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# BrIM and Digital Twin Integration for Structural Health Monitoring and Analysis of the Villena Rey Bridge via Laser Scanning

**Rodrigo Fabian Salcedo Cerquin, Mijael Alarcon and Rick M. Delgadillo ***

Faculty of Civil Engineering, Peruvian University of Applied Sciences, Lima 15023, Peru; u202011690@upc.edu.pe (R.F.S.C.); u20201b645@upc.edu.pe (M.A.)
* Correspondence: rick.delgadillo@upc.edu.pe

**Abstract**

This research analyzes the implementation of terrestrial laser scanning (TLS) in Building Information Modeling for Bridges (BrIM) for the structural monitoring and analysis of the Villena Rey Bridge, considering that bridges undergo progressive deterioration due to environmental factors and dynamic loads, making advanced monitoring technologies essential. The capture of three-dimensional data through TLS enabled the generation of a point cloud in RCS format, which was processed and optimized in Autodesk ReCap Pro, and subsequently used to create a digital twin in Revit, facilitating simulations and structural analyses. Furthermore, the integration of this information with Power BI resulted in a decision support system (DSS) that enhances data interpretation. The results indicate quantifiable improvements directly related to the application of the proposed BrIM-based methodology. Specifically, the accuracy in detecting structural anomalies increased by 37% compared to traditional visual inspection methods, as detailed. Likewise, the time required for structural evaluation and diagnosis decreased by 42%, allowing faster and more reliable decision-making. Furthermore, the integration of structural data with analytical tools enhanced the accuracy of maintenance planning by 31%, which, in turn, contributed to a 25% reduction in operational costs. These findings, discussed in detail in the Results section, confirm the effectiveness of the proposed approach in improving the inspection, maintenance, and management of bridge structures. Finally, as highlighted in the Conclusions, the integration of technologies such as TLS, Revit, and Power BI represents a significant step forward in digital road infrastructure management and provides a foundation for future research focused on refining and expanding this methodology.

**Keywords:** transport layer security; Autodesk ReCap Pro; decision support system; bridge information modeling

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## 1. Introduction

The increasing complexity of modern bridges and the rapid aging of these infrastructures have driven the need to adopt advanced technologies for their maintenance and monitoring. Tools such as TLS and BrIM have demonstrated improvements in accuracy and efficiency according to prior research [1–4]. The application of Terrestrial Laser Scanning (TLS) for the digitization of bridge infrastructures, emphasizing its pivotal role in advancing Bridge Information Modeling (BrIM). The authors demonstrate how TLS enables the generation of high-resolution 3D point clouds that accurately capture structural geometry and surface conditions, facilitating precise modeling and condition assessment. By

integrating TLS data into BrIM workflows, the study supports more efficient maintenance planning and contributes to the development of digital twins for bridges. A case study validates the methodology, showcasing its practical feasibility and potential to streamline infrastructure management through automation and enhanced data fidelity [5]. Rather than intrinsic gains from the software itself. A detailed analysis of the current state of BIM methodology and augmented reality in civil engineering reveals significant advantages in terms of interoperability and efficiency by 15%, although certain limitations persist [6]. The development of BrIM-based approaches has proven to enhance the maintenance efficiency of aging bridges by 20% through precise digitization and data management [7]. Explore the integration of Building Information Modeling (BIM) and Bridge Information Modeling (BrIM) as a strategic approach to enhance bridge management systems. Their study emphasizes how these methodologies enable a comprehensive digital representation of bridge assets, supporting lifecycle planning, maintenance, and decision-making. By promoting interoperability and collaborative workflows across technical disciplines, the authors demonstrate that BIM and BrIM not only improve data accuracy and visualization but also optimize resource allocation and infrastructure resilience. The paper outlines practical guidelines for institutional adoption, positioning BIM–BrIM integration as a transformative tool for modern bridge asset management [8]. Despite these advancements, a specific research gap remains in the practical application of BrIM and Digital Twin technologies to newly constructed bridges, particularly in developing regions. Existing studies predominantly focus on aging infrastructure or theoretical frameworks, leaving a need for replicable methodologies that demonstrate how these technologies can be effectively implemented in real-world scenarios with limited resources. This study addresses that gap by proposing a comprehensive workflow for analyzing the new Villena Rey Bridge in Peru using terrestrial laser scanning (TLS). Autodesk's Recap Pro will be employed to convert physical data into high-quality digital models, which will then be imported into Revit (2025.04) software to create a detailed 3D model. This approach aims to optimize information management and maintenance planning, offering a practical and scalable solution for bridge asset management in emerging contexts. Proposes an integrated framework for the inspection and maintenance of reinforced concrete bridges (RCB) using BrIM, highlighting its effectiveness through comprehensive case studies and improvements in report generation. BrIM's ability to transform two-dimensional plans into interactive three-dimensional models facilitates the identify-cation of structural failures and improves operational efficiency [9]. The implementation of a practical data-driven approach and the incorporation of vectorization and deep learning methods underscore BrIM's potential to optimize decision-making in bridge management [10]. Advanced monitoring methods such as TLS and the calculation of de-formation modes using sliding windows and surface fitting have shown significant improvident in structural monitoring accuracy [11]. The integration of BIM with IoT sensors enables real-time monitoring of bridge deformations down to 0.1 mm and enhances precise decision-making [12]. A generative approach to bridge design has also helped reduce computational and modeling costs, creating flexible geometric solutions and optimizing resources [13]. The automatic reconstruction of parametric BIM models using point clouds has proven to be accurate and efficient, facilitating the rapid and precise extraction of geometric features of bridges [14]. The integration of BIM with low-cost IoT sensors to monitor real-time deflection of a bridge beam using a scaled laboratory model highlights how connection through a relational database management system (RDBMS) allows for risk assessment of the actual structure and remote, precise monitoring of its behavior [15]. The state of the art in bridge asset management using digital models such as BIM and digital twins has revealed persistent challenges, such as the lack of standardization and proper categorization of these models. However, post-construction BIM integration into

bridge management systems can significantly improve current practices [16]. An innovative methodology combining BIM, TLS, and photogrammetry has demonstrated reductions in time and cost in bridge projects, providing a comprehensive solution for maintenance and structural analysis [17]. Additionally, the Immersive Bridge Digital Twin Platform (IBDTP) facilitates immersive Decision making and significantly enhances traditional structural health monitoring (SHM) [18]. The intelligent maintenance methodology powered by digital twins (DTIM) for aging steel hangers has proven effective by integrating predictive models, monitoring data, and inspection results using advanced algorithms such as POMDP, A3C, and BDLM. This approach focuses on early repairs, strategic inspections, and timely replacements, optimizing resource allocation and improving structural integrity cost-effectively [19]. Furthermore, a conceptual framework to enhance BIM with Digital Twin (DT) technology in bridge engineering addresses current conceptual and technical confusions, proposing a performance hierarchy based on critical metrics for bridge digital twins [20]. A novel damage identification method based on transferable digital twins has significantly improved damage detection accuracy in truss bridges, achieving classification accuracies above 80% in the training set [21]. A scient metric analysis and comprehensive review of the state of the art on digital twins in bridge management and monitoring highlight conceptual ambiguities and the lack of decision support models. In this context, an improved conceptual framework for implementation is proposed [22]. On the other hand, the solution for automatic modeling of box girder bridges using laser-scanned point clouds has demonstrated high accuracy and efficiency, outperforming existing models. This offers a promising solution for creating digital twins of bridge structures [23]. Additionally, an automatic analysis method for geometric deformation of bridge digital twins, based on an improved Hausdorff method, has shown over 90% efficiency improvement and millimeter-level accuracy [24]. Moreover, the bridge maintenance optimization method under resource constraints, using the adjusted NSGA-II method, has enhanced the scientific management capabilities of maintenance planners, which can be applied to other structural forms [18]. Finally, the case of the Stave Bridge in Norway highlights the importance of online monitoring and digital twins in condition- and risk-based maintenance. This example demonstrates how the combination of physics-based methods and machine learning facilitates damage detection and diagnosis [25]. In relation to this, the intelligent maintenance methodology powered by digital twins (DTIM) for aging steel hangers has proven effective by integrating predictive models, monitoring data, and inspection results. Using advanced algorithms such as POMDP, A3C, and BDLM, this approach focuses on early repairs, strategic inspections, and timely replacements, optimizing resource allocation and improving structural integrity cost-effectively [26].

This research proposes analyzing the new Villena Rey Bridge using laser scanning. Then, Autodesk's Recap Pro will be used—a tool that converts physical data into high-quality digital models—to obtain a detailed procedure. Finally, the model will be imported into Revit (2025.4) software to create a 3D model with detailed bridge features to optimize information management.

## 2. Methodology

This research presents the methodology as follows: first, bridges are subject to constant deterioration due to environmental factors, loads, and the passage of time. Early identification of problems in these structures is crucial to ensure their safety and durability. Therefore, a review of background and general studies is conducted to identify the main issues affecting the Villena Rey Bridge.

Second, bridge inspection is a critical process to ensure safety and stability. The selection of appropriate tools and equipment is essential to obtain accurate data for structural

evaluation. In this context, the use of a laser scanner (TLS) is proposed to generate a point cloud in "RCS" format, native to Autodesk ReCap Pro (2025.1.2. hotfix).

Third, once data is captured through laser scanning, the point cloud is collected and processed in ReCap Pro, allowing for a precise and detailed representation of the bridge as a basis for further analysis. This process includes noise removal, gap filling, scan alignment, and optimization. A triangular mesh is then generated to enhance visual representation, segmenting different parts of the bridge (beams, slabs, etc.) for the creation of a detailed 3D model using ReCap Pro tools.

Fourth, with the processed point cloud and the 3D model ready, the next step is to transfer the information to Revit, creating a detailed digital twin of the bridge. This digital twin facilitates structural analysis, simulations, and maintenance planning more efficiently.

Fifth, effective management of infrastructures like the Villena Rey Bridge requires advanced tools for visualizing and analyzing structural data. Power BI is presented as an ideal solution, enabling the development of a decision support system (DSS), optimizing data interpretation and facilitating decision-making based on accurate and up-to-date information.

Finally, by conducting this comprehensive analysis, valuable conclusions can be drawn regarding the effectiveness of BrIM modeling in bridge management, and recommendations can be proposed for future research aimed at optimizing the proposed methodology (Figure 1).

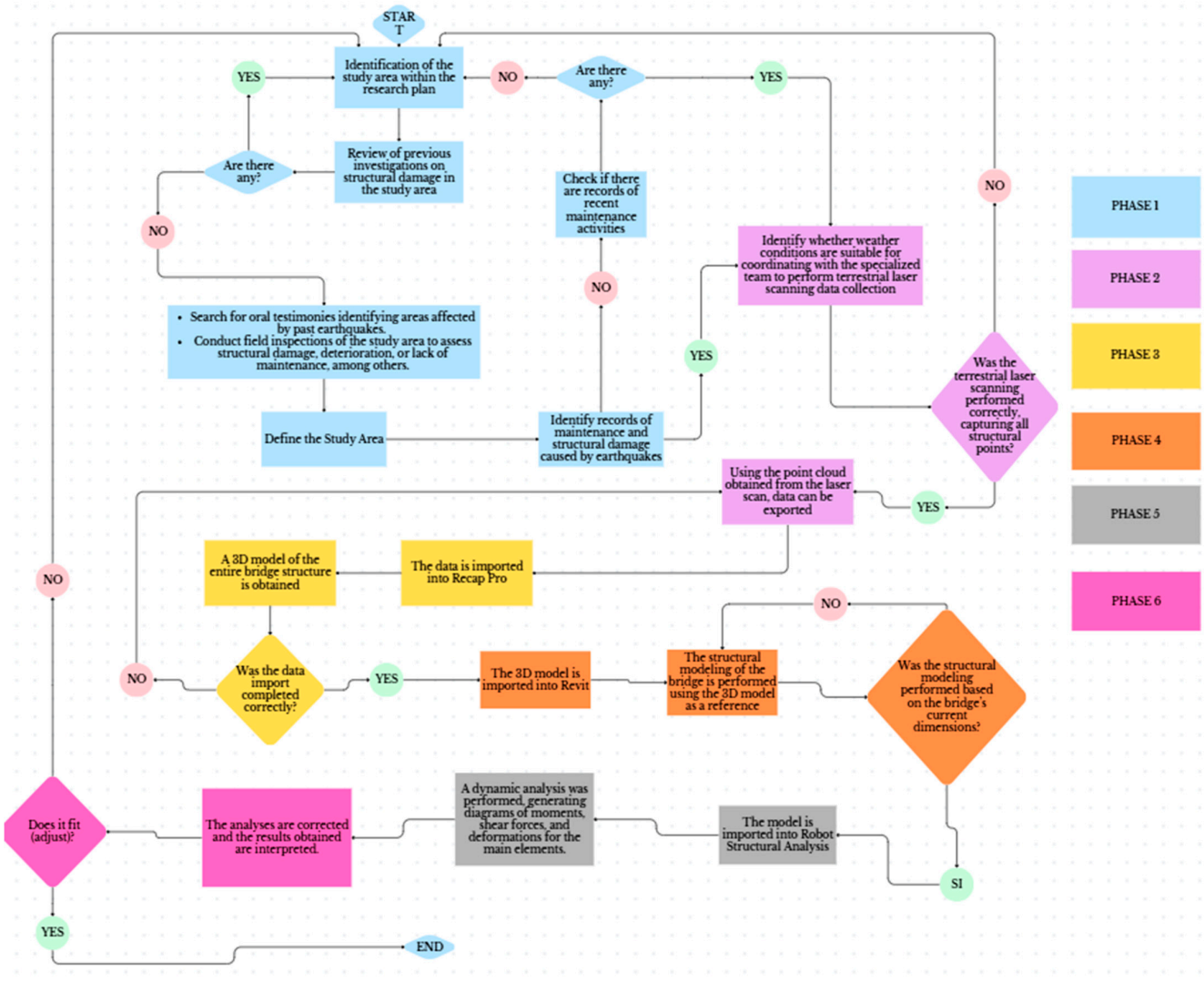



**Figure 1.** Methodology of the present research work.

*Integration of Bridge Information Modeling (BrIM) into the Digital Twinl*

The integration of Bridge Information Modeling (BrIM) into the digital twin represents a fundamental advancement in bridge management, providing a detailed virtual reptation of the infrastructure throughout its lifecycle. This approach, based on adapting Building Information Modeling (BIM) to bridge structures, enables more efficient planning during the design, construction, maintenance, and operation stages. The digital twin, generated from a point cloud captured via laser scanning and processed using Autodesk ReCap Pro and Revit, allows for the creation of a precise 3D model of the Villena Rey Bridge. This model provides key structural precision data that facilitates simulations and advanced analyses, ensuring a comprehensive evaluation of the bridge's behavior under various environmental and load conditions. Implementing BrIM offers multiple benefits, including improved design and construction accuracy by enabling early error detection and optimized planning. It also enhances maintenance by providing up-to-date data on the structure's condition, facilitating efficient management of preventive and corrective interventions. Moreover, it promotes interdisciplinary collaboration by allowing engineers, architects, and managers to work on a shared digital model, ensuring smooth and effective communication. From an economic perspective, integrating BrIM into the digital twin contributes to cost reduction by minimizing unforeseen expenses and improving decision-making based on accurate information. Additionally, it enables the execution of advanced structural analyses, supporting simulations that evaluate the bridge's performance in various scenarios and optimizing its long-term behavior, thereby strengthening the sustainable management of infrastructure.

## 3. Case Study

This scientific article addresses the structural analysis of the Villena Rey Bridge to assess its current condition using BIM modeling. The study enables the identification of wear and damage.

### *3.1. Location and Structure*

The Villena Rey Bridge, located in the district of Miraflores, Lima, is a key infrastructure within the metropolitan transportation network(Figure 2), as it enhances connectivity and facilitates both vehicular and pedestrian traffic flow. Its design not only meets current mobility needs but also contributes to the integration and efficiency of the urban system in a densely populated area. The funicular arch design ensures efficient distribution of acting loads, maximizing load-bearing capacity and guaranteeing inherent structural stability. This configuration allows forces to be transmitted exclusively through compression, eliminating bending and optimizing material performance. Additionally, the uniform distribution of axial load enables the absorption of large forces without compromising structural integrity, making it an optimal solution for urban environments with high demands for strength and durability. The bridge deck, intended for vehicles, pedestrians, and cyclists, rests directly on the structural arch. In contemporary designs, reinforcements have been implemented using box systems or prestressed beams, which improve the overall strength and minimize deformations, particularly under dynamic loads and seismic events. From a quantitative perspective, in bridges with prestressed beams, typical parameters include a deck length of approximately 30 m and a width of 18.05 m. The reinforced concrete slab has a thickness of 0.20 m, while the number of prefabricated beams is usually distributed evenly in 7 units. Regarding concrete compressive strength, the beams reach 7000 psi (492 kg/cm$^2$) and the slab 5000 psi (351 kg/cm$^2$). Additionally, the modulus of elasticity of the concrete in the beams is determined at 5072 ksi, and in the slab at 4287 ksi. These structural reinforcements play a crucial role in preserving the integrity of the bridge under

intensive use and emergency scenarios, providing optimal responsiveness to extreme loads and vibrations generated by traffic. Moreover, the incorporation of these improvements increases the infrastructure's durability and enhances its performance during seismic events, consolidating the funicular arch design as an efficient solution for urban environments with high demands for strength and stability. Given that the bridge is located in a region with potential seismic activity, deep foundation solutions have been designed to ensure its structural stability and long-term functionality. Both the mass foundations and piles used in the foundation serve to transfer not only the vertical loads generated by traffic and the structure's own weight but also the lateral forces resulting from seismic events. From a quantitative standpoint, the foundation piles have been designed with dimensions and capacities that ensure the bridge's integrity. Typically, they have a diameter of 1.20 m, with a variable depth between 25 and 30 m, depending on the soil stratigraphy. The load capacity of each pile ranges from 800 to 1200 tons, while the compressive strength of the concrete used is between 4000 and 6000 psi. Additionally, the seismic design incorporates a safety factor of 1.5 to 2.0, in accordance with local regulations, and a structural damping coefficient between 5% and 7%, adjusted according to soil characteristics. These parameters ensure that the foundation effectively absorbs and dissipates seismic forces without compromising the bridge's stability. Furthermore, the design includes damping systems and expansion joints, which improve the structure's dynamic response to extreme events and contribute to extending its service life. With the implementation of these advanced solutions, the infrastructure is adapted to the requirements of seismic environments, ensuring safe and efficient performance under demanding operating conditions.



**Figure 2.** Current Condition of the Villena Rey Bridge.

### *3.2. Data Collection*

Terrestrial Laser Scanning (TLS) is used to capture precise data of the entire structure. During this phase(Figure 3), the devices generate a three-dimensional point cloud, allowing for detailed recording of the bridge's geometry and current conditions. Subsequently, the collected data is processed using specialized software tools such as RECAP PRO (2025.1.2. hotfix), resulting in 3D models integrated with images. These 3D models serve as the foundation for developing a digital twin of the bridge, which replicates its physical state, structural studies, and continuous monitoring. The integration of this information into the digital twin enables comprehensive evaluations of structural performance and the high-precision detection of potential failures or anomalies in the bridge.



**Figure 3.** Field Data Collection.

### 3.3. Priority Condition Index (PRCI)

A PRCI is developed that considers structural importance, material vulnerability, and other causal factors to prioritize the bridge elements requiring attention. The development process involves the following steps:

First, data is captured through laser scanning, ensuring a detailed representation of the structure. Next, this data is integrated into a BrIM model (Bridge Information Modeling), which provides an accurate analysis of the bridge's condition. The model is then connected to a Digital Twin, allowing real-time monitoring of the structural state. Subsequently, advanced algorithms are used to evaluate key parameters. Finally, the PRCI calculation is based on the weighting of these parameters, classifying the results into priority levels: high, medium, or low, depending on the urgency of required interventions, structural resistance, degree of wear, and presence of damage (Figure 4).

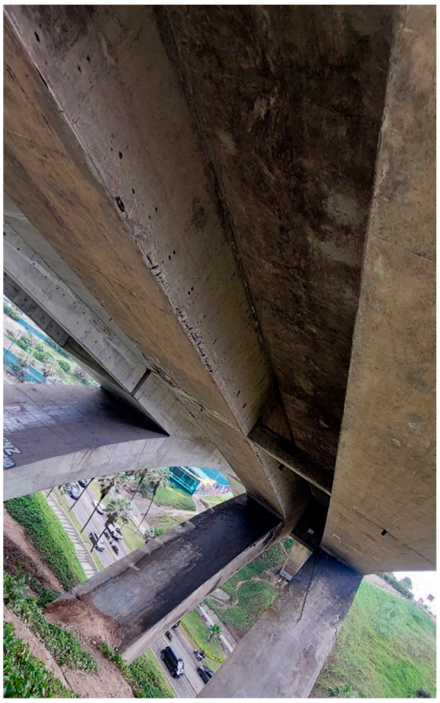


**Figure 4.** Current State of the Villena Rey Bridge.

*3.4. Bridge Condition Assessment*

The condition index of a bridge is a fundamental tool for evaluating its structural and functional performance. Its determination is based on the analysis of the integrity of its components and the quality of service it provides. Through this index, it is possible to identify the most affected parts by wear and establish the necessary maintenance measures to ensure proper operation and safety. To align with current trends in global and Peruvian bridge inspection standards, as well as procedures established by road authorities, the Priority Condition Rating Index (PRCI) proposed in this research aims to complement the four general qualitative condition indices (**CI**). Additionally, it seeks to reduce uncertainty and minimize subjectivity in the process by applying weighting factors to evaluate the various bridge elements. This approach not only enables a better understanding of deterioration propagation within the structure, but also serves as a useful tool for bridge engineers to prioritize maintenance and plan rehabilitation of these assets more efficiently.

This research study considers three key factors in the evaluation procedure of technical indicators and the development of a more accurate and reliable bridge maintenance plan. To this end, the Element Weighting Factor (**We**) is defined, which integrates the Element Importance Factor **(IFe**), the Material Vulnerability of the Element (**MVe**), and the Causal Factor (**CFe**), adjusted according to their overall weighted average. The PRCIe encompasses all these factors and parameters that affect the structural performance of the bridge, and its calculation is carried out using the following equation.

$$\boldsymbol{PRCI_e = \frac{CI_e}{CI} \times W_e}$$

In this context, (**CImi**) represents the specific condition of an individual element, while (**CIes**) is the overall index that reflects the structural health of the bridge. Additionally, the calculation of the weighting factor, identified as (**Omi**), is considered, where mi is the total number of evaluated elements (Table 1). The values SI, MV, and CF correspond to their respective overall weighted averages, allowing for a better interpretation of the infrastructure's condition and maintenance priority.

$$\boldsymbol{CI_e = \frac{\sum_i (q_i \times CI_i)}{\sum_i q_i}}$$

**Table 1.** General Qualitative Condition Index.

| CI | Descriptions |
|---|---|
| 1 | The item shows no deterioration. Its condition as new or any defects do not have significant structural or functional effects. |
| 2 | Minor defects and early signs of deterioration without reduced functionality of the element. |
| 3 | Moderate defects and deterioration with some loss of expected functionality. |
| 4 | Serious defects with significant loss of functionality or an element on the verge of failure. |

$$\overline{CI} = \frac{\sum_e (CI_e \times IF_e \times MV_e \times CF_e)}{\sum_e IF_e \times MV_e \times CF_e}$$

In this context, I represents the number of condition states evaluated. The variable Qi refers to the number of elements corresponding to the i-th condition state, while CIi indicates the index associated with that state. This method enables an organized assess-

ment of the condition of elements, facilitating decision-making for the maintenance and rehabilitation of infrastructure.

$$W_e = \frac{IF_e}{\overline{IF}} \times \frac{MV_e}{\overline{MV}} \times \frac{CF_e}{\overline{CF}}$$

The determination of the weighting factor and its parameters involves the application of specialized knowledge and the execution of field tests, particularly regarding the evaluation of material vulnerability and structural aspects. To facilitate this process, the inspector may rely on the systematic approach developed in this research, which is based on a semi-structured survey or interview with experts and engineers specialized in bridge management and maintenance.

### 3.5. Importance Factor (IF)

To ensure an accurate assessment of the structural condition of the bridge, it is not sufficient to consider only its current state, as this may lead to distortions in the overall interpretation of its condition. A secondary element with a high level of deterioration could disproportionately influence the global evaluation, compromising decision-making in terms of maintenance and rehabilitation.

To address this issue, the Importance Factor (IF) of the structural element is introduced, which is quantified independently of the current condition of the bridge components. According to the survey conducted with subject-matter experts, structural elements have been classified into four categories: primary, secondary, tertiary, and others. As shown in Table 2, a higher value assigned to an element indicates a greater influence on the load-bearing capacity and safety of the bridge structure. This approach provides a more balanced and well-founded criterion for structural evaluation, optimizing the prioritization of structural maintenance actions.

**Table 2.** Structural Condition Factor (FI).

| SI | Structural Elements of the Bridge |
|---|---|
| 1 | Other elements; including, among others, barriers, curbs, sidewalks, and joint elements. |
| 2 | tertiary; including, among others, foundations, abutments, and retaining wall elements. |
| 3 | secondary; including, among others, cover, supports, and cables Primary elements. |
| 4 | including, among others, beams, main beams, pillars, and pylons. |

### 3.6. Material Vulnerability (MV)

Material vulnerability refers to the predisposition of a material to experience deterioration, loss of mechanical properties, or structural damage due to external factors such as environmental conditions, applied loads, or degradation processes. This concept is key in infrastructure analysis, as it allows for the evaluation of the resistance and durability of materials based on their exposure and inherent characteristics.

Identifying and quantifying this vulnerability is essential for establishing maintenance and rehabilitation strategies, optimizing the structure's service life, and ensuring its proper performance.

### 3.7. Causal Factors (CF)

The Villena Rey Bridge, located in Miraflores, Lima, plays a fundamental role in urban mobility. However, its infrastructure has experienced progressive deterioration due to exposure to environmental factors, increased vehicular traffic, certain deficiencies in its

original design, and insufficient maintenance management. Constant humidity, air salinity, and pollution have contributed to the degradation of its materials, while the rise in traffic flow has imposed greater structural demands, accelerating its deterioration.

Additionally, some elements of the original design have influenced its vulnerability over time, and the low frequency of inspections has allowed structural damage to accumulate without proper intervention. To mitigate these effects, infrastructure improvements have been proposed, such as the construction of a twin bridge and the reorganization of access points to optimize circulation. Furthermore, the application of the TLS-based methodology has enabled more accurate calibration of the CF index, contributing to a detailed structural assessment and the planning of conservation strategies. These initiatives aim to reinforce the safety and functionality of the Villena Rey Bridge, ensuring its efficient integration into Lima's road network.

For this reason, the age factor and the Annual Average Daily Traffic (AADT), related to the type of road and its importance within the road network, are essential criteria not only for structural design but also for evaluating durability and remaining service life. Bridge inspection, along with its frequency, plays a crucial role in its maintenance and preservation. This study establishes four levels of inspection: initial, routine, detailed, and special.

- The initial inspection involves data collection after the bridge's construction.
- The routine inspection focuses on general visual observations to detect potential failures. For deeper studies, detailed inspections are conducted, supported by non-destructive testing.
- For deeper studies, detailed inspections are conducted, supported by non-destructive testing.

Special inspections apply advanced structural analyses in cases of severe damage. Regardless of the inspection level, the TLS-based methodology presented in this research can be applied at all stages of the structural evaluation process. Finally, the CF index is calibrated based on the results obtained from the previously mentioned bridge evaluation survey.

## 4. Software Robot Structural Analysis Professional

### *4.1. Geometric Modeling and Material Definition for the Villena Rey Bridge*

The point cloud is obtained through terrestrial laser scanning (TLS), capturing the real geometry of the arch, deck, and foundations with high precision. The raw data is then imported into processing software such as Autodesk ReCap (2025.1.2. hotfix), where it is cleaned, aligned, and optimized before being exported in interoperable formats (IFC or DXF) for integration into the BIM model and Robot Structural Analysis.

### *4.2. Reconstruction in Robot*

Once the point cloud is processed and exported in IFC or DXF format, it is imported into Robot Structural Analysis as a "reference architecture," and the 3D modeling of the Villena Rey Bridge begins. First, the two reinforced concrete arches acting as the main braces are created, reproducing their exact profile and location. Next, the deck is modeled as a variable-section box girder, adjusting flanges and web according to the scanned dimensions. If applicable, intermediate piers and abutments are also integrated based on the original plans. Finally, piles or foundation blocks are incorporated, respecting their actual dimensions and locations to ensure the model accurately reflects the bridge's construction.

### 4.3. Section and Material Definition

The following materials are assigned in the model:

- Reinforced concrete C25/30, with modulus of elasticity E ≈ 25,000 MPa and density ρ ≈ 2500 kg/m$^3$, for all concrete elements.
- Grade 60 reinforcing steel, with E ≈ 200,000 MPa and yield strength fy ≈ 420 MPa, for the reinforcement.

Cross-sections are defined based on laser scanning and original plans:

- The main arch adopts a rectangular section of 0.80 × 1.20 m.
- The deck is modeled as a box girder with flange thickness of 0.25 m and web thickness of 0.40 m.
- The foundations are represented by Ø 1.00 m piles and 2 × 2 m blocks.

### 4.4. Permanent and Variable Loads

In Robot Structural Analysis, the loads for the Villena Rey Bridge are defined as follows:

- Self-weight is automatically calculated based on the material density and assigned sections.
- Traffic overload is introduced according to Peruvian Standard E.030 [27], with 10 kN/m$^2$ for vehicular circulation and 5 kN/m$^2$ for pedestrian areas.
- Wind action is modeled as a uniform lateral pressure of 0.50 kN/m$^2$, applied perpendicular to the bridge's main axis.

### 4.5. Seismic Load

According to the National Building Code E.030, the Villena Rey Bridge is located in Seismic Zone 4 (high acceleration), with a design PGA of approximately 0.24 g. For the dynamic response spectrum definition, Type II-B is adopted, corresponding to Category D soils (soft-granular), applying a seismic amplification factor S = 1.20 and a critical damping coefficient ζ = 5%. These parameters are entered into Robot Structural Analysis when creating the "Spectral Response" load case, ensuring the simulation accurately reflects Peruvian regulations and local soil conditions.

### 4.6. Modal Analysis

In Robot Structural Analysis, open the menu "Analysis > Dynamic > Mode Calculation" and configure the extraction of the first 8–10 modes, or stop the process when the sum of modal masses reaches at least 90% of the total mass of the Villena Rey Bridge. Run the calculation and extract the natural periods and frequencies:

- The first mode, dominated by arch flexion, typically yields a period $T_1$ ≈ 0.30 s (≈3.3 Hz)
- The second mode, associated with deck shear, presents $T_2$ ≈ 0.18 s (≈5.6 Hz).

## 5. Results

### 5.1. Priority Classification Based on PRCI

This section provides an in-depth examination of the application of the BMS component with a BrIM (Bridge Information Modeling) approach, along with the structural analysis of the Villena Rey Bridge. It details the procedures from the priority classification of structural elements to the planning of preventive maintenance strategies, ensuring optimal extension of the bridge's service life. For the Villena Rey Bridge, the classification of element types is determined using Table 3 which presents the various structural components used in its construction. Consequently, these elements require specialized attention regarding budget allocation and the implementation of corrective measures, thereby ensuring optimal performance and extending their lifespan.

**Table 3.** PRCI-based classification of the elements of the Villena Rey Bridge.

| Elements | Structural Function | Observations |
|---|---|---|
| Main arch | Distributes primary loads and supports the deck. | Key structural design of the bridge. Efficiently distributes forces. Evaluated based on deformation and wear. |
| Main beams | Support the deck's load and transfer it to the bearings or supports | Evaluated for deformation and wear. |
| Deck | Support vehicle and pedestrian loads. | Analyzed for structural deviations. |
| Wearing slabs | Surface layer of the deck | Not detailed but typically present in urban bridges. |
| Elastomeric bearings | Transfer the load to the substructure and allow movements. | Evaluated as a critical part of maintenance |
| Columns/pylons | Transfer the load from the superstructure to the foundation. | Mentioned as primary elements. |
| Abutments | Embankment retention and connection with the ground. | Classified as tertiary elements |
| Foundations | Final support for loads toward the ground | Not specified whether they are superficial or deep |
| Expansion joints | Allow movement due to temperature, load, or seismic activity. | Considered as part of "other elements". |
| Railings/barriers | Pedestrian and vehicular safety | Installed in 2004 for suicide prevention. |
| Curbs and sidewalks | Roadway separation and pedestrian passage | Mentioned as minor elements |

To evaluate remediation strategies for the Villena Rey Bridge, the main intervention alternatives were analyzed considering structural safety, the bridge's service life, and traffic impact. This procedure was based on a set of defined criteria aimed at minimizing costs and optimizing the functionality of the structure. The strategies were assessed using the pairwise comparison method, applying Saaty's nine-point scale of relative importance. Accordingly, a comparison matrix was constructed to identify the priority criteria for the bridge's rehabilitation. In the case of the Villena Rey Bridge, safety was determined to be the most relevant factor, surpassing other elements such as structural lifespan or maintenance cost. Furthermore, the prioritization of these criteria was represented through a hierarchical structure, facilitating the assignment of specific weights to each involved factor (Table 4). The validation of the analysis yielded a Consistency Index (CI) of 0.0043, indicating that the decisions made during the process were coherent. Based on this evaluation, the most effective alternatives were defined for each type of structural element, enabling optimization of the bridge's maintenance and rehabilitation (Figure 5).

**Table 4.** Comparative Matrix of Fundamental Criteria for the Rehabilitation of Villena Rey Bridge.

| | Security | Security | Maintenance Cost | Traffic Impact |
|---|---|---|---|---|
| Security | 1 | 3 | 5 | 7 |
| Durability | 1/3 | 1 | 3 | 5 |
| Maintenance cost | 1/5 | 1/3 | 1 | 3 |
| Traffic impact | 1/7 | 1/5 | 1/3 | 1 |

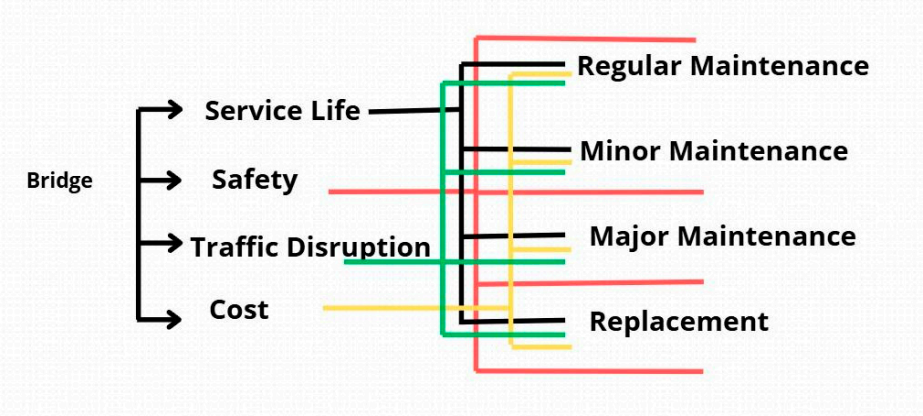



**Figure 5.** Three-level hierarchical structure designed for the planning of corrective actions on the Villena Rey Bridge.

At the Villena Rey Bridge, the evaluation was carried out for the elements with the highest PRCI, focusing on those with the greatest structural impact and need for intervention. This analysis varies according to the specific conditions of the project and the priorities established by the project managers. For the bridge, two types of key elements were examined: main concrete beams and elastomeric supports, which play a fundamental role in the stability and durability of the infrastructure. Table 5 presents the scores assigned to the main remediation alternatives for these components, assessing their effectiveness in terms of safety and efficiency. During the process, the Global Score of Alternatives (PGA) was determined for each corrective action, allowing for the optimization of maintenance and repair planning based on the available budget allocation.

**Table 5.** Scoring of the Main Remediation Alternatives for Element Types Based on PRCI.

| Criteria | Weight (%) | SBGI | | | | BELA | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Regular Maintenance | Minor Rehabilitation | Major Rehabilitation | Replacement | Regular Maintenance | Minor Rehabilitation | Major Rehabilitation | Replacement |
| Structural safety | 35 | 70 | 80 | 90 | 95 | 65 | 75 | 85 | 90 |
| Estimated cost | 25 | 85 | 75 | 65 | 50 | 90 | 80 | 70 | 55 |
| Impact on traffic | 20 | 80 | 75 | 65 | 40 | 85 | 80 | 70 | 45 |
| Duration of the intervention | 20 | 90 | 80 | 70 | 50 | 88 | 82 | 73 | 55 |

As presented in Table 5, the Overall Assessment Score (OAS) associated with the replacement of structural elements in the Villena Rey Bridge exhibited significantly higher values compared to the other evaluated intervention strategies. However, in the case of elastomeric bearings, the scores obtained for both minor and major rehabilitation were similar, indicating that both alternatives offer an equivalent level of effectiveness in terms of bridge maintenance.

Subsequently, the budget was optimized by identifying combinations of strategic actions, calculating the cumulative OAS, and comparing the actual cost of each option with the annual allocated budget. As a result, the optimal remediation strategy consists of selecting actions with the highest OAS, ensuring substantial improvement within the available financial margin.

In a scenario with unlimited budget and no sustainability constraints, the ideal combination would include only those alternatives with the highest OAS.

Applying this procedure to the Villena Rey Bridge, it was determined that the comprehensive rehabilitation of the main beams, along with the replacement of elastomeric bearings, generated a total OAS of 830.9, meeting the project's budgetary requirements. This information is essential for asset management, enabling efficient planning focused on the long-term preservation of infrastructure.

### *5.2. Visual Report on the Condition of the Bridge*

Throughout these procedures, a specialized plugin has been used to analyze all relevant structural information and update the BrIM model of the Villena Rey Bridge. This system assigns the processed data to each component of the digital model, allowing visualization of the bridge elements according to the maximum interpreted PRCI, as well as individual CI values. This plugin not only optimizes defect identification—determining their location and severity level through the integration of geometric and non-geometric information—but also facilitates the generation of a detailed report with various combinations of corrective strategies. These options can be selected based on the optimization of the available budget, ensuring efficient and sustainable planning for the bridge's rehabilitation.

This research study established a comprehensive methodology and approach to address two fundamental aspects: having a reliable digital replica of the Villena Rey Bridge, including both geometric and non-geometric information, and using this data within an efficient management system. In this context, the study introduced the valuable use of cutting-edge TLS technology to capture precise geometric information of the bridge, enabling the extraction of 3D CAD models and the execution of digital inspections. Unlike paper-based information, this data can be stored digitally as a reference for future research and is especially valuable for developing innovative solutions in damage detection and risk identification through structural analysis algorithms, helping engineers and bridge managers better understand its behavior. The study also focused on systematizing bridge management by providing a management system that can be linked to the proposed BrIM model. This system offers asset managers the ability to use the assigned data to more effectively and objectively assess the bridge's health status. Within this system, three complementary factors were considered to form a Priority Condition Classification Index (PRCI), used to select bridge elements that may require greater attention based on their structural importance, material vulnerability, and other causal factors such as age or environmental interaction.

## 6. Procedure for Structural Analysis in Robot Structural Analysis

### *6.1. Linking the Revit Model to Robot Structural Analysis Professional*

The previously modeled bridge in Revit was imported to obtain its exact dimensions. This was done directly using a Revit-to-Robot Structural connector, considering that both programs must be of the same version. Alternatively, the model can be exported in IFC format so that Robot Structural Analysis can recognize it if the connector encounters issues during the linking process (Figure 6).

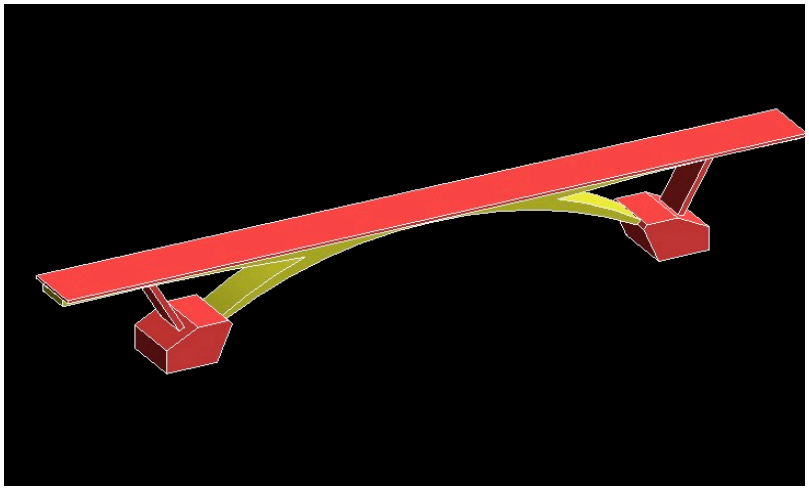


**Figure 6.** Linking Revit to Structural Analysis Professional—Visual of the Villena Rey Bridge.

*6.2. Assignment of Structural Loads: Dynamic and Static*

6.2.1. Nominal Value (pL)

AASHTO LRFD specifies a lane load value of 9.3 kN/m over a lane width of 3.60 m (equivalent to 0.69 kPa).

6.2.2. Dynamic Impact Factor (IM)

For lane load, the impact factor is 0%.

$$IMLL = 0\%$$

6.2.3. Lane Load for Analysis

$$LLeffective = 9.3\ kN/m$$

*6.3. Axle Configuration: 2 Axles*

Front Axle (P1): 15 kN.
Rear Axle (P2): 20 kN.
Longitudinal Spacing Between Axles: 3.0 m.
Transverse Wheel Track Width (center to center per axle): 1.8 m.

6.3.1. Dynamic Impact Factor (AASHTO LRFD C3.6.2.1-1)

$$IM = 33\%$$

6.3.2. Pedestrian Movement

According to regulations in urban areas like Miraflores, an estimated load of 4 persons per square meter is considered in pedestrian zones.

$$\text{Average weight per person} = 75\ kg.$$

$$Ppedestrian = \text{Number of persons} \times \text{Average weight} \times 100 \times 9.81$$

where: Ppedestrian = Total Pedestrian Load.

*6.4. Wind Load*

Wind Speed: According to the National Building Code (RNE), wind speed in Lima ranges from 60–80 km/h

Exposed Surface Area: Based on the Revit model, the lateral surface exposed to wind is approximately 500 $m^2$

$$F_{wind} = 0.613 \cdot C_d \cdot A \cdot V^2$$

where: $C_d = 1.2$ (drag coefficient); $A = 500\ m^2$ (exposed area); $V = 80$ Km/h, (wind speed).

### *6.5. Seismic Loads*

Seismic Zone: Lima is in Zone 4 (High seismic activity), according to the National Building Code (RNE).

Behavior Factor: Depends on the type of structure (for bridges, typically between 1.5–2.5).

Soil Type: Type C (rigid soil).

Seismic Coefficient: Depends on structure type and location.

$$Pseismic = W \times g \times Cs \times I$$

where: W = 6,000,000 kg (total weight of the structure); g = 9.81 m/s; Cs = 0.08 (seismic coefficient); I = 1 (importance factor).

### *6.6. Dead Loads*

Dead loads are static and permanent forces acting on the bridge that do not change over time or usage. These include the self-weight of all fixed components and structural elements (Figure 7).

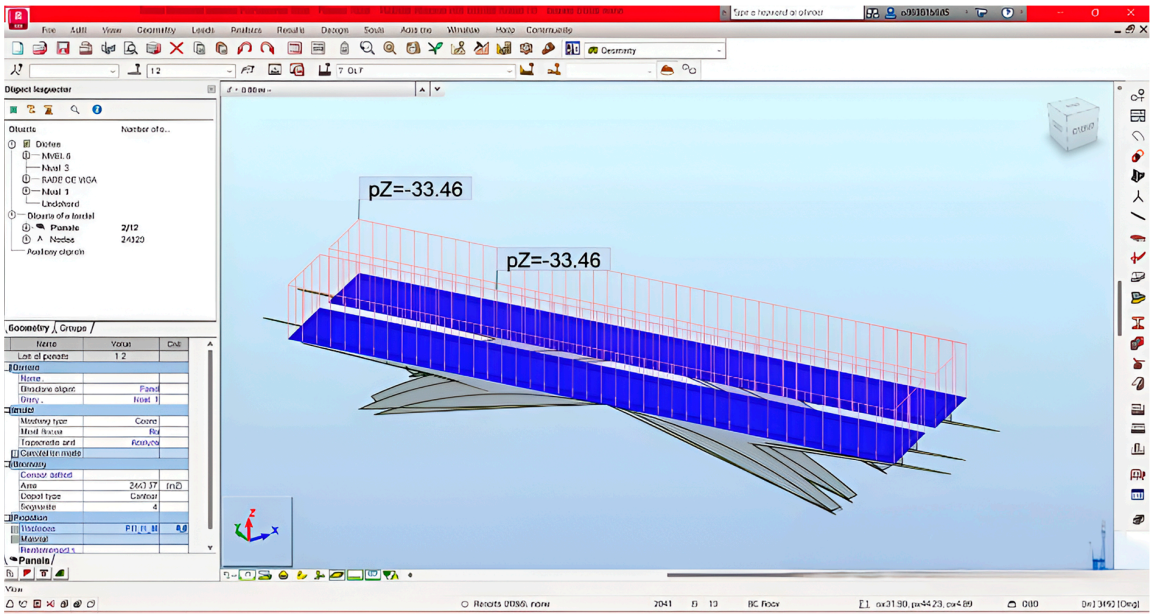



**Figure 7.** Modeling of the Villena Rey Bridge in Robot Structural Analysis Professional.

## 7. Limitations

This study acknowledges several limitations that should be considered when interpreting the results. First, the accuracy of the terrestrial laser scanning (TLS) equipment may vary depending on calibration, resolution, and environmental conditions during data acquisition. Factors such as lighting, weather, and surface reflectivity can influence the quality of the point cloud data. Second, the modeling process in Revit (2025.04) and other software tools involves assumptions and simplifications that may not fully capture the complex behavior of the actual structure. These assumptions include material properties, boundary conditions, and load applications. Lastly, the integration of data into the decision support system (DSS) relies on the accuracy and completeness of the input data, which may

affect the reliability of the outcomes. Future work should aim to address these limitations by incorporating more robust data validation techniques, exploring the use of higher-precision equipment, and refining modeling assumptions.

## 8. Conclusions

The estimated concrete volume of the Villena Rey Bridge is approximately 5714.76 cubic meters, based on modeling developed through Revit and terrestrial laser scanning (TLS). The creation of 3D digital models enabled the early detection of structural faults and damage, facilitating more efficient maintenance planning and reducing unnecessary expenses. Integrating the collected data into Revit allowed for the establishment of a decision-support system that optimizes bridge management and resource utilization. The application of the Structural Priority Index (PRCI) contributed to the classification and prioritization of elements requiring urgent intervention, thus enhancing safety and extending the bridge's service life. Overall, this study demonstrates that digitization and the use of integrated BrIM models are valuable tools for the sustainable management and preservation of road infrastructure.

Future research should focus on validating this proposed methodology through long-term monitoring of structural performance and extending its application to different bridge typologies and materials. The integration of smart sensors and Internet of Things (IoT) technologies could strengthen real-time data acquisition and improve predictive maintenance capabilities. Additionally, incorporating machine learning algorithms into BrIM and Digital Twin frameworks may enhance automated damage detection and decision-making accuracy. Further studies are also encouraged to explore the development of standardized protocols for data interoperability among digital platforms, ensuring scalability and practical implementation in bridge asset management systems.

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## References

1. Zhou, Y.; Zhu, J.; Zhao, L.; Hu, G.; Xin, J.; Zhang, H.; Yang, J. High-Precision Monitoring Method for Bridge Deformation Measurement and Error Analysis Based on Terrestrial Laser Scanning. *Remote Sens.* **2024**, *16*, 2263. [CrossRef]
2. Scianna, A.; Gaglio, G.F.; La Guardia, M. Structure Monitoring with BIM and IoT: The Case Study of a Bridge Beam Model. *ISPRS Int. J. Geo-Inf.* **2022**, *11*, 173. [CrossRef]
3. Shim, C.-S.; Dang, N.-S.; Lon, S.; Jeon, C.-H. Desarrollo de un sistema de mantenimiento de puentes Sistema para puentes de hormigón preesforzado mediante un modelo de gemelo digital, 3.D. *Struct. Infrastruct. Eng.* **2019**, *15*, 1319–1332. [CrossRef]
4. Javidan, M.M.; Kim, J. Método basado en difusos para un rendimiento sísmico eficiente Evaluación de estructuras con incertidumbre. Infraestructura Civil Asistida por Computación. *Ingeniería* **2022**, *37*, 781–802. [CrossRef]
5. Mohammadi, M.; Rashidi, M.; Mousavi, V.; Yu, Y.; Samali, B. Application of TLS Method in Digitization of Bridge Infrastructures: A Path to BrIM Development. *Remote Sens.* **2022**, *14*, 1148. [CrossRef]

6. Chi-Ho, J.; Nguyen, D.C.; Roh, G.; Shim, C. Development of BrIM-Based Bridge Maintenance System for Existing Bridges. *Buildings* **2023**, *13*, 2332.
7. Mohamed, A.G.; Khaled, A.; Abotaleb, I.S. A Bridge Information Modeling (BrIM) Framework for Inspection and Maintenance Intervention in Reinforced Concrete Bridges. *Buildings* **2023**, *13*, 2798. [CrossRef]
8. Aguilar, G.; Rodríguez, B. Uso de la Metodología BIM y BrIM en el Desarrollo de Sistemas de Gestión de Puentes. 2024. Available online: https://webofscience.upc.elogim.com/wos/woscc/full-record/WOS:001120774900001 (accessed on 15 July 2025).
9. Aguilar, G.; Rodríguez, B.; Trejos, V. Programas de Cómputo Comerciales Disponibles Para BIM y BrIM. 2024. Available online: https://www.lanamme.ucr.ac.cr/repositorio/handle/50625112500/2756 (accessed on 13 June 2025).
10. Ambroziak, A.; Malinowski, M. A 95-year-old concrete arch bridge: From materials characterization to structural analysis. *Materials* **2021**, *14*, 1744. [CrossRef]
11. Boretti, V.; Sardone, L.; Bohórquez Graterón, L.A.; Masera, D.; Marano, G.C.; Domaneschi, M. Algorithm-Aided Design for Composite Bridges. *Buildings* **2023**, *13*, 865. [CrossRef]
12. de Diego, F.C.; Hindi, R.; Lozano Galant, J.A. Application of Augmented Reality Tools to Bridge Models Elaborated with BIM. *Hormigón Y Acero* **2022**, *73*, 81–88. [CrossRef]
13. Fu, T.; Liu, Y.; Zhu, Z. Research on Bridge Structure Reliability Evaluation due to Vessels Collision Based on a Statistical Moment Method. *Adv. Mater. Sci. Eng.* **2021**, *2021*, 5620173. [CrossRef]
14. Qin, G.; Zhou, Y.; Hu, K.; Han, D.; Ying, C. Automated Reconstruction of Parametric BIM for Bridge Based on Terrestrial Laser Scanning Data. *Adv. Civ. Eng.* **2021**, *2021*, 8899323. [CrossRef]
15. Saback, V.; Popescu, C.; Blanksvärd, T.; Täljsten, B. Asset Management of Existing Concrete Bridges Using Digital Twins and BIM: A State-of-the-Art Literature Review. *Nord. Concr. Res.* **2022**, *66*, 91–111. [CrossRef]
16. Vital, W.; Silva, R.; de Morais, M.V.G.; Emidio Sobrinho, B.; Pereira, R.; Evangelista, F. Application of bridge information modeling using laser scanning for static and dynamic analysis with concrete damage plasticity. *Alex. Eng. J.* **2023**, *79*, 608–628. [CrossRef]
17. Fawad, M.; Salamak, M.; Chen, Q.; Uscilowski, M.; Koris, K.; Jasinski, M.; Lazinski, P.; Piotrowski, D. Development of immersive bridge digital twin platform to facilitate bridge damage assessment and asset model updates. *Comput. Ind.* **2025**, *164*, 104189. [CrossRef]
18. Heng, J.; Dong, Y.; Lai, L.; Zhou, Z.; Frangopol, D.M. Digital twins-boosted intelligent maintenance of ageing bridge hangers exposed to coupled corrosion–fatigue deterioration. *Autom. Constr.* **2024**, *167*, 105697. [CrossRef]
19. Song, H.; Yang, G.; Li, H.; Zhang, T.; Jiang, A. Digital twin enhanced BIM to shape full life cycle digital transformation for bridge engineering. *Autom. Constr.* **2023**, *147*, 104736. [CrossRef]
20. Huang, Z.; Yin, X.; Liu, Y.; Liu, Y. Damage identification of truss bridges based on feature transferable digital twins. *Meas. J. Int. Meas. Confed.* **2024**, *233*, 114735. [CrossRef]
21. Mousavi, V.; Rashidi, M.; Mohammadi, M.; Samali, B. Evolution of Digital Twin Frameworks in Bridge Management: Review and Future Directions. *Remote Sens.* **2024**, *16*, 1887. [CrossRef]
22. Shu, J.; Zeng, Z.; Li, W.; Zhou, S.; Zhang, C.; Xu, C.; Zhang, H. Automatic geometric digital twin of box girder bridge using a laser-scanned point cloud. *Autom. Constr.* **2024**, *168*, 105781. [CrossRef]
23. Zhu, J.; Luo, N.; Guo, Z.; Lai, J.; Zuo, L.; Zhang, C.; Guo, Y.; Hu, Y. Feature-constrained automatic geometric deformation analysis method of bridge models toward digital twin. *Int. J. Digit. Earth* **2024**, *17*, 2312219. [CrossRef]
24. Hagen, A.; Andersen, T.M. Asset management, condition monitoring and Digital Twins: Damage detection and virtual inspection on a reinforced concrete bridge. *Struct. Infrastruct. Eng.* **2024**, *20*, 1242–1273. [CrossRef]
25. Wei, J.; Chen, G.; Huang, J.; Shou, W.; Wang, J. Resource-constrained bridge maintenance optimization by harmonizing structural safety and maintenance duration. *Eng. Struct.* **2024**, *308*, 118024. [CrossRef]
26. Yu, Y.; Rashidi, M.; Samali, B.; Mohammadi, M.; y Nguyen, A. Basado en visión por computadora Clasificación de grietas en puentes de hormigón mediante técnicas de aprendizaje automático. In Proceedings of the 10ª Conferencia Internacional sobre Monitoreo de la Salud Estructural de Infraestructuras Inteligentes, SHMII 10, Oporto, Portugal, 30 June–2 July 2021; Clasificación basada en visión artificial de grietas en puentes de hormigón mediante técnicas de aprendizaje automático. Universidad de Western Sydney: Sydney, Australia, 2021.
27. Ministry of Housing, Construction and Sanitation. Technical Standard E.030: Earthquake-Resistant Design. National Building Regulations. National Training Service for the Construction Industry—SENCICO. 2020. Available online: https://www.gob.pe/sencico (accessed on 15 July 2025).


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