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Mapping structural deformation on Bridges using InSAR data and Digital Twin for Disaster Risk Management in the future: A review

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Structural deformation monitoring is critical for sustainable infrastructure management and disaster risk reduction, particularly in rapidly urbanizing or geologically sensitive regions with important bridges. The integration of Interferometric Synthetic Aperture Radar (InSAR) and Digital Twin (DT) technology enables millimeter-accurate mapping of bridge deformations, as demonstrated in recent literature. By merging satellite-derived point clouds with Bridge Information Modelling (BrIM) among dimensionality reduction techniques, this approach facilitates 3D visualization of deformation patterns linked to specific structural components. This supports early detection of anomalous movements from subsidence, mining, or tectonic stresses, enabling proactive risk management through prioritized maintenance, spatial planning, and early-warning systems. This review identifies a proposed framework to integrate these technologies and shows the key challenges, including data latency, atmospheric interference, computational demands, and digitization gaps, to inform scalable frameworks for long-term bridge safety monitoring under a growing risk environment.

Keywords: Interferometry Satellite Aperture Radar, Digital Twin, bridge deformation, disaster risk management, Bridge Information Modelling, Persistent Scatterer.

1. Introduction

In structural maintenance, damage denotes alterations that adversely affect its performance, encompassing modifications to boundary conditions, system connectivity, material performance, and geometric properties (Sun et al., 2025). Bridge structural service life is affected by environmental exposure, traffic loading, and material aging. These processes often induce deformations and progressive degradation that evade detection by conventional visual inspections, thereby increasing the risk of latent structural failures (Brighenti et al., 2024). Therefore, integrating new technologies and tangible measurements constitutes an effective approach to minimize significant negative impacts and propose risk management strategies, such as enhancing communication systems and preparedness (Liew et al., 2025).

Real-time information within satellite-based technologies enables millimeter-accurate deformation mapping across extensive networks without physical instrumentation. When integrated with 3D models, these tools facilitate real-time information management and DT updates, thereby supporting more effective management. This could offer a scalable and cost-effective framework for bridge monitoring, enabling proactive mitigation of long-term structural risks (Ribeiro et al., 2025).

This review examines the synergy between InSAR and DT for the structural monitoring and risk management across the databases, Dimensions, Scopus, and Web of Science. It provides a comprehensive analysis of these applications, emphasizing how their integration facilitates decision-making. Furthermore, this research values the InSAR capabilities, post-processing integration with other technologies, and inherent limitations of data acquisition for structural management, identifying the critical challenges that necessitate its fusion with DT to overcome the constraints of stand-alone monitoring and risk management (Kumalawati et al., 2024).

2. Background in Bridge risk monitoring

2.1. *Interferometry Synthetic Aperture Radar*

InSAR is an advanced microwave remote-sensing technique that processes multi-temporal satellite imagery across multiple frequency bands, including Sentinel-1 (C-band), TerraSAR-X (X-band), and PALSAR-2 (L-band), to detect surface displacements with millimeter-level precision (Lee et al., 2025). These images often use reference points of information, known as PS, which are radar targets that exhibit high phase stability over time due to consistent radar backscatter properties and could be merged with GIS information. These points with extractable Point-like Targets (PTs) created by man typically correspond to corner reflectors of structures such as concrete elements or metallic fixtures.

PS on complex structures are statistically selected based on amplitude dispersion index, temporal coherence, and phase stability thresholds to form grids or to calculate information such as displacements, velocities, and anomalies (Buelvas Moya et al., 2026). Due to the above, InSAR has adaptability in recording geophysical changes, making it particularly effective for post-seismic damage assessment and rapid risk quantification in impacted zones (Al Shafian & Hu, 2024).

2.2. Digital Twin

DT constitutes a dynamic data model of a physical asset that continuously mirrors attributes and functional behavior through an operational lifecycle. It could represent the structural components, engineered products, or integrated systems, incorporating all pertinent information required from conceptual design and commissioning through operational service and eventual decommissioning. As a new technological paradigm within infrastructure asset management, DT implementations have demonstrated significant efficacy in augmenting evidence-based decision-making across critical project stages, particularly during long-term Assessment of structural conditions (Ribeiro et al., 2025). See Fig 2 to resume the process.

In Bridge Management Systems (BMS), DT integrates real-time sensor telemetry, remote sensing observations, and historical performance records to mirror behavior (Ribeiro et al., 2025). Furthermore, by embedding regulatory guidelines and technical standards within its data architecture, the Digital Twin functions as a dynamic compliance framework, enabling real-time comparative analysis, scenario optimization, and evidence-based decision-making during maintenance interventions (Casas et al., 2024).

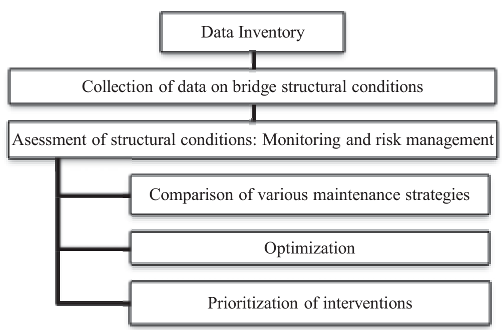

Fig.2. BMS according to (Brighenti et al., 2024).

3. Review Study Methodology

This review evaluates the current state of research by systematically querying the Dimensions, Web of Science, and Scopus databases. Guided by predefined exclusion criteria, the methodology ensures comprehensive coverage while mitigating selection bias and enhancing evidence synthesis consistency. This transparent framework critically analyzes journal and conference publications and was designed to uphold procedural rigor, ensuring transparency in the identification, screening, and selection of relevant scholarly sources for future research.

3.1. *Review search*

Systematic queries were executed across Dimensions, Web of Science, and Scopus (2005–January 2026) using keywords: 'Digital Twin,' 'InSAR,' 'bridge,' 'risk management,' and 'deformation.' Initial screening yielded 11,639 records; after duplicate removal, language filtering, and relevance assessment of titles/abstracts, 151 documents underwent full-text analysis after information in Table 1.

Table 1. Methodology screening documents

Searching Index	Specific Content
Article Type	Technical/scientific articles, seminars, and conferences published in journals.
Search Keywords	"Digital Twin" "InSAR", "bridge", "Risk management", "deformation"
Search Period	From January 2005 to January 20 of 2026
Field of Research	Engineering, Civil Engineering, Remote Sensing

A robust, multidimensional analysis includes a bibliometric analysis and concludes with a thematic content analysis. The contributions to the main topic were to synthesize commonalities and distinctive claims; ten (10) duplicate files were removed, and one (1) non-English publication (1) was discarded, resulting in 151 documents for abstract analysis. Search strings were developed around core concepts, then titles and abstracts were reviewed for topical relevance, and finally, full texts were assessed against inclusion criteria focusing on methodological rigor and applicability to structural monitoring (Buelvas Moya et al., 2026).

3.2. *Bibliometric analysis*

Bibliometric analysis is structured around a performance review that quantifies scientific output through indicators such as citation frequency, publication year, publication sources, and individual research contributions. This performance analysis provides insights into the productivity and impact of researchers, institutions, and nations, facilitating a multidimensional understanding of the field. Furthermore, it enables the identification of dominant themes, emerging trends, and underexplored areas regarding the integration of InSAR and DT into risk management. The bibliometric analysis of 727 unique authors across the Dimensions and Scopus databases reveals a highly collaborative and expanding landscape.

The study identified fifty diverse journals, with a significant concentration in high-impact Q1 venues. Remote Sensing (21 articles), Buildings (11), and Applied Sciences (8) emerged as the primary sources. The prominence of MDPI-published journals reflects the interdisciplinary nature of the field, spanning Civil Engineering, Geomatics, and Computer Science. This distribution underscores the rapid publication cycles and emerging technological focus necessary for the research topic.

3.3. *Thematic content analysis*

Among the articles included in this review, 18 have accumulated more than 50 citations, indicating a notable level of scholarly engagement. This eminent citation count reflects both the procedural significance and broad pertinence of the work within the context of large-scale infrastructure monitoring using DT technologies for deformation risk management. The analyzed corpus features high-impact publications focused on integrating advanced technologies for infrastructure monitoring.

Leading the citations, Huang et al. (Huang et al., 2021) explore the synergy between BIM, machine learning, and computer vision in underground construction. Substantial contributions to Ground Penetrating Radar (GPR) applications and best practices are provided by Solla et al. (Solla et al., 2021) and Rasol et al. (Rasol et al., 2022). Furthermore, Rashidi et al. (Rashidi et al., 2020) evaluate a decade of terrestrial laser scanning in bridge monitoring, while Samadzadegan et al. (Samadzadegan et al., 2025) offer a contemporary perspective on multi-sensor data fusion, reflecting the interdisciplinary evolution of risk monitoring.

Later, a full text analysis was conducted to ensure the relation between the documentation and the objectives of this review, which is the reason why, from the 151 documents, just the relevant ones are considered in the content analysis. 55 documents from the Dimensions database and 8 from the Scopus database using the keywords relation in the abstract, title, introduction, and the same keywords.

4. Process of Mapping Structural Deformation on Bridges for Disaster Risk Management

This section outlines the application of the InSAR-DT integration that enables stakeholders to assess anomalous or progressive deformations that compromise structural integrity, thereby safeguarding public safety and asset value.

4.1. *Mapping process of deformation*

Although BMS has demonstrated significant utility in overseeing infrastructure assets, several critical limitations persist. Current diagnostic and prognostic practices are intrinsically linked to the data acquisition methodologies employed. Persistent Scatterer Interferometry (PS-InSAR) or Multitemporal InSAR (MT-InSAR) can extract coherent measurement points from SAR image stacks to generate millimeter-accurate displacement time series, derived into points clouds processed from multi-frequency information gathered in satellites such as Sentinel-1 C-band, TerraSAR-X X-band or PALSAR-2 L-band (Lee et al., 2025). These technologies identify "persistent scatterers", stable objects like concrete elements from bridges that maintain constant backscattering of spatial datasets that monitor movement speed and trends (Kumalawati et al., 2024).

InSAR gives a high-resolution sensing capability and enhances the recurrent deformation measurements by enabling a continuous feedback loop between physical assets and their digital counterparts (Lee et al., 2025). Over the past decade, advancements in Global Navigation Satellite Systems (GNSS) hardware have catalyzed research into its efficacy for dynamic monitoring, particularly regarding long-span bridges, and serve to define reference points for auxiliary sensors or to transform optical and topometric data into specific reference frames. The synergy between GNSS-derived reference frames and wide-area displacement mapping provides a more comprehensive displacement analysis, bridging the gap between high-frequency local point monitoring and large-scale structural health assessments. (Casas et al., 2024; He et al., 2025)

4.2. Digital Twin Process

The DT framework includes the generation of this synthetic environment with open-source generation, like the Industry Foundation Classes (IFC) format, and the post-processing and performance evaluation, obtained by applying post-processing algorithms and machine learning (Yang et al., 2025). These fusions employ Uniform Manifold Approximation and Projection

(UMAP) dimensionality reduction with a specialized distance metric integrating movement correlation and proximity, followed by Hierarchical Density-Based Spatial Clustering of Applications with Noise (HDBSCAN) to map displacement patterns to specific structural components, facilitating early detection of anomalous deformations, millimeter per year (mm/yr), and if it is correlated with the environment (Marra et al., 2025).

According to Hakimi et al. (Hakimi et al., 2024), the DT model is characterized by six interrelated capabilities: AI-driven predictive maintenance protocols; real-time physical integration for dynamic visualization; digital facility management supported by BrIM modeling; intelligent prognostics and health monitoring for bridge structures; comprehensive asset lifecycle management; and semantic interoperability across heterogeneous data sources. These dimensions collectively represent the current research frontier in DT facility management.

4.3. *Integration Process*

The synergy between DT and InSAR enhances predictive maintenance by enabling continuous, millimeter-accurate structural monitoring. DTs provide superior sensing capabilities compared to conventional systems and, through simulation-based diagnostics, forecast structural behavior to detect deterioration. An integration platform establishes communication between remote sensing data and real-time simulation processes, achieving fault prediction accuracy up to 89% in specific applications. This precision enables timely, evidence-based maintenance interventions, optimizing resource allocation, minimizing operational disruptions, and extending the service life of the bridge (Casas et al., 2024).

A significant recent advancement involves the development of a framework that leverages the recurrent applications. ML and Deep Learning (DL), specifically Convolutional Neural Networks (CNNs) and transfer learning, are technologies that enable real-time and precise evaluations essential for immediate disaster response and long-term urban resilience planning. Developing user-friendly platforms for data fusion and real-time processing with UMAP and HDBSCAN is critical to democratizing these tools. Such advancements will empower local governments and emergency responders with practical, scalable solutions for disaster mitigation and recovery (Al Shafian & Hu, 2024).

4.4. *BMS*

The digital approach of Sections 4.1 to 4.3 generates synthetic data to train Anomaly Detection Algorithms (ADAs) capable of detecting structural decay in quasi-real time, and it allows stakeholders to make informed decisions and implement predictive maintenance that optimizes resources and extends the service life of bridge networks (Jiménez Rios et al., 2023). The use of BMS as an undistinguished guide to use integration between DT and InSAR is important to management and monitoring. Current approaches prioritize interventions using indices that balance structural conditions against remedial costs (Brighenti et al., 2024).

4.4. Comprehensive bridge risk management

Technology allows administrations to transition from reactive to risk-based maintenance by identifying "hotspots" across thousands of assets simultaneously (Quqa et al., 2025). The integration of geospatial datasets with precise structural coordinates facilitates a comprehensive understanding of deformation phenomena. Such multidimensional information can be effectively managed, analyzed, and visualized within GIS frameworks. The maturity of this technological approach is well established in contemporary literature, with significant advancements including Web-based GIS platforms and the emerging DT paradigm to extract information with delocalization data (Cao et al., 2023; Gaspari et al., 2025; Khan et al., 2023; Mohammed et al., 2026; Popov et al., 2025). Fig 1 shows a process related to the above.

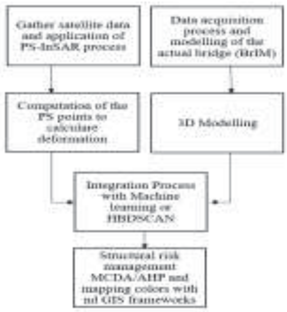

Fig 1. Modified methodology in this review.

The extraction of time-series vertical and horizontal deformation rates with millimeter-level accuracy is subsequently incorporated into a Multi-Criteria Decision Analysis (MCDA) or an Analytic Hierarchy Process (AHP) framework to develop early warning systems and risk layer superposition indicators (Medaa et al., 2025; Zhan et al., 2025). This analysis allows for the prediction of future issues and the identification of potential structural risks or significant damage that could occur in the structure from a 3D model, allowing for important structural considerations. The system can use associative rules to map deformations onto model surfaces, triggering visual alarms through color changes when a predetermined safety threshold is exceeded (Genovese & Barrile, 2025).

4.6. Challenges to overcome

According to this review, some barriers impede the autonomous application of these technologies, and there is a need to overcome them in future developments or research related to map deformations, such as data latency of the real-time physical-digital synchronization, atmospheric and vegetative interference compromising radar measurement accuracy, exponential computational demands for heterogeneous data integration, limited public accessibility to deformation information, and resource-intensive digitization efforts required for aging infrastructure lacking historical digital records.

5. Conclusions

This review demonstrates that integrating InSAR and DT technologies enables continuous, millimeter-accurate deformation monitoring through a closed-loop feedback system between physical infrastructure and its virtual representation. DT frameworks, machine learning algorithms (UMAP for dimensionality reduction; HDBSCAN for clustering), map displacement patterns to individual BrIM-defined components, and allow anomaly detection, transforming maintenance protocols from reactive to predictive.

Although barriers to autonomous implementation persist, including data latency and computational demands, emerging developments in data fusion, GIS relationship, and real-time processing hold promise for scalable, cost-effective bridge safety monitoring and long-term risk mitigation. Operationally, GNSS-derived reference frames validate displacements, while MCDA-AHP frameworks process deformation rates for early-warning indicators.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing does not apply to this article.

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