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Enhancing Infrastructure Resilience with Non-Destructive Evaluation: GPR and IE Integration for Delamination Detection

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ABSTRACT

This investigation explores the effectiveness of Ground Penetrating Radar (GPR) and Impact Echo (IE) techniques in identifying delamination defects in a concrete drop panel, crucial components of infrastructure projects. Delamination, a prevalent problem in concrete structures resulting from cracks caused by corrosion, presents considerable hazards to both public safety and structural integrity. Conventional techniques for detecting delamination, like destructive testing and visual inspection, are expensive and time-consuming. Consequently, promising substitutes include non-destructive assessment (NDE) methods like GPR and IE. The study conducted field investigations using GPR and IE at the Madinat Al-Mawater Teyseer Service Centre in Doha, Qatar. GPR offered data regarding subsurface conditions and reinforcement spacing, whereas IE precisely measured slab thickness and identified delamination issues. The results showed that IE and GPR are useful for detecting delamination and providing accurate information for maintenance and repair decisions. The significance of routine inspections utilising cutting-edge NDE technology to identify delamination early and ensure structural integrity and public safety was highlighted by key findings. The investigation proposes a strengthening scheme to enhance structural capacity and prolong service life. Among the recommendations were to advance NDE technology for delamination detection, integrate GPR and IE into routine concrete structure inspection procedures, and optimise interpretation techniques through research and training. Conclusively, the integration of GPR and IE signifies a significant advancement in non-destructive evaluation (NDE) methodologies, offering essential decisions regarding structure integrity and subsurface conditions without invasive methods. By utilizing these techniques, infrastructure managers can prevent delamination-induced deterioration, streamline maintenance processes, and preserve public infrastructure for future generations.

1. Introduction

Delamination is an event by which the concrete cover separates from the subsurface concrete as a result of cracks that are caused by corrosion in the steel rebar. It causes the structure to deteriorate more quickly and lose structural strength [1] According to Jana [2], delamination is defined as a

planar displacement of the element parallel to the surface with a lateral expansion substantially greater than the concrete cover. Delamination occurs frequently in bridge decks because reinforcement corrodes more quickly than other components of concrete structures. Reinforcements are basic components to assure the load-bearing capability of a concrete bridge [3]. According to Gucunski et al. [4], delamination is one of the most prevalent deterioration types and can even be a sign of severe corrosion of steel reinforcement [5]. Additionally, persistent corrosion-related delamination defects in concrete can develop into open spalls and ultimately weaken the structural integrity of reinforced concrete components. Delamination defects in particular can have a significant impact on the structural integrity and/or durability of concrete elements, compromising the safety of public users in infrastructure and building structures (such as concrete bridge decks, continuous concrete pavement, and building slabs). Delamination is a corrosion-induced issue that is quite concerning for concrete structures, necessitating periodic inspection. There are numerous techniques available for identifying concrete delamination. According to Warhus et al. [1] and Gucunski et al. [6], these techniques include ultrasonic testing, conventional chain drag method, ground penetrating radar, impact-echo, infrared thermography, and imaging radar.
There has been an attempt to broaden, enhance, and integrate existing methods. In addition to funding new construction, infrastructure management organisations in several countries have allocated a significant amount of the construction budget for maintaining existing or damaged concrete structures [6, 7]. Although conventional approaches have proven effective in the past, they can be highly expensive due to the requirement for professional personnel to be deployed to field sites with devices and traffic control. According to estimates from Broomfield [8] and Li et al. [9], the yearly maintenance and repair costs associated with corrosion for concrete infrastructure reach $100 billion globally. Delamination in such a crucial concrete component must be assessed, and if required, a suitable maintenance decision for concrete structures must be made. It will therefore extend the service life of concrete elements and preserve them in good shape. Whatever the process, delamination will eventually turn into open spalls that compromise the integrity of the structure and descend on quality if repairs are not done promptly [10, 11]. That is why it is critical to have efficient techniques for identifying and tracking the advancement of existing delamination. It has long been known that one possible NDE technique that could assist in resolving the aforementioned issue is GPR. For example, the first research carried out in the US in 2001 focused on using GPR to image concrete delamination in bridge decks [12]. Both rigid pavement [13] and bridge decks [14, 15] have been the subject of ongoing initiatives. Regretfully, the inconsistent findings shown in those investigations have created the perception that GPR cannot detect delamination directly [10].

Additionally, it has been demonstrated that the impact-echo test is an effective method to evaluate delamination defects in concrete elements [16, 17, 18]. Nevertheless, early research in the field and laboratory testing revealed that the conventional IE test, which makes use of a single IE sensor, has various practical limitations. Initially, concrete velocity information cannot be obtained from single-channel measurement. The P wave velocity is often found from cores or by running a test over the structure's known-dimension region in field implementations of the IE approach [19]. However, this technique requires extra work for core extraction and/or wave velocity measurement using different test equipment, which could slow down test speed and be more labour-intensive.
Although there are numerous non-destructive testing techniques, the focus of this paper is on the application of ground-penetrating radar (GPR) and Impact Echo for evaluating a structure (drop panel) for the construction project under investigation. Visual delamination was noted in this drop panel, raising serious concerns about the potential effects on the concrete structure's durability and/or structural integrity, as well as the potential to endanger the safety of end users. Where the maintenance of structural integrity is a top priority, this type of inspection could be crucial to identifying the real defects [20]. The presence and location of objects are ascertained by reconstructing the waves that are reflected from them. Furthermore, the properties of the host

material can be determined from the observation of the wave characteristics [21, 22]. Nonetheless, proficient interpretation of GPR and Impact Echo data is necessary for accurate analysis.

The integration of Impact Echo (IE) and Ground-Penetrating Radar (GPR) techniques represents a significant advancement in NDE techniques for concrete constructions, particularly in identifying delamination issues in concrete slabs, as seen in Figure 1.

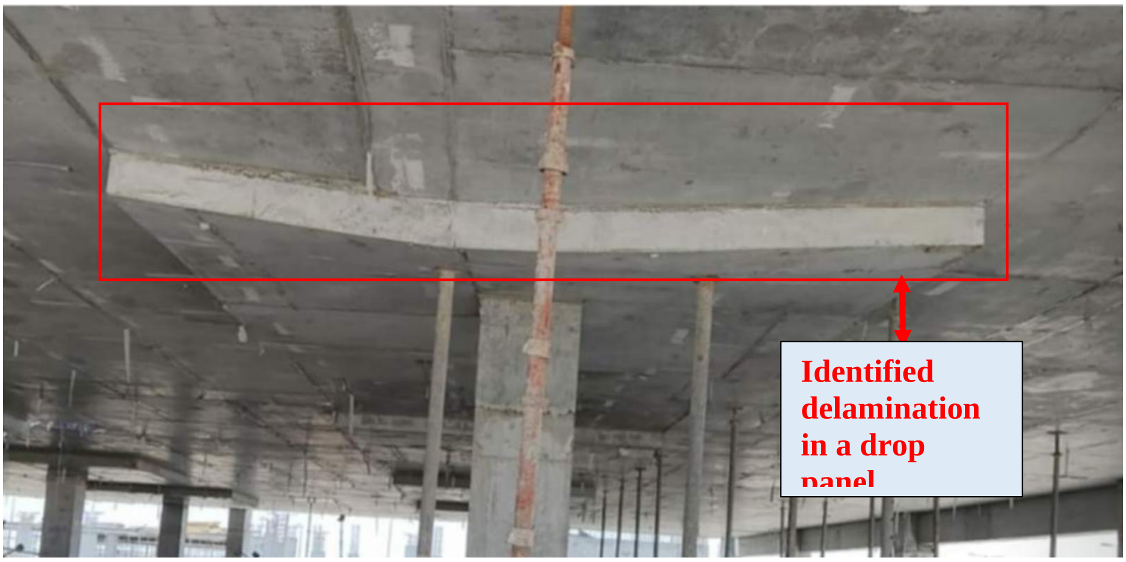

Figure 1. A visible sign of delamination of delamination

These techniques offer a precise approach for evaluating the existence, extent, and severity of delamination, safeguarding structural integrity, and ensuring public safety.
Employing electromagnetic waves and mechanical impact to provide deep insights into subsurface conditions without invasive procedures, GPR and IE limit disruption and associated costs related to conventional technologies. This investigation offers significant importance for improving infrastructure resilience, developing NDE techniques, and optimising maintenance procedures. Ultimately, it contributes to the preservation of public infrastructure and prolongs the life of concrete structures, which is consistent with international initiatives to tackle the pressing issues of ageing infrastructure and high repair costs.

This investigation aims to evaluate the effectiveness of Ground-Penetrating Radar (GPR) and Impact Echo (IE) techniques in detecting delamination defects in a concrete drop panel. The primary objective is to ensure public safety by ensuring informed maintenance decisions and assessing structural integrity. The objective of the investigation is to improve maintenance practices and safeguard infrastructure by utilising non-destructive evaluation techniques to ascertain the extent, severity, and location of delamination concerns in the concrete drop panel, develop a comprehensive strengthening scheme based on the investigation results, and optimise maintenance procedures to safeguard infrastructure and prolong its service life. The results of an investigation using a 2.7 GHz GPR system (The StructureScan Mini XT) and Impact Echo (IE) Freedom PC data to identify a visually identified drop panel with delamination defects at the construction of the Madinat Al-Mawater Teyseer Service Centre, Doha, Qatar, are presented in this paper. First, the principles of IE and GPR are addressed. The second section presents the GPR interpretation of the scanned image and the relationship between the measured thickness values acquired from Impact Echo. The position and shape of the reinforcement in the concrete slab were ascertained using the GPR.

Meanwhile, the advantages and limitations of the system for particular situations were outlined for both IE tests and GPR.

1.1. Principles of Ground Penetrating Radar (GPR)

The method of operation for GPR, a geophysical inspection technique, involves sending electromagnetic (EM) waves in the direction of a surface and then receiving the transmitted or back-reflected signal. The electromagnetic wave's ability to propagate is determined by the dielectric characteristics of the medium it passes through, namely the magnetic permeability (μ), electric conductivity (σ), and dielectric permittivity (ε). Specifically, ε and σ have a significant impact on the propagating wave's performance as a result of wave velocity and wave attenuation, respectively, while μ is invariant to the free space magnetic permeability (μ_0) for all non-magnetic materials and has no effect on the EM wave's propagation. In practical terms, the EM impulse released by a transmitting source is partially reflected and transmitted due to the dielectric differences in the medium. Depending on the mode of operation, a receiving antenna gathers the transmitted or reflected portion of the signal, which enables two- or three-dimensional subsurface imaging. The type of material being analysed and the frequency of the signal transmitted are two important elements that affect penetration depth and spatial resolution. GPR usually operates in the frequency range of 100 MHz to 2000 MHz in civil engineering applications [23]. Due to its significant practicality and ease of data interpretation, impulse radar systems are primarily used in conjunction with GPR in road engineering. These devices work by using one or more antennas to send a very short pulse (~10-9 s) with an established central frequency towards the target. The dielectric discontinuities then record the signal that is back-reflected. After that, the two-way travel time signal is captured in the temporal domain, and at last, a map of the reflections produced in the subsurface can be shown. On the other hand, frequency domain operation is used by Stepped Frequency Continuous Wave (SFCW) radar systems. Within a predetermined frequency range, the frequency increases linearly by a fixed step, and the amplitude and phase of the transmitted and received signals are sampled and gathered accordingly. In terms of antenna layouts, a GPR system is said to be mono-static when a single antenna serves as both a transmitter and a receiver. However, a GPR system is considered bi-static when the transmitter and receiver are separated. In addition, GPR systems can be classified as air-coupled or ground-coupled based on the type of antenna used. The antenna is in direct touch with the ground in the first case. Higher penetration depths across the medium are made possible by this. The typical range of central frequencies for this setup is 80 MHz to 1500 MHz. The antenna in the second survey arrangement is normally maintained at a fixed altitude above the ground, usually between 0.15 and 0.50 metres. The majority of air-coupled GPR systems that are commonly used are pulsed systems that function within the 0.5·2.5 GHz range, usually with a 1 GHz central frequency. For pavement applications, the penetration depth of an air-coupled system is rarely greater than 0.9 m and depends upon the central frequency [24]. Air-coupled devices, when mounted on instrumented equipment, enable surveying at traffic speed despite this primary limitation [25]. The most popular equipment for road surveys is the air-couple GPR system, which has the benefit of not interfering with traffic.

1.2. Principles of Impact Echo (IE)

Sansalone [26] and Tawhed & Gassman [27] devised the IE method as a dependable technique to inspect concrete slabs and pavements for dimensions or lamellar cracks. The immediate resonance of a plate-like structure exposed to mechanical impact is the basis of the IE method's basic theory. The acceleration, displacement, and velocity reactions at a surface near the resonance source are used to calculate the instantaneous timing reaction of a sound structure. Fast Fourier transform (FFT) analysis is used to analyse the response signal in the frequency domain, as illustrated in Figure 2. The thickness of the slab and the presence or absence of delamination are determined using the amplitude and frequency parameters in the frequency domain for a particular resonance mode [28].

Equation (1) describes the relationship between the slab thickness (h), the P-wave velocity (Cp), and the peak frequency in the frequency spectrum for numerous reflected waves of the stress wave [28].

$$h = \frac{\beta CP}{2f} \tag{1}$$

where
β is the form factor in an infinite plate structure, which is approximately equal to 0.96.

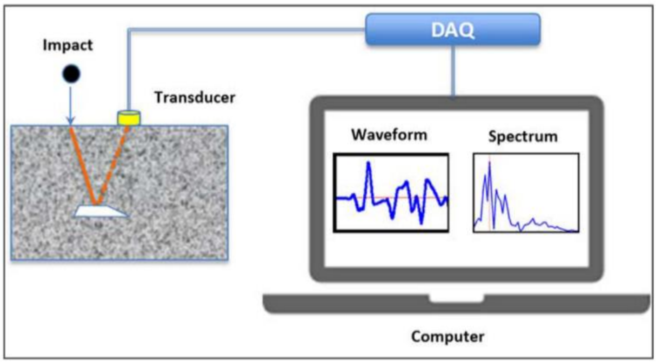

Figure 2. Schematic of impact-echo method [29]

The contact sensor is switched out for a non-contact sensor in the non-contact IE test system. The non-contact IE test method's fundamental idea is to use a microphone to measure a leaky wave produced by a surface wave. Numerous investigations have demonstrated that non-contact IE measurements yield outcomes equivalent to those obtained from a traditional contact sensor [30]. When there is air beneath the test site, errors can be found using the IE approach, which is ineffective when there are closed fractures [31]. Equation (1) can be used to estimate the depth of a significant area of delamination that is parallel to the surface.

1.3. Advantages of Concrete Drop Panel Investigations using IE and GPR

i. Non-Destructive Evaluation (NDE): Since IE and GPR are both non-destructive evaluation methods, it is possible to inspect concrete structures without causing harm. This keeps the concrete drop panel intact and offers significant data about their condition.
ii. Complementary Capabilities: Complementary capabilities of IE and GPR allow for the provision of extensive data on various aspects of the concrete drop panel. While GPR provides detailed information on subsurface conditions and reinforcement spacing, IE is proficient at providing accurate measurements of slab thickness and detecting delamination defects.
iii. Precise Detection of Delamination Defects: Both IE and GPR are useful methods for precisely identifying delamination defects in concrete structures, such as the ones observed in the drop panel. While GPR's capacity to detect dielectric contrasts in the medium aids in the identification of subsurface defects, IE's immediate resonance of platelike structures enables accurate detection of delamination.
iv. High Accuracy: IE and GPR are highly accurate when it comes to identifying defects and evaluating the condition of concrete structures. The data gathered using these methods helps to preserve structural integrity and public safety by facilitating well-informed decision-making about maintenance and repair interventions.
v. Cost-Effectiveness: When assessing concrete structures, IE and GPR are more affordable alternatives than destructive testing techniques. They lessen the need for invasive

procedures, cause less disturbance to ongoing operations, and effectively deliver significant data.

vi. Efficiency in Field Investigations: GPR and IE are field investigation techniques that are both portable and effective. They allow for prompt decision-making and intervention decisions by providing an on-site means of rapidly evaluating the state of the concrete drop panel.

vii. Enhanced Safety: IE and GPR help to improve user safety for concrete infrastructure by detecting delamination defects and other structural issues earlier. Risks related to structural deterioration are reduced when timely repairs and maintenance are performed using NDE data.

viii. Integration into Routine Inspection Procedures: Long-term advantages can be obtained by incorporating IE and GPR into periodic concrete structure inspection processes. Proactive maintenance methods are made possible by routine evaluations utilising these cutting-edge NDE techniques, which eventually lower repair costs and increase the service life of infrastructure.

1.4. Limitations using (Structurescan Mini XT) and (Freedom Data PC) during the Investigation

Here is a summary of some of the limitations the author encountered when using IE and GPR.

i. Flat concrete surfaces are required for the StructureScan Mini-XT to execute error-free rebar grid mapping. Because steel has a distinct dielectric value, subsurface defects like voids and delamination are discovered but often do not affect rebar mapping.

ii. It can be challenging to maintain alignment while repositioning the equipment on the grid and any misalignment affects the results

iii. Positioning the equipment on the side or beneath a slab or superstructure makes it very difficult to operate.

iv. A thick or tightly spaced upper layer of reinforcement can prevent the signal from penetrating the concrete section.

v. Due to the high sensitivity of IE transducers, the background noise level must be reduced to the maximum level possible to avoid any wave interference.

vi. IE calibrated velocity should be performed on well-known good concrete quality, otherwise the result may be misleading.

vii. When the Ground Penetrating Radar (GPR) equipment locates the reinforcement embedded in the concrete, the accuracy of the reinforcement diameter measurement may be compromised. The uncertainty arises from the possibility of multiple factors influencing the radar signal's reflection off the reinforcement. As such, the GPR machine gives an estimate of the diameter of reinforcement rather than the expected measurement.

2.1. Ground Penetrating Radar

The case of delamination of a drop panel was identified visually during the field investigation at the Madinat Al-Mawater Teyseer Service Centre. Similarly, Rathod and Gupta (2019) created simulated structural deficiencies in lab environments and used Ground Penetrating Radar (GPR) in conjunction with Impact Echo techniques to identify these defects. In this investigation, each concrete slab that was examined had dimensions of 2.0 m by 2.0 m and thicknesses of 0.45 m (bottom slab) and 0.25 m (top slab), respectively. When the slab was cast, the concrete that was used had a compressive strength of 40 MPa. The present investigation aims to evaluate the extent to which GPR identified these defects, especially when analysing B-scan data. The commercially available GSSI Structurescan Mini XT, manufactured by Geophysical Survey Systems Inc., was the

GPR equipment used for this task. his portable device can be handheld, as depicted in Figure 3. The following settings influence how the GPR device functions: (1) Pulse Repetition Frequency of 700 KHz, (2) Dielectric Range of 4 to 12 (selectable in steps of 0.1), (3) Monostatic antenna with a centre frequency of 2700 MHz, and (4) Penetration Depth of 50 cm. Interestingly, a monostatic antenna system means that there is just one antenna and that the transmitting and receiving antennas operate as one.

Figure 3. GSSI: Structurescan Mini XT

The first step in the GPR survey on a 600 mm by 600 mm grid using the StructureScan Mini XT was to determine the line spacing. Given the limited space, 10 cm was deemed suitable for line spacing for the x and y axes. This allowed for comprehensive coverage with a reasonable number of lines. Consequently, 6 lines were drawn in each direction, for a total of 36 lines, with each axis measuring 600 mm and the spaces between them being 10 cm. The StructureScan Mini XT effectively collects data in a single pass along each axis, reducing the number of passes needed. Hence, the complete grid area was successfully covered with a single pass down the x-axis and a second along the y-axis, negating the need for additional passes. The equipment was carefully positioned at the beginning of the first line along the x-axis to begin the scanning process. Afterwards, one pass was conducted on the x-axis, moving methodically and evenly across every grid line. The equipment was moved to the beginning of the first line along the y-axis once the x-axis pass had concluded. After that, a second pass was carefully made along this axis using the same methodical process. The equipment was placed on the concrete drop panel's surface for the duration of the scanning process preventing reflections from extending beyond the edge. Data in the A- and B-scan formats were produced by the line scans. When processed with appropriate software, the A-scan data displays the signal on the radargram over a certain horizontal distance, making it attainable to visualise signal reflections in a time-based. However, the absence of numerical amplitudes means that results must be evaluated exclusively through picture analysis and not by numerical evaluation. This particular equipment's image processing software lets users change the linear gain (measured in dB) and time-gain compensation (measured in dB/ns). Time gain compensation modifies amplitudes or gains from bottom to top, while linear gain makes it easier to modify them from top to bottom. Since the slab depth in this investigation was less than 0.5 m, time gain compensation was set to zero, making data acquired beyond that depth pointless. To improve the visibility of amplified forms, a 15 dB linear increase was applied. During scanning, the application has an auto-gain option, however, users can manually modify these settings for improved clarity. Using a linear gain of 15 dB and time-gain compensation of 0 dB/ns, image processing steps were standardised across all scans to ensure uniformity in result interpretation. This procedure was carried out for the top and bottom slabs, respectively.

2.2. Impact Echo

When using the Freedom Data PC, there is a preliminary calibration procedure that was completed to ascertain the velocity speed in the concrete. This requires that the expected thickness of the component being investigated be established. After calibration, more tests might be carried out. For an expected thickness of 0.45 m for IE1 (bottom slab) and 0.25 m for IE2 (top slab), the velocity was calibrated to 3,418 m/s. Determining how the expected thickness might affect the test results, this calibration value was set for each location. The amplitude against frequency data obtained from the point of test results is analysed to determine errors and the expected thickness. Out of all the impacts that were performed, the Fast Fourier Transform (FFT) amplitude provides the most accurate estimate of the identified thickness. This function uses auto gain, which determines thickness automatically. A thickness that was measured less than expected raises the possibility of a defect. A greater frequency is indicative of delamination detection; however, the precise frequency is dependent on the size of the delamination. Tables 1 and 2 in the following section provide the data obtained for the concrete drop panel thickness based on the test results of IE1 (bottom slab) and IE2 (top slab). The observed values for IE1 and IE2 range from 0.13 m to 0.67 m (IE1) and 0.08 m to 0.31 m(IE2), respectively, raising questions about overall safety and structural integrity. On the bottom slab, 37 impact echo tests were carried out, and on the top slab, 36 impact echo tests.

2.3. Strengthening Scheme

A strengthening scheme was proposed to improve the section within the drop panel and its surrounding area's strength capacity in both flexure and shear. To ensure finish level uniformity and to increase the section within the drop panel, this technique entails multiple processes as outlined below.

1. First, to ensure consistency in finish level, the current concrete cover within the drop panel that extends 500mm into the 250mm thick slab was maintained. Furthermore, all sections were recast back with a 50mm top enlargement, and the section within the drop panel was increased by 150mm from the bottom.
2. The concrete surface that was enlarged was roughened to at least a 6 mm amplitude. There was a minimum of 25 mm of space between the newly installed longitudinal reinforcements and the concrete's roughened surface.
3. GPR scanning of the existing post-tension (PT) was undertaken before the dowels were drilled to prevent drilling of the proposed dowels in it. When clashing was unavoided, a minor compromise in the existing reinforcements was permitted. But, to preserve the structural integrity, drilling within the existing PT was never done.
4. T10@300 through and through dowels were installed within the specified enlargement to preserve the integrity of the concrete and appropriately transfer forces between the top and bottom enlarged sections. To enable drilling, a small amount of existing top rebar compromise was permitted because the additional top (T12@100 in either direction) and bottom (T12@150) reinforcement was made up for any small amount of existing reinforcement damage.
5. The increase in flexural and punching shear (concrete) capacity with this modification was calculated. The X-axis of the drop panel width, which has extra T16@125 centre-to-centre c/c reinforcement, was used to compute the flexural capacity. Only the concrete shear capacity was evaluated for punching shear, and the results indicated a 100% improvement in both flexural and shear capacity.
6. To ensure a proper concrete-to-concrete bond between the new and existing concrete surfaces, it was observed that bottom enlargement was achieved using either the form and pump approach or the shotcrete technique.

Figures 4, 5, and 6 present a strengthening schematic of the various stages of repair and strengthening.

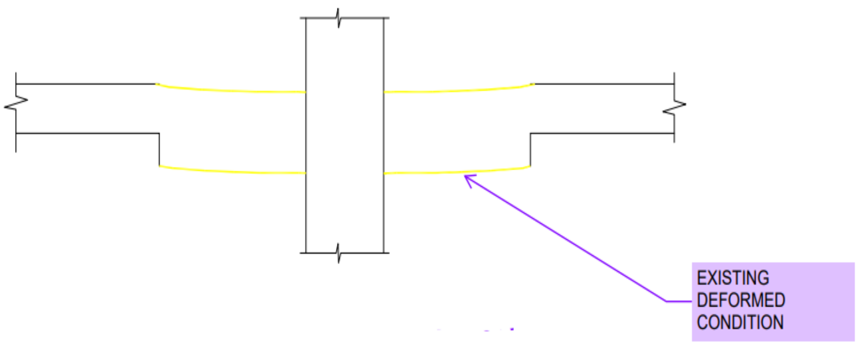

Figure 4. Existing Condition

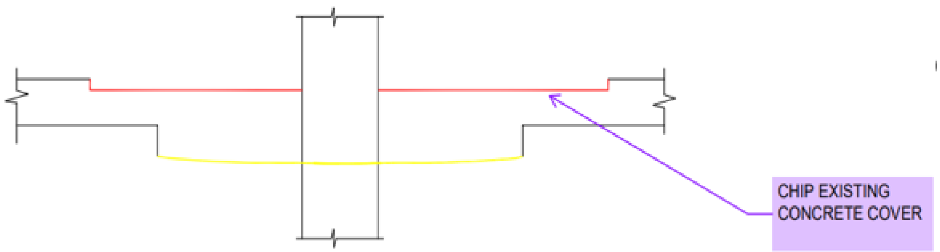

Figure 5: Chipping of existing concrete cover detail

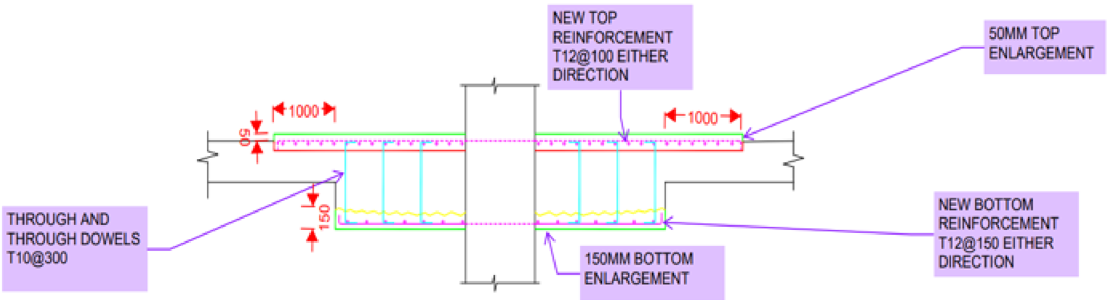

Figure 6. Schematic Strengthening Details

3.1. Impact Echo (IE) Test Results

As was previously indicated, the Impact Echo tests (IE1) on the concrete drop panels with a calibrated velocity of 3418 m/s were part of the investigation. Several frequencies were analysed in these investigations to evaluate the primary thickness echo, which was determined using an expected thickness of 0.45 m for (IE1) and 0.25 m for (IE2). The tests' results, which illustrate the differences between the measured and the expected thickness, are displayed in Tables 1 and 2. These data provide significant information on the quality of the concrete drop panel and its structural integrity, which contributes to the investigation's key objectives.

Table 1. Impact Echo Test Results (IE1) for Reinforced Concrete Slabs

ID	Calibrated Velocity (m/s)	Frequency (Mhz)	Primary Thickness Echo (m)	Expected Thickness (m)	Difference from Expected Thickness (%)	Concrete Quality
1	3418	2539	0.65	0.45	43.59	Poor
2	3418	7617	0.22	0.45	-52.14	Poor
3	3418	3613	0.45	0.45	0.91	Sound
4	3418	3418	0.48	0.45	6.67	Sound
5	3418	4297	0.38	0.45	-15.15	Questionable
6	3418	12988	0.13	0.45	-71.93	Poor
7	3418	2441	0.67	0.45	49.36	Poor
8	3418	3223	0.51	0.45	13.12	Questionable
9	3418	7422	0.22	0.45	-50.88	Poor
10	3418	3223	0.51	0.45	13.12	Questionable
11	3418	3516	0.47	0.45	3.69	Sound
12	3418	3613	0.45	0.45	0.91	Sound
13	3418	3320	0.49	0.45	9.82	Sound
14	3418	3320	0.49	0.45	9.82	Sound
15	3418	3320	0.49	0.45	9.82	Sound
16	3418	3320	0.49	0.45	9.82	Sound
17	3418	3711	0.44	0.45	-1.76	Sound
18	3418	3418	0.48	0.45	6.67	Sound
19	3418	3418	0.48	0.45	6.67	Sound
20	3418	3711	0.44	0.45	-1.76	Sound
21	3418	4004	0.41	0.45	-8.94	Sound
22	3418	4004	0.41	0.45	-8.94	Sound
23	3418	3711	0.44	0.45	-1.76	Sound
24	3418	3906	0.42	0.45	-6.66	Sound
25	3418	3906	0.42	0.45	-6.66	Sound
26	3418	3809	0.43	0.45	-4.28	Sound
27	3418	3906	0.42	0.45	-6.66	Sound
28	3418	3711	0.42	0.45	-6.66	Sound
29	3418	4004	0.41	0.45	-1.76	Sound
30	3418	3711	0.44	0.45	-8.94	Sound
31	3418	3809	0.43	0.45	-1.76	Sound
32	3418	3906	0.42	0.45	-4.28	Sound
33	3418	3809	0.43	0.45	-6.66	Sound
34	3418	3809	0.43	0.45	-4.28	Sound
35	3418	3809	0.43	0.45	-4.28	Sound
36	3418	3809	0.43	0.45	-4.28	Sound
37	3418	3711	0.42	0.45	-1.76	Sound

The results of the Impact Echo test (IE1 and IE2) on the concrete drop panel under investigation provide significant data regarding the durability and quality of the concrete structures. As per IE1, almost 29 spots (78.4%) of the spots under investigation had sound concrete quality, indicating that a significant portion of the slab exhibited satisfactory integrity. Additionally, 3 spots (8.1%) of the investigated spots were labelled as questionable, suggesting potential areas of concern, while 5 spots (13.5%) of the tested spots were categorised as poor, indicating sections that required immediate attention or repair. `

Table 2. Impact Echo Test Results (IE2) for Reinforced Concrete Slabs

ID	Calibrated Velocity (m/s)	Frequency (Mhz)	Primary Thickness Echo (m)	Expected Thickness (m)	Difference from Expected Thickness (%)	Concrete Quality
1	3418	7422	0.22	0.25	-11.58	Poor
2	3418	19922	0.08	0.25	-67.06	Poor
3	3418	20117	0.08	0.25	-67.38	Poor
4	3418	6836	0.24	0.25	-4.00	Sound
5	3418	7031	0.23	0.25	-6.66	Sound
6	3418	6152	0.27	0.25	-6.67	Sound
7	3418	5371	0.31	0.25	22.19	Questionable
8	3418	6738	0.24	0.25	-2.60	Sound
9	3418	6738	0.24	0.25	-2.60	Sound
10	3418	6348	0.26	0.25	3.38	Sound
11	3418	5762	0.29	0.25	13.89	Questionable
12	3418	5566	0.30	0.25	17.9	Questionable
13	3418	5566	0.30	0.25	17.9	Questionable
14	3418	5176	0.32	0.25	26.79	Poor
15	3418	5469	0.30	0.25	20.00	Questionable
16	3418	5566	0.30	0.25	17.9	Questionable
17	3418	5762	0.29	0.25	13.89	Questionable
18	3418	6543	0.25	0.25	0.30	Sound
19	3418	6738	0.24	0.25	-2.60	Sound
20	3418	6445	0.26	0.25	1.82	Sound
21	3418	6641	0.25	0.25	-1.18	Sound
22	3418	6250	0.26	0.25	5.00	Sound
23	3418	5859	0.28	0.25	12.01	Questionable
24	3418	6348	0.26	0.25	3.38	Sound
25	3418	5762	0.29	0.25	13.89	Questionable
26	3418	6543	0.25	0.25	0.30	Sound
27	3418	6738	0.24	0.25	-2.60	Sound
28	3418	6738	0.24	0.25	-2.60	Sound
29	3418	6836	0.24	0.25	-4.00	Sound
30	3418	7715	0.21	0.25	-14.49	Questionable
31	3418	6641	0.25	0.25	-1.18	Sound
32	3418	6543	0.25	0.25	0.30	Sound
33	3418	6445	0.26	0.25	1.82	Sound

34	3418	5957	0.28	0.25	10.17	**Questionable**
35	3418	6934	0.24	0.25	-5.36	**Sound**
36	3418	6934	0.24	0.25	-5.36	**Sound**

In contrast, IE2's sound-tested point percentage (58.3%) in 21 spots was marginally lower than IE1's, indicating a worse overall quality. Furthermore, the percentage of questionable-tested sites rose to 11 spots (30.6%), indicating that a greater area requires investigation. In contrast, the percentage of poorly indicated spots was nonetheless significant at 4 spots (11.1%), highlighting the concrete drop panel's potential weak highlights or structural integrity deterioration. These results emphasise the significance of the concrete drop panel structure carefully and methodically using NDE techniques such as Ground Penetrating Radar and Impact Echo.

3.2. Ground Penetrating Radar (GPR) Image Scanning

The concrete cover and the spacing between the reinforced sections of the structure under investigation are crucial details revealing the scanned images from Ground Penetrating Radar (GPR) that are displayed in Figures 7, 8, and 9. The results demonstrate a consistent reinforcement spacing of 20 cm along the x-axis and approximately 18–20 cm along the y-axis, closely complying with the design specifications as shown in Figure 10. Furthermore, it was discovered that the concrete clear covers varied by 4 cm from the expected values specified in the design drawings, demonstrating the structural integrity of the drop panel and its compliance with construction guidelines.

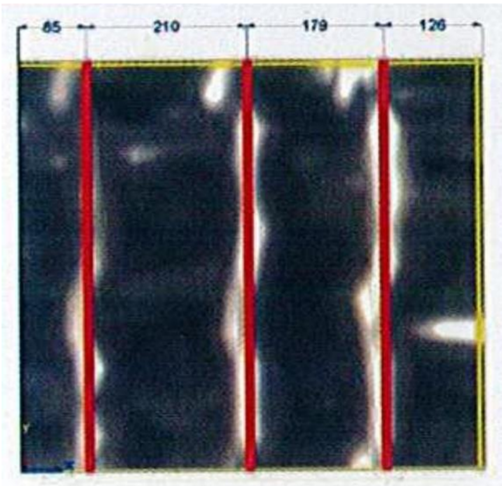

Figure 7. Y-axis 2D Image

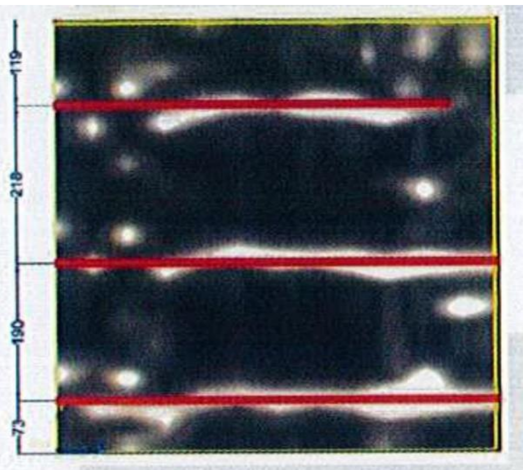

Figure 8. X-axis 2D Image

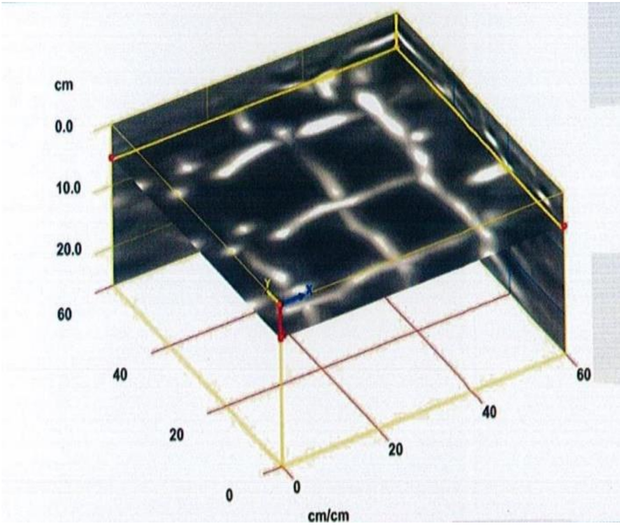

Figure 9. 3D Scanned Image

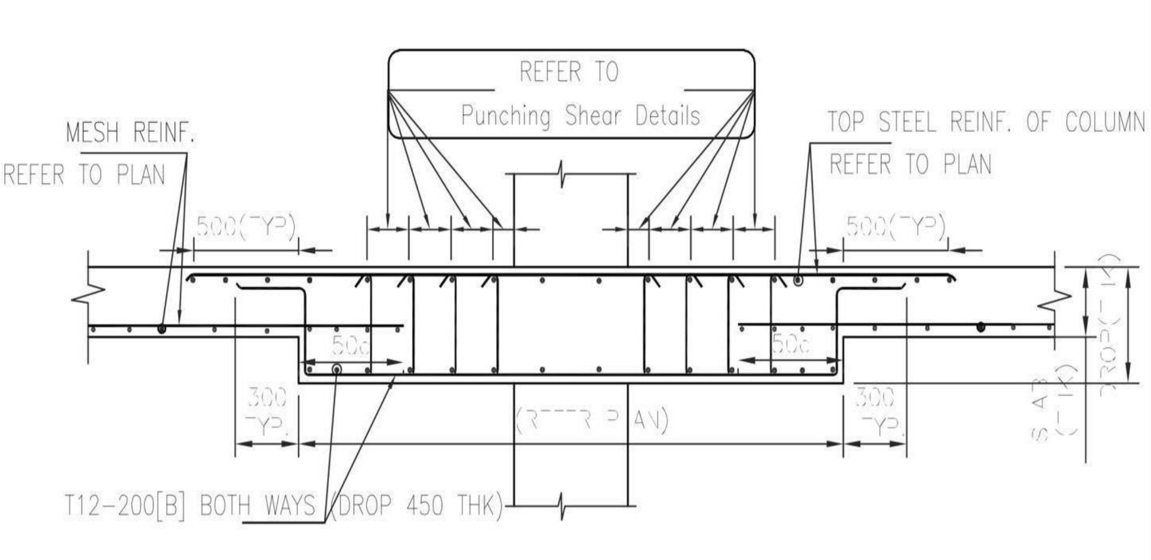

Figure 10. The Drop Panel Detail

4.0 Conclusion

In conclusion, the investigation examining the effectiveness of Ground-Penetrating Radar (GPR) and Impact Echo (IE) techniques in identifying delamination defects in concrete structures resulted in significant results regarding the structural integrity of the investigated concrete drop panel. The existence, amounts, and severity of delamination issues were successfully analysed using a mix of non-destructive evaluation techniques, yielding significant data for well-informed maintenance and repair decision-making. The results indicate that GPR and IE are viable methods for locating delamination defects in concrete structures. GPR provides comprehensive data on the subsurface conditions and the spacing between the reinforcements, whereas IE provides accurate measurements of the thickness of the slab and the presence of defects.

Furthermore, this investigation's recommended strengthening strategy illustrates a proactive approach to repairing delamination defects and enhancing the structural capacity of concrete elements. The strategy intends to increase the drop panel's flexural and shear capacity by using

methods including dowel installation and concrete enlargement, extending its service life and ensuring public safety.
The investigation further emphasises the significance of routine maintenance and inspection of concrete infrastructure, especially when it relates to reducing the risks of delamination-induced deterioration. Infrastructure managers can take preventive measures to preserve structural integrity, enhance the life of concrete structures, and ensure public safety by utilising advanced non-destructive evaluation techniques such as GPR and IE. The results of this investigation offer a useful tool for addressing the challenges of ageing infrastructure and high repair costs globally.

Lastly, the integration of IE and GPR offers deep insights into structural integrity and subsurface conditions without invasive approaches, which is a significant achievement in the field of non-destructive evaluation. While maintaining and repairing concrete structures that are already in place continues to be a top priority for infrastructure management agencies, applying GPR and IE has enormous potential to enhance resilience, optimise maintenance procedures, and ultimately safeguard public infrastructure for future generations.

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