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Corrosion Assessment of Reinforced Concrete Structures using Ground-Penetrating Radar

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Abstract – Corrosion affecting reinforced concrete structures is a critical concern in civil engineering in terms of structural integrity, especially in critical infrastructure, safety risks to users, and long-term durability and safe operation over time, as well as for environmental impact and financial implications. Within this context, early detection of corrosion in reinforced concrete structures is crucial for time intervention, enabling preventive maintenance and anticipating future deterioration. This work proposes the Ground-Penetrating Radar (GPR) as a recognized method for assessing corrosion in concrete structures. First, an overview of the effects of corrosion on the GPR signal, and how it can be detectable from the GPR data, is presented. Next, two different case studies are addressed, including the evaluation of a precast bridge deck in Galicia, and the unique structures of the UNESCO World Heritage Site of Park Güell in Barcelona. New trends on the development of robots to improve accessibility and autonomous data collection are also commented, as well as the use of artificial intelligence for automatic corrosion detection and the possibilities for data digitization into interoperable Building Information Modelling (BIM) and digital twin environments. Finally, it should be highlighted that identifying corrosion at an early stage allows engineers to take proactive measures to prolong the lifespan and serviceability of structures.

Keywords: GPR, corrosion detection, reinforced concrete, signature.

1. Introduction

Corrosion is a critical phenomenon in reinforced and pretensioned concrete structures. The process occurs when rebar deteriorates due to chemical or electrochemical reactions, caused by increased humidity and salt presence in concrete. The corrosion can affect the behaviour of the structure, its integrity, and, consequently, reduce the life spam [1-2]. The corrosion occurrence is mainly related with the permeability of the concrete, the concrete cover thickness, and the level of exposure to chloride, increased in aggressive coastal environment or by winter maintenance actions.

The corrosion, when associated to phenomena such as alkali silica reactions can lead to cracking and structural failure. The detection of the corrosion in an incipient stage is crucial for the structural health assessment. It is possible, in this way, to adopt maintenance or repairing actions to mitigate the corrosion effect [1].

For corrosion detection, there are traditional and non-destructive methods. The traditional ones, such as visual inspection, hammer testing, half-cell potential measurement, and coring, enable the detection of the corrosion only on punctual locations and if it is already in an advanced stage, with visible signs of concrete deterioration [3]. On the other hand, more efficient non-destructive testing (NDT) methods, such as GPR, Ultrasonic Testing (UT), Electrical Resistivity Measurement (ERM), acoustic emission (AE) and infrared thermography enable an early and continuous detection of corrosion and concrete degradation [4]. Among these, the GPR has been recognized as one of the most promising methods for concrete damage assessment such as corrosion, cracking, or delamination [5-7].

This work presents an overview of the feasibility of the GPR method for corrosion detection in reinforced concrete structures. Additionally, two case studies are included, both located in coastal zones (Galicia and Barcelona, in Spain) significantly affected by exposure to saline and chloride content that accelerates corrosion processes.

2. Effects of corrosion on the GPR signal

The strength (amplitude) of reflected electromagnetic fields is directly proportional to the magnitude of the dielectric constant change in the medium. The GPR method has been proven effective in detecting and evaluating corrosion in concrete structures, demonstrating that the characteristics of reflected signals change depending on the phase of corrosion. Initially, the velocity of propagation of the signal decreases due to high water content in the concrete [8]. Next, during the expansion phase of iron oxides, there is an increase in signal amplitude due to the presence of particles released from the oxidation process of the steel bars occupying concrete pores [9]. During this phase of migration of chlorides and corrosion products, there is a decrease in the frequency spectrum of the reflected signal [10]. However, later during the stage of reduction in bar section diameter, the amplitude of the reflected signal decreases [11], while increasing the propagation time of the signal to the bar surface due to the presence of corrosive products in the medium (higher dielectric constant). The penetration capacity of the signal and the intensity of reflection decrease as chloride and moisture content increase. The concentration of iron oxides, which expand through the fissures and pores of the structure, also affects signal attenuation or total loss of information [12-13]. The increase in electrical conductivity of the concrete medium contributes to signal attenuation [14]. Signal attributes such as amplitude of reflection, frequency spectrum, velocity, propagation time, and dielectric constant in media can be analyzed to understand signal attenuation due to corrosion or concrete deterioration. However, this signal attributes can be affected by signal scattering or diffraction, generally influence by the increase in porosity and cracking of damage concrete.

Figure 1 shows a comparison between a healthy reinforced concrete slab (a) and a damage slab (b). Observing the healthy slab (a), all bars are detected, in the form of consecutive hyperbolic reflections, at the same travel-time distance (ns). Additionally, the base of the slab produces a continuous flat reflection. This consistency in reflections suggests homogeneity in the condition state of the material. Conversely, in the case of the damage slab, the bars' reflections are registered at different travel-time distances. This discrepancy is likely caused by changes in the dielectric constant of media, possible due to differences in moisture content. Corrosion of steel bars leads to the deterioration of surrounding concrete, resulting in significant alterations in the dielectric properties of the medium. Consequently, this leads to a decrease in the propagation velocity of radar waves through the corroded areas.

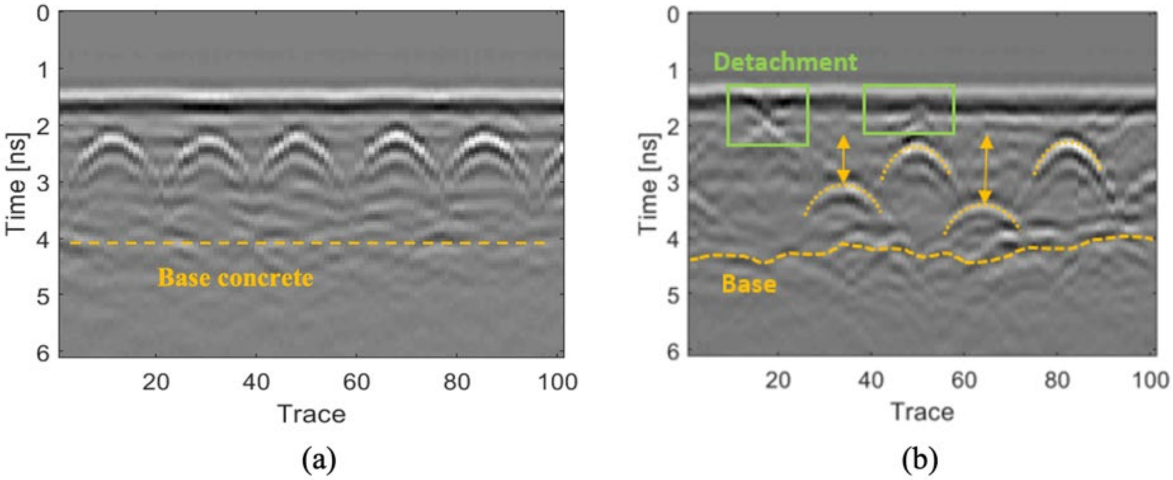

Fig. 1: Comparison between a healthy reinforced concrete slab (a) and a damage slab (b). Adapted from [15].

3. Case studies

3.1. Detection of corrosion in concrete bridge's decks

This case study presents the analysis of a pedestrian bridge in A Coruña (Galicia, Spain), in service since 1987 (Fig. 2a). It is a typical precast reinforced concrete bridge with T-section beams of variable cover depths (Fig. 2b). The central span of the bridge consists of an isostatic beam with articulated supports at the edges. Similar beams are mounted on abutments and concrete piles, at each side of the central span, to act as cantilevers beams. A longitudinal compression layer is applied on the beams, comprising the assembly, and working as a continuous beam. Two ramps, coming from the abutments, allow access to the bridge.

The GPR investigations were conducted on the central span of the bridge, where different signs of corrosion have been superficially detected, mainly cracks and fissures affecting the coating and leaving steel bars almost visible (Fig. 2c-e). This indicates a significant deterioration that needs immediate attention to prevent further structural degradation and to ensure the long-term safety and durability of the structure. The most probable causes of this degradation are the continued exposure to adverse weather conditions and the location of the bridge near the sea (and the saline influence that accelerate corrosion processes), as well as the abrasion and wear of surface coatings from pedestrian traffic. Over time, this wear and surface deterioration can lead to the loss of protective coatings (loss of passivation), exposing the concrete structure to moisture ingress and chemical attack towards reinforcement, accelerating degradation in concrete layer.

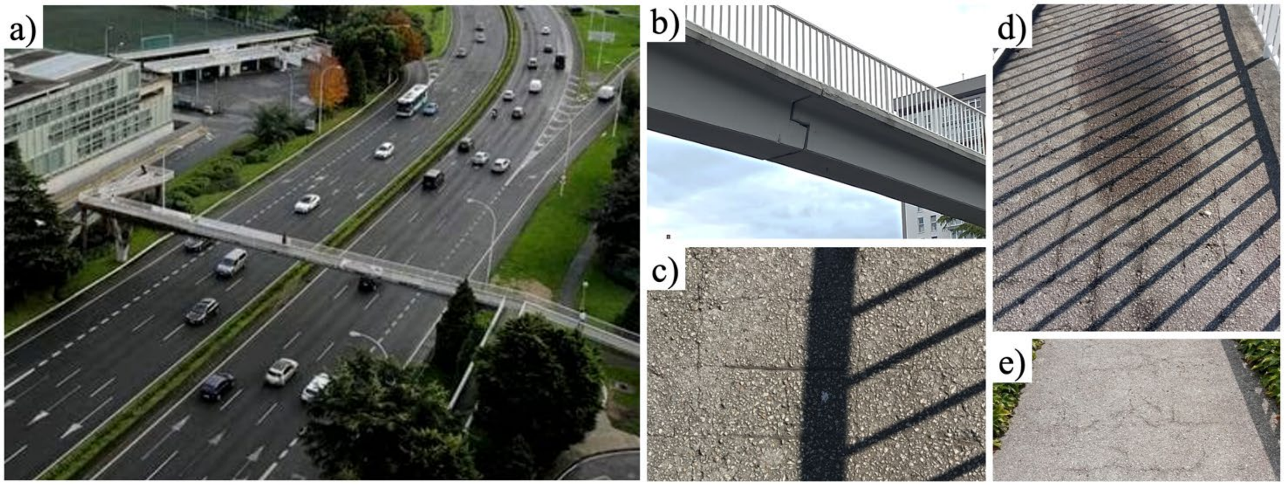

Fig. 2: General view of the pedestrian bridge in A Coruña (Galicia, Spain) and pictures of visible deterioration.

The GPR survey was carried out with a ProEx system using a ground-coupled antenna of 2.3 GHz. The data acquisition parameters selected were 2 mm of trace-interval distance and a total time window of 13 ns (composed of 432 samples per trace). A total of 6 longitudinal 2D profile lines were registered at regular intervals of 5 cm spacing, centered on central span (the section showing the most severe deterioration). To measure the profile length and to control the trace-interval distance, the antenna was mounted in a survey cart with an odometer wheel. All the GPR data was processed with the ReflexW software, by applying a basic processing sequence: time-zero correction, gain function, dewow filter, background removal, and bandpass filter.

Figure 3a shows one of the radargrams produced and its interpretation. As observed, severe concrete deterioration and rebar corrosion was identified in the central section of the bridge (highlighted into a red box). In this section, the typical hyperbolic reflections produced by the bars are not distinguished. Also, polarity inversion and travel-distance decay are observed in this part of the bridge (remarked into a dashed blue box), which is coincident with the accumulation of rainwater (or puddle) on the surface (Fig. 2d). Outside this region, rebar is detected at similar travel-time distances (dashed yellow lines), suggesting healthier (or less damaged) concrete. However, cracked and delaminated areas were detected along the entire span of the bridge (dashed pick boxes in Fig. 3b).

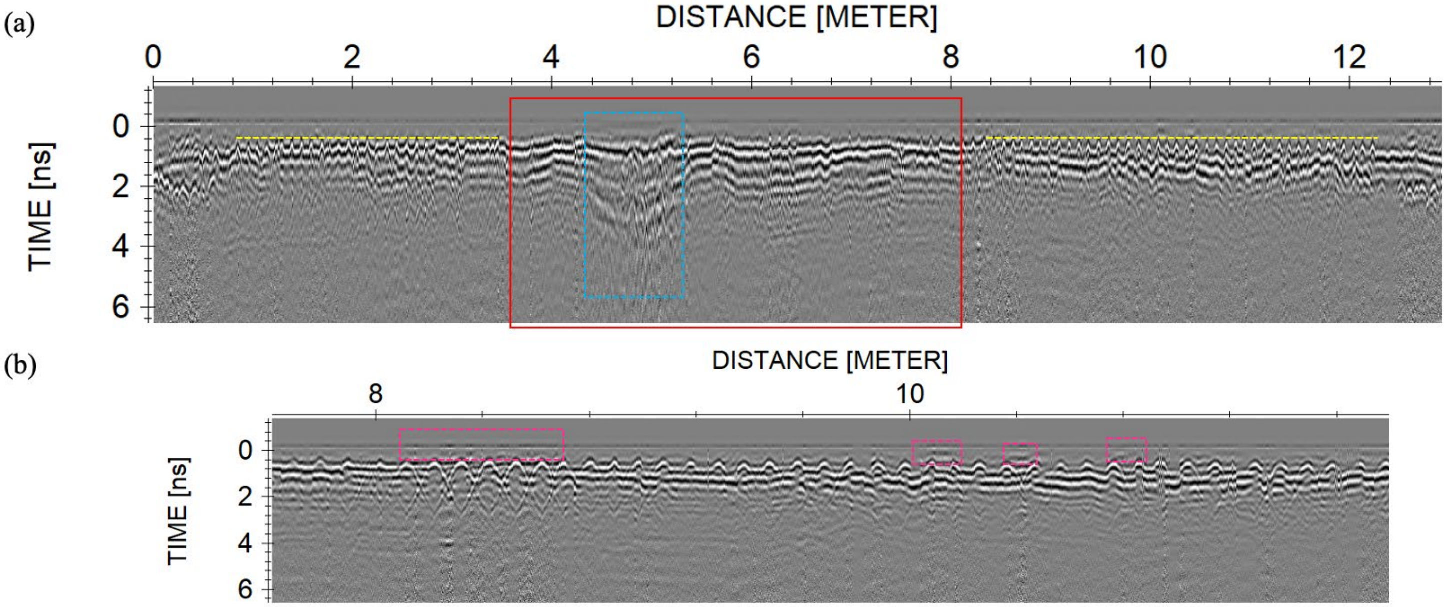

Fig. 3: Radargram produced showing concrete deterioration and rebar corrosion at the central part of the bridge (highlighted into a red box). A more detailed section is presented in (b) to show cracked and delaminated areas (highlighted into dashed pick boxes).

3.2. Detection of corrosion in cultural heritage structures

The use of iron as structural reinforcement in combination with mortar and masonry appeared in the late XIX and early XX Centuries. In *Modernista* (Art Nouveau developed in Catalonia) buildings a common technique involved using reinforcing fibers within the mortar, and in some cases the use of iron bars embedded in mortar and masonry was also used to reinforce the structures. One notable example is the work of the renowned Catalan architect Antoni Gaudí. In their structures, iron bars were often concealed within the masonry or incorporated into decorative elements, contributing to the structural integrity and aesthetic appeal of these iconic structures. In the Park Güell, Gaudí employed various innovative techniques for the construction of the structures, including the reinforcement of the roofs. The construction of these roofs and other structural elements included iron reinforcement often embedded within the concrete framework. This reinforcement allowed to create large, cantilevered structures and vaulted ceilings without compromising on safety or durability. However, although the advantages using iron reinforcement, with the pass of time, some damages appeared on the surfaces (see Fig. 4). The main causes of damages were: (a) water infiltration: if the waterproofing layers on roofs or walls degrade over time, rainwater can infiltrate into the structure. This can lead to dampness, mold growth, and deterioration of the building materials; (b) corrosion of reinforcement: this corrosion weakens the structural integrity of the building and can lead to cracking and spalling of concrete; (d) damage to decorative elements: Modernist structures often feature intricate decorative elements, such as ornate stonework, ceramic tiles, or delicate ironwork. prolonged exposure to rainwater and corrosion of the supporting elements can cause these decorative elements to deteriorate, fade, or become dislodged. After a visual inspection, a GPR assessment was carried out with 500 MHz and 2 GHz centre frequency antennas. The zones studied with GPR were the columns, the ground of the square and the ceiling of the hypostyle room, acquiring data in a total of 88 profiles. A grid of radar lines was placed on the square, over the hypostyle room. Figure 4 presents an example of the B-scans obtained in this zone and their position with respect the ceiling of the hypostyle room. Metallic targets produce high reflections with hyperbolic shape. Image from radar line 1 indicates the higher reinforcement existing on the vaults structure. It is also possible to distinguish anomalies associated to cracks on the surface. Along the profile exists a longitudinal metallic bar that is crossed in radar line 2. In this second B-scan, several targets denote the existence of metallic bars [16]. The hyperbolas at right of the image present lower amplitude and a narrower shape, indicating possible higher humidity and corrosion in this zone. The irregular distribution of the anomalies indicates the existence of metal reinforcement without a regular pattern. However, the analysis of several parallel profiles on the square allowed to determine the existence of a regular rebar layer, the existence of isolate metallic targets and the zones that could be affected by corrosion (Fig. 5).

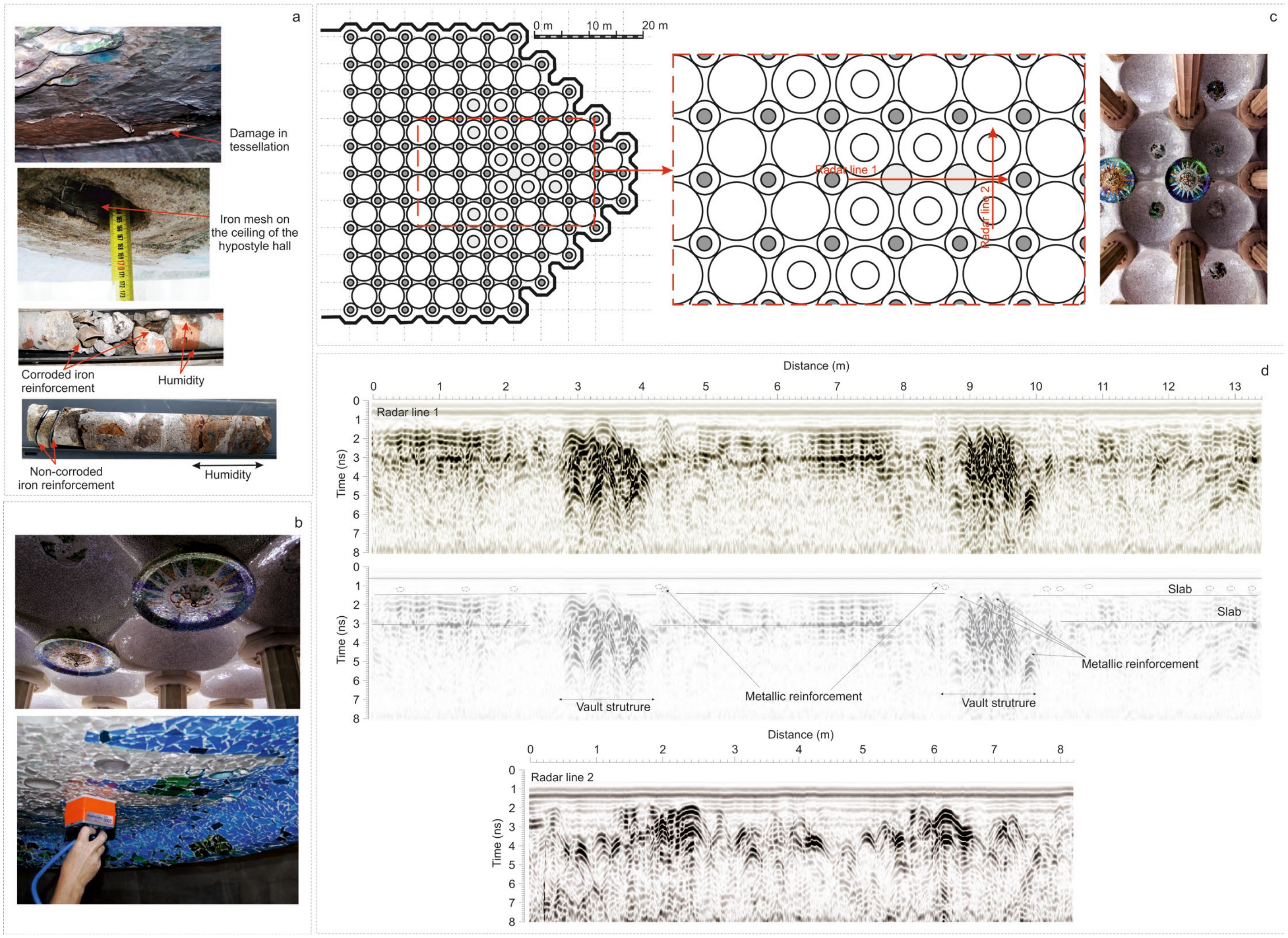

Fig. 4: Radar images obtained with a 500 MHz antenna on the square, over the ceiling of the hypostyle room. a) Damages and cores showing the existence of iron and humidity. b) The ceiling of the hypostyle room and data acquisition. c) Position of the radar lines with a 500 MHz antenna on the square. c) Radargrams and interpretation.

In the radargrams in Figure 5, the bars that could be damaged due to corrosion exhibit hyperbolic images of lesser amplitude and, at the same time, narrower. On the other hand, in areas where moisture appears, the two-way travel time increases slightly. Clutter is also observed in some zones, most likely due to the effect of moisture and corrosion. The shape of the hyperbolas and the travel time changes because the wave velocity decreases as water content increases. All these effects allow to determine the zones that can be affected by higher water content and the possible corroded metallic reinforcements. The final result allowed to determine the most damaged zones with higher humidity, where reinforcement present corrosion, and the parts with non-corroded targets (Fig. 5).

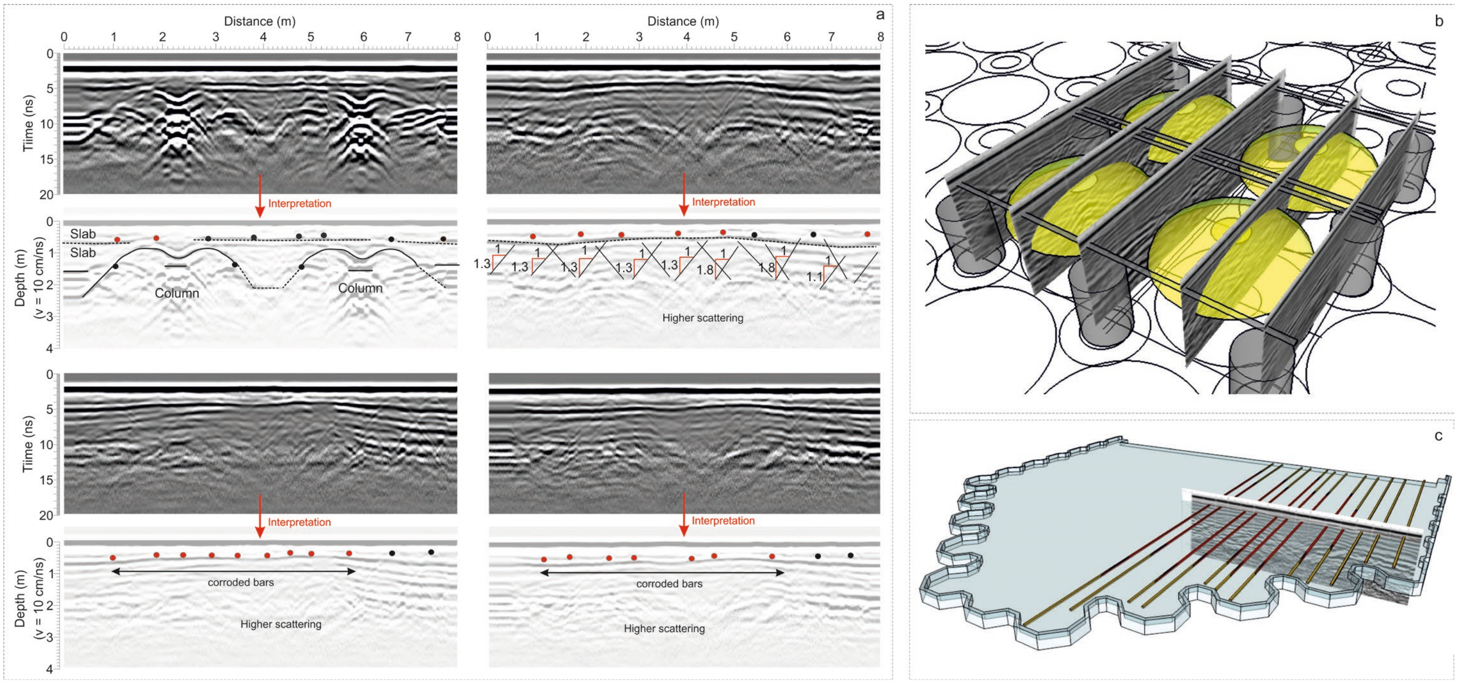

Fig. 5: Detection of corroded rebar. a) Examples of radar data and interpretation, being the anomalies due to possible corroded metallic bars are marked in red. Other targets and the comparison between hyperbolas are also indicated on the data interpretation. b) Position of the radar data with respect the vaults and the columns of the room. c) Final interpretation of part of the rebar: in brown, the non-corroded zones; in red, corroded parts; in black: possible moist zones but with non-corroded bars.

4. Conclusions and further perspectives

The GPR application for corrosion detection in different types of structures is an important non-destructive way tool for early detection and thorough inspection of structures health and safety. The case studies presented herein have shown the versatility and reliability of the method, and the particularities of its application when humidity, corrosion and concrete deterioration are present. The changes in the shape of the hyperbola, travel time, signal amplitude and polarity are the main indicators of the possible damage and susceptibility to condition for corrosion development. If humidity and corrosion increases, the hyperbola is narrower. Scattering of the signal indicates concrete deterioration, cracking, and possible existence of corrosion. The travel time increases, and the signal amplitude decreases drastically, as the mineral salts, humidity, and corrosion increases. It is possible, in this way, to detect the presence of conditions for corrosion development and estimate the level of concrete damage. Complementary methods are always useful for an accurate diagnostic of concrete structures.

Further advances in construction inspection include the development of mobile autonomous vehicles with GPR systems and other sensors. Some recent studies have demonstrated the ability of monitored robot systems to obtain 3D models of the subsurface, for example in utilities detection [17] and beams inspection [18]. In these cases, the robot acquires the data without human intervention and combines the GPR data with artificial vision and GPS to define accurate position. Moreover, the development of driving strategies of unidirectional mobile robots [19] will contribute to improve the accessibility to the entire structure (walls, columns, under bridge deck, etc.). Also, for a better accessibility, an emergent methodology is the use of GPR on drones [20].

In parallel, artificial intelligence has emerged as a promising tool to process GPR data in subsurface distress detection and real-time analysis [21-22]. Deep Learning (DL) techniques, such as Convolutional Neural Networks (CNNs), have demonstrated remarkable capabilities in signal processing and object detection, surpassing traditional image processing methods in terms of speed and accuracy. CNN-based models are used, for example, to detect the concrete cover depth [23]. Moreover, object detection algorithms such as single-shot multibox detector (SSD) and You Only Look Once (YOLO) are used for detecting and localizing features such as corrosive environments [24] and steel bars within the subsurface. Furthermore, DL techniques offer the potential to estimate parameters such as rebar diameters by combining methods like YOLO with 1D CNNs [25]. Despite the significant progress made, there are challenges associated with the limited availability of real-world GPR data. To address this limitation, the use of synthetic data generated by numerical modelling and data augmentation methods is recommended to create larger datasets, thus facilitating more robust training of the DL models and enhancing generalization. What is more, the automatic extraction of the information of interest opens the possibility for the digitalization of information, such as the integration of GPR data and complementary methods in BIM or Digital Twins, enabling the visualization and manipulation of data in real-time and early mitigation of corrosion effects [26].

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