Structural design in the era of digital twins. A case study

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Abstract –

Digital Twins (DT) represent a technology that provides a way to encompass useful information of built assets for the sake of productivity enhancement in the AECO sector. Its adoption in the industry is still at early developmental stages. Significant strides have been made in establishing frameworks and workflows for effective DT implementation. This paper analyzes a case study in which a DT of a built bridge is developed during the particular episode of a load test, to understand how structural design can benefit (and potentially adapt) to the specific demands this innovative technology may generate. The bridge under twinning was already built and its design was neither determined nor influenced by the fact that load testing procedures were meant to be twinned. By identifying the link between the development of the DT of the bridge and its design, a conceptual diagram illustrates the key components to consider during the structural design phase. The main objective of this diagram is to present an encompassed vision of design that already accounts for the future existence of the DT of the asset, beyond the delivery of a BIM model. The implementation of the proposed diagram for the case study is described. As a result, it is observed that the proactive integration of structural engineers' specialized knowledge holds promise for enhancing the efficiency of DTs for construction and maintenance tasks.

Keywords –

Digital Twins; Structural Design; FEM; BIM; IFC Sensor-based data

1 Introduction

The AECO (Architecture, Engineering, Construction and Operation) sector has presented lower productivity indexes compared with other industries [1]. This can be attributed to the reluctance of a traditional sector to adopt technologies that can genuinely help enhancing capabilities. The involvement of diverse stakeholders in infrastructure projects and the dynamic environment of the construction sites with constant variations in site layout, equipment, materials, and other components, contribute to the complexity of delivering projects avoiding unforeseen issues, delays, or cost overruns [2].

Recent years have witnessed the extensive adoption of Building Information Modeling (BIM), elevating the efficiency of data generation and exchange within collaborative environments. Nevertheless, as digitalization and process automation, fueled by technologies like Internet of Things (IoT) and Artificial Intelligence, continue to advance, the BIM path encounters new hurdles in adapting to a broader interconnected context for delivering more sophisticated construction services [3][4]. Digital Twins (DTs), defined as a sophisticated information construct that enables a timely and useful connection between real and virtual assets, hold the potential to effectively address digitization and smart management needs within the sector [5].

Recent research concerning DTs has been focused on proposing frameworks and workflows for a successful application of the technology [6][7][8]. It can be observed that during the last years, several assets in construction and maintenance stages have been fully (but mostly partially) twinned. However, these assets may not have been designed consciously with the knowledge of the potential of their twinning. A gap regarding the role of the structural design phase in meeting the specific requirements of a DT in subsequent stages is identified. In addition, structural design is not directly connected to long term assessment of the asset (for instance, a direct connection with risk assessment involving structural components or structures). Structural engineers have the specialized knowledge to identify critical construction or maintenance processes that may need monitoring to ensure quality or enhance the management of an infrastructure. During the design phase, engineers consistently grapple with uncertainties. It is of interest to track these uncertainties during subsequent stages. Numerical models require calibration, and this holds particular significance in assessing the structural performance of infrastructures. Over the design stage, defining expected physical values at critical locations within a monitoring plan, and seamlessly integrating them, along with sensors and simulations data into a centralized digital system, can boost the potential of a DT, simultaneously reducing working hours for validation and verification. Risk assessment procedures used on the long run can also benefit from early identification of crucial aspects of the structure.

In this paper, an example of a twinned infrastructure (a bridge) is provided. In this example, the bridge is twinned after the asset is designed and constructed. It represents a common procedure for the new generation of digitally twinned assets. However, structural engineering design offices may contribute to more sophisticated twinning by providing crucial insights at early design stages. Through a conceptual diagram, four key components are depicted: (1) Monitoring plan, (2) Sensors-data processing (3) Verification and validation, and (4) Simulations data exchange. Afterward, the applications of the conceptual diagram are showcased for the case study.

The practices presented in this research presumes the existence of a CDE (Common Data Environment) framework that enables access and updates of simulations for validation and verification during the lifecycle of an asset within a user-friendly interface, supporting risk management and decision-making. Section 6 outlines the work-in-progress associated with this topic.

2 Structural Analysis and Digital Twins

A DT as a virtual representation of a physical asset requires constant updates to the state and conditions of that real infrastructure. Therefore, varied simulations and predictions must be performed to match with on-site collected data. Ideally, this process can be infused into centralized digital systems where the collection of information of structural models and sensors data allows the validation and verification at both, construction and maintenance stages. This provides valuable information in the form of performance indicators that can support data-driven decision-making [9].

The key challenge lies in effectively bridging the gap between, BIM models, on-site physical data, assessment and structural analysis simulations. This integration should be completed within a flexible framework ensuring the unified use of information while upholding interoperability and maintainability over the infrastructure lifecycle [10].

Literature on the integration of BIM and structural simulations is increasingly growing [11][12][13]. Primarily, the existing research concentrates on facilitating interoperability between structural analysis and BIM software, and on enhancing the workflow for generating a structural analysis model from an architectural model, thereby minimizing the need for rework during initial design cycles.

For instance, Zhao Xu et al. [14] have proposed a new method to transform a BIM model into a connection model using the Brep graphic representation. Then, a discretization of filaments is done to obtain a refined finite element analysis. Additionally, they achieved the visualization of FEM (Finite Element Method) results on an OpenBIM environment following the IFC (Industry Foundation Classes) schema.

The primary goal of this paper is to align the structural design phase as a way to provide crucial information for subsequent DTs. Thus, facilitating the gathering of BIM models, measurements, processing, assessment, and structural analysis simulations in a centralized digital system.

3 The Case Study

This research is performed within the frame of a H2020 European project called Ashvin [15]. Its main goal is to pull out methodologies and cohesive solutions for many kinds of data flows to implement DTs during the design, construction, and maintenance phases. One of the demo cases of the project is La Plata viaduct (see Fig. 1), which belongs to a high-speed train network in Extremadura, Spain. The bridge is a 4-spanned post-tensioned slab with a total length of 114 meters and represents the case study of this research.

Figure 1. Viaduct La Plata during the load test

An IFC-based BIM model was generated from existing 2D drawings. The administration provided access during the load test of the bridge. Accelerations, displacements, and strains were acquired for dynamic and static tests. The collected data was synced and uploaded to an IoT (Internet of Things) platform. Mechanical properties of the materials were defined from the original design reports. Information regarding the construction process was not provided. Structural analysis models were generated to match expected against measured values, validating the structural performance of the bridge. The DT paradigm was approach through the integration of multiple layers of information. BIM, FEM models, measures, and related standards (see Fig. 2), were knitted together to generate a virtual asset within a CDE, encompassing information pipelines from on-site measurements to risk assessment applications. Extended details about the procedure are described in [16].

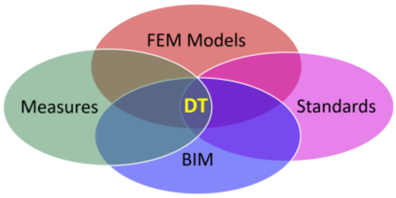

Figure 2. DT information layers of the case study

From the lessons learned in the digital twinning of the case study, which involved dealing with an existing asset without construction procedure data and the participation of the bridge structural designers, the proposed conceptual diagram displays key components for the design stage as a way to anticipate the development of its DT. As a result, singularities about the structural behavior of an infrastructure can be considered *a priori* incorporating the technical knowledge of the designers. In section 5, the application of the conceptual diagram is described for the case study, guiding future implementation.

4 The Conceptual Diagram

Anticipating a DT during the structural design stage of an infrastructure is crucial for meeting technical requirements and effectively monitoring key construction or maintenance tasks.

To address this procedure, a conceptual diagram is presented in Fig. 3. Within the diagram, beyond the deliver of a BIM model, four main components should be integrated into the DT: 1) A comprehensive *Monitoring Plan* delineating critical construction or maintenance activities, defining physical values for measurement, specifying the location and scale of the measures, recommending the type of sensors, and generating a schedule for data collection. 2) Code-based *Sensors Data Processing* techniques for each physical magnitude, to convert raw sensor-based data into meaningful information. 3) *Verification and Validation* processes identifying Key Performance Indicators (KPIs) aligned with standards or quality control requirements. These KPIs must be converted into machine-readable formats such as JSON or XML for seamless integration into a DT. 4) A *Simulation Data Exchange* to the target CDE, meeting its framework requirements for exporting structural analysis models facilitating accessibility and updates of simulations.

The integration of these components into a CDE will ensure a robust foundation for the implementation of DTs over the construction and maintenance phases.

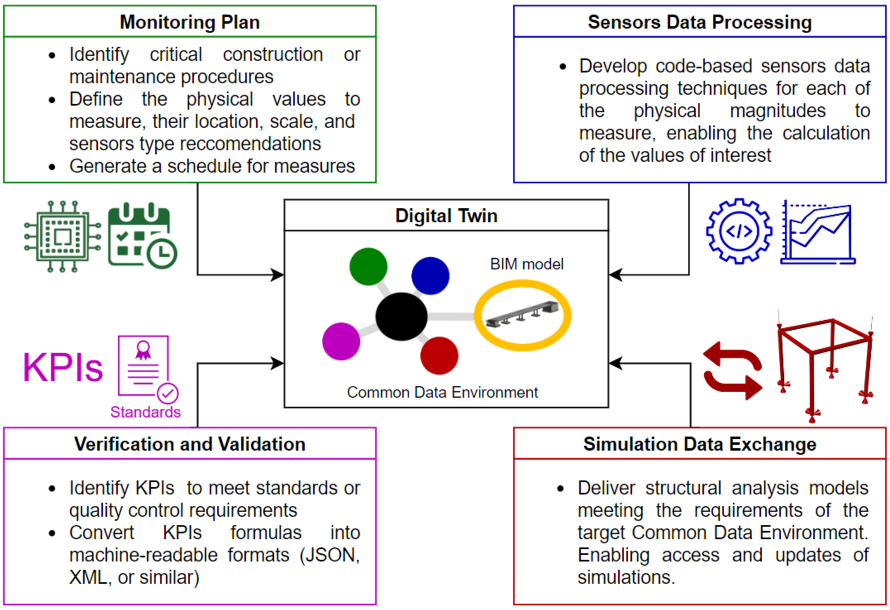

Figure 3. The conceptual diagram

5 Application to the Case Study

As the access to the bridge was provided during the load test, the actions executed for developing the DT of the bridge were directed on digitizing the components and processes for checking structural performance [16]. From the results and the lessons learned over the developments, in this section a knowledge transfer is done by applying the proposed conceptual diagram, considering a scenario where the structural design anticipates the digital twinning of the load test. Procedures were carried out following the Spanish national standard NAP 2-4-2.0 [17], which regulates the load testing of railway bridges.

5.1 Monitoring Plan

For the case study, the critical construction procedure to monitor was the validation of the structural performance to approve the start of the operation. The physical magnitudes to measure were accelerations, displacements and strains at mid-span and supports. The sensors and their description were added to the IFC-BIM model at the required locations employing the *IfcSensor* entity. The schedule of the measures was generated within the IFC-BIM model as metadata using the entities *IfcWorkPlan*, *IfcWorkSchedule*, *IfcWorkCalendar*, and *IfcTask*. The entities and relations of the IFC schema to perform this procedure are depicted in Fig. 4.

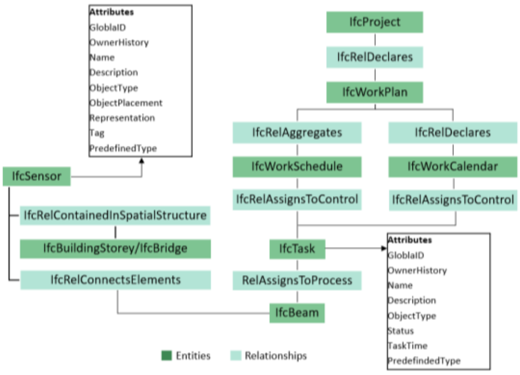

Figure 4. IFC entities and relationships to generate a Monitoring Plan

By generating an IFC-based Monitoring Plan, the digitization of the information is achieved, and its integration into a CDE is facilitated, given that the IFC schema is a well-known open standard.

5.2 Sensors Data Processing

To calculate the values of interest for displacements and strains, it was required to develop Python scripts for processing the collected data from LVDTs and strain gauges, considering the characteristics of the sensors. On the other hand, for accelerometers, an application able to identify vibration modes of a structure has also been implemented. This Python-based application estimates the vibration modes of a structure based on synced accelerometers data [18].

Furthermore, scripts were developed following the cloud computing framework of an IoT platform [19] to upload and retrieve sensors data.

5.3 Verification and Validation

To decide whether the structural performance of the bridge is satisfactory to initiate operation, the NAP 2-4-2.0 standard defines parameters and limits that must be within acceptable ranges. In this sense, the results of the load test should be available in the form of indicators.

To achieve the digitization of the validation and verification for the case study, the formulas to estimate the parameters established by the national standard, were integrated into the CDE using python scripts. Moreover, the results of the load test were parametrized and consigned into JSON machine-readable dictionaries to enable the display of indicators for end-users. Fig. 5 presents the JSON defined to verify displacements. These procedures allow the automation of verification by digitizing the national standard. This information can be retrieved at any moment during the lifespan of the asset, reducing working hours and the waiting period to get the results of validations.


```
{
  "Task":"Static Analysis",
  "Date":11-11-24,
  "Responsible": "Hector Posada",
  "Standard": "NAP 2-4-2.0",
  "Results":
  [{
      "Hypothesis": "Hyp 1",
      "Span": "Span 1",
      "SensorID": "5c1ea221-f748-40dc-bc58-6b32ee0427d0",
      "Span deflection(mm)":  "2.21",
      "Measured/Predicted deflection (%)": 64.0",
      "Residual deflection(mm)": 0.057",
      "Recovery rate (%)": "95.43"
  }]
}
```


Figure 5. JSON schema for displacements validation

5.4 Simulation Data Exchange

One of the main challenges of digital twinning is embedding simulations of various kinds within a CDE. Usually, the commercial software for performing structural analysis require development of APIs and expertise to package information, which increases the complexity of exchanging data.

For the case study, JSON dictionaries were generated to include the results of a proprietary license Software package called MIDAS [20] within the target CDE, as shown in Fig. 6.

However, due to the absence of automation, the process was time-consuming. In addition, it would be inefficient in enabling future updates. In section 6, a work-in-progress research project that aims to develop an open-source data model for exchanging structural analysis models is described (O-SAM). The data model will facilitate the delivery of structural analysis simulations to target CDEs, helping to perform a seamless Simulation Data Exchange facilitating accessibility and updates.

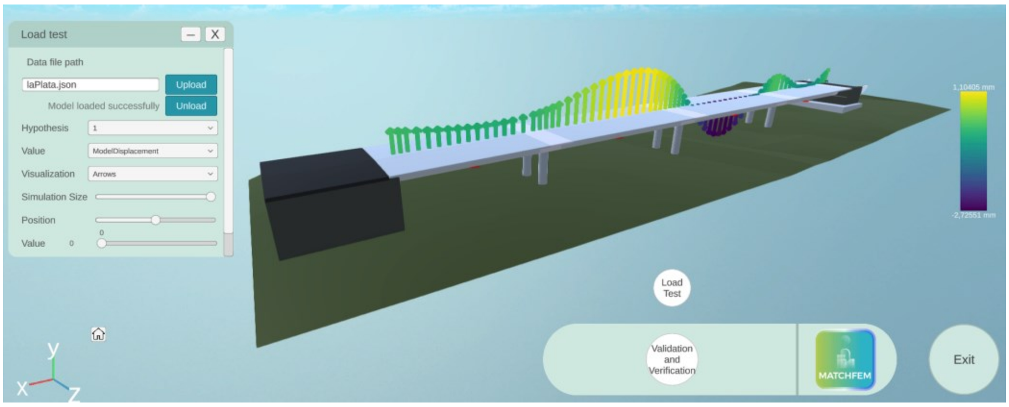

Figure 6. Structural Analysis results within the target CDE

6 Work-In-Progress: The O-SAM Data Model

A DT that pretends to hold various simulations of a real asset must be capable of flexibly exchanging structural analysis models to enable access and updates of these simulations. On the other hand, to perform structural analysis calculations there is a considerable variety of options available in the market. Each of these software generates simulation models and results in its format, hindering interoperability.

The IFC 4x3 schema [21] have tried to cover this issue by its *IfcStructuralAnalysisDomain*. Nevertheless, the standard is limited as it is not possible to properly define structural analysis results and entities such as finite element meshes and 3D solids.

Authors' current research is focused on developing O-SAM data model. It is possible to break down this open-source data model into two parts: Firstly, a unified JSON-based structural simulation model schema. The schema is accompanied by a set of converters that allows multiple FEM software to upload simulation information to the DT. Secondly, the incorporation of a graph-based representation into the existing model will seamlessly unite simulations with other data and models in the DT using knowledge graphs. These graphs streamline the integration and contextualization of information from disparate systems into a cohesive and semantically rich model, characterized by a flexible and intuitive structure that aligns seamlessly with the demands of a DT [22].

7 Conclusions

Through a conceptual diagram, this paper presents the components to consider over the structural design phase for anticipating to a DT. The development of the proposed diagram was executed by transferring the knowledge of digital twinning the load test of a railway bridge.

The purpose of the study was to include the specialized knowledge of structural engineers in planning and preparing the framework for monitoring construction or maintenance procedures within a DT. If these procedures are digitized during the design stage, costs and working hours are reduced. For instance, to check the structural performance of the case study it was necessary to generate new structural models to define the expected physical values. Furthermore, the time gap between data collection and the validation process was significant as there was no automation in processes.

On the other hand, the information provided from the collaborator to develop the digital twin of the case study was limited and delivered as isolated silos. A centralized system which gathers the structural design information will facilitates the execution of construction or monitoring tasks.

There are still obstacles to overcome for DT adoption in the structural engineering domain. There is a lack of civil engineers with expertise in Information Technologies. Moreover, structural design offices may hesitate to share project information, concerned about overexposing their design procedures. Finally, owners or public administrations must include in the infrastructure design contracts the digitization of Monitoring Plans and Verification and Validation procedures, the development of Sensors Data Processing techniques, and the delivery of simulation models and results into a target CDE.

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