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Integrating BIM in experimental tests on bridge beams

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ABSTRACT: Information accessibility is a fundamental aspect for an adequate management of existing infrastructures. While BIM methodology has been proposed as an effective method for design and management activities, few examples exist in the integration of data from several techniques in a unique database for horizontal infrastructures. The present paper describes an innovative framework for integrating testing, inspections and monitoring activities on existing bridges following BIM methodology. Information requirements and model organization are specified for bridge elements and bridge management data following Italian regulations as a reference. A practical application example of this methodology is presented considering data from the Bridge|50 research project. The outcome of this work demonstrates that the approach pro-posed provides functionality and openness of the database for bridge management and testing activities. Furthermore, it confirms the utility of BIM to integrate and correlate data from different sources and improve the procedures of infrastructure management.

1 INTRODUCTION

Existing infrastructures, such as bridges and viaducts, play a crucial role in guaranteeing the social and economic wellbeing of the inhabitants of a territory. Nonetheless, an increasing quantity of European existing bridges have reached or are reaching the end of their life cycle. This affection is worsened due to the increase in traffic loads and the effects of climatic change. Due to this situation, a big interest has been deployed by public entities, motorway concessionaries and research institutes to study the techniques needed for correct infrastructure management.

Activities such as inspection, testing, and monitoring are fundamental to guarantee the functionality of the existing infrastructures. These activities are normally regulated by public administration who release guidelines and monitoring plans for the infrastructure. The great amount of data needed on a periodic basis creates further challenges in the bridge management process.

Building Information Modelling (BIM) comes as a logical solution to this problem as it aims for a methodology for infrastructure design and management, where all data is digitalized in a central platform. In fact, the usage of a Bridge Management System (BMS) where concepts such as Geographical Information System (GIS) for the territory and BIM for the single infrastructure is usually recommended. (Wan et al., 2019).

Nonetheless, as BIM was initially created for the design phases of vertical infrastructure, big question mark still exists in its usage for management operations in horizontal infrastructure.

Some examples of BIM usage for bridge management can be seen in the literature. For instance, some authors focus on the application of innovative techniques for digitalizing inspection data (Belcore et al., 2022) while a different research focus is the integration of BIM with data coming from procedures of Structural Health Monitoring. (Davila et al., 2017).

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These examples give a notion of the existing procedures that can be used for the management of infrastructures, however a standard procedure and a clear explanation regarding the information that should be included in a BIM model for bridge management is still needed.

2 DATA REQUIREMENTS AND CODES

2.1 *Bridge and viaducts management data*

In Italy, an official guideline for bridge risk evaluation was first issued in 2020 and then ratified in 2022. (Ministero delle Infrastrutture e dei Trasporti, 2020).

The guideline proposes a multilevel risk analysis, where the level of information to be retrieved increases as the level of analysis increases. All bridges in the Italian network are subjected to level 0,1 and 2 (census, visual inspection, and risk classification). According to the classification given in level 2, further visual inspections are scheduled, or the passage to a further level of analysis (3 or 4) that includes testing activities, structural modelling, or the application of a monitoring system, is decided.

Following this guideline different information requirements can be defined according to the level of analysis. For example, in level 0, general aspects regarding the bridge and the context where it is located are determined. In level 1, a list of common defects and a criterion for defect characterization is given. Clearly, bridges with a higher risk attention class have higher information demand. For instance, a bridge that goes to level of analysis 4 needs to consider information regarding non-destructive testing, monitoring systems and structural analysis, other than the basic information of the initial levels.

Regarding the single test procedures and its data requirements, reference is made from normative standard such as ISO, EN or from Italian specific guidelines (UNI).

2.2 *Bridge BIM model*

As digital transformation gained interest in the public sector, regional and national administrations have also issued legislation regarding the usage of open-BIM (models that are readable and functional regardless of the software). In Italy the most relevant legislation regarding this topic is the so-called BIM decree (DM 560-2017) where deadlines are established for the public administrations to progressively adopt open-BIM methodology in civil works procedures. This legislation has been latter updated and currently states January of 2025 as final date for the mandatory implementation of BIM in Italian public processes (works of over 1 million euros).

Nonetheless, regarding the technical specification about BIM modeling, international organizations like UNI, EN and ISO set the basic principles. For open-BIM models the main guidelines are given by BuildingSmart association. The central recommendation given to guarantee the exchangeability of data is the usage of Industry Foundation Classes (IFC) data format. This means setting the BIM model following an object hierarchic organization that is standard depending on the type of infrastructure that is modelled. In the update IFC4.3 the BIM model organization as well as the different categories -*IFCclasses*- and attributes for the bridge and viaducts elements are described. (BuildingSmart, 2020).

2.3 *Management activities in BIM*

A bridge BIM model that is useful for management activities needs to merge information from both previous subchapters; this means, following BIM standards for bridge BIM modeling when it can be developed (e.g. bridge geometrical elements), but adapting the information and elements included in the model according to the needs of the risk assessment guidelines.

Evidently, not all types of data stated in the bridge risk assessment guideline can/should be included in a digital model of a bridge for maintenance purposes. In this sense, a clear differentiation needs to be made between a BIM model and a Common Data Environment (CDE).

A CDE is a cloud-based space in which information regarding a project is available for the participants (Werbrouck et al., 2019). The main principle is that all models, technical drawings, and documents are stored and managed in the CDE and not in the single BIM model. In this sense, the bridge BIM model should include only the basic information to understand the bridge geometry, its context, and the inspection/testing activities performed over time. For further information regarding these activities the BIM model should include links to the external documents (situated in the CDE).

This paper intends to give a general framework of BIM methodology for existing bridges specially focusing on the treatment of data coming from infrastructure management activities.

This work is included in the BRIDGE|50 project, a research collaboration between universities, public and private partners to perform a large number of experimental tests on bridge beams previously dismantled from a demolished viaduct in the city of Turin, Italy. Arguments such as the digitalization of defect inspections, the BIM modelling of testing and monitoring activities, the updatability of models on time and the organization of BIM model and CDE will be treated.

3 CASE STUDY

The Bridge|50 project is among the largest research projects on bridge beams currently in Europe and in the world (Bridge50.org). The project studies the structural performance of 29 prestressed beams and 2 pier caps that were dismantled in 2019 from a viaduct at the end of its life cycle (50 years). The viaduct presented a simple supported scheme with 10 prestressed concrete I-section beams and 2 prestressed U-shaped edge beams supporting a 14 cm thickness concrete slab (Savino et al., 2020). Since the campaign started, the beams have been moved to a testing site and a series of visual inspections and testing (rebound hammer, corrosion potential, concrete drilling, etc.) have been performed. The most peculiar testing activity is a large-scale static and dynamic loading test protocol that is performed in a reaction-frame specifically built for the project. The response of the beams to the loading tests is measured using sensors positioned on their surface and the load capacity up to collapse is determined (Savino et al., 2023). Once the beam has been tested, it is moved away from the reaction frame and further inspection/testing activities are performed to analyze the effects of the generated damage. In this research work the digitalization process of the first 7 beams tested up to collapse will be explained.

Even though this case study treats single bridge beams instead of an operating bridge, a parallel can be made between the information needs of the project and the one of a bridge still in service. The large quantity of inspections and testing data obtained from each beam can be compared to the amount of information that is obtained from a complete analysis of an existing bridge; furthermore, the requirement to update the information in time as the campaign goes on gives a valuable example of how digital strategies can be applied for long-time inspections/testing activities for existing bridges.

4 APPLICATION OF THE BIM METHODOLOGY

4.1 *CDE and organization of project data*

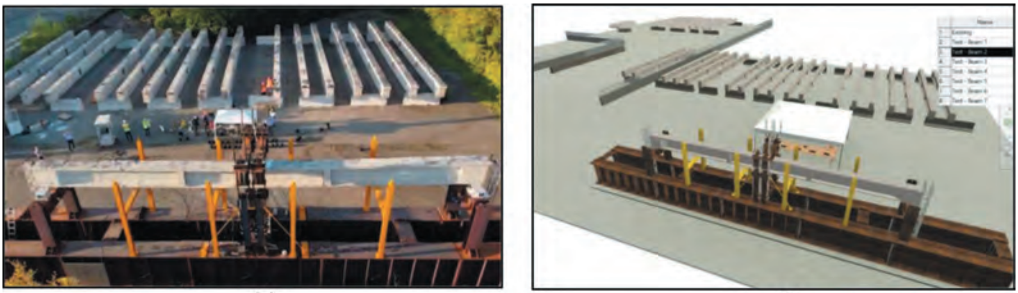
It was decided in an initial phase of the experimental campaign that a cloud based CDE was going to be used to manage all project related data. In the CDE, data is allocated differentiating between general data about the project and data regarding the single beam elements. For each beam in the project a specific data folder is assigned and information regarding the technical/historical documents, testing and inspection activities and the models created for the single beam are stored inside. This means that every beam studied has a unique BIM model, and the latter is linked together with the external information located in the respective data folder. On the other hand, the general information about the project (historical documents, project schedule, technical documents, global models, etc.) is stored in a different folder inside the CDE. This global information folder also includes a BIM model (federative testing campaign model), that acts as a collector of all the single beam models and is used to get a general perspective of the testing campaign and the different campaign phases. The federated model as well as the single BIM models are created using *Autodesk Revit*, however they are exported in IFC format, following the BuildingSmart indications for open-BIM.

4.2 *Federative testing campaign model*

Based on previous work on digitalization of the testing campaign (Rodriguez et al, 2022), the general BIM model is created. This general model is a virtual replica of the testing site, where all components present on site (testing reaction frame, new jersey barriers where the beams are supported, etc.) are modeled either as internal components or as external families. Similarly, in this model, every single BIM model of the beam elements is linked and positioned according to the real location of the beams in the different phase in the testing site.

Regarding the data included in this model, the level 0 of the Italian guidelines for bridge risk assessment is taken as a reference. This information is also complemented with general data about the specifics of the research project that is needed for an understanding of the campaign. This data is added following either pre-compiled options according to the guideline (e.g. bridge alignment options: straight or curvilinear) or free fields (text/number/yes-no) options. Information regarding technical documentation of the project is available using URL hyperlinks that correlate external documentation in the CDE with the data requirements of the model.

Finally, to be able to follow the different stages of the testing campaign the “phase-filter” tool of the software is used. This tool allows the creation of a timeline in the model, where digital objects attributes can be linked to the data selected. The timeline is created with the different dates when the full-scale loading tests were performed in the beams. For example, in the data-phase “Beam – 1”, the respective beam moves location to a testing position, inside the reaction frame and in data-phase “Beam – 2”, the beam-1 changes to the location after the large-scale test and the beam 2 occupies its place on the reaction frame. Evidently, the information about the model as well as the data of the single beam model also changes according to the data-phase.



(a) (b)

Figure 1. (a) Testing site. (b) Federative model of testing site in phase -Beam 2-.

4.3 *Building the single beam models*

Different BIM models were created in single files following the unique characteristics and particularities of every beam. The family class in *Revit* was defined as *StructuralBeamElement* (translates into *IfcBeam* in open-BIM specifics). Then, once again, the Italian guideline is used as reference for the data included in the model. In this case, information about level 0 as well as information about inspections (ordinary and extraordinary) was included.

To be able to manage the big amount of information needed for every defect finding (cracks, delamination, etc.) it was decided to manage this data as an external family element that is dependent or hosted by the main *IfcBeam* element. The same consideration is made for the testing data, that is treated as an external family, but also dependent on the main beam element.

A final step in the modelling procedure is the usage of the phase-filter tool to update information in the beam models according to the evolution of the testing campaign. Different phases were created in the project according to when the main testing activities took place (see Table 1). The selected phase updates all the general information in the model as well as the specific information about the damage and testing families.

Table 1. Campaign phases for beam 3.

Phase	Tests
Testing phase 1 (NOV.2021)	Visual inspection, Rebound Hammer, Corrosion potential
Testing phase 2 (APR.2022)	Core drilling
Testing phase 3 (OCT.2023)	Full scale loading test
Testing phase 4 (NOV.2023)	Visual inspection, Tensile of steel, Residual prestress, Compression of concrete, Elastic modulus of concrete

4.4 *Defect data elements*

Following a similar procedure as explained by Isalovic et al. (2020) external dependent families were created using the *IfcSurfaceFeature* class. The geometry was created following a semiautomatic procedure taking advantage of an accurate defect modelling performed in an initial phase (Rodriguez et al, 2021). Then information regarding the defect characterization was added to the single families following the defect characterization of level 1 of the Italian guidelines. External documentation regarding the single defects was linked with URL hyperlink.

The defects families were modelled locally with respect to the beam families to ensure the correct placement and connection between defect and structural element.

As explained before, the information regarding beam damage needs to be updated with re- spect to the same timeline created in the beam family object; therefore, a second defect inspec- tion was made in the mechanical tested beam elements -after the full-scale loading test- and the information about new cracking was updated in the respective phase of the digital model.

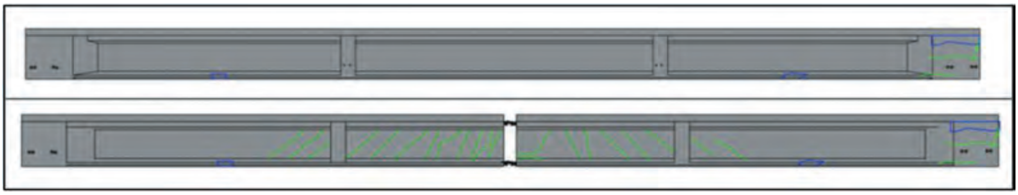


Figure 2. Defect families positioned in beam 1 before and after large-scale mechanical test.

4.5 *Testing results data elements*

Considering the lack of standards for the digitalization of testing information, an experimental approach was tested, using once again the *IfcSurfaceFeature* class to generate a link between beam element and test element. Then, to represent the testing activities in terms of type and location, different conceptual, basic geometries were assigned to the area where the different typologies of tests were performed. (e.g. square for rebound hammer test, circle for pull-out test, etc.). This test geometry was positioned locally with reference to the beam families to ensure the correct placement according to the actual test location. To standardize the test-data objects and considering that every typology of test has different data requirements it was decided to include just general information about the test activity in the BIM objects and leaving other type of documentation (technical specifications, normative documents, test reports, etc.) linked through hyperlinks. This data was also connected to the phase-filter tool to be updated according to the phases of the testing campaign.

This procedure was replicated for all the different non-destructive tests applied to the beams: rebound-hammer, concrete pull-out (compression, tension, and alkalinity tests), corrosion potential, tensile test, residual prestress test.

Table 2. Example of data for the different model elements.

Data in model			
Category	PropertySet	Parameter name	Parameter Type
	AINOP Code		Text
IfcBridge	Bridge Identification	Type of connection	Text
		Structural typology	Text
		ID	Number
IfcBeam	Element identification	Bridge element type	Text
		Bridge span	Number
		Defect code	Text
IfcSurfaceFeature - Defects	Defect characterization	Weight - G	Text
		Extension	Text
IfcSurfaceFeature -		Type of test	Text
Tests	Test data	Operator	Text
		Link to test report	URL

4.6 *Sensors/monitoring data elements*

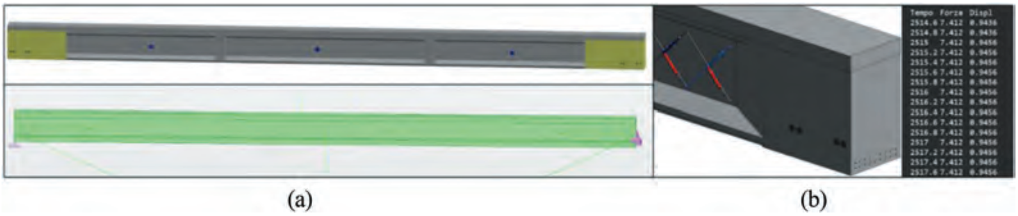
Four different data sensor families were created corresponding to the 4 typologies of sensors used during the large-scale loading-test (Used to read displacement and strains due to bending and shear-placed on concrete, and steel-stirrups and strands-). The families were created using *Revit* category *DataEquipment* that automatically translates into *IfcSensor* according to the specifics of open-BIM. The geometry of the sensors was created following the geometrical specification sheets. This typology of family is also hosted by the main *IfcBeam* element and in this sense positioned locally with reference to the beam families. Once again, to standardize the typology of family used and not create a great number of parameters for every single object, it was decided to include basic data regarding the sensor to the BIM object (e.g. sensor code, typology, connection type, connection server, data receiver, etc..) and connect it through a URL hyperlink to the sensor database. This decision is beneficial also considering the operation and manageability of the BIM model preventing data overloading using an external database. This procedure was applied for sensors deployed on the beam surface during the full-scale loading test but could be replicated with any type of structural health monitoring solution.

4.7 *Structural models*

Different structural models were created through the different stages of the life of the beam during the experimental campaign. These structural models represent the typology of data that needs to be retrieved in bridges at further levels of analysis according to the risk assessment guidelines (level 3 and 4). Taking into account that with every additional inspection/testing phase more information was acquired about the beams in study, the level of reliability of the proposed structural models should increase as well.

To be able to link the evolution of the structural models with respect to the evolution of the testing campaign, a correlation of structural/BIM models was created. Software from the same software house -*Autodesk Robot*- was used in the structural analysis to facilitate the interoperability of different software.

A specific structural model was created according to every phase of the model where a certain specification in the *IfcBeam* was updated (e.g. material properties). The variation of the required property was transmitted to the structural model by an export/update task available thanks to the existing connection between the two software.



```
Tempo  Forze Displ
2514.6 7.412 0.9436
2514.8 7.412 0.9436
2515   7.412 0.9456
2515.2 7.412 0.9456
2515.4 7.412 0.9456
2515.6 7.412 0.9456
2515.8 7.412 0.9456
2516   7.412 0.9456
2516.2 7.412 0.9456
2516.4 7.412 0.9456
2516.6 7.412 0.9456
2516.8 7.412 0.9456
2517   7.412 0.9456
2517.2 7.412 0.9456
2517.4 7.412 0.9456
2517.6 7.412 0.9456
```

Figure 3. (a) Test families inside beam model and connection with structural model. (b) Sensor detail and link with sensor database.

4.8 *IFC export*

To ensure the openness and readability of the created files a passage from *Revit* file to IFC file needs to be established. In this sense operations called class-mapping and parameter-mapping are implemented. This means checking that the software native element category corresponds to the correct *IfcClass* specified for the bridge elements in the Open-BIM guidelines. Moreover, to ensure that the data included in the model is exported as attributes to the *IfcClass* an external text file is created to “guide” the software in the exportation settings. In this external file the data parameters included in the model are enumerated and organized to be exported in *IfcPropertySets* according to the different object classes.

The IFC standard does not include a function that updates data in time as the phase-filter tool; therefore, different BIM models are exported according to the different phases created.

5 RESULTS AND CONCLUSIONS

In the present paper a framework for the creation of BIM models for bridge maintenance activities is proposed using a testing campaign on bridge beam as a case-study. The integration of information from inspection, testing, monitoring, and structural analysis using BIM methodology is specified. Maintenance data requirements were defined following Italian normative for bridge risk assessment while data modelling requirements were defined following open-BIM standards. Even though the case study treats single bridge elements and not an operating bridge, a parallel can be made considering the big quantity of data retrieved and the duration of the project.

Firstly, a clear differentiation between CDE and BIM model information requirements was stated. This differentiation is the basis of the BIM methodology applied as external documentation is stored in the CDE and single BIM models are created containing only basic information of bridge management activities.

The first model described was the global federative model that assists the tracking of the experimental campaign phases. This federative model acts as container of the other digital models of the beams and gives context to the experimental campaign. The fundamental characteristic of this model is its possibility to be updated thanks to the phase-filters. The time-integration demonstrated to be an excellent tool for the organization of bridge management data, as it allows an easy follow-up of the testing phases. In fact, this tool demonstrated such good results that it was also used to treat the inspection and testing activities in the single beam models.

Regarding to the latter, a description about the modelling characteristics of bridge elements following open-BIM standards was specified. Nonetheless, the innovation in the procedure was emphasized in the modelling methodology for inspection, testing and sensor/monitoring data. In this sense, specifics about the included data, the BIM characteristics and geometric characteristics of the elements was stated.

Starting by the BIM format, specific *IFCclasses* (external families) were used to treat this type of information. This external families were, however, dependant to the "main" structural element. Hence, they were attached to the main family and positioned with a local reference to this element. This methodology demonstrated to be satisfactory solution to treat bridge maintenance information as specifics about every single defect/test can be given, but also a direct correlation between the "host" object and the element is created. Likewise, the possibility to position the external element taking as a reference the structural main element helps the rapid visualization and contextualization of data with respect to the structural element analysed.

Regarding the geometry of the elements modelled, the real geometry about defects and sensors was considered. On the other hand, for the testing activities just basic geometry to differentiate between the different tests was created. Considering the global purpose of the model, this type of geometrical simplification does not compromise its functionality as a rapid differentiation between tests can still be determined according to the selected shape and the position and extension of the test is still respected.

With respect to the data that was included in these external objects, the basic idea was to standardize the data regardless of the type of defect/test to be treated. In this sense, a certain number of parameters were created in the BIM objects and external documentation (such as tests results, inspection documents, sensor data, etc.) were related to the model elements through the usage of dynamic links. This decision is beneficial for the model as it allows a correlation of information from different sources in a single database, without adding extra-computational demand to the visualization of the information.

A final explanation regarding the correlation of structural analysis models with BIM models was also stated. In this sense, the link between both typologies of models was established performing exports/updates of the BIM model to the structural analysis software once the characteristic of the same were updated. This process exhibits ones again the benefits of creating a timeline in the model as more information from tests/inspection means a better understanding of the beam characteristics and thus, a better structural analysis model.

Finally, the export of the BIM model following open-BIM standards was performed. This example showed the passage from software-constrained model to an open model without losing information regarding the categories of the objects or their attributes. Nonetheless, the inability of the IFC standard to keep track of the timeline created resulted in multiple files corresponding to the phases created.

The conclusions of the work demonstrate the possibility of treating bridge management data with BIM methodology including basic information about the bridge characteristics -level 0 of guideline- but also complex information corresponding to the superior levels of analysis. Even though a first standardization framework was proposed, future developments are needed in the IFC guidelines to better include information regarding defects and testing.

The result of the methodology demonstrates that time integration with the data inserted in an open-BIM model results in a key-aspect to consider for a BIM model for bridge maintenance. Therefore, a future upgrade in the IFC schema is also needed to consider this sort of information allowing the creation of a unique database for all management phases.

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