

Implementation of a Structural Health Monitoring System on the Mosteirô Bridge for BrIMe-Based Management

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Abstract

This paper presents the implementation of a Structural Health Monitoring system on the Mosteirô Bridge, designed by Professor Edgar Cardoso and built in 1973. The monitoring system aims to support the digital transition of bridge management by integrating sensor data into BrIMe (Bridge Information Modelling enhanced) platforms.

The first phase of the project involves the identification and planning of critical sections to be monitored, based on structural behaviour and accessibility. The selected monitoring sections include measurements of: (i) vertical and horizontal displacements at expansion joints near the abutments, (ii) strain at predefined transverse critical sections, (iii) rotations at the top of the piers, (iv) concrete temperature, (v) ambient temperature, and (vi) relative humidity. A network of sensors was installed to enable automated and continuous data acquisition. The system includes displacement transducers, strain gauges, inclinometers, and environmental sensors, all connected to a remote data logging and transmission unit. This configuration allows for real-time monitoring and long-term data storage, supporting both routine inspections and emergency assessments. The collected data will be processed and exported to BrIMe-compatible formats, enabling integration with geometric and structural models. This linkage enhances the bridge's digital representation and supports predictive maintenance strategies, structural diagnostics, and decision-making processes.

The paper discusses the technical specifications of the monitoring system, the criteria for selecting critical sections, and the methodology for data integration into BrIMe. The approach demonstrates how sensor-based monitoring can be effectively combined with digital modelling to improve infrastructure management and extend the service life of existing structures.

Keywords: SHM, Concrete truss bridges, Mosteirô bridge, BrIMe.

1. Introduction

Bridges are essential components of modern transportation networks, ensuring mobility, economic connectivity, and territorial cohesion. As the structures age, the challenges associated with their maintenance and management become increasingly complex. Many bridges built during the second half of the twentieth century are now approaching or exceeding their original design life, while simultaneously being subjected to higher traffic volumes, evolving environmental conditions, and more stringent safety expectations. In this context, traditional inspection-based maintenance strategies—often periodic, subjective, and labour-intensive—are no longer sufficient to guarantee long-term structural performance and resilience.

The emergence of Structural Health Monitoring (SHM) technologies has transformed the way engineers assess and manage civil infrastructure. By enabling continuous, automated, and data-driven evaluation of structural behaviour, SHM systems provide valuable insights into the condition of bridges, allowing for early detection of anomalies, improved understanding of long-term degradation mechanisms, and more efficient allocation of maintenance resources. When combined with digital modelling environments, SHM becomes a cornerstone of next-generation asset management frameworks.

In parallel, the digitalisation of the construction and infrastructure sectors has led to the development of Bridge Information Modelling Enhanced (BrIMe) platforms, which extend the principles of Building Information Modelling (BIM) to the domain of bridge engineering. BrIMe enables the integration of geometric, structural, and operational data into a unified digital environment, supporting advanced simulations, lifecycle analysis, and collaborative decision-making. The convergence of SHM and BrIMe represents a significant step toward the creation of intelligent, data-rich digital twins capable of reflecting the real-time condition of bridges.

The Mosteirô Bridge, designed by the renowned Portuguese engineer Edgar Cardoso and completed in 1973, provides an ideal case study for exploring this integration. As an important crossing within the regional road network, the bridge exhibits structural characteristics and operational demands that justify the implementation of a modern monitoring system. The present work describes the design, installation, and operation of an SHM system tailored to the bridge's specific needs, as well as the methodology adopted to integrate sensor data into a BrIMe environment.

2. State of the art

The management of bridge infrastructure has undergone a profound transformation over the past two decades, driven by advances in sensing technologies, data processing, and digital modelling environments. Traditional inspection-based approaches, largely dependent on visual surveys and periodic assessments, are increasingly being complemented or replaced by SHM systems capable of providing continuous, objective, and high-resolution information on structural performance.

Modern SHM systems have evolved from early experimental setups with limited instrumentation to sophisticated, multisensor networks capable of capturing a wide range of structural and environmental parameters. Key developments include: (i) high precision displacement and strain measurement technologies; (ii) wireless and low power communication systems; (iii) automated data processing and anomaly detection algorithms; and (iv) integration of environmental monitoring. These advancements have made SHM a practical and scalable tool for bridge owners.

Parallel to the evolution of SHM, the digitalisation of the construction and infrastructure sectors has led to the emergence of Bridge Information Modelling (BrIM) as an extension of BIM. BrIM platforms provide a structured digital environment that integrates geometric, material, and structural information throughout the bridge's lifecycle. Recent developments have expanded BrIM capabilities to include the parametric modelling of complex geometries and interoperability standards such as IFCBridge.

The convergence of SHM and BrIM represents a major step forward in bridge engineering. While SHM provides real time data on structural behaviour, BrIM offers a comprehensive digital framework for organising, visualising, and interpreting that data. Recent research has focused on Developing interoperable data formats to ensure seamless transfer of sensor data into BrIM environments, linking sensor measurements to geometric and analytical models to support model updating and structural diagnostics, embedding monitoring data into digital twin workflows for predictive maintenance and risk-based decision making, and automating inspection and reporting processes through integrated dashboards and visualisation tools (Nhamage *et al.*, 2025).

Recent developments in digital modelling for infrastructure have led to the extension of the Industry Foundation Classes (IFC) standard to better support bridge projects, resulting in the creation of IFCBridge (ISO 6707-1, 2020). Historically, IFC was primarily focused on buildings, but increasing

international demand prompted buildingSMART International (2021) to initiate a dedicated extension for bridges, developed between 2017 and 2019 as part of its Infrastructure Room initiatives. IFCBridge provides a formal semantic definition of bridges and introduces entities, predefined types and property sets tailored for bridge components, enabling an interoperable representation of geometry, materials, structural systems and asset-management data. The extension follows established IFC-Infra guidelines and integrates with related infrastructure schemas such as IFC-Alignment, ensuring consistency across linear infrastructure domains. These advances address a critical gap in BIM interoperability for bridge engineering, supporting applications ranging from design and analysis to inspection, SHM and lifecycle management (TMU, 2025).

Despite these advances, practical implementations remain limited, particularly in existing bridges where installation constraints, documentation available, and complex geometries pose challenges. Demonstration projects have shown promising results, but widespread adoption is still emerging. By bridging the gap between monitoring technologies and digital modelling platforms, this work intent to present a tentative practical pathway toward the digital transformation of bridge asset management.

3. Case study

3.1. Description

The Mosteirô Bridge connects the banks of Baião and Oliveira do Douro (Cinfães) across the River Douro in Portugal and was designed by the distinguished engineer Edgar Cardoso. The Bridge, completed in 1973 to replace a metal bridge submerged by the Carrapatelo Dam reservoir, reuses the original end piers but required partial demolition of the central pier, allowing adequate river navigability. It has a total length of 192 m, with a large 110 m central span (Pinho *et al.*, 2012). The deck is a reinforced and prestressed concrete trussed beam of variable depth, with a 9 m-wide upper flange supporting two traffic lanes and footways. Load transfer at supports uses cross-diagonals and fixed cylindrical bearings (Figure 1 and 2). The bridge's piers and abutments were strengthened from the existing masonry structures using reinforced concrete. In 2011, major strengthening works included external prestressing, CFRP laminates over 50 m at mid-span, and steel plate reinforcement of some diagonals. Due to the long central span, downward reactions at the abutments required anchorage with high-strength steel bars, which were later upgraded with a steel truss system and prestressing cables.



Figure 1. General upstream view of the Mosteirô Bridge, from the north bank.

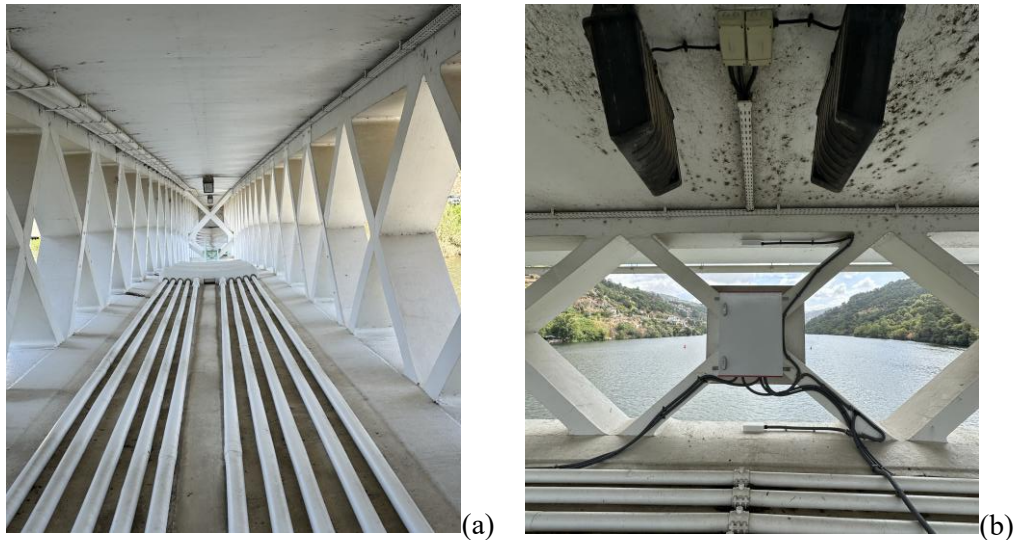


Figure 2. Mosteirô Bridge: (a) internal view, including the pre-tensioning cables on the lower deck; (b) Central mid-span section, interior of the upstream side.

3.2. Instrumentation

A detailed structural assessment was conducted to identify the most relevant locations for instrumentation (Figure 3). The selection process considered expected deformation patterns, accessibility, and the potential for early detection of anomalies. The monitoring layout includes: (1) vertical and horizontal displacements at expansion joints, where thermal movements and support conditions can significantly influence global behaviour; (2) strain measurements at predefined transverse critical sections, selected based on structural analysis and historical inspection records; (3) rotations at the top of the piers, providing insight into foundation behaviour, stiffness variations, and potential settlement; (4) concrete temperature, essential for interpreting strain and displacement data and distinguishing structural effects from thermal influences; (5) ambient temperature and relative humidity, enabling correlation between environmental conditions and structural response.

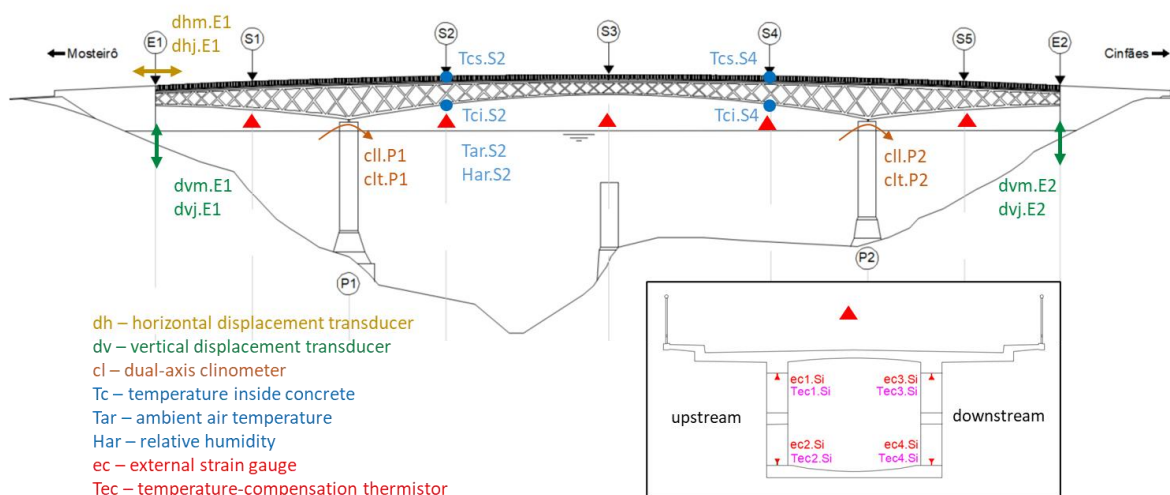


Figure 3. Instrumentation set-up location

This instrumentation provides a comprehensive view of the bridge's behaviour, for global and local effects. All sensors are connected to a remote data logging unit equipped with automated data transmission capabilities. The system supports continuous acquisition, real-time visualisation, and long-term storage of monitoring data. Power supply and communication infrastructure were designed to ensure reliability and minimal maintenance requirements.

4. Methodology

4.1. General

The methodology adopted for the implementation of the SHM system on the Mosteirô Bridge can be divided into three main stages: the habitual design stage and application stage, and the new stage to define the integration of all information into BIM models. The first stage follows the workflow encompassing the definition of monitoring objectives and critical sections, and the selection of sensors, and the second stage, consider the configuration of data acquisition system, data collection and processing. Finally, a new stage for integration of all data into BrIMe environment is added to the traditional stages. The approach ensures that the monitoring system provides reliable, continuous, and interoperable information to support structural assessment and lifecycle management. The flowchart of this methodology is presented in Figure 4.

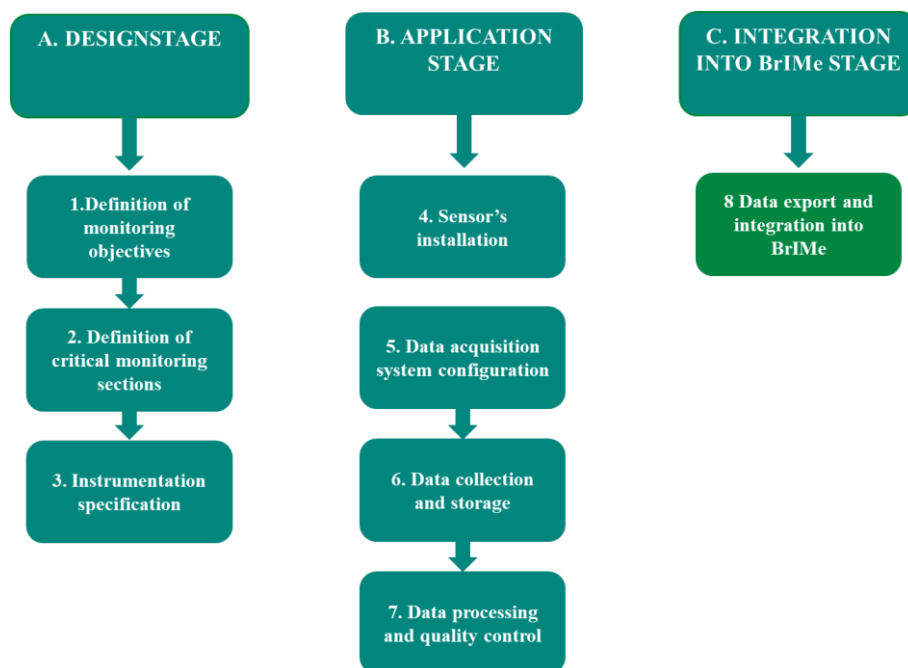


Figure 4. Flowchart of methodology proposed.

A. DESIGN STAGE

1. Definition of monitoring objectives

The first step involved defining the functional requirements of the SHM system based on the bridge's structural design, characteristics, age, and operational context. The objectives included:

- Capturing global and local structural responses under operational and environmental loads
- Tracking long-term trends associated with ageing and material degradation
- Supporting predictive maintenance through continuous data availability
- Enabling integration with BrIMe for enhanced digital representation

These guided the selection of monitoring locations, sensor types, and data acquisition frequency.

2. Selection of critical monitoring sections

A structural analysis, complemented by historical inspection records, was conducted to identify the most relevant locations for instrumentation. The selection criteria included:

- Sensitivity to structural behaviour
- Accessibility and feasibility of installation
- Potential for early detection of anomalies
- Representation of global and local effects

Final layout included expansion joints, critical sections, pier heads and environmental exposure zones.

3. Sensor specification

The multi-sensor system was defined according to the measurement needs and structural behaviour targets. The instrumentation selected included:

- Displacement transducers to measure vertical and horizontal movements at expansion joints
- Strain gauges at predefined transverse sections
- Inclinometers positioned at the top of the piers
- Concrete temperature sensors embedded in the deck
- Ambient temperature and humidity sensors placed in representative sheltered locations

Technical requirements such as accuracy, durability, environmental protection, and expected ranges were defined during this stage.

B. APPLICATION STAGE

4. Sensor installation

The selected multi-sensor network was installed following manufacturer specifications, team experience and site constraints. Installation included:

- Mounting displacement transducers at the expansion joints
- Bonding and protecting strain gauges
- Fixing inclinometers on the pier tops
- Embedding concrete temperature sensors
- Positioning environmental sensors in appropriate locations

Special attention was given to anchorage, cable routing, environmental protection, and minimisation of electrical noise or measurement drift.

5. Data acquisition system configuration

A centralised data acquisition unit (DAU) was installed to manage sensor communication, power supply, and local data handling, and was configured to:

- Record data from all sensors periodically
- Synchronise timestamps across all channels
- Apply initial filtering to remove outliers or communication errors
- Transmit data remotely to a secure server for long-term storage

The one-hour sampling frequency was selected to balance structural insight with data volume and energy consumption.

6. Data collection and storage

The system operates continuously, and each acquisition cycle involve:

- Capturing raw sensor readings (displacement, strain, rotation, temperature, humidity)
- Buffering data locally within the DAU to avoid losses
- Automatically transmitting data to a remote server using secure protocols
- Archiving all records in a structured database for long-term analysis

Redundancy measures were applied to ensure data preservation during communication interruptions.

7. Data processing and quality control

Collected data undergo a multi-stage processing workflow to ensure reliability and usability:

- Signal filtering to remove noise or spikes
- Environmental compensation to distinguish structural effects from temperature variations
- Trend analysis to identify long-term behavioural patterns
- Cross-correlation between sensors to consistency check (e.g., strain vs. temperature validation)
- Event detection for unusual movements or rotations

Quality-control tasks include periodic calibration and comparison with expected structural responses.

8. Data export and integration into BrIMe

Processed data are exported in standardised formats to ensure interoperability with the BrIMe platform.

Integration includes:

- Mapping sensor locations onto the geometric model
- Linking time-series data to corresponding structural elements
- Updating the digital twin with real-time and historical measurements
- Visualising structural responses within the BrIMe environment
- Supporting model calibration through comparison of measured and simulated behaviour

This workflow enhances the bridge's digital representation and supports diagnostics and maintenance planning.

A final stage of the methodology, focuses on the practical use of monitoring outputs by engineers and asset managers, can be defined between all stakeholders. This supports routine condition assessment through dashboards and automated reports, enables emergency evaluation after extreme events such as thermal anomalies or unusual traffic loads, facilitates predictive maintenance planning based on long-term trends, and enhances decision-making models.

4.2. Data integration into BrIMe

This main contribution of the current work is focused in enabling the integration of the actual SHM procedures in BrIMe. The IFCBridge schema provides the formal, standardised data structure required to represent bridges digitally within open BIM environments. As part of the IFC 4.3 family, IFCBridge defines the semantic, geometric and organisational structure of bridge components, enabling vendor-neutral interoperability across design, analysis and asset-management software. In this sense, it forms the foundational information layer on which BIM is built. The model uses the IFCBridge schema to represent bridge elements, relationships and properties consistently throughout the project life-cycle, allowing engineers to develop coordinated information (TMU, 2025). Building on BrIMe extends this concept by integrating additional data streams – particularly those derived from SHM systems – into the digital model. Because IFCBridge provides a structured and spatially coherent representation of bridge elements, SHM measurements can be mapped directly to the corresponding model components, enabling time-series data, inspection records and performance indicators to be linked to the physical asset.

Figure 5 illustrates the workflow used to structure the digital representation of a superstructure element within the IFCBridge environment. The workflow begins with the *IfcBridge* entity, which defines the highest level of representation of the infrastructure in the IFCBridge schema (buildingSMART, 2021). From this root entity, the model is subdivided using *IfcBridgePart*, which categorises major subsystems such as the superstructure or substructure. In this case, the relevant element belongs to the superstructure. The structural component of interest is represented by *IfcBeam*, which constitutes the central object within the workflow and serves as the container for the geometric and semantic information associated with the bridge trust. Once the trust entity is defined, it is enriched

with three key types of information: material, structural properties, and geometry. Material assignment is carried out using the `IfcMaterial` entity, which specifies the physical composition of the element, such as concrete class, reinforcement characteristics, or prestressed concrete options. This level of material detail supports downstream engineering applications, including numerical modelling and structural performance assessments (ISO 16739-1, 2020). In parallel, structural behaviour is captured through `IfcStructuralElementProperties`, which stores engineering attributes such as modulus of elasticity, prestressing force, load-bearing capacity, and natural vibration frequencies. These properties support integration with structural analysis software and are aligned with openBIM interoperability requirements for infrastructure (Petersen *et al.*, 2022).

The geometric definition of the beam is achieved using a swept solid geometry, where the cross-section profile and dimensional characteristics are defined and extruded along a specified path. This representation is consistent with the standard methods used in IFC for prismatic structural elements (buildingSMART, 2021). After defining the geometry, the `IfcLinearPlacement` entity assigns a precise spatial position to the trust along the bridge alignment. This method is particularly suitable for infrastructure assets such as bridges, where longitudinal chainage, curvature, and super-elevation must be accurately reflected (Krukar *et al.*, 2021).

The lower section of the workflow focuses on integrating the BIM model with SHM data streams. External sensor data, represented as “Sensor XYZ”, may originate from strain gauges, displacement sensors, or other monitoring devices typically installed. These data are not stored directly within the IFC model but are linked through external references or dynamic data interfaces, consistent with current best practices for Digital Twins (Sacks *et al.*, 2020). The enriched IFCBridge model, when connected to real-time sensor data, forms the basis of a bridge BrIme, enabling structural performance tracking, anomaly detection, and predictive maintenance strategies (Opoku *et al.*, 2021).

5. Example of application

A key objective of the case study is the integration of monitoring data into a BrIme digital model of the bridge. The geometric and structural models were developed based on original design documentation, complemented by recent inspection data. Sensor locations, measurement types, and data streams were mapped onto the digital model to create a dynamic representation of the structure. The sensor data is represented as an IFC entity with: (1) location coordinates (XYZ); (2) sensor type; (3) measurement units; (4) data stream identifiers. This allows SHM data to be linked directly to BrIme.

In Figure 6, Section S2 illustrates an example of the implementation of two strain gauges installed on the upstream side of the bridge. The BrIme model provides an intuitive interface that enables easy access to structural geometry, sensor metadata, and installation records. Sensor locations are clearly marked along the bridge profile, and a zoomed-in view highlights the precise placement of the selected sensor, in this case, S2. A metadata panel displays key information about the device, including its type, model, and other relevant properties. Installation and maintenance details, accompanied by photographs, are also documented within the interface.

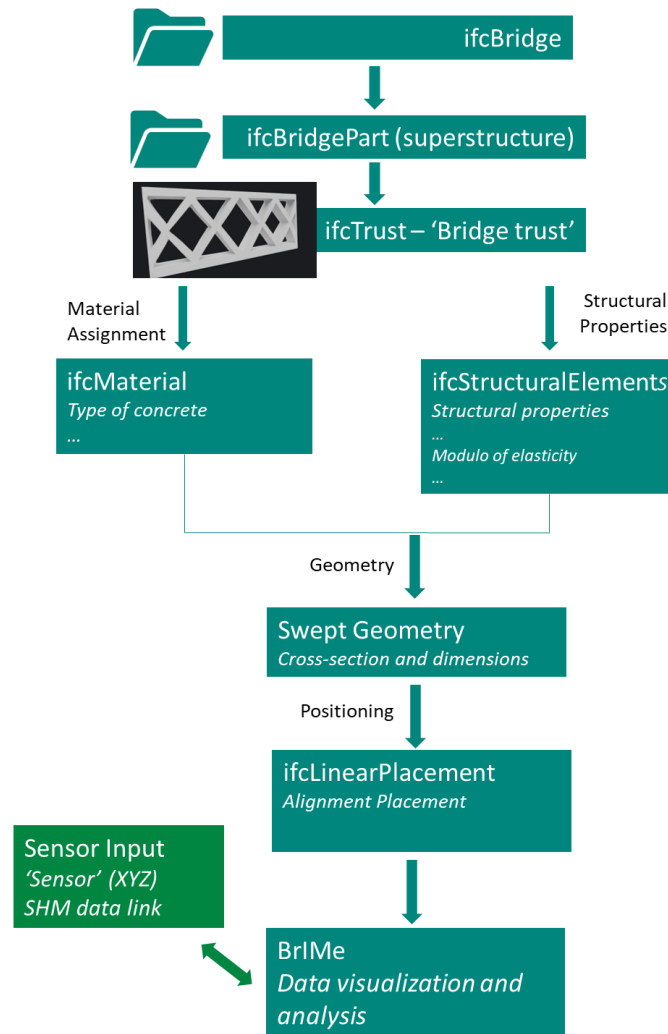


Figure 5. Flowchart for adding SHM into BrIMe

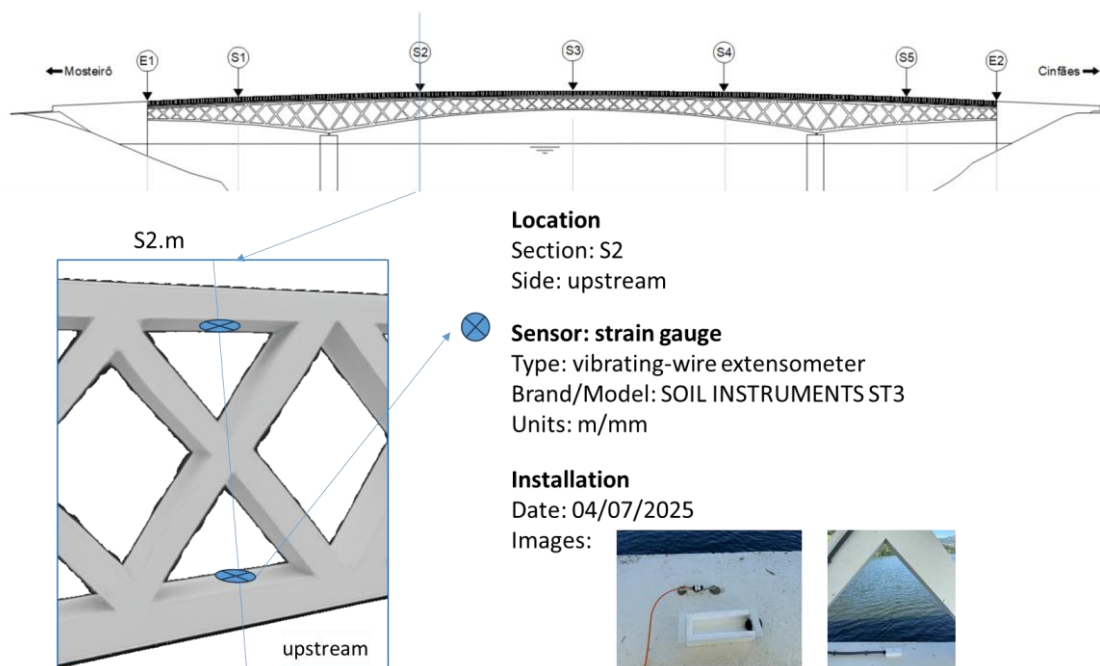


Figure 6. Example of BrIMe interface with the users'

6. Final considerations

The SHM system implemented on the Mosteirô Bridge demonstrates the feasibility and value of combining continuous monitoring with a BrIme digital environment for management of bridges. The integration of monitoring data into BrIme can significantly enhanced the bridge's digital representation, enabling real-time visualisation, model validation, and predictive maintenance planning.

Overall, the work demonstrates a practical pathway toward the digital transformation of bridge asset management. By linking sensor-based monitoring with advanced modelling tools, infrastructure owners can transition from reactive maintenance to proactive, data driven strategies that extend service life, improve safety, and optimise resource allocation. The Mosteirô Bridge serves as a case study for the broader adoption of SHM–BrIme integration. This is an ongoing work, in which the proposed methodology is currently being implemented and tested.

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