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Seasonal analysis of an 846 long steel box girder bridge using Terrestrial Laser Scanners (TLS) and FE-models

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Abstract
This investigation presents the seasonal analysis of an 846 long steel box girder bridge using Terrestrial Laser Scanners (TLS) and FE-models. The Bridge is both vertically and horizontally curved with a tapered, stiffened steel box girder. The sequential seasonal measurement of the plates using a TLS provides a set of point clouds that can be systematically used to feed advanced inelastic FE analysis. Since the bridge experiences considerable seasonal displacements, the effect of these displacements on the ultimate load capacity of the composite bridge is under study.

In the FE-analysis, comparisons between defining imperfections of the plates as adequately scaled Eigenshapes or, as real measurements, are performed. Different scenarios (seasonal and shape-related) are thus assessed.

In addition, another challenge in this investigation is to digitize realistically and seasonally the “as built” shape of the plates. The definition of the resulting 3D geometry must be versatile enough to be used by different stakeholders (simulation, BIM managers, IoT). The outcome of this pipeline of information covering measurement-FE-analysis and assessment is of great interest to maintenance managers. Understanding the seasonal geometrical configuration of this bridge may represent an accurate starting point for subsequent forecasting of structural engineering scenarios.

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1. Introduction

Composite bridges are all around. The advantages of combining the characteristics of concrete bridges and steel bridges drive efficient and economic structural solutions (Pipinato 2022). These structures are generally formed by a combination of concrete slabs supported by steel plate- or box girders. Often, beams are an arrangement of welded steel plates with transversal and longitudinal stiffeners where material efficiency, weight and cost are the main constraints for the design of such structures. This results in the confection of slender steel plates that may be prone to buckling under certain stress levels, which would cause out-of-plane deformation that would affect the overall structural integrity of the bridge.

During design processes, advanced numerical models are often employed to predict plate buckling or any other instability-related phenomena. Initial imperfections of steel plates are considered prior to the construction phase being based on theoretical assumptions. However, after the construction of the bridge, the "as-built" shape of the plates is seldom used to verify such assumptions, and its evolution in time is not monitored. As a matter of fact, the potential feedback that as-built models may provide to designers is presently disregarded. Performing geometrical assessments at the bridge scale with enough detail to obtain such shapes with traditional methods may be an unbearable task. Nowadays, many of the activities that encompass the term *Construction 4.0* foster the utilization of more advanced monitoring techniques which opens the possibility to perform and manage such data-intensive assessments. The use of reality scanning devices such as the Terrestrial Laser Scanner (TLS) allows for capturing highly detailed geometries at long distances within short periods of time. Furthermore, digital twins as comprehensive information constructs in the construction industry (Dávila Delgado 2021) are also providing a common data environment of great interest for many stakeholders.

In this study, a composite bridge located in the Metropolitan Area of Barcelona represents one testbed demonstrator for understanding how feasible continuous geometric assessments using TLS are for structural evaluation purposes. The study is framed in the H2020 European project ASHVIN standing for "Assistants for Healthy, Safe, and Productive Virtual Construction Design, Operation & Maintenance using a Digital Twin" (ASHVIN 2023). The bridge represents one of the ten sites for the demonstration of digital twin capabilities. Design, Construction and Maintenance stages are covered in the project. The digital twin of the bridge is used to store measurements, simulation models and BIM models that jointly provide support for efficient maintenance planning.

The objective of the ongoing study is to understand how to develop automated procedures for introducing both BIM geometries and real TLS measurements within digital twins. For the former, it will help to perform systematic, structurally-concerned assessments of plates, stiffeners, diaphragms or other subsets of the asset in an orderly fashion. Accessing open BIM standards such as the Industry Foundation Class (IFC) (ISO 2018) is vital when integrating bridge information in vaster information constructs. For the latter, measurements require establishing semi-automated processes of identification of initial imperfections of the steel plates for subsequently, integrating such geometries in potential advanced inelastic FE simulations for structural analysis at different levels.

2. The Bridge

2.1 Physical asset

This demonstration site is the PR-04-B015 bridge, which is located in the national highway network surrounding the Metropolitan Area of Barcelona (Spain). It connects two of the main highways in the network the AP-7 Highway (heading North) and the A-2 Road (Heading West).

The PR-04-B015 bridge provides a strategic connection between those two highways. It provides users with a bypass to avoid driving into the suburbs of the metropolitan area in the transition from north-south to east-west corridors or in reverse. Consequently, it has become a strategic asset for the transportation of goods from Catalonia to Northern Europe. strategic asset for transporting goods from Barcelona port to other parts of northern Europe.

Figure 1. Location and general view of PR-04-B015 bridge

The bridge, with an approximate length of 846 meters, was opened to traffic in September 2021. As can be seen in Figure 1, the bridge is composed of a continuous horizontally-curved composite beam that crosses over a river (Llobregat), a creek (Rubi), several roads, and railway lines. The bridge splits into two different viaducts, one for each driving direction. Both viaducts are divided into 12 spans of varying lengths supported by concrete piers. The cross-section is composed of a steel box section with a varying web height between 3,5 and 5,0 meters and a concrete slab of width varying from 11,50 to 17,00 m. The steel box is provided with transversal and longitudinal stiffeners and diaphragms.

2.2 Digital asset

Digital assets are essential entities for the management of bridges. Building Information Modelling (BIM) is now well established in the design and construction stages and dictates how built assets' information is stored and transferred among stakeholders. However, during the maintenance stages, the implementation of long-term digital support strategies remains a challenge.

Presently, bridge management involves gathering and analysing information from a variety of sources, such as geometric models, structural simulation models, and structural health monitoring systems. Information is presently loosely stored in manifold types of bridge management systems (BMS) that are usually developed by the owners. These diverse types of information are usually handled using unconnected digital tools. With the advent of comprehensive information constructs with more robust Common Data Environments (CDE) such as digital twins, BIM models become dynamic entities that are integrated with information coming from multiple sources. These models may become continuously updated to represent the current state of the bridge, establishing a reliable digital replica that supports decision-making through a single digital interface for the deployment of efficient and productive maintenance plans. The PR-04-B015 bridge is being digitally twinned within the frame ASHVIN project. The digital twin of the bridge is aimed at hosting maintenance plans, geometric models, structural simulation models and measurement data within a single system that provides support to infrastructure managers.

The original design project of the bridge was delivered many years ago. At that time, digital tools and BIM were not sufficiently developed. Most of the information about the bridge was stored in pdf files containing all relevant information in the form of deliverables and 2D drawings. Thus, the 3D geometrical model was built from the pdfs using Rhino and Grasshopper, a parametrical design tandem software in which computational geometry is employed to considerably speed up the model generation process. The BIM model was subsequently developed according to the IFC open standard, which in its last release, allows modelling bridge constitutive parts, which are assigned a geometric representation, physical properties and additional semantic information (Borrmann 2019). The developed model contains detailed representations of bridge plates, slabs, piles and stiffeners as can be observed in Figure 2.

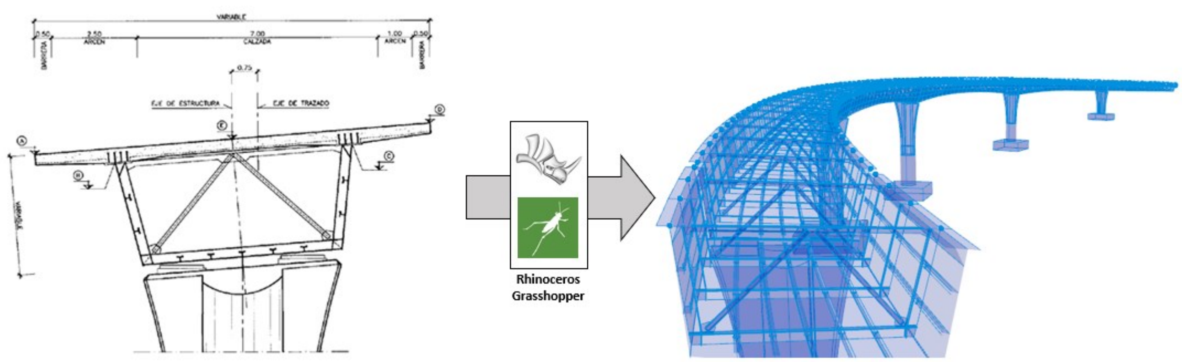

Figure 2. From drawings to IFC-accessible geometries

Finally, the IFC model is uploaded to the ASHVIN digital twin platform, where it is integrated with an IoT platform and set of databases that altogether constitute a comprehensive CDE. The CDE acts as a single source of truth to which stakeholders and computational agents are referenced to add or withdraw information snippets at different levels that are needed for all sorts of analysis scenarios. Figure 3 shows a view of the platform provided with a set of tools (see ribbon at the bottom of the screen) for design, construction and maintenance management.

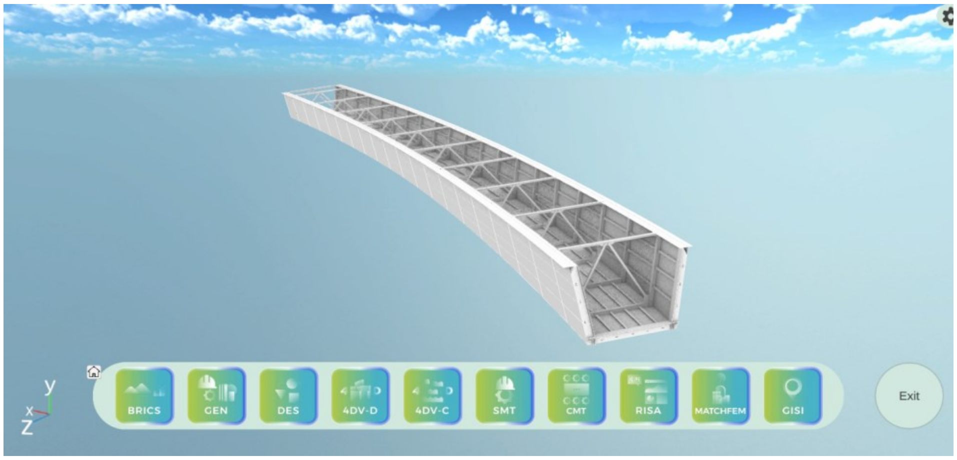

Fig. 3. A span of the bridge within the ASHVIN digital twin platform

2.2 Twinning the bridge

From such an asset, many automated pipelines of information can be developed. Information from many sources (such as sensors, cameras, radars) may give hints on the condition of the bridge. For instance, accelerometers may help understanding vibrations and inertial movements of the beams. Cameras may help understanding patterns and non-inertial movements such as corrosion. Remote sensing techniques may give information about geometries. In all cases, measurements, transmission, simulation, analysis and decision-making processes follow different paths that are refereed to as “automated pipelines of information”. All these pipelines should ideally be integrated by potentially different stakeholders into any comprehensive CDE.

In this paper, two automated pipelines are described. The first one is related to the systematic extraction of parts of the model (IFC-based) for subsequent use in stability analysis. Information from plates, stiffeners or diaphragms is stored in the form of a model within the Ashvin digital twin platform. Users can select specific areas or plates under request for specific stability analysis. This situation may arise during the operation stage of the bridge after warning events occur (corrosion, extreme temperatures, accidents). The second one is related to the systematic monitoring of the shape of the box girder using a TLS. One span of the bridge has been continuously monitored along an episodic program of seasonal measurements of the plates. The result is a model of seasonal shapes of the bridge that can episodically integrated within its digital twin with a corresponding time stamp. The point clouds of the imperfect plates (or realistic) are also linked to the geometrical entities of the perfect plates that define the bridge. These imperfect plates are referred to as seasonal “as-built” plates. In section 3, the measurement procedure as well as the point cloud process are described. This process is necessary to activate requested advanced inelastic stability analyses. In section 4, hitherto obtained exemplary results on FE analysis are presented.

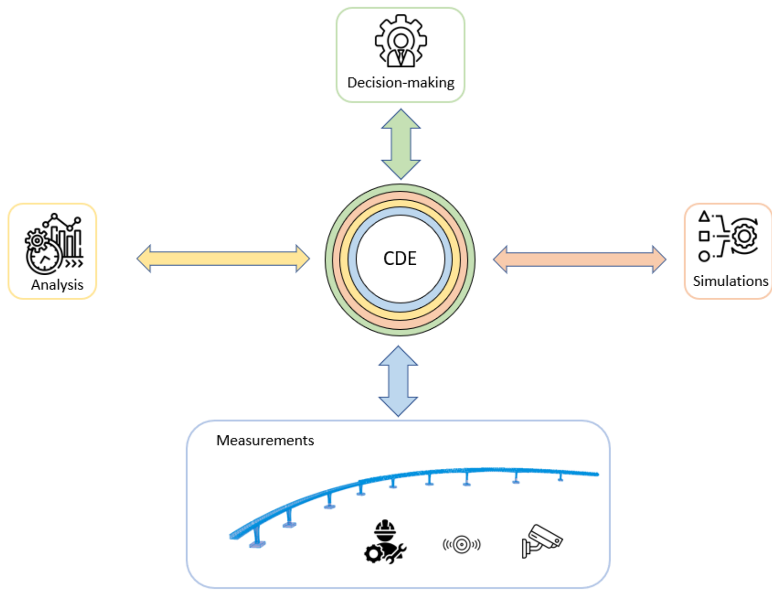

Fig. 4. Conceptual view of automated pipelines using and delivering information from a CDE

3.TLS Measurements

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, zi) 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 2019). which usually contain millions of unstructured points from which geometrical features need to be abstracted. This chapter elaborates on the measurement process as well as the data processing and results obtained using a laser scanner.

3.1 measurement process

During a given episodic scanning process, two measurements are taken from different points of view in order to capture the whole geometry of the steel box of the bridge. Each measurement takes 30 minutes and generates a point cloud representing a 360 view from the device standpoint with a density of one point every 3mm at a distance of 10m. Both measurements are co-registered into the same reference system using 7 spherical targets placed on fixed points on the ground. As a result of the co-registration process, a single point cloud is obtained containing over 100 million points. Figure 5 shows an example of the point cloud resulting from the scanning process in which the spheres and the positions of each measurement are marked. During the first measurement, the position of the spherical targets is precisely marked in order to replicate the measurement throughout the year

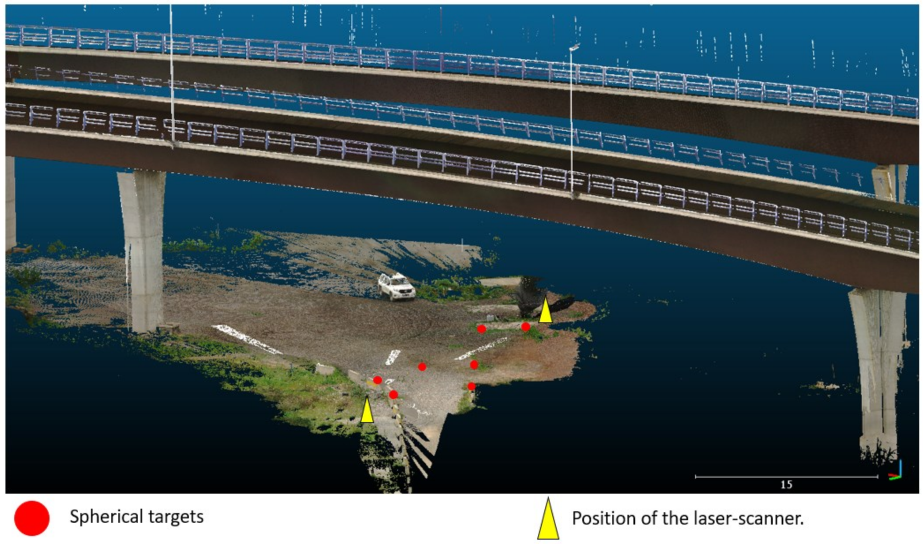

Figure 5. Final point cloud after the registration process. The position of the scanner and spherical target is highlighted.

A total of 4 seasonal episodic scans have been performed, the first scan was taken on March 2022, the second on July 2022, the third on September 2022 and the last in January 2023. Two more episodes are planned for the following months. The measurements were arranged to representatively capture the environmental conditions present during a year. It is worth pointing out that the particularly mild Mediterranean climate neither present extreme heat nor cold. In any case, to capture variations in the geometry provided by the point clouds, all the scans and the digital model need to be correctly superimposed in the same reference system (Fig. 6). The coordinate system of the geometrical model contained in the digital twin of the bridge is used as the reference. The model and the first scanned point cloud are co-registered using the Iterative Closest Points (ICP) algorithm (Li 2020). After a new scan is performed, spherical targets are systematically used to transform the new point cloud into the reference coordinate system.

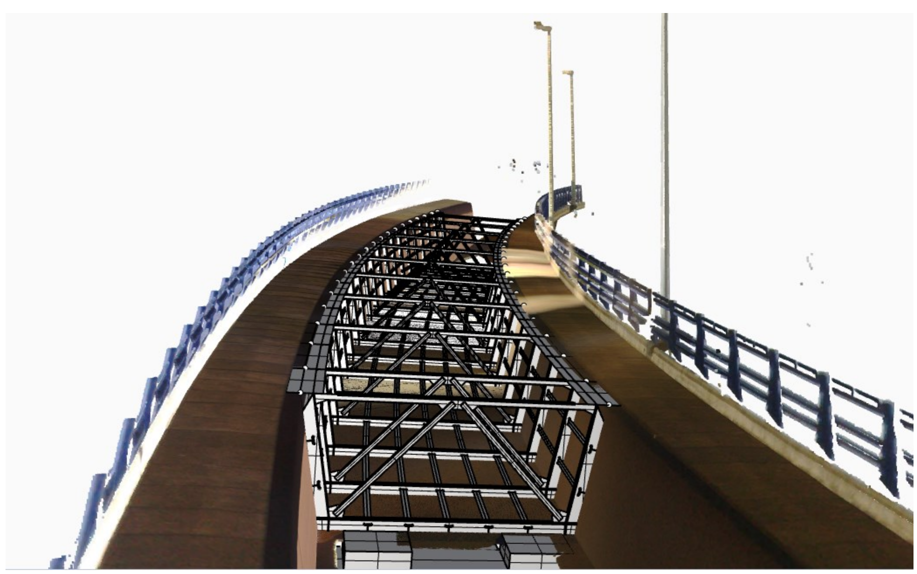

Figure 6. Geometrical model and pointcloud after the registration process.

3.2 Data pre-processing
Subsequently, scans and the ideal as-designed geometrical model of the bridge are registered into the same coordinate system. Two automated data pipelines have been established within Grasshopper. The first pipeline is a two-step process to clean and make the point cloud more manageable. First, the point cloud is cropped using the bounding box of the bridge region that is being studied (Fig. 7-A). Then, the size of the point cloud is reduced using voxel subsampling, in which points contained in each voxel are collapsed into a single averaged point. This pipeline considerably reduces the weight of the point cloud, which is convenient if the point cloud is to be used by intensive computational processes. The second pipeline associates the reduced point cloud with each steel plate in the geometrical model of the bridge steel box girder. Point clouds are segmented using the oriented bounding boxes of each individual subpanel in the geometrical model (see Figure 7-B).

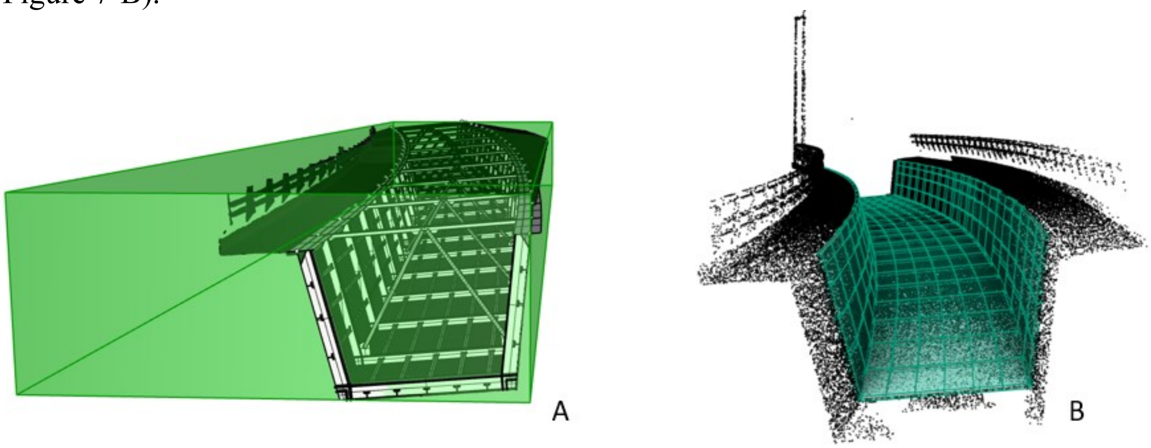

Figure 7. A: bounding box used to reduce the pointcloud to points contained in the region of study. B: Pointcloud segmentation using oriented bounding boxes of the box girder sub-panels

This automated process provides a way of systematically adding new measured information to the digital twin of the bridge and allows linking individually the as-designed geometry in the model with as-built information provided by the point cloud at global and local levels (Fig. 8).

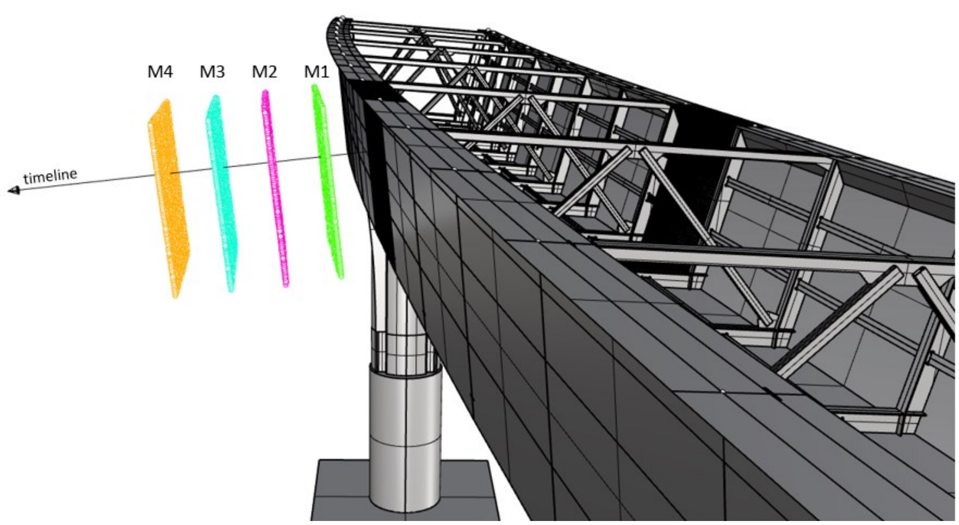

Figure 8. Multiple scans (M1 to M4) result in overlayed pointclouds that are associated with the elements of the bridge.

3.3 Analysis and results

The deviations between the as-designed surface of the geometrical model and the hitherto obtained as-built point clouds have been computed. The deviation is calculated as the perpendicular distance vector between the measured points to the surface of their corresponding sub-panel in the model. The global results are visualized in Figure 9. Seasonal effects are observed since the results for measurements taken in March and September (similar environmental conditions) present similar deviation patterns, while in measurements taken in January and July, deviation distributions are shown with different configurations. The initial imperfections of the sub-panels of the steel box girder are captured by the global deviation analysis previously presented. A new as-built surface for each panel is calculated interpolating their corresponding points. The new surfaces can be stored and queried with different levels of granularity (See Figure 10), and subsequently be submitted to non-linear FE analysis as explained in the next section.

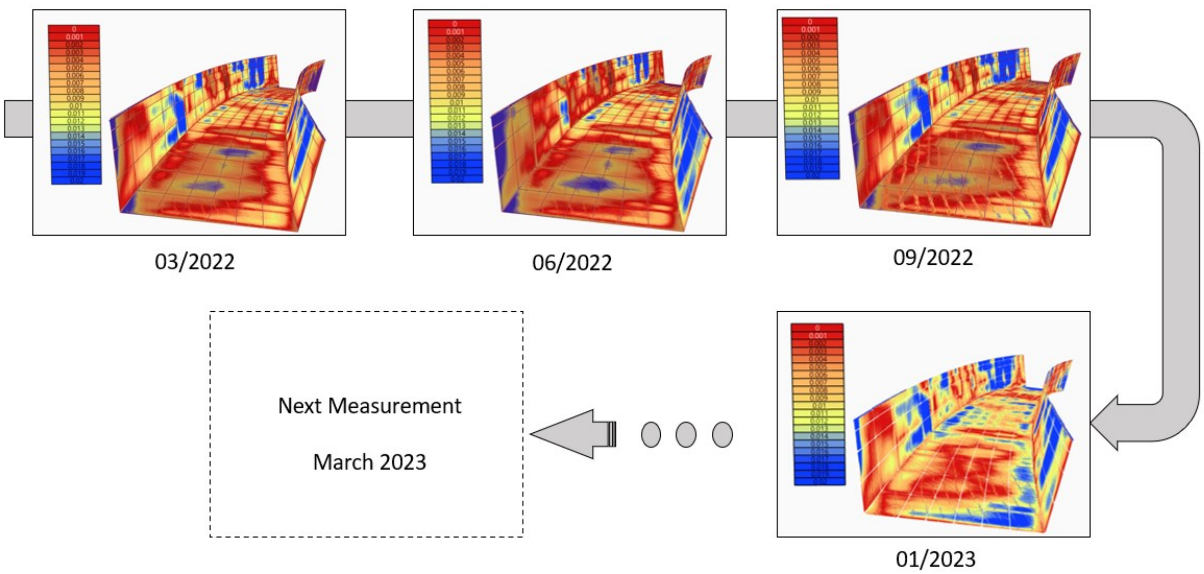

Figure 9. Results of the deviation analysis conducted on the bridge span for all the scans up to date.

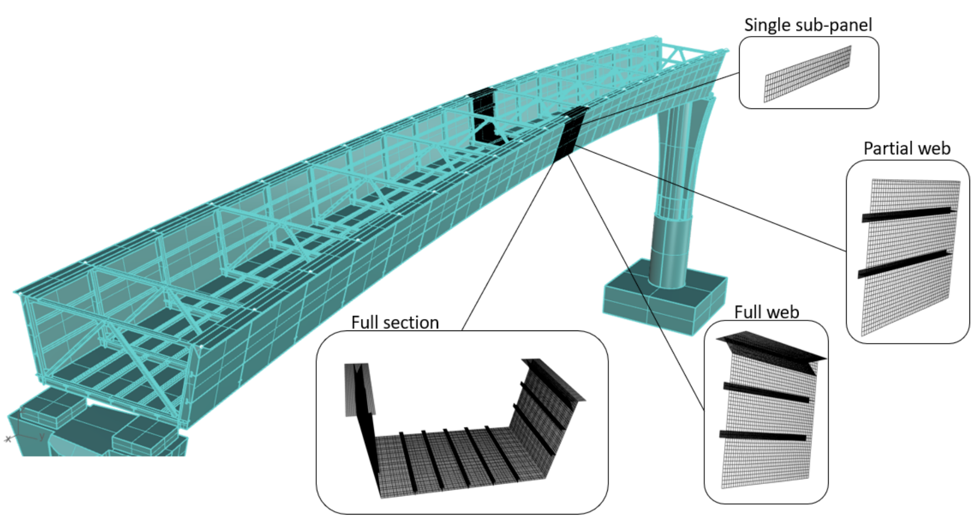

Figure 10. Different levels of available as-built information, from full sections to single web sub-panels

4. Numerical models

The developed digital twin aims to be an information construct for decision making at various levels. As a result, during operation, different types of numerical models may be requested (according to different complexity levels shown in Fig. 10). Namely, one can request: i) Instability Eigenvalue analysis of isolated plates, ii) inelastic analysis of stiffened partial or full webs or among others iii) cross-sectional analysis of the composite bridge considering the full section at given locations and iv) full advanced inelastic analysis of the whole asset (which may be computationally intractable nowadays though). In the following, brief discussions of this potential are discussed.

4.1 IFC-based geometries for plates.

The developed BIM model stores metadata and information related to all elements. Geometrical configurations of bottom flanges or webs (both stiffened) are stored in the IFC model with all necessary information about the girder (thicknesses, widths, heights, stiffeners dimensions and locations). From this model, users can select given panels and retrieve necessary information useful to develop plate buckling analysis. Early versions of these models include the use of EBPlate (Centre Technique Industriel de la Construction Metalique 2022), a Software aimed at predicting Eigenvalues and Eigenshapes of in-plane loaded stiffened plates. Figure 11 shows a selected stiffened web plate subjected to bending, compression and shear stresses. The results help the structural modellers to understand the stability behaviour of this specific portion of the web. The simulations are based on discretization and Fourier Series. Figure 11 shows the results obtained with EBPlate. Presently, the development of the ASHVIN digital twin platform is focused on integrating these results in the precise location of the panel under scrutiny integrated in the Ashvin platform presented in Figure 3.

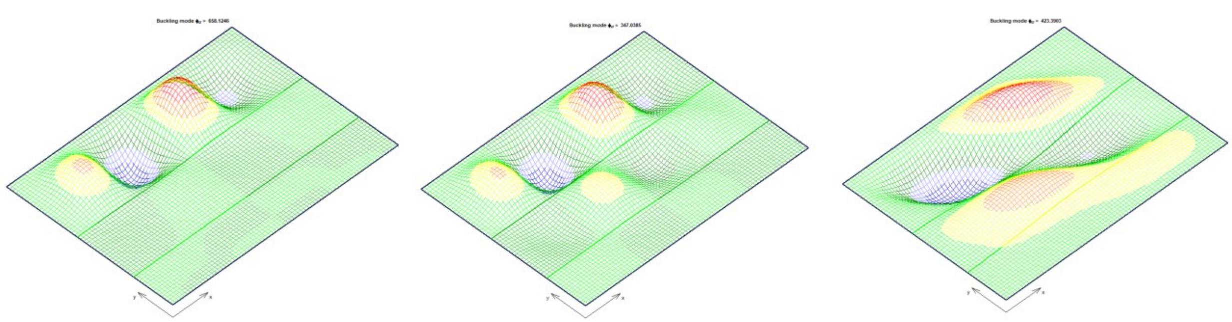

Figure 11. Stability analysis of a longitudinally stiffened partial web.

4.2 Structural analysis based on realistic shapes of plates.

The developed digital twin stores metadata and information related to point clouds and links this information to the IFC model. Geometrical configurations of bottom flanges or webs (both stiffened) are stored and processed. Different levels of simulation models can be then activated from these realistic shapes.

For the sake of understanding the realism and accuracy of these models based on imperfect plates, preliminary advanced inelastic analyses have been developed. Figure 12 shows a linear perturbation analysis of a strip of the web (partial web shown in Fig. 10) when subjected to pure compression. A region between longitudinal stiffeners is thus analyzed using Abaqus Simulia (Simulia 2013). Boundary conditions are assumed as simply supported at this level.

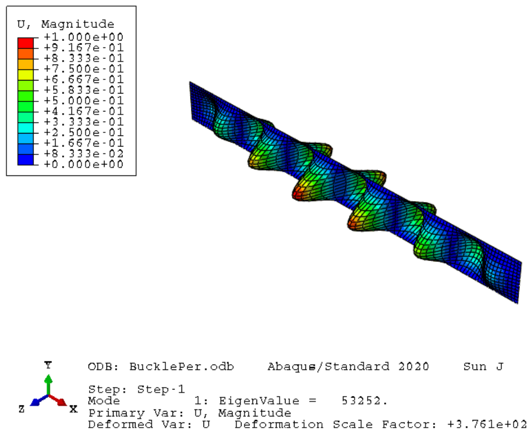

Figure 12. Eigenvalue analysis of isolated panels.

Subsequent use of this Eigenshape as the initial imperfection for advanced inelastic analysis provides numerical solutions for the assessment of this sensitivity. Assumptions related to the magnitude of these imperfections are always a designer's concern (Chacón et al. 2007). Figure 13 shows a plot in which the sensitivity to the magnitude of this imperfection (affine to the Eigenshape) is addressed.

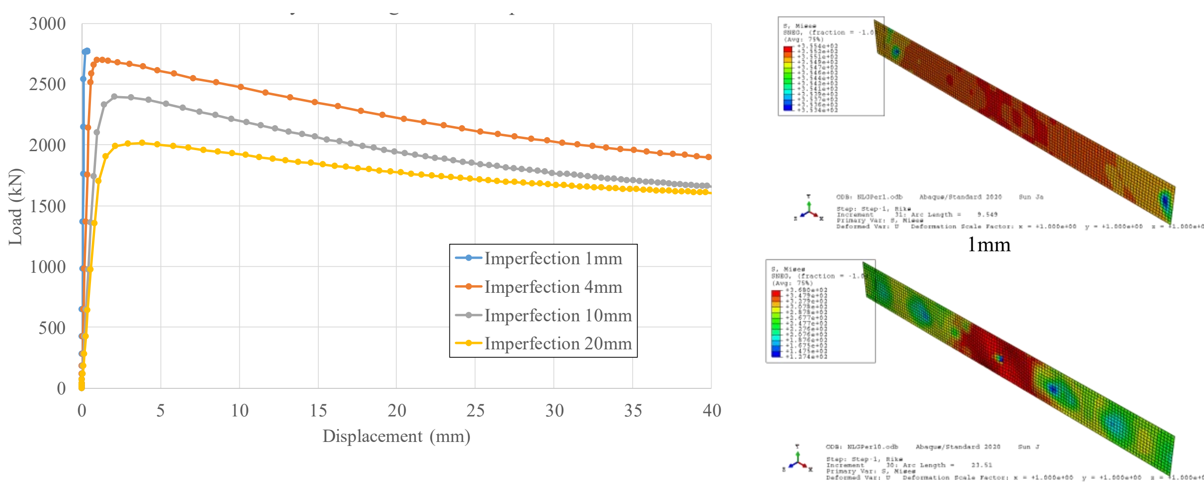

Figure 13. Sensitivity of the magnitude of imperfection on the load bearing (pure compression)

Structural analysis of the same isolated plate but in this case, using realistic imperfections are under development. Special care must be taken with the boundary conditions of the edges to avoid local failure in those regions. Likewise, the automated generation of FE-friendly meshes from the as-built model is still a work in progress. The resulting imperfect surfaces require detailed meshing.

Small deviations on the surface imply that meshes must generally be unstructured. In some cases, sizes and elements are conditioned by the meshing algorithms. Additionally, special attention must be given to contact regions between elements in the IFC model (for example, between the plates and the stiffeners) which, due to the small deviations introduced, generate small gaps that condition the quality and usability of the meshes and, thus, may require a human-in-the-loop re-modelling process for those specific regions.

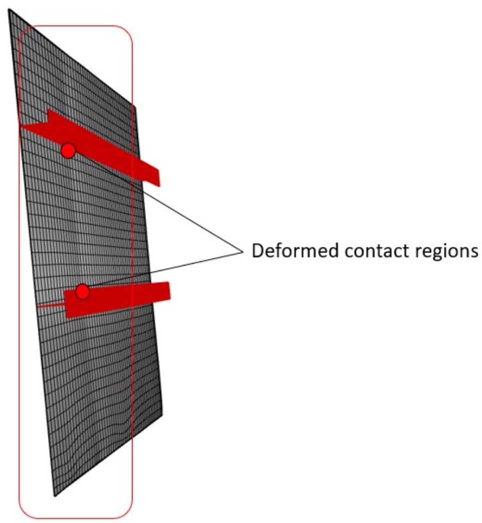

Figure 13. Imperfect contact between 'as-built' surfaces derived from the pointcloud measurements and 'perfect' stiffeners from the model

The hitherto used data transfer files between surfaces (fitted from point clouds) and FE-friendly meshes are serialized in STEP, a standardized 3D model exchange format that is widely recognized by computer-aided engineering software (STEP-file, ISO 10303-21). Fig. 14 shows an unstructured FE- mesh developed with a medial axis mesh generator.

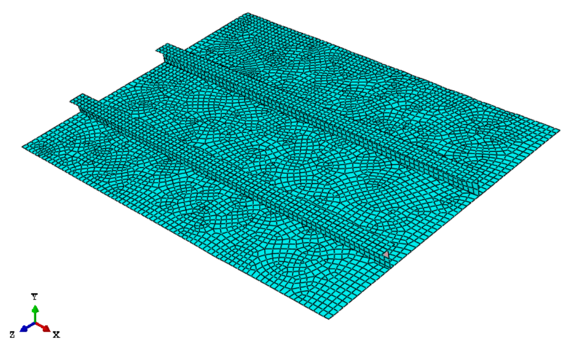

Figure 14. Mesh generated from surfaces fitted to the point cloud measurements.

Once measurements are completed, establishing systematic use of both the IFC model and the seasonal measurements is the next step in this research.

5. Conclusions

This study explores the feasibility of performing systematic seasonal geometrical assessments on a horizontally curved steel-concrete composite bridge in the Metropolitan Area of Barcelona with the support of a digital twin and Terrestrial laser scanner measurements. To that purpose, a BIM model has been generated and introduced in the ASHVIN digital twin platform, which combines the information in the model with a set of databases that can host measurement data and makes them available for stakeholders. Multiple geometrical assessments have been performed scattered throughout the year to representatively capture different environmental conditions.

Point clouds resulting from the measurements have been systematically uploaded to the platform. Automated pipelines have been successfully developed to clean, lighten, and segment the point cloud, and associate BIM elements to their corresponding region in the point cloud.

From point cloud data, BIM steel plates located in the box girder of the bridge can be linked to its 'as-built' geometry, which can be accessed granularly to be used for multiple analysis scenarios. As-built geometries contain measured imperfections that can be subsequently employed for inelastic analysis of the plates. An exploratory instability analysis has been conducted on a single panel, in which the sensitivity to 'theoretical' imperfections has been evaluated.

Further research is needed to automatically submit the as-built geometries to structural analysis. The generation of meshes the assignment of the boundary conditions and the contact between elements need to be carefully addressed.

The study points out the potential that the combination of Information Modelling, simulations and different types of measurements within complex information constructs such as digital twins have. To efficiently manage and operate with maintenance information, Digital Twins are meant to accommodate many different layers of information. As a result, different stakeholders will be able to provide and extract value from these assets. The structural engineering community will be able to leverage the existing knowledge to another level.

Acknowledgments

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