 2017.
68. Dinh, K.; Gucunski, N.; Duong, T.H. An algorithm for automatic localization and detection of rebars from GPR data of concrete bridge decks. *Autom. Constr.* **2018**, *89*, 292–298. [CrossRef]

69. Asadi, P.; Gindy, M.; Alvarez, M. A Machine Learning Based Approach for Automatic Rebar Detection and Quantification of Deterioration in Concrete Bridge Deck Ground Penetrating Radar B-scan Images. *KSCE J. Civ. Eng.* **2019**, *23*, 2618–2627. [CrossRef]
70. Rahman, M.A.; Zayed, T.; Bagchi, A. Deterioration Mapping of RC Bridge Elements Based on Automated Analysis of GPR Images. *Remote Sens.* **2022**, *14*, 1131. [CrossRef]
71. Viola, P.; Jones, M. Rapid object detection using a boosted cascade of simple features. In Proceedings of the 2001 IEEE Computer Society Conference on Computer Vision and Pattern Recognition. CVPR 2001, Kauai, HI, USA, 8–14 December 2001; Volume 1, pp. I-511–I-518.
72. Rizzo, E.; Fornasari, G.; De Martino, G.; Boldrin, P. *Report Tecnico Sulle Indagini Georadar Effettuate sui Piloni del Viadotto Moliano Nell'ambito Dell'or4*; Progetto Mitigo; FESR, PON Ricerca e Innovazione: Rome, Italy, 2022.