# Innovative AR and GPR techniques for enhanced modelling and condition assessment of bridge structures

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**Abstract**

The integration of Structural Health Monitoring (SHM) and diagnosis data into Building Information Modelling (BIM) workflows enables engineers to optimize the planning, design, and maintenance of infrastructure projects, fostering a more efficient, sustainable, and data-driven approach throughout the lifecycle of the structures. This contribution presents an innovative approach for the advanced documentation and deterioration assessment of a pedestrian concrete bridge structure. Augmented reality (AR) devices were used to create a deterioration map for SHM, focusing on mapping the observed surface defects. For this purpose, a new "AR Scanner-Labeller" tool was developed for on-site real-time hand scanning and labelling of damages (cracks, detached concrete, etc.). Moreover, a path was developed to assign RTK-GPS coordinates to the geometric labels created. In addition, a terrestrial laser scanning (TLS) was used to generate a 3D model of the whole structure, as a ground truth of the point cloud generated with the AR devices.
For more advanced modelling and structural reliability, a Ground-Penetrating Radar (GPR) survey was conducted to know the real condition of the internal structure. A multichannel stepped-frequency GPR system, with modulate frequency range 500 – 3000 MHz, was used to further define the extent and depth of the damage labelled with the AR tool. All this data was finally integrated in a common Building Information Modelling (BIM) model, providing a more realistic scenario of the real condition of the structure and a more reliable analysis. The geometry of the BIM was adopted from the TLS point cloud based on Scan-to-BIM approach.
Additionally, the openBIM IFC (Industry Foundation Classes) standard was adopted to ensure interoperability and data exchange. The resulting model demonstrated interoperability by retaining both geometry and semantic information across different BIM platforms. This workflow has shown significant value as a decision-making tool for the maintenance and rehabilitation of civil infrastructure.

## 1. INTRODUCTION

The current landscape of Building Information Modelling (BIM) has been widely reviewed in the literature (Parsamehr et al., 2023; Papuraj, Izadyar, and Vrcelj, 2025; Faraji et al., 2024; Cepa et al., 2023). BIM methodology has primarily been developed for building construction projects, thus its application to infrastructure such as pedestrian bridges remain relatively underexplored.

Although BIM is well established in the context of buildings, its application in pedestrian bridges presents unique challenges. These structures require specific consideration owing to their dynamic load factors, environmental conditions, and integration into urban landscapes. Leveraging technologies such as scan-to-BIM, Augmented Reality (AR), and Ground Penetrating Radar (GPR) offer significant potential for developing accurate and adaptable models that address these complexities, enhancing both design and long-term maintenance strategies.

Nevertheless, in the context of infrastructure management, BIM offers several compelling advantages over its traditional use in vertical construction. Its ability to support interoperable environments allows a wide range of stakeholders and digital tools to collaborate through a shared dataset, thereby promoting consistency and reducing information loss across the project lifecycle. This centralized access not only strengthens collaboration, but also improves decision-making by providing reliable, real-time data.

In recent years, BIM has emerged as a cornerstone of the Fourth Industrial Revolution (4IR) because of its ability to consolidate all project data into a unified digital model and support collaboration across disciplines. By streamlining workflows, optimizing schedules, and integrating with additional data sources, BIM enhances coordination and management, ultimately saving time and reducing costs throughout the asset lifecycle.

A technique that enhances the use of BIM is scan-to-BIM, which bridges the gap between physical environments and their digital representation. This solution captures real-world conditions and translates them into detailed 3D models, thereby complementing BIM capabilities. A key strength of scan-to-BIM lies in its ability to generate highly accurate geometric representations of existing structures, which is especially valuable in retrofitting and renovation projects. This level of detail ensures that the digital model faithfully reflects physical assets, enabling more informed assessments, clash detection, and planning strategies.

Scan-to-BIM plays a pivotal role in the Architecture, Engineering, Construction, and Facility Management (AEC-FM) industry. This method has been applied across various contexts, including the collection of data on historical structures (Rocha, Mateus, and Ferreira, 2024; Nieto-Julián, Bruno, and Moyano, 2024; Panayiotou and Kontovourkis, 2024) and the analysis of bridges (Mognon, Ruparathna, and Van Engelen, 2022; Liu and Li, 2024).

In a recent study Ramli et al. (2024) defined Scan-to-BIM as a process that involves digitally capturing a physical space or site using 3D laser scanners and then using the captured data to create and maintain a BIM model. The conversion of point cloud data into a 3D Building Information Model (BIM) has predominantly been performed using manual methods. However, in the research


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field, discussions are being held regarding different automated and semi-automated techniques.

Rocha et al. (2024) introduced automation algorithms for efficiently converting point cloud data into accurate BIM models using Dynamo, a visual programming tool integrated with Autodesk Revit. This integration simplifies the workflow and highlights the broader applicability of scan-to-BIM in industry practice.

In another contribution, Mahmoud et al. (2024) put forward a deep learning-based framework specifically tailored for indoor 3D modelling from raw point cloud. Their method is structured in three main stages: initial data preprocessing to improve quality, applying a deep learning model for semantic segmentation, and reconstructing 3D building models, particularly interior spaces, through clustering and denoising algorithms. The final model was integrated into Autodesk Revit via parametric algorithm, enabling a largely automated scan-to-BIM process.

For instance, Lee et al. (2020) presented a system designed to automatically extract key geometric parameters of bridge components, such as height, length, and width, from point cloud data, thereby significantly reducing the time and resources required in the scan-to-BIM workflow. Their approach involves the implementation of statistical outlier removal filter, which employs the k-nearest neighbors (kNN) algorithm to effectively eliminate noise, while also applying the MSAC algorithm to accurately identify planar elements within the point cloud.

Regarding semi-automated approaches, Vieira et al. (2024) focused on the modelling of architectural ornaments and developed a workflow that incorporates multiple software tools to produce reliable BIM components. An important feature of their method is the mesh refinement step prior to mesh-to-BIM conversion, which improves the fidelity and quality of the final BIM objects.

Pepe et al. (2024) also explored a semi-automatic process, involving four primary stages: the 3D survey, generation of a refined point cloud through feature extraction, geometry reconstruction using Rhinoceros/Grasshopper software, and BIM implementation. Their use of the ShrinkWrap algorithm allowed the creation of accurate polygonal meshes free from common geometric issues, such as holes or non-manifold surfaces, resulting in models that closely replicate the original structures.

Furthermore, in recent years, technologies such as Virtual Reality (VR), Augmented Reality (AR), and Extended Reality (XR) have evolved from niche innovations to widely accepted tools, valued for their advanced visualization and interaction capabilities. The integration of AR with Building Information Modelling (BIM-AR) plays a crucial role in enhancing BIM models. Current literature highlights various studies that focus on this topic (Assila, Dhouib, and Monla, 2022; Wang et al., 2024). This combination not only promotes collaborative attributes but also enables realistic 3D visualization, making it an essential step for enriching BIM. This study focused on implementing BIM-AR integration to explore its potential benefits in bridge infrastructure.

Fawad et al. (2024). introduced an innovative approach for smart bridge inspection by combining Structural Health Monitoring (SHM) data with an Augmented Reality (AR) system. Through the development of an AR application compatible with HoloLens, their system enables real-time remotely or onsite visualization of structural defects, presenting a promising tool for improving bridge maintenance strategies and supporting more efficient decision making in this field.

Alongside BIM-AR integration, Ground Penetrating Radar (GPR) data offer significant advantages for analyzing infrastructure (Solla, Pérez-Gracia, and Fontul, 2021; Elseicy et al., 2022). In the context of bridges (Solla, Elseicy, and Alonso-Díaz, 2024), GPR excels as a non-destructive testing (NDT) method by enabling efficient assessment of structural conditions without causing damage. Transmitting high-frequency electromagnetic waves into materials and analyzing their reflections allows GPR to uncover critical subsurface details that are essential for evaluating safety and reliability.

This article focuses on the development of a BIM model for a pedestrian bridge that integrates data derived from AR and GPR. These advanced technologies are incorporated to capture both surface-level and subsurface information, thereby enhancing the model's accuracy and utility. The model is designed to be interoperable using the IFC (Industry Foundation Classes) standard, ensuring that the data can be seamlessly transferred and utilized across various software platforms. This approach simplifies the information exchange and promotes efficient collaboration among stakeholders in infrastructure planning and management.

## 2. MATERIALS AND METHODS

### 2.1 LiDAR data acquisition and processing

LiDAR technology was used to obtain 3D geometry to generate the BIM model of the pedestrian walkway. The equipment used was Terrestrial Laser Scanner (TLS) Faro Focus X330 (Rashi et al., 2024) which was positioned in 12 scanning positions, providing information on both the footbridge surface (with 3 positions) and the base (4 scans in the west zone and 5 scans in the east zone). Figure 1 shows the position of each scan.

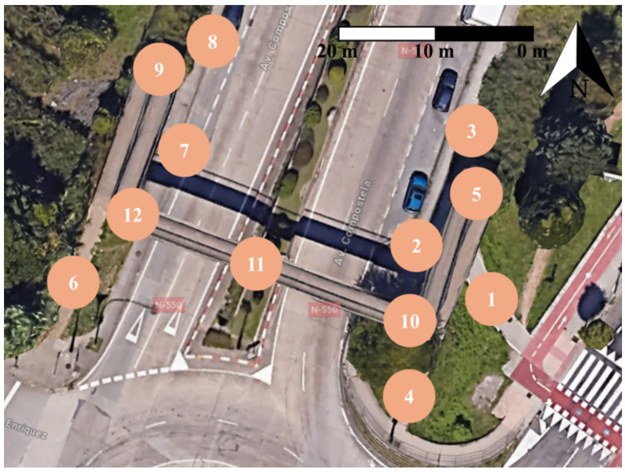


Figure 1. Top view of scanning positions.

Subsequently, the 12-point clouds were registered and georeferenced. The registration was done taking as reference the central scan (No. 11) and consecutively registering the scans of each wing. Georeferencing was performed by taking four points with the GNSS Stonex S900A GPS RTK (Real-Time Kinematic) at the corners of the pedestrian walkway. The resulting point cloud is shown in Figure 2.

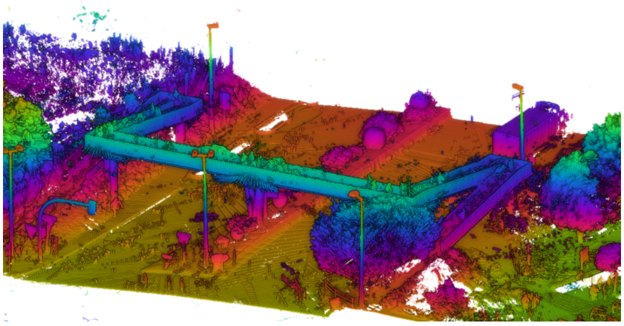

Figure 2. Registered point cloud colored by height ramp.

In addition, since the data collection was done without closing the bridge, numerous dynamic elements were scanned, hindering the subsequent use of the point cloud for BIM generation. These elements were removed manually.

### 2.2 GPR data acquisition and processing

A multichannel stepped-frequency GPR system (GS9000 GX1) of the company Screening Eagle Tech., with modulate frequency range 500 – 3000 MHz, was used. This system consists of 35 VV channels and 15 HH channels, with channel spacings of 2.5 cm (VV) and 5.5 cm (HH) and a scan with of 0.85 $m^2$. The scan rate is 27500 scans/$s^2$. The GPR data is directly recorded with GNSS trajectory. The setting parameters used for data acquisition were, 1 cm in-line, 400 samples and time window of 20 ns.

Time-slices were generated for the first 12 cm of the slab depth at 1 cm interval between consecutive time-slices, and then exported as PNG files (pixel information) and corresponding PGW files (coordinates information for georeferencing) for further integration into the BIM model.

Figure 3 shows an example of a time-slice (XY image) produced.

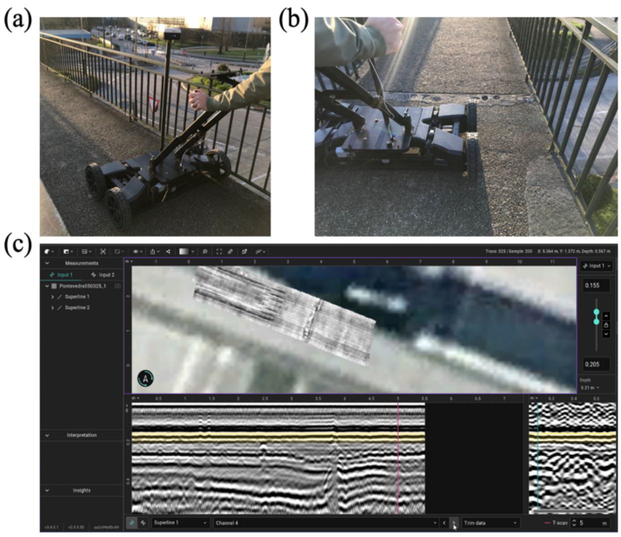


Figure 3. Multichannel GPR system used (a), main region under study (b), and time-slice produced at 0.05 m in-depth (c) with the Insights (web-based application software).

### 2.3 AR data acquisition

AR data was captured with Microsoft HoloLens 2. An application was designed to access the hand tracking sensors and the automatically generated mesh. A human graphic interface was designed to allow real-time positioning of virtual tags on bridge damages. Thus, the most appropriate geometric shape (point, line, polyline or polygon) was selected depending on the type of damage and by means of hand tracking the marker was positioned in the appropriate place. A detailed explanation of the interface is available in GitHub (AR-GeoTag, 2024). An example of the AR visualization is shown in Figure 4.

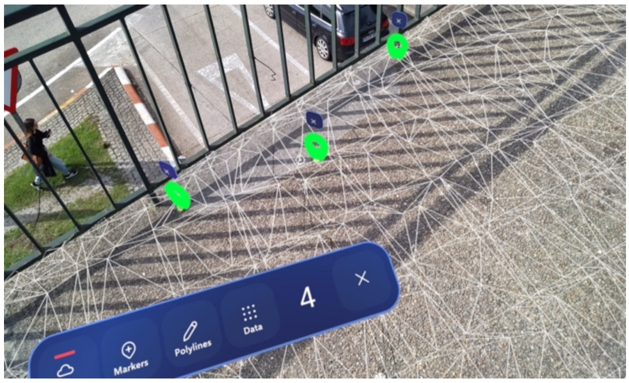


Figure 4. AR view of virtual tags, mesh and interface over real pedestrian pathway.

### 2.4 Scan-to-BIM

To create a BIM model of the A Xunqueira bridge using a LiDAR point cloud, the initial step involved positioning the georeferenced point cloud in Autodesk Revit after processing it in Autodesk ReCap. Once correctly aligned, the focus shifted to developing parametric families tailored to the project requirements.

Distinct families were designed for key structural elements, including columns, central columns, beams, balustrades for railings, and guardrails. The creation process begins with the selection of a Metric Structural Column template. Within this template, the elements were meticulously drawn in plant view and subsequently extruded to the desired height or length.

A slightly different approach is necessary for balustrades. Unlike other components, the balustrade family was not directly loaded into the project. Instead, it was integrated into a railing editor. Crafting the railings presented a challenge because, even after utilizing the editor's customization options, each longer balustrade required manual placement to achieve the desired configuration.

In contrast, floors are created directly from the “architecture” tab selecting the “structural floor” option and drawing its dimensions. Using different views, elevations and floor plans for each level and section is very useful for adjusting these elements as best as possible to the point cloud.

Once all the families were successfully created, they were seamlessly imported into the project containing the point cloud. They were carefully aligned and adjusted using levels and shared parameters to ensure an accurate representation of the bridge in the BIM model.

### 2.5 BIM data Integration and IFC modelling

After the BIM model has been developed the next stage involves the integration of Augmented Reality (AR) and Ground Penetrating Radar (GPR) with Building Information Model

(BIM). The convergence of these cutting-edge technologies signifies a huge leap forward for the AEC-FM sector.

The objective of the AR integration was to illustrate the damaged areas and cracks on the bridge surface. To accomplish this, a CSV file will be utilized, containing data gathered from Microsoft HoloLens, which has been accurately georeferenced and organized into polygons and polylines. Having the coordinates in the CSV file properly organized provides a significant advantage when using Dynamo in the context of the bridge model developed in Revit.

In this case study, four distinct elements were represented: two polygons and two polylines. Therefore, in Dynamo, the coordinates of each element are separated and individually configured. This enables us to represent them in the project using a DirectShapeByGeometry node, which also facilitates the potential export of damaged areas and cracks to the IFC format at a later stage. Figure 5 provides an overview of the workflow used for the proposed methodology in this work.

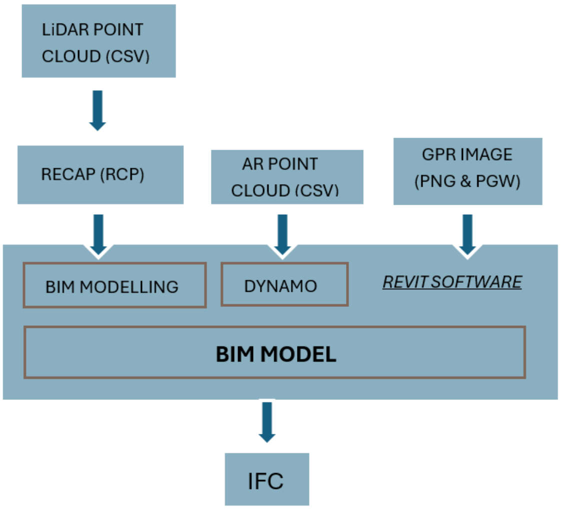


Figure 5. Workflow

Once completed, the next phase integrated the PNG and PGW files of the GPR data into the BIM model, thereby providing critical insights into the actual depth of the detected defects. This integration aids in accurately assessing the severity of defects and supports informed decision-making.

The 3D GPR data was split into 13 time-slices, and it was therefore necessary to divide the floor beforehand. This division was made at one-centimetre intervals (interval between consecutive time-slices), and each image was positioned starting from the one at depth level 0. Once this step is completed, it becomes possible to analyse defects at each depth level.

At this stage, a new mass element must be created using the "In-Place Mass" option. This tool allows the generation of a custom mass within the Revit environment, facilitating the modelling of irregular or complex shapes that correspond to the detected defects. This process involves tracing the contours of the defects in each layer and then selecting the "Create Form" option after finalizing the contour design. Next, a suitable solid shape represents the defects.

## 3. RESULTS

After creating the BIM model and integrating the Structural Health Monitoring data from the AR and GPR devices, the result is a detailed and highly informative mock up that provides valuable insights into the structural integrity, potential weaknesses, and overall current condition of the pedestrian bridge.

Since IFC modelling has already been performed with the Dynamo nodes, the next step is to export the BIM model as an IFC file. To ensure compatibility and maximize interoperability, the latest IFC 4.3 version (ISO16739-1:2024), and the *IfcBridge* schema, was selected. The geodetic datum (EPSG) code was then established for georeferencing the IFC file. This step is crucial for aligning the digital model with real-world coordinates and facilitating accurate positioning and integration with other GIS and BIM datasets.

(a)

(b)

(c)

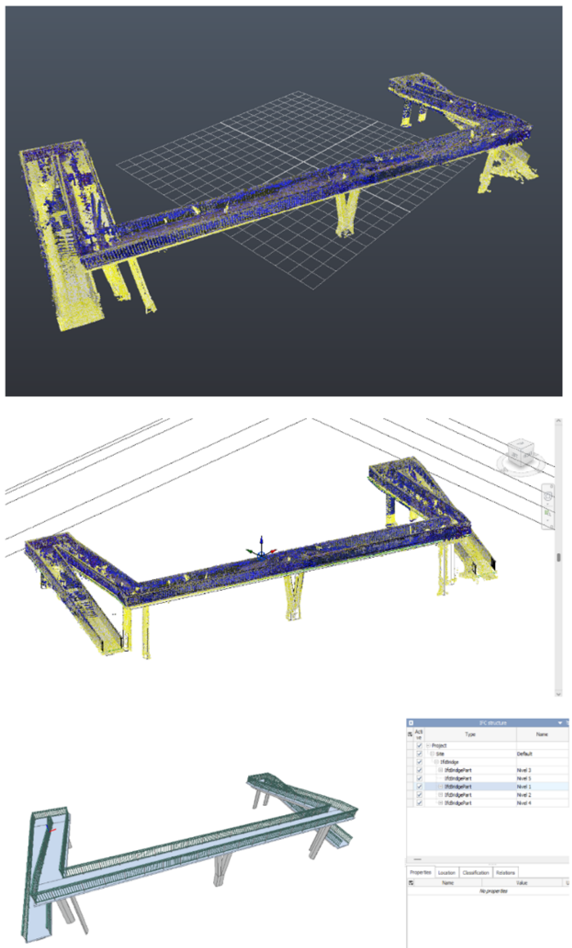

Figure 6. Point Cloud Data (PCD) in Autodesk ReCap (a), BIM model developed in Autodesk Revit (b) IFC file in BIMVision (c).

The IFC 4.3 schema represents an advancement in the standardization of BIM for infrastructure. Unlike previous versions, IFC 4.3 introduces enhanced support for horizontal infrastructure, including roads (*IfcRoad*), railways (*IfcRailway*), waterways (*IfcMarineFacility*), and bridges (*IfcBridge*). By integrating *IfcBridge*, the standard supports the growing need for open and efficient data exchanges in the infrastructure sector. This is particularly beneficial for large scale projects that require collaboration across multiple disciplines and software solutions.

With IFC 4.3, the BIM industry has moved closer to achieving full interoperability in infrastructure design and construction, paving the way for more efficient and sustainable projects.

As illustrated in Figure 6, the raw point cloud was processed in Autodesk Recap (a), the BIM model was developed in Autodesk Revit (b), and the IFC file was directly opened in the free-viewing platform BIMVision (c), enabling seamless 3D visualization while preserving the assigned attributes. This workflow ensures that all relevant project data are accessible and interpretable across multiple platforms, reducing information loss, and enhancing project transparency. By combining different software tools, this approach improves coordination in infrastructure projects, facilitating better planning, visualization and interdisciplinary collaboration. Ultimately, this methodology enhances efficiency, reduces errors, and supports a more integrated and sustainable approach to bridge asset management.

In Figure 7, we can observe the Augmented Reality (AR) defects represented within the BIM model (a). After being exported using the IFC schema, these defects are also visible in BIMVision software (b), where they retain all their associated properties. This ensures that the defects are correctly integrated into the BIM environment, allowing for accurate visualization and analysis across different platforms.

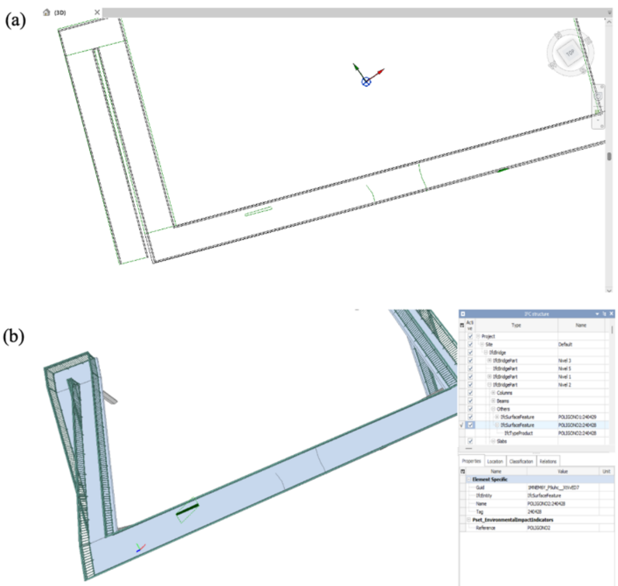

Figure 7. Augmented Reality (AR) defects represented within the BIM model in Autodesk Revit (a), After being exported using the IFC schema, IFC Augmented Reality (AR) defects represented within the BIM model in BIMVision (b)

To properly export the defects represented by the polylines, it was necessary to establish a symbolic depth value. This can be done using the "Curve.Extrude" node in Dynamo, which allows for creating a symbolic extrusion on the curves, providing a volume representation that leaves untouched the actual geometry but plays an important role in how the defects are analysed within a BIM environment. This step was crucial to ensure that the defects could be correctly interpreted and processed within the IFC format. By assigning a symbolic depth, not only is the geometry of the defects retained but their spatial relationships are also maintained, which ensures that the IFC file reflects a complete and accurate representation. This allows the defects to be effectively visualized, analysed and incorporated into various BIM and GIS applications.

Once we obtain the representation of surface level defects provided by the AR data, the next step is to integrate the depth values obtained from the GPR data. This integration is essential because it allows us to enhance the accuracy of the three-dimensional representation of defects by providing crucial subsurface information. By incorporating depth measurements, we can better understand the size, shape, and severity of the detected anomalies, enabling a more comprehensive analysis of the structural condition of the bridge.

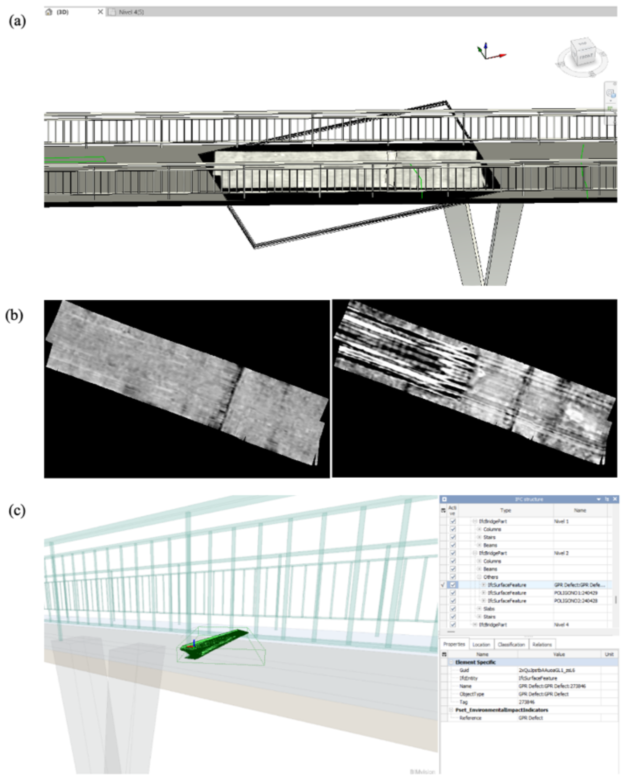

Figure 8. Ground Penetrating Radar (GPR) and Augmented Reality (AR) defects represented within the BIM model in Autodesk Revit (a) time-slices produced at 0.01 m and 0.09 m in-depth (b) After being exported using the IFC schema, IFC Ground Penetrating Radar (GPR) defect represented within the BIM model in BIMVision (c).

Figure 8 illustrates a defect designed using GPR data. Identifying these surface-level defects is the first step in diagnosing problems that could compromise the integrity of the bridge over time. In the case study examined, the defect under analysis in terms of its depth and extent is a patched area situated directly adjacent to the expansion joint in the central section of the pedestrian bridge. This location is critical because areas near expansion joints often experience significant stress and movement, which can intensify existing defects over time. These factors make it essential to monitor and evaluate the region carefully to prevent further structural degradation.

Furthermore, by utilizing the images obtained from the GPR data, we can determine the depth and extent of subsurface defects, allowing us to analyse their spatial distribution and potential impact on the structure. GPR is particularly useful for detecting hidden deterioration, reinforcing bar positioning, moisture infiltration, and other subsurface conditions that may not be visible by surface inspection alone. This capability is crucial for detecting early-stage issues that may otherwise remain undetected until they pose a serious risk. Using this data, we can create a detailed three-dimensional design of the defect, which is crucial for developing accurate predictive models and optimizing maintenance and repair strategies.

## 4. DISCUSSION AND CONCLUSION

This study not only introduces a trustworthy tool but also provides a comprehensive guideline for incorporating data gathered from NDT surveys into BIM environments. The integration of AR and GPR information was successfully carried out yielding a digital model of the analysed bridge and some of its defects.

Furthermore, the findings thus far offer a starting point for developing an accurate model enriched with valuable information aimed at extending the lifecycle of pedestrian bridge structures. The Autodesk Revit platform demonstrated its ability to accommodate all these additional types of information and exporting it to the IFC 4.3 standard, which plays a key role in BIM standardization for infrastructure and interoperability.

In recent years, this topic has been explored in literature. For instance, previous studies have explored a methodology to integrate information from different sources into an HBIM model (Solla et al., 2020), leveraging data obtained from laser scanning, thermography, and GPR, among others. These methods have enabled the creation of enriched digital representations of heritage buildings. These studies have laid the groundwork for the methodology being developed in the current research, highlighting the potential for future enhancements and broader applications in this field. Our study goes beyond traditional HBIM approaches, as it integrates the IFC standard, which significantly enhances the interoperability between different software platforms and the entities involved in the project, facilitating more efficient data exchange and long-term accessibility.

Moreover, the representation of distress and structural damage in BIM models has garnered significant attention, particularly in road and building environments. This focus stems from the fact that a high level of detail regarding existing defects can significantly improve the lifecycle management of the infrastructure. Accurate digital models allow for better-informed decision making and proactive maintenance planning, especially in cases where visual inspection methods are unreliable or insufficient.

For instance, Bertolini et al. (2023) developed a methodology to integrate data obtained from NDT surveys into the digitalization process of a BIM model of a linear transport infrastructure. This approach enabled the identification of pavement sections potentially affected by damage and deterioration in the deeper layers of the superstructure.

Additionally, Fernandez-Mora et al. (2025) introduced a building performance analysis tool called Endurify, which was designed to assess the preservation state of concrete structural elements. This BIM plug-in employs four damage indicators, carbonation, transversal cracking, creep, and deflection, to evaluate and document the condition of the structural components.

By integrating advanced data collection and visualization techniques, these studies underline the importance of precise defect documentation in extending the lifespan and performance of infrastructure systems.

Although this methodology represents a significant advancement in terms of data integration and interoperability, considerable potential remains for further development. The future evolution of this approach is anticipated to follow three primary directions, each aimed at enhancing the accuracy, comprehensiveness, and reliability of the model:

- First, enhancing the BIM model by integrating more diverse sources of information regarding the structural health of the bridge, such as thermographic and ultrasonics data. This integration will allow for a more holistic representation condition of the bridge, enhancing the utility of the model for damage monitoring, maintenance planning, and long-term monitoring.

- Second, refining the integration of GPR data by utilizing the GPR point cloud to represent defects alongside AR data, thereby increasing the reliability of depth variations. Additionally, the inclusion of a complete PNG/PGW image of the entire base of the bridge and detailed information about bridge reinforcement bars (rebars), such as their positioning, spacing, and potential corrosion, will significantly enhance the precision of the model. These refinements not only improve defect detection but also provide more actionable insights for structural assessments and repair strategies.

- Third, the implementation of deep learning methods enables the automatic extraction of defects detected through GPR data, followed by their export into CSV format, thus generating a defect point cloud that can be efficiently integrated into the BIM model for further processing. By incorporating these advanced methodologies, the detection system can be significantly enhanced, leading to a more seamless, accurate, and organic workflow for defect identification and structural assessment.

Together, these advancements promise to expand the capabilities of the methodology, paving the way for more robust, data-driven approaches to infrastructure management, and ensuring the long-term safety and functionality of critical structures such as bridges. As digital transformation continues to reshape engineering and construction practices, this research underscores the importance of integrating innovative technologies into infrastructure modelling. By doing so, it lays a foundation for smarter, more sustainable infrastructure systems that not only meet current demands but also adapt to future challenges with resilience and efficiency.

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