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BIM-based mixed reality application for bridge inspection

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ABSTRACT

Traditional bridge inspection methods have limitations, driving the need for advanced techniques. The primary objective of this paper is to explore and evaluate the potential of combining Mixed Reality (MR) technologies with Building Information Modeling (BIM) and damage information to overcome these challenges. The paper aims to improve communication, collaboration, and the accuracy of structural damage identification during inspections. Parametric objects were developed to accurately represent and locate damage within the BIM model of the Coimbra I Viaduct in Brazil, using detailed geometric parameters. On-site inspections leveraged MR technologies, enabling real-time integration of damage information into the BIM. This approach allowed full-scale interaction with the model in augmented reality (AR), facilitating direct comparison with actual structural features and improving the accuracy and efficiency of inspections. The findings demonstrate the feasibility of a simplified MR-based inspection process, offering a complementary method within a multi-platform Bridge Management System, thereby enhancing bridge maintenance.

1. Introduction

The conventional visual inspection method for bridges has inherent limitations, such as safety concerns for the inspection team, difficulty in accurately identifying subsurface defects, and subjectivity. These factors can impact the efficiency of decision-making and resource allocation in maintenance programs [1–6]. A bridge incurs annual operating, inspection, and maintenance costs and demolition expenses at the end of its service life, which usually vary between 0.4 % and 2.0 % of its initial construction cost. Ultimately, these costs can make up to 80 % of the total construction expenditure [7]. Conducting inspections to assess the condition of bridges is crucial for evaluating the status of deteriorating structures. It helps identify the nature, extent, and location of any issues, ensuring ongoing functionality, operability, and safety for users [8].

Globally, there is a significant demand for annual structure inspections. In China, about one-third of its 800,000 highway bridges exhibit structural failures, necessitating safety monitoring and maintenance [9]. Japan, which has about 730,000 bridges, 39 % of them to be over 50 years old by 2023 [10]. In the United States, of the 617,000 bridges averaging 44 years of age, 7.5 % are considered structurally deficient [11]. Brazil has an estimated 137,000 bridges, managed by various government agencies [12], with the National Department of Transportation Infrastructure (DNIT - *Departamento Nacional de Infraestrutura e Transportes*) overseeing 6833 bridges' operation, maintenance, and rehabilitation.

During the operational phase of a bridge, various inspections are carried out, including regular, detailed, and special ones, using diverse methods and technologies. The lifecycle of a structure generates substantial data, and inefficient management of this information hinders the assessment of structural conditions and maintenance decision-making [13].

To address these limitations, Mixed Reality (MR) has been chosen for its advanced integration and visualization capabilities. MR combines Augmented Reality (AR) and Virtual Reality (VR) to overlay digital information in the physical environment, allowing interactive and detailed visualization of structural damages. This technology provides several benefits, such as the ability to inspect and simulate interventions directly on-site, improving the accuracy of problem identification, and facilitating inspection team training [13,16–19].

MR is complemented by Building Information Modeling (BIM), an efficient methodology for digitally representing a structure's physical and functional characteristics, acting as a repository of information

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throughout the life cycle [14,15]. When integrated with MR, BIM enables digital data to be visualized and manipulated in a real-world context, enhancing the analysis and communication of structural conditions. The IFC (Industry Foundation Classes) schema standardizes this data, ensuring consistency and precision in the representation of project elements. IFC is an open standard created by BuildingSMART and is widely used for sharing data [20]. This model uses an object-oriented data structure, making it possible to organize geometric data and design information in a standardized manner [21]. The BIM Collaboration Format (BCF) supports communication about issues in a BIM model, working independently of the 3D model and including descriptions, status, and illustrative images of problems [22,23].

Researchers have explored immersive technologies like MR and VR to enhance bridge inspection and maintenance, demonstrating on-site inspection prototypes [24], point cloud data integration for database management [25], BIM-based MR applications for remote inspections [13,26], and holographic overlays for precise damage detection [27]. To the best of our knowledge and according to the review, this article presents an unprecedented approach in the literature that deals with the MR technologies and BIM methodology integrated with inspection techniques and specific damage information to improve bridge maintenance management.

This novel methodology involves the development of specific parametric models to represent damage information in the model, enabling the identification, classification, sharing, and exchange of information on structural issues. An on-site case study was conducted in a small Brazilian town. The aim is to help establish an inspection routine based on simplified MR, with the insertion of specific information for the pathological manifestations identified in the BIM model. This will make information available to other users in the model, assisting in the decision-making process for maintenance, estimating the budget for repair interventions, and creating a history of active and repaired damage to the structure throughout its service life.

2. Literature review

A concise survey of the infrastructure inspection domain employing immersive technologies was conducted to scrutinize primary research themes, technological advancements, scholarly output, and challenges highlighted in recent and pertinent studies within this domain. The Scopus Database was selected for analysis, given its status as one of the principal academic search engines encompassing the subject. The search was carried out in April 2024, using the terms “bridge” OR “infrastructure” AND “inspection” AND “reality” AND “augmented” OR “virtual” OR “mixed” search within “Article title, Abstract, and Keywords”. Only Journal Articles and Conference Papers in English published in the last years (2019–2024) were considered. A total of 42 Journal Articles and 61 Conference Papers were found.

From this set, a systematic approach was applied to identify and select the most relevant studies. This selection involved an initial screening of titles and abstracts to filter out irrelevant papers, followed by an analysis of the full text of the selected studies. The final selection included only those articles and documents that directly addressed the use of immersive technologies in visual inspection and damage identification, which were then analyzed in depth.

2.1. Conceptualization

Virtual Reality (VR) offers a computer-generated reality in which the users have immersive experiences in an environment that enables them to interact with the virtual features or objects of the virtual models. A head-mounted display (HMD) or multi-projected environment is the most common VR tool [13,16–19,28]. Augmented Reality (AR) enhances the interaction between the real and virtual worlds by overlaying through smartphones, tablets, and AR glasses. AR applications generally enhance the real-world environment with digital objects, creating minimal interaction with the virtual content [13,16–18].

Mixed Reality (MR) combines the resources provided by VR and AR, merging the real and virtual environments somewhere through the mixed-reality spectrum; a real-world object interacts with a virtual object [13,17,29]. MR blends the 3D project model in a real-world representation based on computing technologies. It augments virtual information into the actual environment and allows the user to change information in real-time [13,17,18,30].

An MR environment has three main features, which are (1) combining the real-world object and the virtual object; (2) interacting in real-time; and (3) mapping between the virtual object and the actual object to create interactions between them [29]. Thus, MR, based on a BIM model, presents itself as an alternative for inspection, given that it is possible to interact with the model created in VR, insert it in full scale in AR, and compare it with the physical characteristics.

2.2. Mixed reality inspection vs. conventional visual inspection

Mixed reality inspection and conventional visual inspection represent two distinct approaches to assessing bridge conditions. The current bridge inspection procedure relies primarily on experienced inspectors manually recording data through checklists and paper notes, by observation, while the mixed reality inspection incorporates advanced digital technologies such as BIM models, VR and AR devices. The conventional visual inspection approach is subjective, inefficient, and costly, particularly for complex bridges [1,18,36,37]. These inspections, conducted element by element, are time-consuming, with the duration depending on the size of the bridge. They can lead to considerable disruption in traffic flow. Moreover, inspectors encounter various safety risks, particularly when utilizing lifting equipment to access hard-to-reach areas of bridges [1,37].

Conducting field inspections with the assistance of digital BIM models and MR technology holds significant potential for supporting bridge inspections. This approach streamlines the visualization process, aids in damage identification, and enhances information gathering for inspectors [13,24]. Utilizing new equipment such as tablets, smart glasses, and technologies like Unmanned Aerial Vehicles (UAVs), Terrestrial Laser Scanner (TLS), Ground Penetrating Radar (GPR), and Infrared (IR) thermography in the field has accelerated the collection of inspection data, automated processes, improved safety for inspection teams, enhanced reliability, and proven more cost-effective [6,38,39].

Numerous studies explore the utilization of mixed reality glasses to streamline the inspection and maintenance of structures [13,25,27,30,40,41]. These intelligent glasses function as autonomous holographic computers, enabling users to interact with 3D digital content in the real world hands-free. Additionally, they facilitate image capture using the glasses' integrated camera. Nevertheless, certain studies indicate that experienced inspectors prefer tablets as their primary field inspection tool over smart glasses like Microsoft HoloLens [24,34].

The tablet is considered a practical tool with a more intuitive shape and handling, and it is also more cost-effective and readily accessible compared to smart glasses. The estimated cost of a HoloLens is approximately three times higher. Moreover, smart glasses exhibit limitations in terms of field of vision, individual user experience, and gesture input systems, while tablets offer the advantage of simultaneous viewing of the actual structure and the digital model. Additionally, tablets facilitate interaction and collaboration among multiple users [33,34].

2.3. Related works

Riedlinger et al. [24] developed MR and VR prototypes to provide digital support for on-site bridge inspectors utilizing BIM data. The MR system was implemented on a tablet, and the authors established the process requirements through expert interviews with nine field specialists. The inspection process was delineated into three primary phases: (1) preparation of the bridge inspection using a computer or tablet, synchronizing the required data from a CDE (common data environment) with the terminal device; (2) structural inspection including investigating and documenting damage using photos and additional details, storing in a BCF file with photos and coordinates, and synchronizing with the CDE online or in the office for collaborative analysis; (3) post-processing of the structural inspection in the office, using VR/AR to visualize the existing damage on the bridge.

Nguyen, Kang, et al. [25] introduced an innovative concept of a Mixed Reality (MR)-based Digital Twin Model (DTM) designed to enhance the visualization of semantic information within a Bridge Maintenance System (BMS). This involved collecting a point cloud with geometric information about the bridge, which was then incorporated into a visual programming routine. Parametric families of structural elements were created for Revit. The study focused on integrating the DTM with MR using Microsoft HoloLens 2 through Unity, facilitating the visualization of bridge data in an office setting. The DTM model efficiently integrates, overlays, and manages maintenance databases. However, the pilot implementation of MR indicated potential enhancements in visualizing and integrating maintenance data.

In a subsequent study, Nguyen, Nguyen, et al. [13] proposed "HoloBridge," a novel framework that integrates a BIM-based Mixed Reality (MR) application and HoloLens to enhance off-site bridge inspection and maintenance. This system includes a Bridge Information Model (BrIM) and an MR-based application with functional modules, such as inspection, evaluation, and damage mapping modules, enabling users to make decisions about inspection and maintenance progress. HoloBridge brings the 3D bridge model into the real world, allowing users to query the inspection database for real-time structural condition monitoring. Using a damage mapping algorithm, users can assess damage progression over time, aiding in more reliable decision-making for maintenance.

Al-Sabbag et al. [27] presented a visual inspection method for the interactive detection and quantification of structural defects. The method involves a holographic overlay of information on the spatial environment, utilizing the advanced 3D spatial mapping capabilities of the Microsoft HoloLens 2. Inspectors can capture structure images, identify visual damage, estimate its area, and visualize it as holographic objects overlaid on the scene. This allows real-time interaction with the damage detection process, providing quantitative damage information. The study demonstrated that the system can accurately estimate spalling damage extent with less than 10 % error through image processing. The system facilitates human-machine collaboration, real-time analysis, and immersive data visualization.

In another study, Al-Sabbag et al. [30] introduced a pioneering system termed Human-Machine Collaborative Inspection (HMCI). This system facilitates collaboration among inspectors through the utilization of MR and a robotic data collection platform for structural inspections. The MR headset's holographic display is spatially aligned to the robot in real-time, creating an interactive and immersive environment for the user to conduct visual inspection tasks. This capability enables the inspector to visualize and localize real-world information efficiently.

A general workflow of HMCI involves collecting data from 2D sensors (visual, thermal, stereo cameras) and 3D sensors (LiDAR) mounted on a robot targeting a structure. This data, encompassing a substantial volume, is transmitted to a remote server. Subsequently, vision-based inspection algorithms are applied to identify and locate structural damage. Once detected, the MR headset receives this information, generating holograms of the damaged regions overlaying the actual defect location. Accompanying details, such as defect type, estimated sizes, inspection date, and prior inspection annotations are also displayed. This information can be saved on the reconstructed 3D map, allowing inspectors to revisit sites, reposition their MR headsets, and review annotations from past sessions during future inspections [30].

Wang et al. [26] introduced a novel Immersive Virtual Reality framework, designed with a specific emphasis on enhancing user experience during remote infrastructure inspections for data visualization and decision-making. Damage identification within the framework utilized 3D exclamation marks strategically placed over affected areas, color-coded (green, yellow, and red) to denote severity. Testing the developed IVR prototype revealed its effectiveness in identifying damage during remote bridge inspections, showcasing acceptable usability. Table 1 summarizes the related studies that have used MR.

The literature review demonstrates the potential of Mixed Reality (MR) and Virtual Reality (VR) in integration with Building Information Modeling (BIM) to improve visualization and information management during bridge inspections and maintenance processes. Existing research often lacks a standardized methodology that allows for the efficient exchange of data between platforms, ensuring interoperability and accuracy of information throughout the lifecycle of the infrastructure. Therefore, this research aims to address these gaps by proposing an integrated MR and BIM model that provides a continuous and validated workflow in a real case study. This approach improves the accuracy of damage location, optimizes communication between maintenance teams, and enriches the documentation of inspection and repair processes, contributing to more efficient and collaborative bridge maintenance management.

3. Methodology

This research proposes a study combining mixed reality with inspection procedures and the development of parametric objects for identifying, describing, and localizing damage to the structure. Fig. 1 illustrates the structure of the proposed methodology.

3.1. Research workflow

The inspection methodology proposed in this study was applied to the Coimbra I Viaduct, situated in the city of Coimbra, in the state of Minas Gerais, Brazil, at km 640 of BR 120. This viaduct was designed with cast-in-situ reinforced concrete, featuring a deck supported on two girders. It comprises four lines of columns and a direct support line on the foundation blocks. This structure was previously studied and modeled by Borges et al. [31] with the aid of a point cloud generated with a DKI Matrice 300 RTK drone. There was a lack of information in some of the areas surveyed, especially at the ends of the viaduct. Thus, attempts were made to improve the outline of the structure by meshing the point cloud using interpolation. However, Revit presented some input problems. As a result, filters were applied in CloudCompare v2.13 alpha, a free, open-source program specializing in point cloud processing, which removed some of the disturbances on the bridge deck caused by vehicles passing by at the time of the survey. The modeling process for the viaduct began by delimiting the region of interest, and the point cloud underwent cleaning using Autodesk ReCap Pro 2023 (Fig. 2). Autodesk Revit 2023 was used to model the viaduct's structural elements. The final model is depicted in Fig. 3(a), with an overlay of the point cloud shown in Fig. 3(b) to facilitate an approximate evaluation of the model against the existing structure.

For implementing Mixed Reality (MR), the GAMMA AR software was selected for its prominent features, including Simultaneous Localization and Mapping (SLAM) technology, compatibility with iPhones or smartphones, and lower cost compared to alternatives, as indicated in studies by Vilela [32]. GAMMA AR operates with a BIM Collaboration Format (BCF) extension for recording notes, audio, and photos. The software maintains a website where collected information is registered and stored in a database, organized by record dates, 3D model elements, and the nature of the information (messages, audio, and photos). It is noteworthy that while GAMMA AR was chosen for its specific features, alternative software capable of exporting IFC files for BIM modeling and importing IFC and BCF for MR could be considered.

Utilizing the Revit software framework, a BIM model incorporating

Table 1
Comparative summary table of the studies analyzed.

Ref.	Approach	Devices used	Inspection	Purpose	Results and observations	Challenges
[24]	MR and VR prototypes	Tablet	On-site	Digital support for on-site bridge inspectors using BIM data	Emphasis on BIM data integration, online collaboration, and efficient damage visualization	Lack of BIM data for existing bridges, user interface design, and adoption of norms for public tender
[25]	Mixed Reality (MR)-based Digital Twin Model (DTM)	Microsoft HoloLens 2	In the office	Enhancing visualization of semantic information within a Bridge Maintenance System (BMS)	The goal is to improve the interaction between engineers and the maintenance database	Potential enhancements in visualizing and integrating maintenance data
[13]	BIM-based MR Application and “HoloBridge” Framework	Microsoft HoloLens	Remotely from office	Develop a BIM-based mixed reality (MR) application to enhance and facilitate the process of bridge inspection and maintenance works remotely from office	Real-time monitoring, updating, and informed decision-making about inspection and maintenance progress. Damage mapping algorithm for assessing progression	Workflow complexities during BIM modeling and application development
[27]	Holographic Inspection Method	Microsoft HoloLens 2 and Tublebot2	Inspection results on-site	Real-time interaction with the damage detection process, providing quantitative damage information	Accurate estimation of spalling damage extent with less than 10 % error. Enhanced precision, real-time analysis, and immersive data visualization	Limitations in field of view and gesture input system for smart glasses
[30]	Human-Machine Collaborative Inspection (HMCI)	Microsoft HoloLens 2, robotic data collection platform	Real-time inspection on-site	Collaboration through MR and robotic data collection platforms for efficient visual inspections	Efficient collaboration among inspectors through MR and robotic data collection. Enhanced precision, real-time analysis, and immersive data visualization	Complex workflow involving data collection, transmission, and integration with MR
[26]	Immersive Virtual Reality (IVR) framework	IVR prototype	Remote inspections	Enhancing user experience (UX) during remote infrastructure inspections	Effective identification of damage during remote bridge inspections. Acceptable usability	Device compatibility and potential issues related to remote data visualization

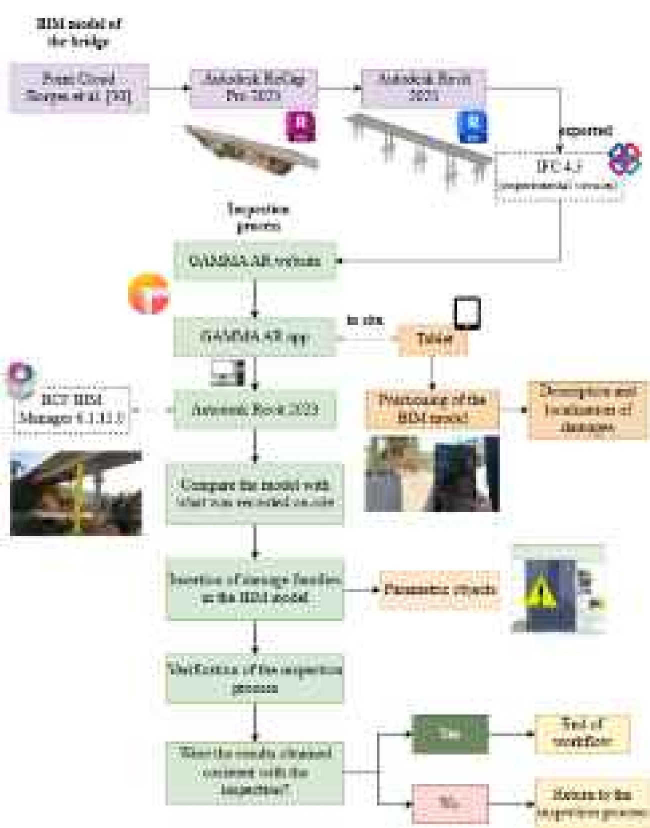

Fig. 1. Flowchart of the proposed methodology.

essential geometric and non-geometric bridge information was developed. Subsequently, the model was exported to an exchangeable 3D format, specifically IFC (experimental version 4.3.1.0, in Revit), for import into the GAMMA AR website (version 3.1.1). This approach facilitated access to the project in the library by inspectors through the GAMMA AR app on a smartphone or tablet. A tablet enables shared

Fig. 2. Point cloud filtered and delimited in ReCap [31].

Fig. 3. (a) proposed bridge model; (b) overlay of the model with the point cloud [31].

experiences, fostering collaboration among multiple users [33,34].

The combined use of MR with the actual bridge model during the on-site inspection assists the inspector in identifying and reporting damage to the structure and possible discrepancies with the BIM model. Consequently, the collected information is documented by the site inspector through the application and made accessible on the GAMMA AR website. In this investigation, the inspection data in BCF format (version 3.0) was downloaded and imported into the BCF Manager. Subsequently, leveraging the integration with Revit through the BCF BIM Manager 6.1.11.0 plugin from BCF Collab, comparisons were made between the reported information in situ and the BIM model, allowing for necessary modifications. A detailed explanation is provided in

Chapter 4.3.

3.2. Creation of families of damage

Parametric objects were generated to characterize and identify damage, along with their corresponding geometric parameters and locations on bridge elements. Within Revit, these are recognized as parametric families, serving to represent pathological manifestations identified during the inspection. Based on insights from prior research by Martins et al. [35], a list of the most common and impactful damages in reinforced concrete bridges was compiled and parameterized (Table 2). To visualize these damages on the BIM model, a generic volumetric object (3D) was modeled, starting with a generic model face-based family template (Fig. 4). This template facilitates the localization, identification, and storage of pertinent information for each identified pathological manifestation within the model.

For precise characterization of each damage during the inspection, input parameters were defined to encompass crucial information within the family structure in Revit. Shared parameters were established to capture inspection and damage identification details (Fig. 5). This solution was adopted to streamline the process of inserting parameters into families, facilitating comprehensive documentation of inspection findings and damage specifics.

Shared parameters are configuration settings that can be utilized in multiple families or projects. It is important to note that information defined in one family or project using a shared parameter doesn't automatically carry over to another family or project utilizing the same shared parameter. While certain parameter categories may repeat for various damages, the values of all parameters can vary based on the specific damage. To capture inspection details, specific parameters were established, including the inspection date, the responsible inspector, and the type of inspection being conducted. Additionally, to effectively characterize damage, dimensional parameters (length, width, and depth) were defined, accounting for the unique configuration of each pathological manifestation. Fig. 6 provides an example of a parameterized family for the "Crack" damage type, highlighting the shared parameters created.

4. Case study

The subject of the case study is the Coimbra I Viaduct, constructed in 1985. This viaduct features reinforced concrete beams and is cast in place, spanning a length of 100 m with four spans, as illustrated in Fig. 7. This viaduct is part of the Brazilian *SGO* (*Sistema de Gerenciamento de Obras de Arte Especiais*), developed by *DNIT* (*Departamento Nacional de Infraestrutura de Transportes*). Fig. 8 presents the workflow of the proposed methodology applied in the Coimbra I Viaduct.

4.1. BIM model tracking and positioning (1st inspection)

Initially, the BIM model of the viaduct was exported from Revit using the experimental version of IFC 4.3.1.0 and then imported into the GAMMA AR website. The IFC file export and import process in the AR software depends on an internet connection and takes place quickly. Once the IFC file has been imported into GAMMA AR, an internet connection is no longer necessary to access it. Upon launching the GAMMA AR app in the field, the bridge model was loaded and prepared for positioning.

Table 2
Recurrent damage in reinforced concrete bridges.

Damage	Unit
Efflorescence	m^2
Crack	m
Concrete spalling	m^2
Water leakage	m^2
Damp patches	m^2
Concrete delamination	m^2
Honeycomb	m^2
Uncoated reinforcement	m^2

The positioning process of the BIM model in the GAMMA AR software involves several steps to ensure the correct overlap between the virtual model and the actual environment. First, it is necessary to select the project in the application, followed by choosing the specific floor or level of the structural model (such as the foundation or pillar level). In this case study, the pillar level was selected, with Pillar P8 (Fig. 7) chosen as the reference element for alignment.

For model alignment, a markerless alignment method was used, which relies on the natural visual features of the bridge to facilitate location. During the research, the only option available in the software was two-point alignment, but in version 6.0.8, updated on August 12, 2024, GAMMA AR also offers QR code positioning.

Choosing the two-point alignment method, as used in the case study, involved the following steps:

1. **Selecting the Reference Element:** A structural element is chosen to serve as a reference for positioning. In this study, the app was configured to select pillars, and Pillar P8 was chosen as the reference point.
2. **Defining a Corner and Direction:** After selecting Pillar P8, one of its corners and a specific direction were chosen to draw a reference vector.
3. **Creating a Plane and Vector:** The final step involves making a plane by moving the mobile device (tablet). The tablet sensors capture the position and orientation in space, allowing a reference vector to be drawn from the initial point (selected corner). This vector helps insert the virtual model of the structure into the actual environment in an aligned manner.

After the initial positioning of the virtual model, meticulous adjustments are made to improve the overlap between the virtual model and the actual environment. These adjustments allow changes to the x, y, and z coordinates as needed (Fig. 9), ensuring the precision of the alignment and the correct visualization of the BIM model integrated into the physical environment.

During this process, continuous analysis is carried out to ensure the accuracy of the positioning. Additional challenges are faced in open environments, where factors such as sunlight can interfere with positioning accuracy. This methodology, although complex, provides a solid basis for the effective integration of virtual models into real environments, promoting significant advances in the application of Augmented Reality in various areas of interest.

4.2. Damage observation and description (1st inspection)

The field inspectors observed and recognized the damage during their on-site assessment, aided by a Samsung Tablet S7 with an MR technology system that helped in documenting and detailing these observations by overlaying the virtual model of the bridge over the physical structure in the field. Other MR devices could be employed to apply the methodology developed in this study, such as smart glasses like the Apple Vision Pro, Hololens, Quest 3, and Quest Pro. The choice of tablet was motivated mainly by the economic issue and practicality in the field with interaction between different inspectors.

In the GAMMA AR app, inspectors can document the damage comprehensively, including additional details such as photographs, text descriptions, and status updates. The description section allows to provide specific information about the damage, including the precise location of the bridge's structural components. This collaborative approach, which combines real-world inspection with digital tools, increases the accuracy and efficiency of damage documentation and analysis.

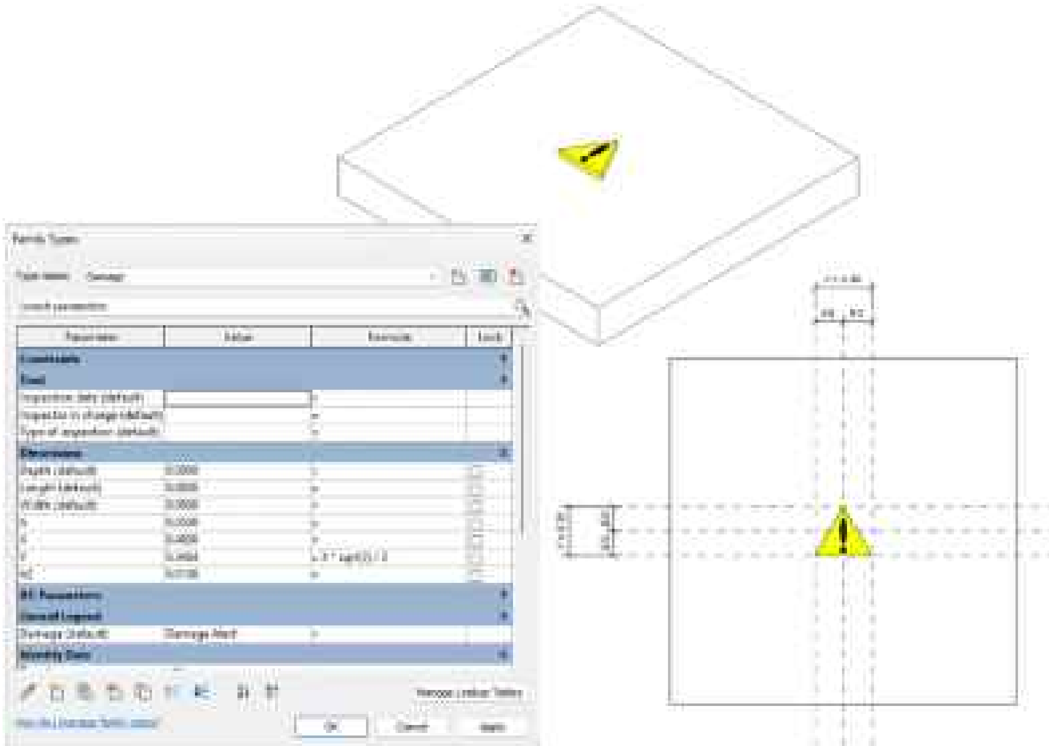

Fig. 4. Generic representation for damage with associated parameters.

The inspection data is automatically transmitted from the GAMMA AR app to the company portal, necessitating internet connectivity on the tablet. Users can access the inspection data and export the file in BCF format within the GAMMA AR website. BCF notes within the file can be interpreted by BIM software. To enable Revit to read the BCF file, the inclusion of the BCF Managers plugin (version 6.2.19.0) from the BIM Collab company was essential. This is crucial because REVIT is software in its native format that does not inherently interpret BCF files.

It is important to emphasize that this first inspection could be carried out automatically with the help of new technologies, such as Unmanned Aerial Vehicles (UAVs) and Terrestrial Laser Scanner (TLS) with AI processing capabilities. A literature review developed and recently published by the authors Martins et al. [6] addresses the use of these technologies in the inspection and damage detection process. In this way, the inspector would be essential to process the BIM model with the damage detected in the field in an automated way.

4.3. Comparison of the BIM model with BCF notes

The Revit and the BIM Collab BCF Managers facilitated a thorough comparison of images and notes generated during the inspection in situ with the BIM model (Fig. 10). The plugin provides functions that significantly streamline this process. Among these tools is “Camera positioning,” which precisely places viewpoints on the model corresponding to the reported damages. It automatically adjusts for discrepancies in coordinate systems, such as topographic survey points in Revit. Furthermore, the plugin allows zooming in on the reported images, enhancing the analysis and evaluation of the damages.

Damage was reported and localized using photos and descriptive texts during the first inspection in situ, with the help of the GAMMA AR App. In the office, the manager imports the file generated in the field into Revit and works with the BIM Collab BCF Manager tool to help insert the parametric families corresponding to each specific damage. This is done by importing the damage families created, with the shared parameters, into the BIM model. With each damaged photo taken, it is possible to use the “Camera positioning” tool to locate the same region in the BIM model, so the parametric families are inserted over the damage located in the element. The information on each damage that was filled in during the inspection in text format will help to fill in the parameters for each parametric damage family.

Once all the damage observed in the structure has been positioned, the Revit IFC file is exported and imported back into the GAMMA AR website for a follow-up inspection. This inspection involved verifying the placement of the damages, and precise measurements were taken to accurately assess the extent of the damages.

4.4. Position analysis and damage measurement (2nd inspection)

A second bridge inspection was undertaken to evaluate the damage placement and to test the application’s measurement tool. Initially, the virtual model must be aligned with the physical structure, repeating the tracking and alignment processes carried out during the first inspection. Fig. 11 illustrates the outcome of this procedure. At this stage, the virtual model that is overlaid on the physical model shows the parametric damage families positioned according to what was reported in the first inspection.

Data on the identified damages were collected using the GAMMA AR App “measure” tool, capturing their width and length. This tool in the AR application allows users to measure the BIM model overlaid on the physical structure, which enables inspectors to measure the actual damage to the bridge using the BIM model with the damage families inserted as a reference.

Damage measurements in the field are an essential part of the inspection process since these damage measurements will guide the decision-making process for the maintenance, repair, or reinforcement of a structure, significantly impacting the budget. As the damage families have specific geometry parameters, it is possible to input these measured values for each damage into the BIM model.

Some examples of damage measurement using the GAMMA AR App tool are shown in Fig. 12 and Fig. 13. Fig. 12 depicts the results of

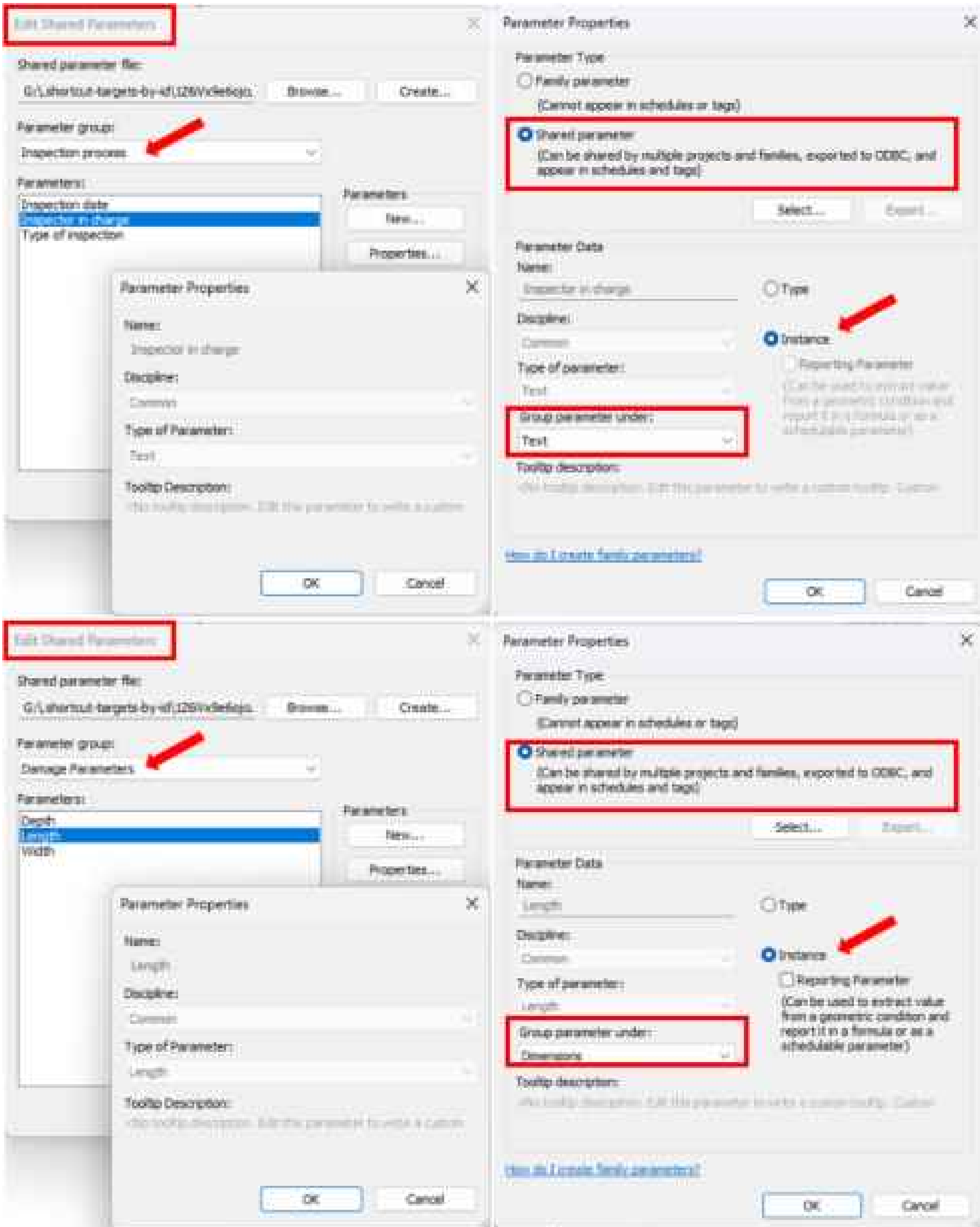

Fig. 5. Creation of shared parameters to the inspection process and damage on Revit.

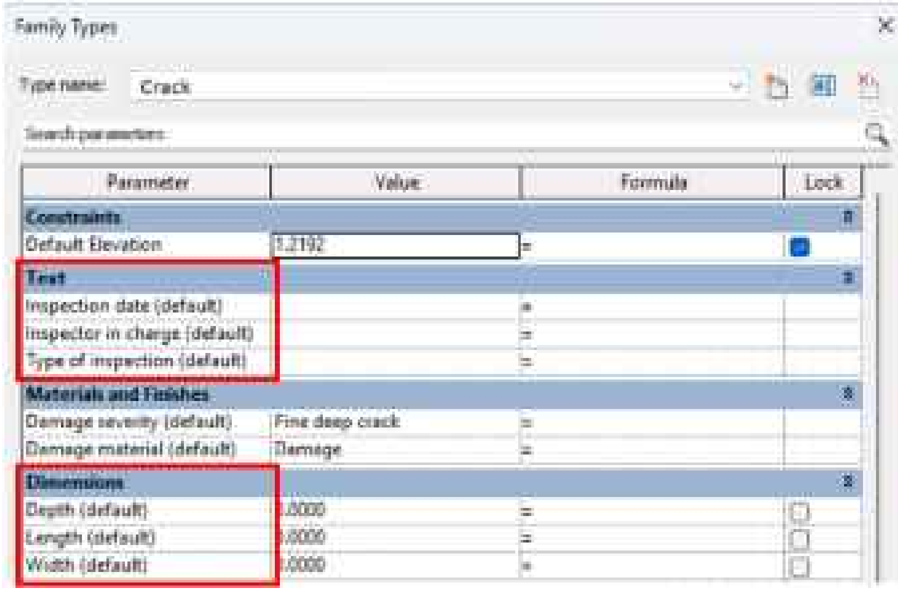

Fig. 6. Shared parameters inserted on family type "Crack".

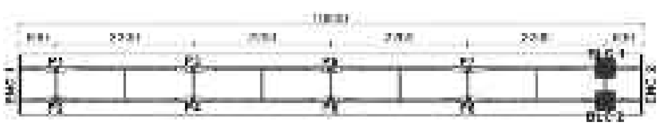

Fig. 7. Longitudinal layout of the viaduct.

measuring the " Concrete spalling " damage at P8. Other damages, such as "efflorescence" and "crack," were also measured (Fig. 13). Furthermore, the positioning of the damages inserted on-site was verified during this assessment. This "measure" tool proved to be practical and very useful for measuring damage in hard-to-reach places, as in the case of the crack on the underside of the slab (Fig. 13).

5. Discussion and considerations

5.1. Considerations on viability

Bridge as-built modeling from the point cloud in a BIM interface: Building the 3D bridge model using the proposed method involves specific UAVs with 3D scanners and BIM modeling software. This stage

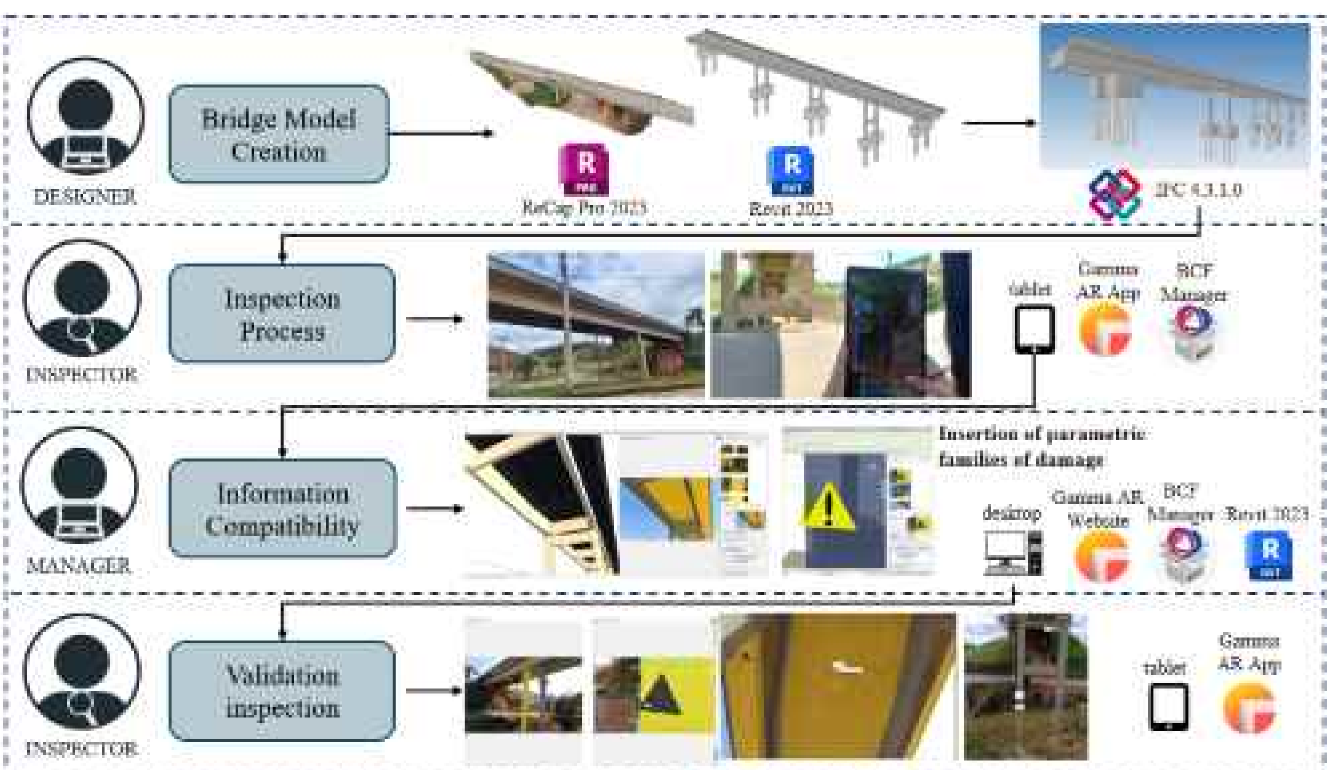

Fig. 8. Workflow of the methodology applied in the case study.

Fig. 9. Positioning the BIM model on the physical structure.

demands expensive equipment and specialized knowledge and is time-consuming due to the detailed processes required for data collection, model creation, and refinement. In contrast, traditional methods use manual measurements, photographs, and 2D drawings. These methods are less expensive and moderately time-consuming but lack the precision and detail of 3D models. It is important to note that accurate BIM models cannot be considered optional in a BIM-based bridge management system. Additionally, the model itself is not part of the inspection method but serves as the documentation of the bridge, provided once and used throughout the bridge's lifespan.

Virtual and Physical Model Alignment: The proposed methodology uses advanced 3D modeling software and tablets to align the virtual model with the physical structure on-site. This stage requires proficiency with the technology and a moderate amount of time due to the initial setup, calibration, and necessary adjustments. In contrast, the traditional method relies on manual measurements and written reports, so this stage is not applicable. However, it is important to consider that the traditional method is less accurate and comprehensive. Additionally, this stage ensures the accuracy and time savings of the following stages.

Inspection: Inspectors using the proposed methodology utilize tablets with specialized augmented reality software to navigate the BIM model, document findings, and verify data in real-time. This approach involves a moderate investment in equipment, software, and proficiency with the technology. Traditional methods can involve smartphones, cameras, 2D drawings, clipboards with paper and pen, and measurement tools. These low-cost methods require a significant amount of time, making the process less standardized and efficient, labor-intensive, and unsafe.

Check and report: The proposed methodology uses AR software and a tablet to check and report the damage in situ and BIM software and a notebook to align and verify the damage, leading to moderate costs and low time commitment. This stage ensures that all identified damages are accurately documented and aligned within the model. The traditional method, which uses visual inspections, photographs, manual notes, and drawings, is low-cost but takes a long time and is more prone to errors and omissions.

Results verification: Results verification using the proposed methodology involves AR software, a BIM model, and a tablet, resulting in moderate costs and low time. This automated and precise process contrasts with the traditional method of manual report reviews, which, although low in cost, requires a significant amount of time and can be less reliable.

Cost-Benefit Analysis: While the proposed methodology involves moderate to high costs and time investments for certain stages, the enhanced accuracy and depth of the information obtained allow for more efficient resource management. This, in turn, enables better-informed decision-making and more effective interventions, resulting in medium-to-long-term cost savings and improved structural safety. Additionally, the traditional methodology lacks the utilization of the BIM model of the bridge as a centralized repository of information. Instead, information is scattered across different media, making it difficult to analyze the structure as a whole. It is also important to note that consistent and accurate information is crucial for implementing current and future data-based and AI-assisted technologies in managing infrastructure assets. Table 3 summarizes the qualitative comparative analysis between the proposed and traditional methodologies.

5.2. Methodology strengths

This study demonstrates Mixed Reality (MR) technologies with Building Information Modeling (BIM) to enhance traditional bridge inspection techniques and improve information flow in Bridge Maintenance Management. The key strengths of this approach are:

- **Integration of damage data into BIM:** The methodology outlines a streamlined process for incorporating damage information directly into the post-inspection BIM model. This ensures that structural data is accurately represented within the digital model, aiding professionals in efficient data management.
- **Localization of damage**: A standout feature is the ability to accurately input the geometric parameters of damage into the BIM model. Using the GAMMA AR application, damage identified in the field is precisely recorded and integrated into Revit models, ensuring alignment with the inspection data and improving the reliability of the digital representation.
- **Enhanced lifecycle documentation**: The methodology strengthens bridge maintenance by documenting damage throughout the bridge's lifecycle within the Industry Foundation Classes (IFC) framework. This consolidated approach improves data storage, accessibility, and the planning of maintenance activities.
- **Improved assessment of hard-to-reach damages**: The methodology also addresses the challenge of inspecting difficult-to-access areas by providing effective tools for damage measurement, thereby increasing the accuracy and thoroughness of bridge inspections.

5.3. Research challenges and limitations

During the inspections, several challenges and limitations were identified in the field:

Fig. 10. Reading of the BCF file in the BIM software.

Fig. 11. Final positioning of the AR and the real structure.

- **Model tracking and positioning:** One of the main challenges was accurately tracking and positioning the model, hindered by the lack of a depth sensor in the tablet used. Incorporating mixed reality glasses could potentially resolve this issue by improving model placement precision.
- **Sunlight exposure**: Excessive sunlight made it difficult to view the tablet screen outdoors. Despite this, all structural damage was effectively reported, and the data was collected efficiently.
- **Uneven terrain**: The bridge's location on uneven terrain presented challenges in tracking a stable plane for model positioning. Addressing this issue may require implementing advanced tracking mechanisms or alternative positioning techniques to ensure accurate model alignment.
- **Technological limitations**: The technology employed for tracking and positioning, mainly through the camera on devices lacking a Time-of-Flight (ToF) sensor, faced considerable hindrances. Future advancements in sensor technology or the adoption of alternative tracking methods may be necessary to mitigate these limitations effectively.
- **Dependence on a single Case Study:** A limitation of this study is its reliance on a single case study, which constrains the generalization of the results. The findings should be considered preliminary, with

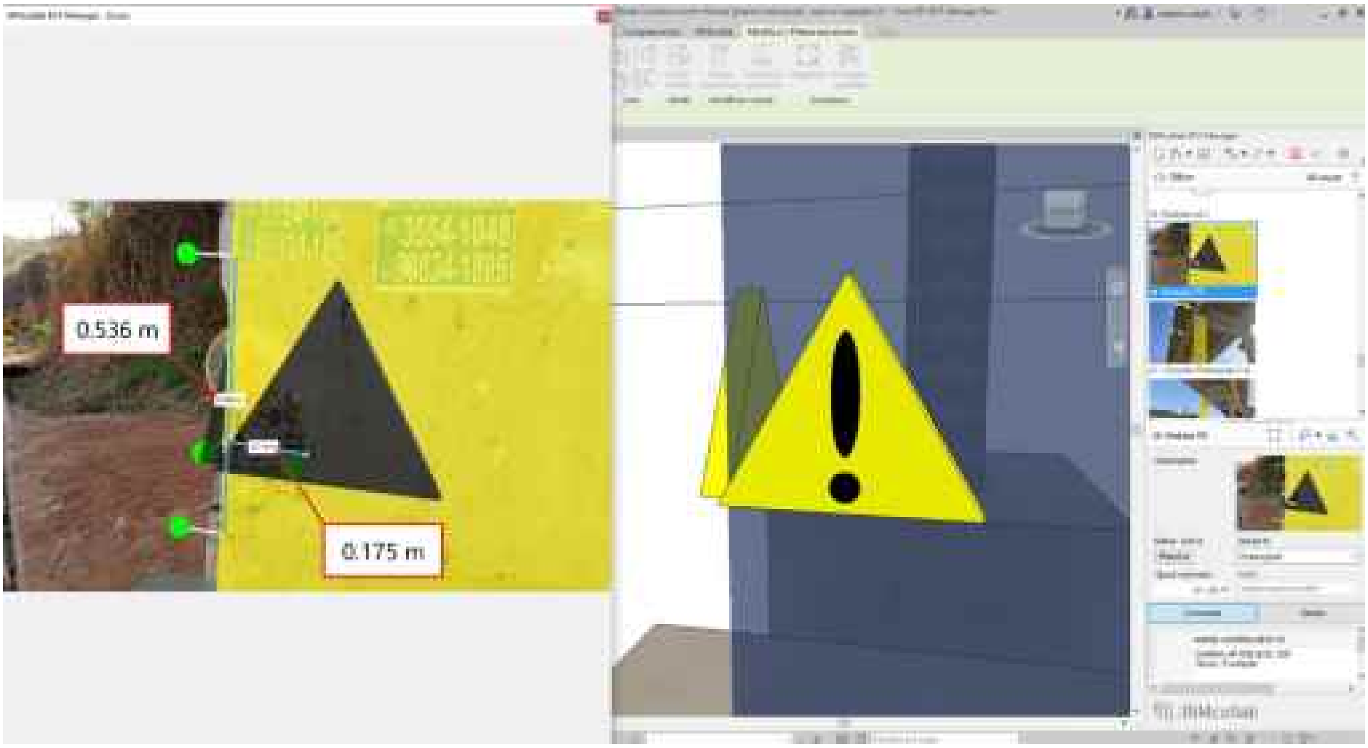

Fig. 12. Concrete spalling measurements at P8.

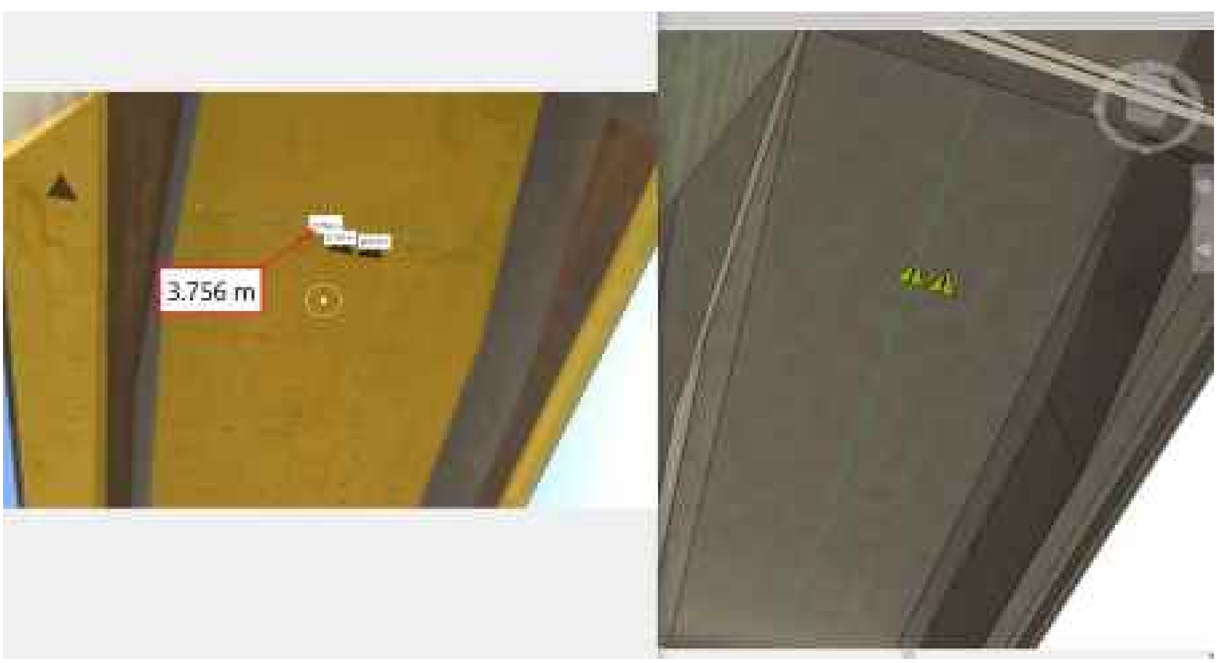

Fig. 13. Efflorescence and crack measurements at the bridge slab.

the understanding that future studies involving a set of bridges are planned to validate the methodology more broadly.

- **Early Stage of BIM with BMS:** It is important to note that the integration of BIM with Bridge Management Systems (BMS) is still in its early developmental stages. Continuous technological advancements and research are needed before these integrated practices become standard in daily operations, highlighting the need for ongoing innovation in bridge maintenance management.

Addressing these challenges and limitations, it is intended to provide insights into areas for improvement and future research directions in the integration of MR technologies and BIM methodology for enhanced bridge maintenance management.

5.4. Improvements

To augment the inspection's precision, strategies should be formulated to refine the positioning of the BIM model. Inaccuracies in

Table 3
Qualitative comparative analysis between the proposed and traditional methodologies.

Item	Proposed	Traditional	Comments
Investment in equipment and software	High	Low	- The proposed methodology involves high initial investment but offers financial returns over the medium to long term from savings generated. - Traditional methodology requires lower initial investment but may incur higher ongoing operational costs.
Training and expertise required	Moderate	High	- Inspectors in traditional methods currently hold significant responsibility and exercise high-level decision-making on-site. - Requires professional expertise and higher education. - Assisted technologies in the proposed methodology require proficiency but entail less on-site decision-making.
As-built model cost	Moderate-to-High	Low	- The proposed methodology requires UAVs, 3D scanners, and BIM modeling software. - Traditional methodology uses manual measurement and 2D models.
Time required in as-built model	Moderate-to-High	Moderate	- The proposed methodology requires time to obtain the BIM model using the point cloud and modeling software. - Traditional methodology involves structuring 2D drawings based on field measurements.
Time required in routine inspection	Moderate-to-low	High	- Reduced need for field professionals to move and access various parts of the structure using tablets and AR software. - Uses parametric models for damage assessment and standardized forms for data collection. - All tools consolidated into a single device in the proposed methodology. - Traditional methods involve smartphones, cameras, 2D drawings, written reports, and various tools to measure and access the bridge elements.
Time required in reporting and documentation	Low	Moderate-to-high	- Data is automatically stored in the model. - Uses parametric models for damage and repair. - Standardized forms streamline the process. - Traditional methods require manual data entry and compilation.
Time required for review and validation	Moderate	Moderate	- Inspection data verification and parametric family insertion directly into the BIM model. - Data is centralized, enabling documentation throughout the structure's lifecycle. - Traditional methods involve manual verification and decentralized data storage.

positioning can result in inconsistencies and uncertainties regarding families of damage. Some improvements could be implemented for greater accuracy in the MR inspection method:

- Development of the GAMMA AR "Description" Tab: Further development of the "Description" tab within the GAMMA AR application could be beneficial. This enhancement would allow for the inclusion of additional information required for the family of damage parameters and the inspection procedure. By expanding the capabilities of this tab, inspectors can provide more comprehensive data related to identified damages, facilitating a more detailed analysis and assessment.
- Increased Level of Detail (LoD) in the BIM Model: Enhancing the level of detail (LoD) in the BIM model would significantly improve the inspection process. While reinforcements were not modeled in the current project, their inclusion would enable inspectors to analyze their condition and identify any associated damages accurately. By incorporating reinforcements into the BIM model, inspectors gain access to crucial information for assessing structural integrity and identifying potential issues, thereby enhancing the overall accuracy of inspections.

By implementing these improvements, the MR inspection method can be enhanced to achieve greater accuracy and reliability. These enhancements would not only address current limitations but also pave the way for more comprehensive and effective bridge maintenance management strategies in the future.

Including concrete reinforcement data in the model could be a possibility to improve the analysis of the risks that the structure is facing and determine the necessary measures for structural reinforcement. This inclusion would provide insights into the size and significance of the reinforcement. Chi et al. [42] propose the creation of a method that uses laser scanning associated with augmented reality to check the execution of rebars. In this study, the positions and shapes of the reinforcement are analyzed to detect incompatibilities concerning the structural design. The results obtained confirmed that the method was effective in detecting and correcting non-conformities in the positions of steel bars, regardless of their type, shape, or complexity. In addition, it promotes accurate inspection of steel bar dimensions and intuitive visualization, contributing to effective quality control of steel bars.

Mixed Reality (MR) enables inspectors to overlay the BIM model with real images of the concrete structure, providing additional information such as dimensions, coverings, reinforcement shapes, spacing, and possible discrepancies with the structural design. Furthermore, this technology allows the responsible engineer to make real-time annotations, which can be shared with project stakeholders afterward.

6. Conclusions

This paper explored the integration of MR technologies and BIM with inspection techniques to enhance bridge maintenance management. The methodology involved utilizing MR for real-time inspection alongside BIM parametric damage models, enabling the classification, localization, and sharing of information on pathological manifestations in the structure. The approach was tested on-site at the existing viaduct

Coimbra I in MG, Brazil. The key conclusions are as follows:

- Mixed reality (MR) inspection represents a significant evolution over conventional visual inspection to assess the condition of bridges. While the conventional approach is manual, subjective, and has limitations when it comes to documenting and sharing information with the structure's database, MR inspection uses advanced technologies such as (BIM) and technological devices to streamline the process and improve accuracy and data documentation. This transition to digital methods offers operational efficiency and significant improvements in the bridge's safety, reliability, and maintenance management.
- MR-aided inspection is feasible with current technology, employing well-established and available computational and interface tools. This facilitates information exchange with a small investment in development, training, and acquisitions.
- The case study successfully demonstrated the feasibility of integrating MR inspection with a BIM model using proposed parametric damage families. It proved to be precise and effective in exchanging information, paving the way for integration with a BIM-based BMS. Tablets, with their practicality, cost-effectiveness, and accessibility, provide a more intuitive and collaborative tool for field inspections.
- This methodology offers several strengths, including the insertion of damage information into the BIM model, the precise localization and integration of damage data, the improved documentation of damage tracking throughout the bridge's life cycle, and the facilitation of damage measurement in hard-to-reach areas. These strengths contribute to more comprehensive and accurate bridge inspections, empowering professionals with efficient tools for planning and executing maintenance while ensuring the overall integrity of the inspection process.
- Similar to other techniques involving BIM models, modeling existing bridges is a resource-intensive task, both in terms of time and cost. Nevertheless, it is a necessary step for implementing a full BIM-based BMS that supports MR-aided inspection methods.
- Limitations related to internet signal availability and the need for adaptations of current tools and technologies for on-site inspection were observed. Addressing these issues is essential for broader and more precise applications. Additionally, typical challenges of conventional visual inspection, such as access to hard-to-reach sites, remain relevant.

The demonstrated approach highlights the potential for implementing a streamlined and cost-effective MR-based inspection routine. However, its effectiveness depends on ongoing advancements in establishing a BIM-based BMS, especially in creating models for existing bridges. This proves challenging for agencies with limited budgets and extensive infrastructure networks. Nevertheless, the method can serve as a supplementary and supportable approach within a versatile BMS capable of integrating diverse input methods into universal and integrated databases.

It is worth acknowledging that this study is based on a single case involving the Coimbra I viaduct. While the results are promising and illustrate the potential of integrating MR with BIM for bridge inspection, they are specific to this context and may not be directly generalizable to all structures or environments. Future research should aim to apply this methodology to a range of case studies, encompassing different bridge types and varied environmental conditions, to validate the findings and assess the scalability and adaptability of the approach. Expanding the scope would help further confirm the benefits and address the limitations identified in this initial study.

CRediT authorship contribution statement

Ana Carolina Pereira Martins: Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Isabele Rocha Castellano:** Writing – original draft, Methodology, Investigation, Conceptualization. **Kléos Magalhães Lenz César Júnior:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization. **José Maria Franco de Carvalho:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization. **Fernando Gussão Bellon:** Writing – review & editing, Formal analysis. **Diôgo Silva de Oliveira:** Writing – review & editing, Validation, Supervision, Resources. **José Carlos Lopes Ribeiro:** Writing – review & editing, Validation, Supervision, Resources, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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