Structure and Infrastructure Engineering
Maintenance, Management, Life-Cycle Design and Performance

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/nsie20

Digital twinning during load tests of railway bridges - case study: the high-speed railway network, Extremadura, Spain

Rolando Chacón, Carlos Ramonell, Hector Posada, Pablo Sierra, Rahul Tomar, Christian Martínez de la Rosa, Alejandro Rodriguez, Ilias Koulalis, Konstantinos Ioannidis & Stefan Wagmeister

To cite this article: Rolando Chacón, Carlos Ramonell, Hector Posada, Pablo Sierra, Rahul Tomar, Christian Martínez de la Rosa, Alejandro Rodriguez, Ilias Koulalis, Konstantinos Ioannidis & Stefan Wagmeister (09 Oct 2023): Digital twinning during load tests of railway bridges - case study: the high-speed railway network, Extremadura, Spain, Structure and Infrastructure Engineering, DOI: 10.1080/15732479.2023.2264840

To link to this article: https://doi.org/10.1080/15732479.2023.2264840

STRUCTURE AND INFRASTRUCTURE ENGINEERING
https://doi.org/10.1080/15732479.2023.2264840

Taylor & Francis
Taylor & Francis Group

OPEN ACCESS Check for updates

Digital twinning during load tests of railway bridges - case study: the high-speed railway network, Extremadura, Spain

Rolando Chacón[a], Carlos Ramonell[a], Hector Posada[a], Pablo Sierra[a], Rahul Tomar[b], Christian Martínez de la Rosa[b], Alejandro Rodriguez[c], Ilias Koulalis[d], Konstantinos Ioannidis[d] and Stefan Wagmeister[e]

[a]Universitat Politècnica de Catalunya, Barcelona, Spain; [b]Digital Twin Technology, Cologne, Germany; [c]Formerly Drace, Madrid, Spain; [d]Centre for Research and Technology, Thessaloniki, Greece; [e]Austrian Standards, Viena, Austria

ABSTRACT

This article presents a case study with various developments of digital twinning of a sample of load tests performed on several railways bridges. The case study is located in Extremadura, South Western Spain and its aim is the generation of a validated, multi-layered information construct in the form of a digital twin as the result of a load test. This result is conceived, not only to verify the assumptions of the design of the bridge but also, to optimize future maintenance plans of the network. This particular case study is framed within a vaster European effort on digitization of the construction sector. Research and Innovation Actions within this demo case are aimed at integrating routine requirements and procedures of load tests with cutting edge digital technologies for the generation of validated virtual replica of these physical bridges. The generated twins during these load tests behaviourally match the obtained response during loading and as such, represent an ideal model for future simulations and behavioural predictions. Different data-gathering techniques and numerical models are integrated within a Common Data Environment (CDE). All efforts related to measurement, simulation, 3D modelling, assessment and validation can be wrapped up systematically for further use during regular operation of the asset.

ARTICLE HISTORY
Received 27 February 2023
Revised 14 June 2023
Accepted 9 August 2023

KEYWORDS
Bridge load testing; building information modelling; cyber-physical bridge; digital twins; internet of things; railway bridges; standardization; unmanned aerial vehicles

1. Introduction

The maintenance of infrastructure systems is crucial to ensure their longevity and reliability. Infrastructure systems, such as roads, bridges, and buildings, play a vital role in society and are integral to economic growth and development. Regular maintenance helps prevent structural deterioration, prolongs the lifespan of infrastructure systems, and minimizes the need for costly repairs or replacements. For these purposes, understanding the structural behaviour of a bridge is essential for ensuring its safety and longevity. By analysing the bridge's structural behaviour, engineers can identify potential weaknesses, predict how the bridge will respond to external forces, and design effective maintenance and repair plans. This knowledge is particularly important for older bridges that may have deteriorated over time, as it helps identify critical areas for maintenance or replacement and ensures the bridge's continued safe operation.

Load tests are an effective method for assessing the condition of bridges. They are carried out both for newly constructed and existing bridges to verify design assumptions, verify finite element models, evaluate material degradation, analyse heritage buildings, or try to determine the remaining life of the structure. Bridge load testing can be divided into two categories: Diagnostic Load Tests and Proof Load Tests (Lantsoght, 2019). Diagnostic Load Tests (DLT) involve applying known loads to the bridge while monitoring its structural behaviour through sensors or other types of data-collection techniques. This data is then used to validate analytical models used during design phases. On the other hand, Proof Load Tests (PLT) are more comprehensive assessments that verify the as-designed full load capacity of the bridge. Test loads are applied in multiple steps, and the structure is continuously monitored for any signs of distress or non-linear behaviour. Additionally, PLT provide a lower bound on the true strength capacity of the bridge and can also be used to validate advanced analytical and numerical models.

Bridge load testing provides a fundamental phenomenological insight about the structural response and behaviour of these assets. Routine DLT are meant to establish verified standards on the design and on the construction of a bridge (Alampalli et al., 2021). Measurements related to the response of the structure when subjected to controlled loads are taken and compared to numerical idealizations similar than those used for design (with potential changes occurred during construction). If results are within tolerances, the bridge is considered as acceptable and operations are open. While nowadays the analytical methods for predicting

CONTACT Rolando Chacón rolando.chacon@upc.edu Universitat Politècnica de Catalunya, Barcelona, Spain.

bridge responses are much more refined, and the need for convincing the traveling public that a bridge is safe has diminished, the uncertainties on the bridge's behaviour increase over time due to the effect of deterioration mechanisms. Load tests are relatively expensive. A quite considerable coordination between owners, machinery, designers, monitoring staff and construction companies is needed. The development of routine DLT represents a precious episode in bridge construction that can also be leveraged in economic terms using digitization. It is thus, interesting to extract the maximum amount of information from the bridge during these load testing episodes for the sake of constructing a comprehensive information construct.

The construction phase of infrastructure systems represents the prequel to DLT whereas the operation phase represents its sequel. Digitizing different phases of assets from the construction sector can bring significant benefits, including improved productivity, cost savings, and better safety outcomes. By using digital tools such as Building Information Modelling (BIM) or its natural evolution, Digital Twins, design. Construction and maintenance companies can collaborate more effectively, reduce errors and rework, and better manage project timelines and budgets. The use of digital tools can also improve safety outcomes by identifying potential hazards and improving communication between workers on-site. Digitization can also enable better tracking and maintenance of buildings and infrastructure, ensuring their longevity and sustainability. When it comes to Architecture, Engineering and Construction (AEC) at design, construction and maintenance phases, digitalization based on emerging and established technologies 4.0 is also called to be a major enhancer (Dallasega, Rauch, & Linder, 2018; Pregnolato et al., 2022).

Consequently, if not created during construction, DLT represent an ideal milestone for twinning bridges in digital platforms. On the one hand, specific, bespoke structural models are performed. On the other hand, measurements quantifying the structural response are taken. If both results are matched using not only basic comparisons but comprehensive digital twinning, the asset enters the service phase not only physically, but also virtually. The Digital Twin (DT) represent the natural evolution of BIM in terms of its capabilities, serving as an information system that connects the physical and virtual worlds to facilitate decision-making throughout the design, construction, and maintenance stages (Dávila-Delgado & Oyedele, 2021). To achieve this, the DT relies on the development of information pipelines, which are carefully defined paths that combine and transform measured data to yield specific insights. While advancements in sensing, data-gathering techniques, internet of things (IoT), cloud technologies, and simulation have made it possible to establish comprehensive DT (Chacón, Casas, et al., 2023), integrating these technologies into pipelines still presents technical challenges from both systems architecture and software integration perspectives. The level of automation in the decision-making process is determined by the readiness of the system of information pipelines defined within the DT.

This article presents the developments on the digital twinning of new bridges for maintenance purposes. This research is performed within the frame of the H2020 European project Ashvin, related to Digital Twins for Design, Construction and Maintenance. The project provides a series of demo cases for all stages. One of the demo cases is a series of new bridges belonging to a high speed train network in Extremadura, Spain. The case study is aimed at deploying different data-collection techniques. Additionally, bridges are geometrically virtualized using IFC Standards. On the othert hand, numerical simulations are performed according to all scenarios deployed during the load tests. All measurements are IoT transmitted and then visualized within a Common Data Environment (CDE). The article also shows how efforts related to sensing, simulation, modelling, assessment and validation can be wrapped up systematically for further use during regular operation of the asset.

2. The infrastructure: a high-speed railway network

Alta Velocidad Española (AVE), Spanish for "Spanish High Speed," is a high-speed rail service in Spain operated by Renfe, the national railway company. The speed of the trains is up to 310 km/h (193 mph). It runs on a network of high-speed rail tracks owned by Administración De Infraestructuras Ferroviarias. The trains use standard gauge, allowing for direct connections to France. Currently, Renfe operates AVE trains but private companies also operate along the line. Figure 1 shows the AVE network status as of December 2022, highlighting the different branches of "in service," "under construction," "projected," and "in partial service" (Administración De Infraestructuras Ferroviarias (ADIF), 2023).

The branch of the Highspeed Railway; Madrid-Bajadoz has been under construction in recent years. It is supposed to connect in the years to come two major European cities in nearly 3 h by train: Lisbon and Madrid. The map provided in Figure 1 also shows its specific location. Its origin is some 50 kilometers South of Madrid and then the line goes South-West direction towards Badajoz. Presently, it has been built only on the Spanish side. The length of the double line from Madrid to Badajoz is 437 kilometers and it includes several viaducts, bridges, culverts and tunnels. European funds (FEDER) under the challenge of sustainable transportation helped developing this strategic infrastructure. Figure 2 displays a schematic overview of the major stations connected by the line in this specific.

In the specific segment between Plasencia and Cáceres, all viaducts and bridges were tested before service by Drace, a Spanish firm that collaborated within the research project. A total of 19 viaducts were tested covering an approximate length of 8 km of Viaducts. Three types of structural types (cross-sections) are identified:

- Pre-stressed twin concrete box girders, which represents approximately 42% of the total length. Eight viaducts with identical prefabricated girders (with varying length though) belong to this category A.

Figure 1. High speed railway network. Spain. December 2022. De HrAd. CC by-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=17338661.

Figure 2. High speed railway network Madrid-Extremadura-Portuguese border. Spain. December 2022.

- Pre-stressed single-cell concrete box deck, which represents approximately 42% of the total length. Eight viaducts with identical prefabricated decks (with varying length though) belong to this category B.
- Continuous multi-cell concrete box deck, which represents approximately 16% of the total length. Three in-situ casted bridges belong to this category C.

In addition, a series of culverts with varying length (up to 20 m span) also belong to the set of assets under testing. Last but not least, the specific segment includes two concrete arches. Almonte Viaduct (384 m) and El Tajo Viaduct (324 m), which represent two milestones of bridge engineering in Spain.

Access to certain load tests was given to the research project by Drace and ADIF. Moreover, available information and measurements performed by Drace were shared for research purposes. Access to the sites together with prior access to the logistics of the load tests (values of loads, distances between axles) allowed the development of actions for the digitalization of three specific assets. The following sub-section depicts these bridges.

3. The assets

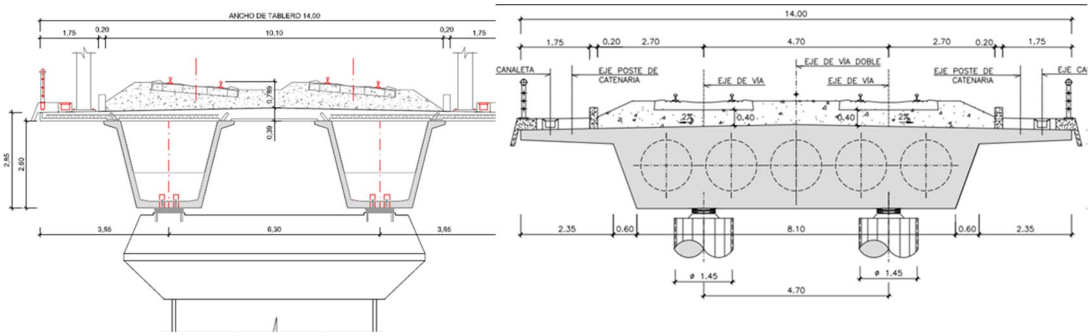
Two viaducts and one culvert have been selected for the development of digital twinning during load testing. For the formers, the study is comprehensive. For the latter, the study is limited to the generation of drone-based point clouds. One viaduct consists of eight simply supported beams whereas the another viaduct consists of a continuous element. Both structural types are repetitive throughout the depicted railway, which adds usefulness to the case study. The former is called Valdelinares Viaduct. It is an 8-spanned structure with a total length of 280.4 m. Figure 3a displays a drone-view of the Viaduct. The latter is called la Plata Viaduct. It is a 4-spanned continuous beam with a total length of 114 m. Figure 3b displays a drone-view of the Viaduct. Valdelinares has a twin concrete girder cross-section (category A, Figure 4a) whereas la Plata has an *in situ* casted pre-stressed concrete deck (Category C, Figure 4b).

The particular case of the culvert has been used for the generation of digital models of the asset using drones. These assets are quite repetitive in these types of infrastructure systems. Drone-based reproduction may represent a cost-efficient way of generating accurate virtual representations. Details on this specific topic are given in section 6.5.

(a) Valdelinares Viaduct. 8 simply supported spans

(b) La Plata Viaduct. 4-spanned continuous concrete beam

Figure 3. Structures under study.



(a) Valdelinares Viaduct

(b) La Plata Viaduct

Figure 4. Structures under study.

4. Load tests in bridges

4.1. Load test practice

The current governing codes and guidelines for DLT in the United States are the 1998 NCHRP Manual for Bridge Rating through Load Testing and Chapter 8 of the American Association of State Highway and Transportation Officials Manual for Bridge Evaluation (AASHTO, 2016). Over the last two decades, the practice of load testing has evolved, and its intersections with other fields have expanded. Given these developments, a new Transportation Research Board (TRB) Circular, Primer on Bridge Load Testing, has been developed. Several countries have national codes or guidelines for load testing. The German guideline (Deutscher Ausschuss für Stahlbeton, 2000) was developed for load testing of plain and reinforced concrete structures that are flexure critical. The guideline for load testing from the United Kingdom (National Steering Committee for the Load Testing of Bridges of the Institution of Civil Engineers, 1998) only deals with diagnostic load testing. In Ireland, a manual for load testing (National Roads Authority [NRA], 2014) considers diagnostic load testing of older metal and concrete bridges as an accompaniment to assessment calculations. In Switzerland, load testing is used for the assessment of existing bridges and is included in the SIA 269:2011 code (Schweizerischer Ingenier- und Architektenverein [SIA], 2011). In Hungary, the serviceability of existing structures can be verified through load testing (Hungarian Chamber of Engineers, 2013).

Load testing requirements for railway bridges in Spain are governed by NAP 2-4-2.0 (Administrador De Infraestructuras Ferroviarias [ADIF], 2021). ADIF is responsible for managing the entire Spanish high-speed railway network. As per Spanish regulations, DLT must be conducted on bridges in newly constructed lines as a transition from construction to operation, but they can also be performed on bridges in existing lines for routine checks or proof load tests in response to specific incidents. NAP 2-4-2.0 outlines the procedures for both static and dynamic tests to assess the structural performance of the bridges. All loads for the described load tests were provided by ADIF in form of locomotives and loaded wagons. A 313 series locomotive (82 tons), a 308 series locomotive (82 tons) and two Requena Wagons (63 tons) and another FACSS (80 tons) were provided for the generation of load combinations, which were designed at less than 60% of the service loads, as indicated in these specifications.

Static tests involve applying various load configurations along the length of the bridge to account for all unfavorable load scenarios. The testing process has five steps: (1) taking measurements with the bridge unloaded, (2) positioning vehicles according to the load configuration, (3) maintaining the load until the deformed shape of the bridge is stabilized, (4) unloading the bridge, and (5) taking measurements until the bridge returns to its original shape. Additionally, a test with quasi-static loading is performed, where a moving load is passed over the bridge at a reduced speed (5–10 km/h).

Dynamic tests evaluate the bridge's response to moving loads. At least three types of tests must be conducted, including the vehicle passing over the bridge at an intermediate speed, the vehicle passing at the maximum authorized speed, and the vehicle breaking while passing over the bridge at maximum speed. These load tests are complex and costly procedures that require experienced personnel, proper planning, and appropriate equipment. The testing process is summarized in a flowchart in Figure 5.

4.2. Sample of results obtained in the case studies

Load tests on the set of bridges located along the Plasencia-Cáceres branch of the network were systematically performed by Drace (formerly Geocisa) according to NAP 2-4-2.0. In the vast majority of load tests, 25 mm range (≈ 0.02 mm accuracy) Linear Vertical Differential Transducers (LVDTs) and PL-60 strain gauges were employed together with accelerometers (PCB Piezotronics 393 B12). LVDTs were placed to measure deflections at mid-spans. Additional LVDTs were deployed at supports for measuring bearing displacements. Strain gages and accelerometers were placed at the centre of each span to measure local strains and accelerations. After measuring, files containing time-series data were collected. Figures 6 and 7 display representative samples of measurements related to static tests (deflections and strains) and dynamic tests (accelerations) respectively. Figure 6a presents measurements on deflection at Valdelinares when loading span 3. The step-wise nature of the plot shows how the load is gradually increased (one locomotive first, two locomotives subsequently) and decreased. As indicated in NAP 2-4-2.0, loads are sustained in time for stabilization purposes.

Figure 6b displays the longitudinal strains measured at mid-span 2. Static data were processed to obtain maximum deflections and strains for each span of the bridge, as well as shape recovery rates after loading. Then, results were compared with deformation and deflection values obtained from the physical model for subsequent calibration. All measured magnitudes provide results as Time-Series. Dynamic measurements were used to calculate vibration modes and frequencies, which are also directly compared with the corresponding results in the physical model.

4.3. Comparisons between predictions and measurements

In all viaducts, measurements from accelerometers were used to calculate vibration modes and frequencies. These values

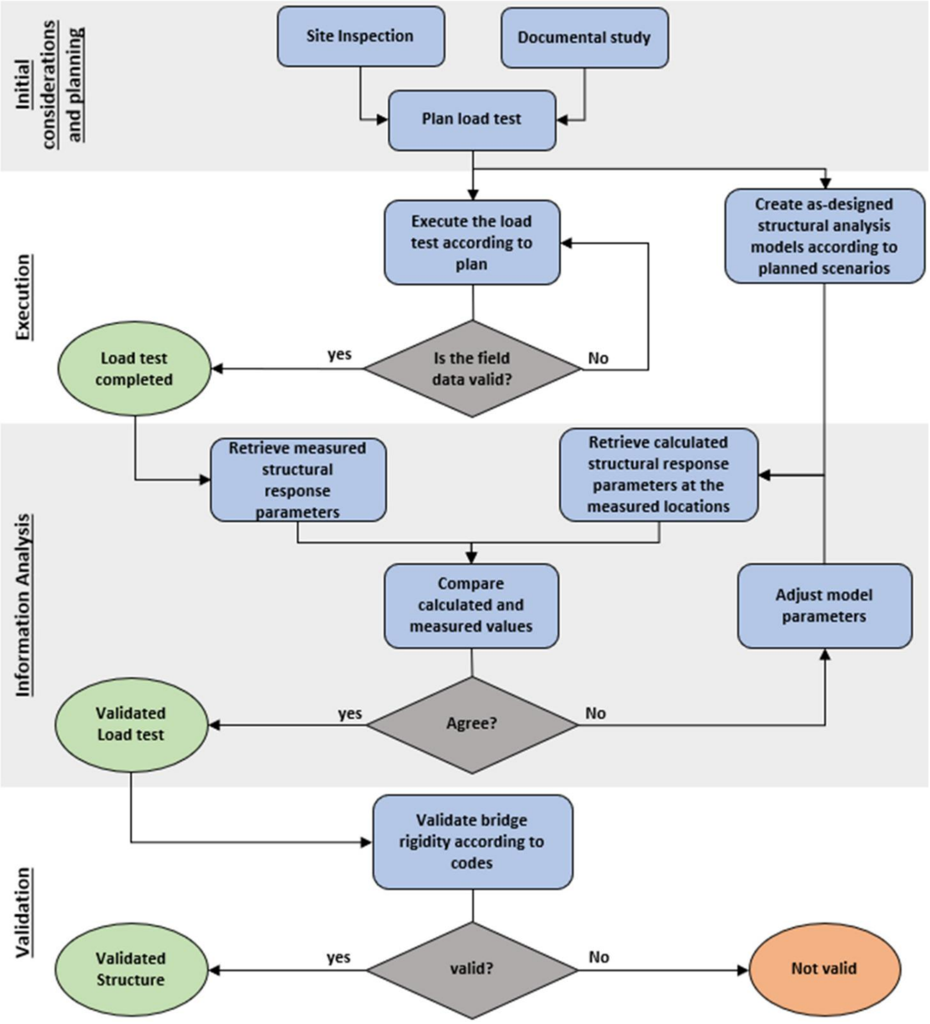


Figure 5. Flowchart of the load test procedure according to NAP 2-4-2.0.

are directly compared with the corresponding predictions given by numerical models. Figure 8 depicts the relationship between the frequency obtained from the measured acceleration and the predictions given by numerical models for four modes.

The obtained values are summarized in Table 1. The predictions correctly reproduce the dynamic behaviour of the structure. The comparison between physical and numerical values range between 91 and 119%, which according to the Standards, satisfy the load test verification of the models. These values are of the utmost importance for the verification of assumptions taken while modelling the bridge during design. These values represent an interesting starting point for these structures. Potential changes in these values may warn about alterations in the structural behaviour of the beams.

5. Leveraging load tests for enabling the digital birth of bridges

Load tests are expensive. Complex logistics, human resources and specialized equipment are mobilized by bridge agencies, owners and construction firms during these episodes. These resources put together result on detailed reports with adequate comparisons between the behaviour of the real asset and its corresponding prediction models as depicted in Section 4.3. Nonetheless, integrating information in a digitally comprehensive way would not add an excessive cost to the episode. Prediction models, measurements and reports are required anyways. As a result, load tests represent an ideal milestone for twinning bridges in digital platforms. On the one hand, specific, bespoke structural models are performed. On the other hand, measurements quantifying the structural response are taken. If the information is stored digitally and coupled with the corresponding geometrical models of the bridge, an open information construct of the asset (namely, its digital twin) can be established as a tool for maintenance purposes.

The challenge consists of integrating different layers of data in an interoperable, useful and retrievable way. Figure 9 shows some of the potential layers one can organize in the form of a digital twin. BIM models, numerical models, measurements, standards for procedures and validation, and many other layers erect the frame of this information

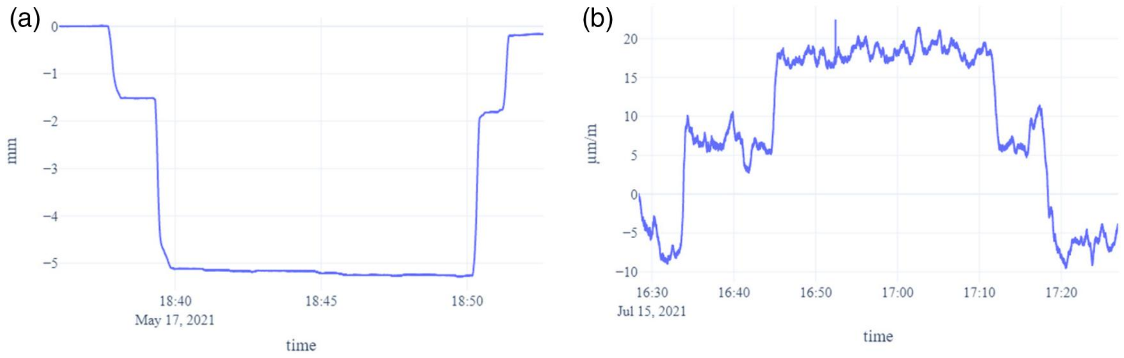


Figure 6. Static test. (a) Valdelinares. Deflection at mid-span 3 (b) La Plata. Longitudinal strain mid-span 2.

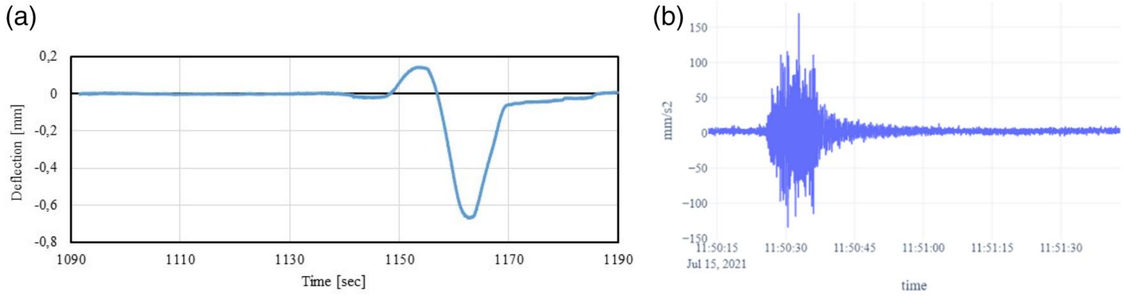


Figure 7. Dynamic test. (a) Valdelinares. Deflection at mid-span 3 (b) La Plata. Longitudinal strain mid-span 2.

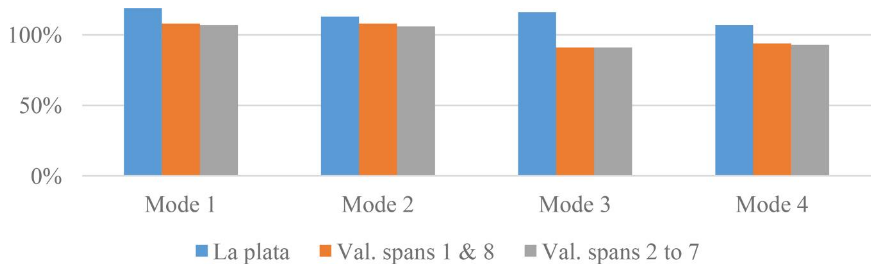


Figure 8. Relation between measured and numerical vibration frequency.

Table 1. Obtained vibration frequency values and comparison.

Bridge under study		Mode 1	Mode 2	Mode 3	Mode 4
Predictions	La Plata	3,82 Hz	5,31 Hz	7,13 Hz	9,42 Hz
	Valdelinares (Outer spans)	3,90 Hz	4,36 Hz	6,81 Hz	7,64 Hz
	Valdelinares (Inner Spans)	3,87 Hz	4,23 Hz	6,74 Hz	7,50 Hz
Measured / Predicted Ratio	La Plata	119%	113%	116%	107%
	Valdelinares (Outer spans)	108%	108%	91%	94%
	Valdelinares (Inner Spans)	107%	106%	91%	93%

construct. Presently, most of this information is already gathered during the life cycle of the asset but stored in a disaggregated form. This information construct is, however, open to many potential formats, layers and forms of organization of the information. One essential aspect though, would be to conceive the load test in such a way that the generated data is useful for many other stakeholders during the operational phase. If information can be embedded seamlessly using compatible formats, seamless pipelines of information are enabled. Scalability and capabilities for updating systems is needed as in all computer systems. Figure 9 illustrates some of the layers of information that may contribute to the same CDE.

6. Exemplary actions for twinning load tests

The depicted routine load tests have allowed developing exemplary actions for the sake of virtualizing the asset. This virtualization is conceived in a way that the result is useful during operation. Maintenance planners can make use of the centralized information, revisit the load test status or track potential changes on those assets. In subsequent inspection episodes, information can also be added to the same information construct. The following subsections show the hitherto developed actions. Further developments are expected to be included by the end of the Research and Innovation (R&I) Action project Ashvin. This article shows an overview of the digital twinning of the assets. Additional technical specs for the informatics of the system in this demo case are provided in Ramonell and Chacón (2022).

6.1. Common data environment and IoT platform

In this R&I Action, the DT platform oriented to end users is conceived as a common data environment in which all sources of information are visualized, treated and leveraged. The platform is vast-scoped and it is based on a game engine developed in Unity Technologies (2021) with several embedded tools conceived for providing assistance and thus improving design, construction and maintenance of infrastructure systems. Assets are twinned with interoperable geometrical entities and on top of the geometry, the toolkit provide access to information, analysis and decision-making capabilities. Users can grasp relevant information from the real asset, from simulations, or from historical data. Accordingly, users can have a comprehensive vision of the asset during its corresponding stage under development. Figure 10 shows a geometrical representation of one of the twinned bridge within the platform (namely, La Plata Viaduct). IFC standard formats can be converted to the platform together with its corresponding metadata. On the other hand, all displayed tools perform specific functionalities at all stages (design, construction, maintenance).

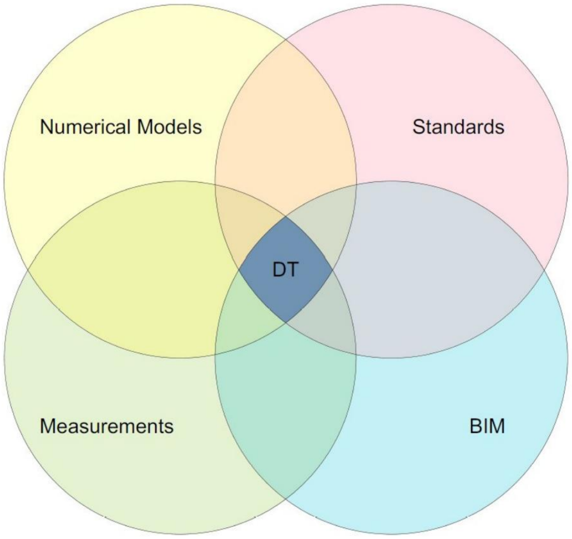


Figure 9. Different information layers that can be added to the digital twin.

Information from sites requires proper collection, transmission and storage. Information is orderly transmitted, stored and retrieved using Mainflux (2023), an open-source IoT platform. Mainflux is high performant, scalable with a small memory footprint that can operate both in the cloud as well as on edge devices. Supports out of the box protocols widely used for sensor data (MQTT, HTTP, CoAP, LoRA) and can be easily be extended with additional protocol support since it is being built following a micro services paradigm. Data can be sent in SenML (standardized format for sensors), JSON or CBOR. Mainflux is based on user-defined entities called: (i) things and (ii) channels. These are managed by the user as building blocks for setting up a meaningful data-collecting environment. Things usually represent devices (although it may also be an application) which publish/consume data. Channels represent a way of organizing, structuring, sharing data between things (devices).

Data being published to the platform is available as a stream *via* MQTT, Web-Socket or alternatively, it can be retrieved from the structured time series database *via* a REST API. The most basic form of the setup requires that the user creates a thing, a channel and then connects both. Each user requires authentication. After a device is set with thing credentials and topics to which the device should send messages (normally measurements from sensors). Additionally, for enhanced security, x509 certificates can be provided for things and deploy them to the device enabling mTLS. It means encryption both on server and on client (device).

During the load tests, both static and dynamic measurements were taken (with a sample rate of up to 200 Hz), a high volume of data has been ingested in a relatively short period of time. Mainflux requires robustness when it comes to such levels of sampling rate to avoid data traffic congestion. Load tests can also include developments based on edge analytics where additional services can be deployed along with a minified version of Mainflux on the edge. For instance, the whole time series can occasionally be characterized by a reduced version of data (a vector of Eigenmodes and its associated damping). Thus, the computation can be performed closer to the data origin and thus minimizing data that needs to be transferred to the cloud. These results can be thus sent to many other specific applications for simulation, calculation, surrogate models, BIM, or many other stakeholders.

6.2. Geometrical models

BIM models were created in Revit from PDF drawings provided by collaborators. The model is shown in Figure 11 and it is based on structural framings and slabs. All models are conceived for IFC subsequent interoperability. Using Rhino.Inside.Revit, a Grasshopper plug-in, parametric models were built in order to access the topological components of a three dimensional Brep (body, face, edge and vertex). This option enables the model for further discretization of cross-sections to perform fiber-based elastic or inelastic analysis or to generate enriched IFC files.

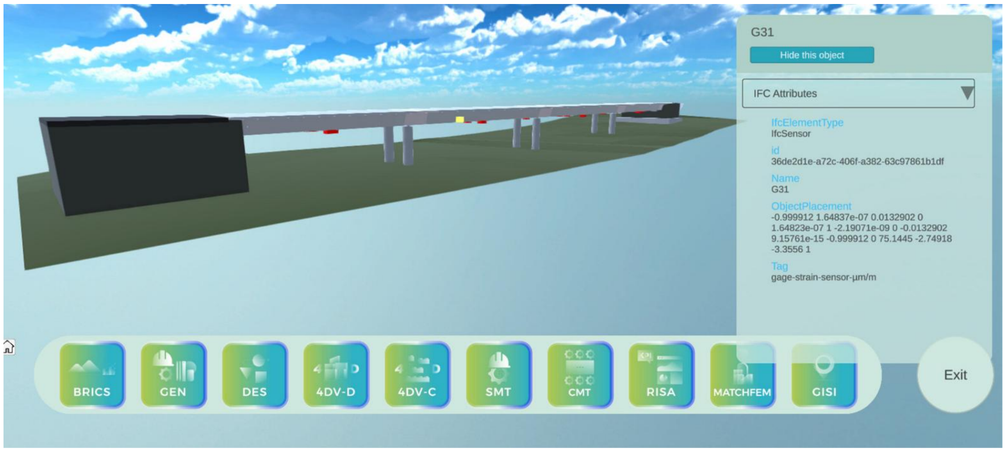
6.3. Numerical models

Numerical models were preliminarily created with propietary Licence Software (MIDAS Civil). Subsequently, the model was updated to the data flow using codes found in MatchFEM (Chacón, Casas, et al., 2023), one of the tools embedded in the CDE depicted in section 6.1. For La Plata, frame elements supported as a continuous beam represents the pre-stressed concrete deck. On the other hand, for Valdelinares, simply supported frame elements were used for idealizing beams with two pre-stressed concrete girders. In the preliminary models, beams are connected with rigid links to shell elements representing the concrete slab.

6.3.1. Static analysis

Statics load tests simulations were performed applying uniform loads on the FE models. These loads represent the actual live loads produced by the locomotives and wagons, considering all loads hypothesis. For dynamic load tests, vibration modes were determined. Figure 12 presents a sample of results.

In the context of load testing, validation and verification of structural performance require a close match between the mechanical properties of the materials and the assumed values at the design phase. Due to the heterogeneous nature of concrete and its evolution overtime, the presumed mechanical properties may not align with the real values. An accurate calibration of the material becomes of utmost importance, especially in singular infrastructures such as bridges.



IfcElementType
IfcSensor

id
36de2d1e-a72c-406f-a382-63c97861b1df

Name
G31

ObjectPlacement
-0.999912 1.64837e-07 0.0132902 0
1.64823e-07 1 -2.19071e-09 0 -0.0132902
9.15761e-15 -0.999912 0 75.1445 -2.74918
-3.3556 1

Tag
gage-strain-sensor-µm/m

Figure 10. La Plata Viaduct featured in the developed platform.

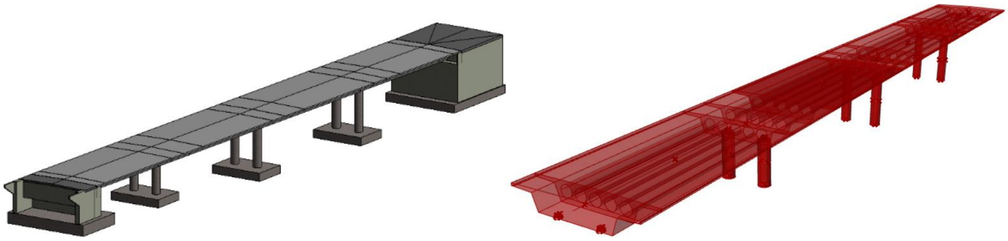


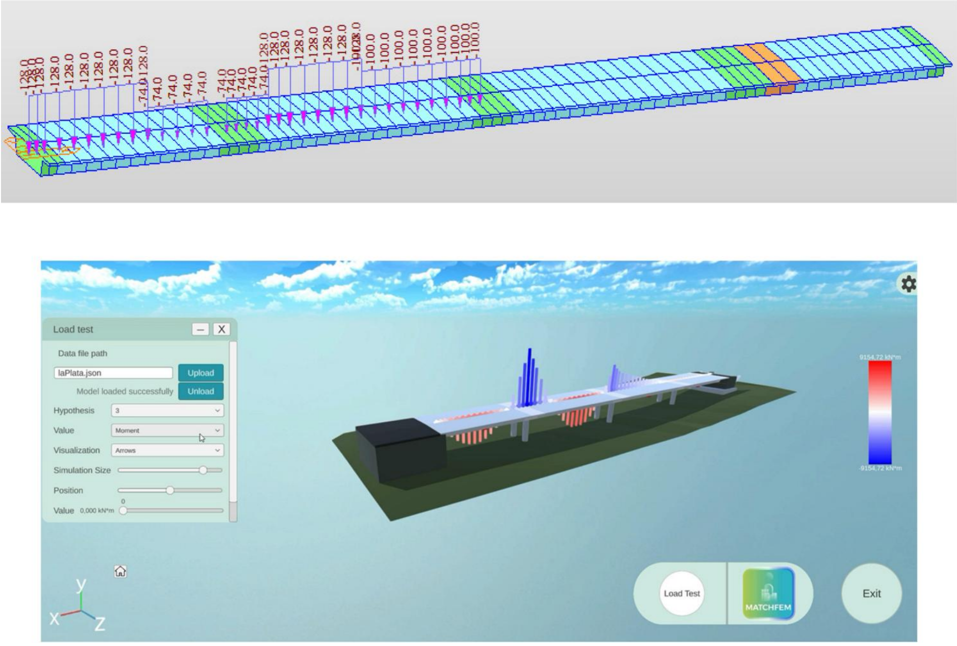
Figure 11. Geometrical representation of la Plata Viaduct.

To perform simulations of the time-dependent structural behaviour of the assets in its Digital Twin, a previously developed numerical model was implemented (CONS, Marí, 2000). The simulations generated by the model were adapted to match sensors, geometries and analysis in the CDE. The model allows for the development of nonlinear and time-dependent analysis for three-dimensional reinforced and pre-stressed concrete. To enhance its functionality, CONS was integrated into a graphical environment utilizing Rhino and Grasshopper parametric software. This environment allows the discretization of complex cross-sections and the construction of fiber-based models. Employing visual programming scripts, multiple parameters such as the bridge cross section shape, filaments for discretization, constitutive models of materials, pre-stressing loads and tendons, and internal loads, are set up. This parametric approach enables a structural analysis where any modification to the input data dynamically changes the results, facilitating the calibration of material mechanical properties by providing a responsive feedback loop.

In Figure 13, the parametric fiber-based model of the La Plata Viaduct's cross section is presented, showcasing the assembly process and results. This model allows the accurate matching of strains measured at sensor locations with the corresponding fiber strains. By employing reverse engineering techniques, it is feasible to calibrate the elastic modulus of the concrete, enhancing the verification of the structural performance. Results are then integrated into the CDE providing valuable data for maintenance during the operation stage.

6.3.2. Dynamic analysis

Regarding the dynamic analysis, the series of acceleration data obtained during the dynamic tests are pre-treated and processed to obtain the main vibration frequencies of the structure, as well as the modal shapes and the associated dynamic damping. For this purpose, Multiple Operational Modal Analysis Platform (MOMAP) was used. This code was developed in Python for signal analysis. The application performs the following steps. In data pre-treatment, the signals are processed to reduce noise and eliminate frequency content outside the range of interest of the signal, to avoid misinterpretation of the analysis results and to increase the accuracy of the structural values obtained. This includes the option of applying a digital high-pass filter, selecting the cut-off frequency, applying a downsampling technique with



Load test

Data file path: laPlata.json

Model loaded successfully

Hypothesis: 3

Value: Moment

Visualization: Arrows

Simulation Size

Position

Value 0,000 kN*m 0

Figure 12. Numerical models of la Plata. Load case 1 and results implemented in the CDE.

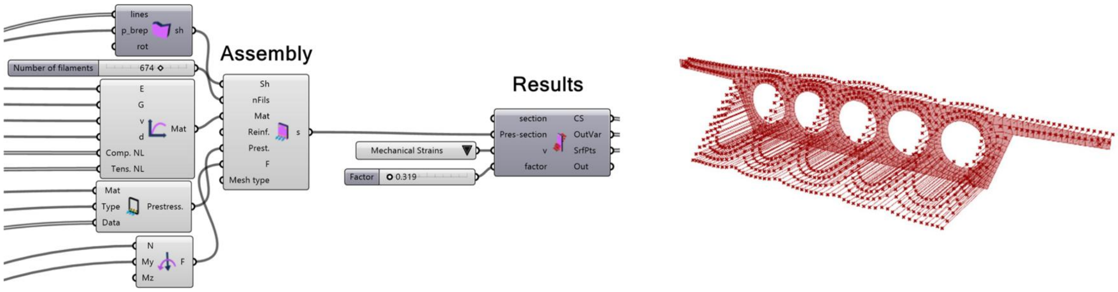


Figure 13. Parametric fibre-based model of La Plata Viaduct cross section.

a selectable factor, and applying a noise reduction algorithm based on decomposing the signal into singular values.

Data analysis consists of obtaining the dynamic parameters of the structure. Various OMA techniques are available, which have the advantage of not needing to control or know the load applied during the test, are fast and data gathering does not interfere with the regular operation of the asset, in comparison of traditional experimental modal analysis, in which loads need to be controlled. These algorithms only require as input the response of the structure, in this case, accelerations to dynamic disturbances. Following methods are available for the analysis, for details see references: Enhanced version of the Frequency Domain Decomposition (Brincker, Zhang, & Andersen, 2001; Gade, Møller, Herlufsen, & Brüel, 2005) and Covariance-driven Stochastic sub-Space Identification (Ho & Kálmán, 1966). MOMAP includes connection with Mainflux and SQL databases, from where measurement data series are obtained. This tool represents an exemplary application of third parties integration within the data environment (Figure 14).

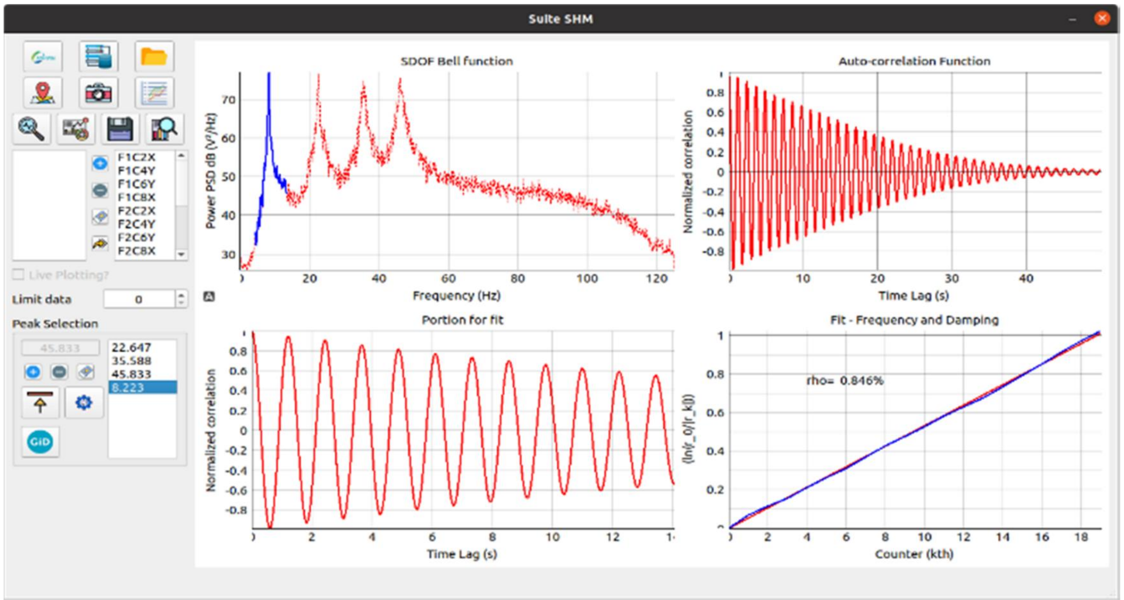
6.4. Images and reports

Many types of data can be collected. Imagery, or other reports can be included as a way of documenting the initial conditions of the asset. All this gathered information can be used in subsequent maintenance or reparation episodes during the asset life-cycle. Basic use of imagery for reporting is already of great use. Load tests often includes many load cases and hypothesis that are further documented. Zenithal and/or isometric views of such instants helps managers to understand and gain confident about the results documented in other forms. Figure 15 show examples of imagery (which is also available in video form) corresponding to La Plata Viaduct when subjected to two different load hypothesis.

6.5. Drone-based 3D digital representation for digital twinning of bridges

Another aspect examined in the context of this work is the use of drones to scan the bridges of our use case scenario autonomously or either with reduced human supervision to deliver a photogrammetry 3D model. High-quality Digital 3D models are key to creating digital twins and visualizations that facilitate the sharing of knowledge between working groups, contributing to a broader understanding of a building or a construction environment. However, obtaining 3D models of the physical buildings and landscapes is labor-intensive when done manually using hand-held devices. The ability to capture an extensive model of the building is often limited due to physical constraints such as the size of large constructions. Alternatively, commercial 3D reconstruction solutions involve using high-end LiDAR sensors, which increase the cost of the 3D scanning (Liao, Zhou, & Yang, 2021).

Recently, the use of unmanned aerial vehicles (UAVs) has increased, particularly with the integration of artificial intelligence, which has opened up new applications that can support the acquisition of a higher level of understanding of an environment (Mauriello & Froehlich, 2014; Spreitzer, Tunnicliffe, & Friedrich, 2020). The success of using drones as remote sensors is based on high-resolution topographic models through inexpensive equipment. Moreover, in the last few decades, a combined interest from both the computer vision and robotics communities have brought them together working on techniques such as Structure from Motion (SfM) (Westoby et al., 2012) and visual Simultaneous Localisation and Mapping (SLAM) (Steder, Grisetti, Stachniss, & Burgard, 2008) for robotic navigation and augmented and virtual reality applications, which are becoming increasingly popular. The interdisciplinary approach to the robotic vision problem promoted further research for real-time methods that could organise the



☐ Live Plotting?

Limit data 0

Figure 14. Signal analysis using operational modal analysis tools.

spatial information of multiple images in a sequential manner to structure 3D models. Recent advances in deep neural network research and the enhanced processing capabilities of GPU graphics have led to the increasing use of neural networks to reconstruct models and extract features from complex 3D scenes.

The parallel success of 3D representation algorithms and drones heightens the interest in developing robust frameworks for building and construction monitoring and inspection (Shim, Dang, Lon, & Jeon, 2019). Furthermore, the latest developments in Instant Neural Radiance Fields (Müller et al., 2022) offer a promising new approach to generating images from unseen viewpoints and creating neural renderings, surpassing conventional 3D reconstruction techniques in both scene accuracy and speed of reconstruction.

The H2020 project Ashvin has leveraged these technologies to implement the Image-Based 3D representation (3DRI) method for the instant representation of 3D models based on visual information captured by drones, as demonstrated in Figure 16. In our examined use cases, bridges pose a significant challenge for digitization due to the unavailability of plans in digital format and the complexity of their geometry. The 3DRI method, employing drones to capture visual data, offers a cost-effective and flexible alternative for generating accurate 3D models of bridges, providing a comprehensive representation of their geometry and contextual information. The 3DRI method's portability and

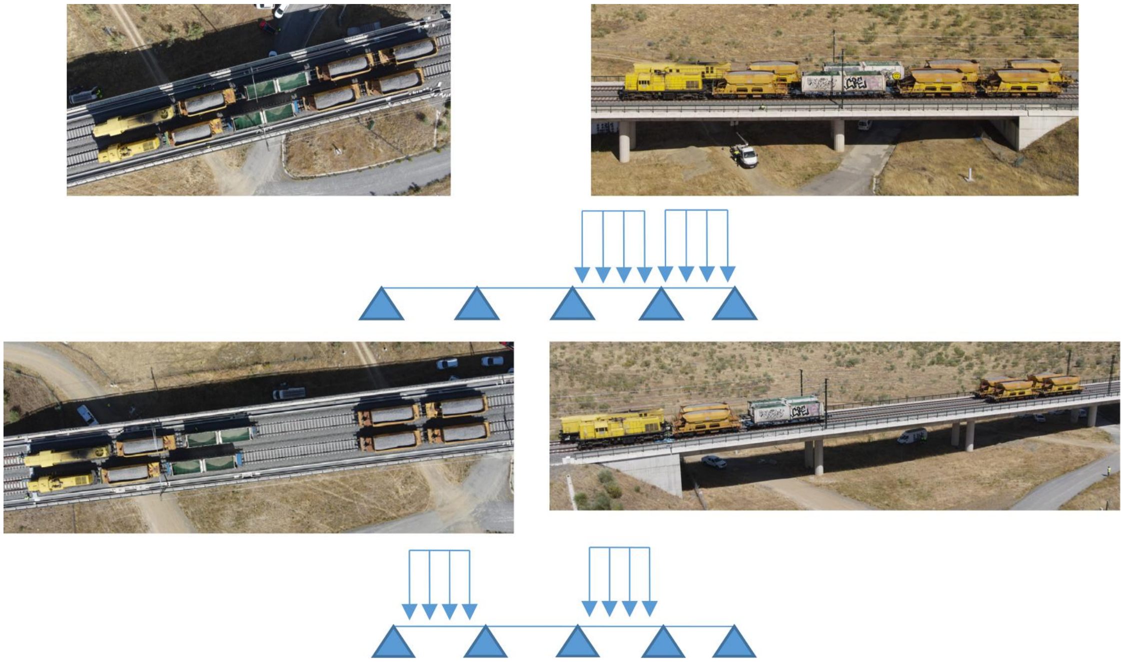


Figure 15. La Plata Viaduct. Exemplary load cases.

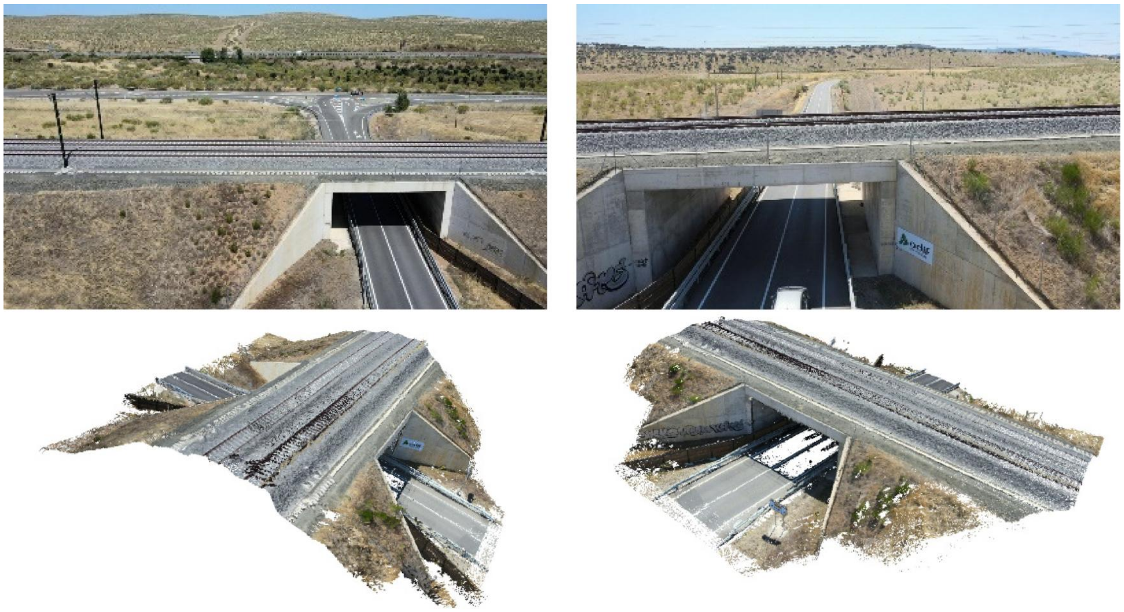


Figure 16. Example of an image-based 3D representation generated using the 3DRI method.

suitability for outdoor environments make it a practical tool for digital twinning of infrastructure assets.

6.6. Lidar-based 3D digital representation for digital twinning of bridges

Laser scanning is a reality capture technique that results in large point clouds that accurately represent the geometry of 3D objects. A point cloud is an unordered collection of points that store its coordinates (x_i, y_i, z_i) in a specific coordinate system, as well as other properties that allow determining the color and the type of surface being scanned. Laser scanners are nowadays readily available in the market, and they are performant devices that are able to capture the geometry of large entities with sub-millimetric accuracy within minutes. The challenge behind using this technique is processing the resulting point clouds (Riveiro & Lindenbergh, 2019) which usually contain millions of unstructured points from which geometrical features need to be abstracted. The assets depicted in this research have not been directly measured with laser scanners. It is, however, interesting to point out its usefulness and potential during episodes of load testing.

6.7. Ground-based interferometric synthetic aperture radars for digital twinning of bridges

GB-InSAR is a reality capture technique of great interest in large span bridges or intricate geometries. RADAR is a short form for Radio Detection and Ranging systems. The basic working principle of all the radio systems is the same. The radio uses a transmitter to produce an electromagnetic signal that is then propagated into the space using an antenna. When this signal strikes an object, it gets reflected back, and this reflected signal is known to be the echo signal. When the antenna detects the echo signal, it gets fed into the receiver. The assets depicted in this research have not been directly measured with GB-InSAR. However, two long-spanned arches of the same highspeed railways were measured using GB-InSAR during load tests due to their size (Rodriguez-González et al., 2022). It is, however, interesting to point out its usefulness and potential during episodes of load testing for some specific cases.

7. Discussion

This article presents actions for collecting data for digitally twinning a bridge during a load test, however, there are still many open gaps to be addressed in future works. First, there is still a gap in how all this layers of information can be effectively contextualized a made accessible through a single API. This is essential for end users, which will generally be infrastructure managers. Information may come from many different sources and third parties (in this exemplary case study, tools and methods come from many sources such as advanced structural analysis (CONS, in its Grasshopper version or MOMAP, in its Python version) or such as photogrammetry-based point clouds (3DRI). End-users require meaningful access to various types of data, thus leveraging existence of these information pipelines.

One key takeaway from this study is that information pipelines for processing data-collected during load tests would benefit from Standardization. These pipelines are developed following the needs and specifications of Spanish NAP 2.0 which provide a representative sample of integration. Time-streams sensor data require seamless allocation within IoT platforms. Accessible Standardized IFC BIM models are also needed. Advances on geometrical Standarization are already tackled by CEN 442 WG9 in Europe. On top of these basic layers, simulations, imagery, point clouds and other types of data can be added, which is more difficult to define in a Standard way. This integration represents one of the core tasks of the research project whose final conclusions are expected to shed light in this respect using Knowledge Graphs-based systems (Chacón, Casas, et al., 2023; Khan et al., 2022; Ramonell & Chacón, 2023).

Standardization paves the way for owners and managers to have clear targets for the information delivery from the construction industry. Procurements, tendering and management can gradually increase the digital needs of the sector for the sake of tackling operation and maintenance of bridges more efficiently, productively and safely. For instance, one realistic scenario would be the following: the load test involves several types of measurements performed by many different unconnected stakeholders. On the other hand, virtual geometrical models (BIM) are provided by designers and constructors. Simulations (structural analysis) are also be delivered by other third parties. Ideally, the co-existence of so many layers would benefit from open pathways, formats, and data-exchange tools that enable cooperation. Examples of data-exchange proposals for virtual entities in bridges represent a research and development trend to be explored in the field of load tests as well (Barrasa, Hodler, & Webber, 2021; Borrmann et al., 2019; Deng, Menassa, & Kamat, 2021; Janowicz, Rasmussen, Lefrançois, Schneider, & Pauwels, 2020).

Another key take away is the use of the Digital Twin for maintenance purposes. Providing stakeholders with Standard open-access digital twin platforms enables interconnection in the future of the asset. As a result, the asset-related information has the potential to improve the overall network of assets. The digital twin platform acts as a single source of truth that not only allows information sharing among contemporary and not necessarily connected stakeholders but keeps the information available for future needs (see Figure 17). Exploitation of these digital assets will become more valuable in time as data accumulation and continuous model update and verification will allow to observe behavioral trends and, thus, represent more accurately maintenance needs of the physical assets. Currently, digitalization of built assets is still low, and if digital concepts such as digital twins are to be implemented, there is the need to design strategies for effective digitalization. Load tests in newly constructed bridges present a good opportunity to establish primeval yet useful digital twins of these type of structures with insignificant additional operative costs.

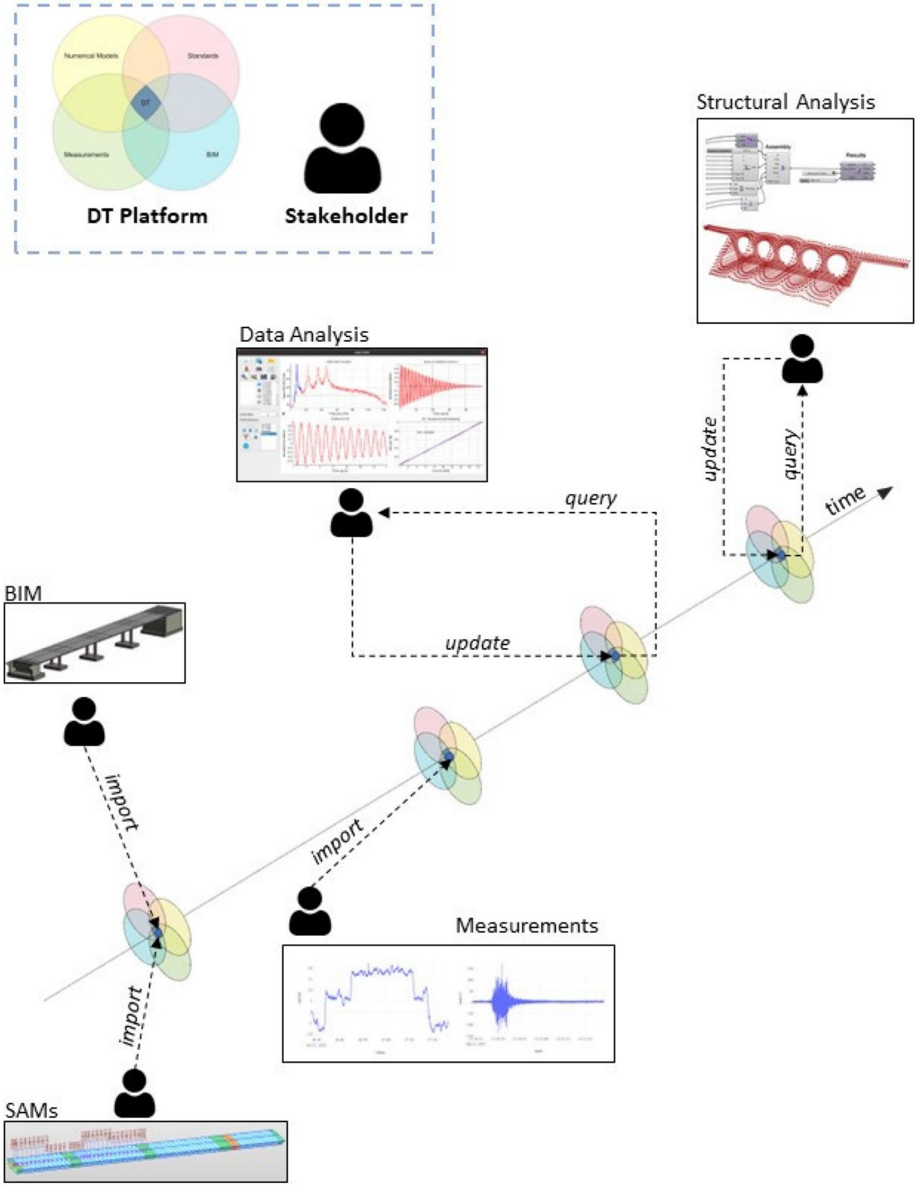


Figure 17. Interaction between the DT platform and the stakeholders.

Presently, additional costs are mostly related to data integration. Measurements, simulations, verifications and other report delivery are needed in a load test. Integrating this information represents the crucial challenge for newly designed load tests with digital twin capabilities.

In addition, one important aspect of digital twinning in bridges is the synchronicity requirements. The load tests are episodes that are typically developed during one day on a Standard bridge. All data acquisition and measurements are taken to office for further analysis and comparisons. The development of DT implies similar time needs. The information construct can be integrated and readily available within the same time span than the delivery of reports that is presently done. However, on the long run, new measurements or new issues that are integrated in the bridge twin are not needed on a "real-time" basis. Rather, this information is needed on a "right-time" basis, which may take days, weeks or even years. As a result, the challenge for DT in bridges would rather be its open integration for various stakeholders rather than the development of high-fidelity, low computational power, and real-time numerical advanced models stored in servers and providing continuous information about the status of the asset. This challenge is more common in other industries (nuclear, aeronautics, manufacture).

8. Conclusions

Digitization of infrastructure is essential for organizations to stay competitive and improve efficiency in today's technological landscape. By automating tasks, accessing and analysing data, and improving the customer experience, digitization can streamline operations and reduce costs. Civil engineering infrastructure systems are also on the verge of this digitization. On the other hand, load tests in bridges are crucial episodes that require significant resources. These tests help ensure the safety and structural integrity of the bridge by simulating various load conditions. While expensive and time-consuming, load tests are necessary to understand the behaviour of the asset as well as to ensure its longevity.

Static and dynamic load tests are common methods used to assess the structural integrity and safety of bridges. Static tests involve the application of a static load to the bridge, while dynamic tests simulate real-life conditions by applying a dynamic load. Both tests help engineers determine the bridge load capacity and identify any potential structural issues that may need to be addressed. Presently, written reports about the performance of a bridge during load testing are delivered by the corresponding stakeholders. Comparisons between numerical models and measurements are established under the assumption of different thresholds given by guidelines and recommendations.

This article presents a vision on the creation of a Cyber-Physical Bridge during load testing. This vision is the result of a multidisciplinary joint effort related to the development of physical-to-virtual pipelines of information for design, construction and maintenance of infrastructure systems in the form of digital twins. The creation of an adequate Digital Birth of those assets represents a very important milestone that will increasingly needed in the verge of digitization. As a matter of fact, efforts related to structural analysis, 3D modelling, measurements, documentation and procurements are nowadays regularly executed during load testing but these efforts are performed in a disaggregated form. A comprehensive digitation of all generated information during a load test episode (measurements, connections, simulations, documentation) can be organized for maintenance purposes. A flexible, scalable digital twin of the bridge developed during load testing may provide added value and a crucial aid to maintenance planners during the life-cycle of the bridge. As a result, an adequate representation of a load test in the form of a digital twin represents an ideal episode of a physical bridge to generate its digital birth.

Acknowledgements

All authors acknowledge the funding of Ashvin, “Assistants for Healthy, Safe, and Productive Virtual Construction Design, Operation & Maintenance using a Digital Twin” a H2020 project under agreement 958161. Special acknowledgements to key collaborators DRACE (formerly Geocisa) and ADIF for allowing access to these load episodes to the Ashvin Consortium. This publication reflects only author’s view and that the European Commission is not responsible for any uses that may be made of the information it contains.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

AASHTO. (2016). *The manual for bridge evaluation: With 2016 interim revisions* (2nd ed.). American Association of State Highway and Transportation Officials, Washington, DC, USA.

Administración De Infraestructuras Ferroviarias. (2023). *ADIF: Quiénes somos*. [ADIF: About us] https://www.adif.es/sobre-adif/conoce-adif/quienes-somos.

Administrador De Infraestructuras Ferroviarias (ADIF). (2021). *Pruebas de carga ferroviarias en puentes de ferrocarril.* [Load Tests in Railways Bridges] (Report No. NAP 2-4-2.0)

Alampalli, S., Frangopol, D. M., Grimson, J., Halling, M. W., Kosnik, D. E., Lantsoght, E. O. L., Yang, D., Zhou, Y. E. (2021). Bridge load testing: State-of-the-practice. *Journal of Bridge Engineering*, *26*(3), 03120002. doi:10.1061/(ASCE)BE.1943-5592.0001678

Barrasa, J., Hodler, A. E., & Webber, J. (2021). *Knowledge graphs: Data in context for responsive businesses.* Sebastopol, CA: O’Reilly Media, Inc.

Borrmann, A., Muhič, S., Hyvärinen, J., Chipman, T., Jaud, S., Castaing, C., Dumoulin, C., Liebich, T., & Mol, L. (2019). The IFC-Bridge project–Extending the IFC standard to enable high-quality exchange of bridge information models. In *Proceedings of the 2019 European Conference on Computing in Construction* (pp. 377–386). doi:10.35490/EC3.2019.193

Brincker, R., Zhang, L., & Andersen, P. (2001). Modal identification of output-only systems using frequency domain decomposition. *Smart Materials and Structures*, *10*(3), 441–445. doi:10.1088/0964-1726/10/3/303

Chacón, R., Casas, J., Ramonell, C., Posada, H., Stipanovic, I., & Škarić, S. (2023). Requirements and challenges for infusion of SHM systems within Digital Twin Platforms. *Structure and Infrastructure Engineering*, 1–17. doi:10.1080/15732479.2023.2225486

Chacón, R., Ramonell, C., & Posada, H. (2023). *Deliverable 5.2: Digital-twin enabled multi-physics simulation and model matching.* Switzerland: OpenAIRE. doi:10.1080/15732479.2023.2225486

Dallasega, P., Rauch, E., & Linder, C. (2018). Industry 4.0 as an enabler of proximity for construction supply chains: A systematic literature review. *Computers in Industry*, *99*, 205–225. doi:10.1016/j.compind.2018.03.039

Dávila-Delgado, J. M., & Oyedele, L. (2021). Digital Twins for the built environment: Learning from conceptual and process models in manufacturing. *Advanced Engineering Informatics*, *49*, 101332. doi:10.1016/j.aei.2021.101332

Deng, M., Menassa, C. C., & Kamat, V. R. (2021). From BIM to digital twins: A systematic review of the evolution of intelligent building representations in the AEC-FM industry. *Journal of Information Technology in Construction*, *26*, 58–83. doi:10.36680/j.itcon.2021.005

Deutscher Ausschuss für Stahlbeton. (2000). DAfStb-Richtlinie: Belastungsversuche an Betonbauwerken. [DAfStb guideline: Load tests on concrete structures].

Gade, S., Møller, N., Herlufsen, H., & Brüel, H. K. (2005). Frequency domain techniques for operational modal analysis. In R. Brincker, & N. Møller (Eds.), 1st International Operational Modal Analysis Conference. Denmark: Aalborg Universitet.

Ho, B., & Kálmán, R. (1966). Effective construction of linear state-variable models from input/output functions. *Auto*, *14*(1–12), 545–548. doi:10.1524/auto.1966.14.112.545

Hungarian Chamber of Engineers. (2013). *Guidelines for interventions in Hungary*.

Janowicz, K., Rasmussen, M. H., Lefrançois, M., Schneider, G. F., & Pauwels, P. (2020). BOT: The building topology ontology of the W3C linked building data group. *Semantic Web*, *12*(1), 143–161. doi:10.3233/SW-200385

Khan, R., Tomar, R., Hartmann, T., Ungureanu, L., Chacón, R., & Ibrahim, A. (2022). Platology: A digital twin ontology suite for the complete lifecycle of infrastructure. In *International Workshop on Intelligent Computing in Engineering*. doi:10.7146/aul.455.c219

Lantsoght, E. O. L. (2019). *Load testing of bridges: Proof load testing and the future of load testing*. Boca Raton, FL: CRC Press.

Liao, J., Zhou, J., & Yang, W. (2021). Comparing LiDAR and SfM digital surface models for three land cover types. *Open Geosciences*, *13*(1), 497–504. doi:10.1515/geo-2020-0257

Mainflux. (2023). Mainflux [Computer software]. Open Source IoT Platform. https://mainflux.com/.

Marí, A. (2000). Numerical simulation of the segmental construction of three dimensional concrete frames. *Engineering Structures*, *22*, 585–596. doi:10.1016/S0141-0296(99)00009-7

Mauriello, M. L., & Froehlich, J. E. (2014). Towards automated thermal profiling of buildings at scale using unmanned aerial vehicles and

3d-reconstruction. In: *Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing, Adjunct Publication* (pp. 119–122). doi:10.1145/2638728.2638731

Müller, T., Evans, A., Schied, C., Foco, M., Bódis-Szomorú, A., Deutsch, I., Shelley, M., & Keller, A. (2022). Instant neural radiance fields. *ACM SIGGRAPH 2022 Real-Time Live!*, *6*, 1–2. doi:10.1145/3532833.3538678

National Roads Authority [NRA]. (2014). *Load testing for bridge assessment* (Report No. AM-STR-06014).

National Steering Committee for the Load Testing of Bridges of the Institution of Civil Engineers. (1998). *Guidelines for the supplementary load testing of bridges*. London, UK: Thomas Telford.

Pregnolato, M., Gunner, S., Voyagaki, E., de Risi, R., Carhart, N., Gavriel, G., Tully, P., Tryfonas, T., Macdonald, J., & Taylor, C. (2022). Towards Civil Engineering 4.0: Concept, workflow and application of Digital Twins for existing infrastructure. *Automation in Construction*, *141*, 104421. doi:10.1016/j.autcon.2022.104421

Ramonell, C., & Chacón, R. (2022). Towards automated pipelines for processing load tests data on a high speed railway bridge in Spain. In *International Symposium on Automation and Robotics in Construction*. doi:10.22260/ISARC2022/0033

Ramonell, C., & Chacón, R. (2023). A Knowledge Graph-based data integration system for digital twins of built assets. Submitted for publication. Revised version under review.

Riveiro, B., & Lindenbergh, R. (2019). *Laser scanning: An emerging technology in structural engineering*. Boca Raton, FL: CRC Press.

Rodriguez-González, A., Fuente, J., Fabregad, R., Alvarez, J., Chacón, R., & Ramonell, C. (2022). Ground-Based interferometer radars for load tests of long-span arch bridges. Case study: Almonte and El Tajo Viaducts, Extremadura, Spain. In *International Conference on Bridge Maintenance, Safety and Management*. doi:10.1201/9781003322641-271

Schweizerischer Ingenier- und Architektenverein [SIA]. (2011). *Grundlagen der Erhaltung von Tragwerken* [Fundamentals of the preservation of supporting structures]. Report No. SIA 269.

Shim, C. S., Dang, N. S., Lon, S., & Jeon, C. H. (2019). Development of a bridge maintenance system for prestressed concrete bridges using 3d digital twin model. *Structure and Infrastructure Engineering*, *15*(10), 1319–1332. doi:10.1080/15732479.2019.1620789

Spreitzer, G., Tunnicliffe, J., & Friedrich, H. (2020). Large wood (LW) 3D accumulation map-ping and assessment using structure from Motion photogrammetry in the laboratory. *Journal of Hydrology*, *581*(1), 124430. doi:10.1016/j.jhydrol.2019.124-430

Steder, B., Grisetti, G., Stachniss, C., & Burgard, W. (2008). Visual SLAM for flying vehicles. *IEEE Transactions on Robotics*, *24*(5), 1088–1093. doi:10.1109/TRO.2008.2004521

Unity Technologies. (2021). Unity [Computer software]. https://unity.com/.

Westoby, M. J., Brasington, J., Glasser, N. F., Hambrey, M. J., & Reynolds, J. M. (2012). 'Structure-from-Motion' photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology*, *179*, 300–314. doi:10.1016/j.geomorph.2012.08.021