Innovative Infrastructure Solutions (2025) 10:59
https://doi.org/10.1007/s41062-025-01864-8

TECHNICAL PAPER

Bridges monitoring and assessment using an integrated bim methodology

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Received: 30 September 2024 / Accepted: 3 January 2025

Abstract

Risk assessment of long-existing infrastructure has become one of the main challenges in civil engineering. Major efforts have been made in recent years to develop new techniques for rapid damage identification and ensure proper management of these structures. This paper presents a data management approach utilizing BIM methodology to create a digital database for bridge monitoring procedures. Initially, two BIM methodologies for creating a damage database are introduced, focusing on beams from a dismantled urban viaduct. Subsequently, the most suitable methodology is applied to an existing bridge in Turin, Italy. Through the chosen methodology a damage identification and classification process based on a triangular mesh is performed, assisted by a convolutional neural network (CNN) for automatic damage detection. Additionally, the paper outlines a digitalization process within a BIM environment, integrating official guidelines for bridge risk evaluation, classification, and monitoring in Italy. By employing programming tools, all data required by the guidelines is efficiently incorporated into the database. The outcomes demonstrate the effectiveness of remote sensing applications for bridge inspection and the possibility of merging BIM methodology into the inspection process to enhance the damage assessment of existing structures.

Keywords Bridges inspection · SHM · Remote sensing · UAV inspection

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Introduction

The accumulation of damage in aging infrastructure is a widespread problem globally [1]. Processes such as corrosion, erosion, and traffic overload significantly affect a structure's behavior, creating hazardous situations for users and undesirable social and economic consequences. This challenge poses a major obstacle for guaranteeing development and economic growth in economies worldwide, given the pivotal role that a reliable infrastructure network plays for economic competitiveness [2, 3]. The direct correlation between well-maintained infrastructure and economic development has been demonstrated through various models, both in the European context [4] and the North American context [5].

Given this fundamental relationship, the importance of effective infrastructure monitoring and maintenance activities becomes increasingly evident. Quick identification and assessment of infrastructure damage are key aspects for an informed maintenance decision-making process. In this context, the field of Structural Health Monitoring (SHM) has emerged to enhance monitoring and retrofitting procedures

Table 1 Levels of analysis present in the Italian guidelines in 2020 for bridge risk evaluation, classification, and monitoring

Level of analysis	Description
Level 0	Census, geolocation, and general characterization of the bridge. Includes also the collection of all information related to existing documentation.
Level 1	Direct visual inspections of the structure and the geo-morphologic characteristics of the area. Inspection sheets are filled for each bridge element to individuate the damage state.
Level 2	Classification of the bridge in terms of vulnerability, exposition and risk parameters based on the information previously obtained. According to the classification given, the following levels may or may not be applied.
Level 3	Simple structural evaluation of the bridge design criteria and structural capacity by comparison to current safety requirements.
Level 4	Accurate verifications according to the structural code to determine an action plan for the bridge. At this level, maintenance activities or traffic limitations can be determined.
Level 5	Is not treated in the current guideline as it refers to bridges of particular importance on the road network and a more refined specific study should be applied.

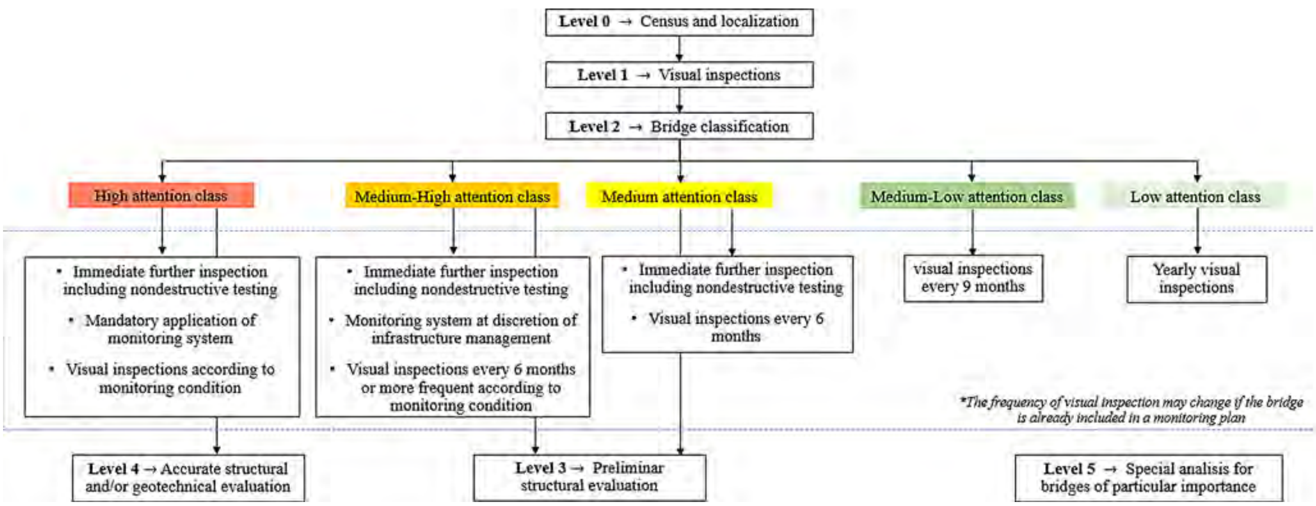

Fig. 1 Decision-making procedure for bridge assessment described in the Italian guidelines in 2020 for bridge risk evaluation, classification, and monitoring

for existing infrastructure. This field is highly multidisciplinary, encompassing a range of strategies, including sensor development, material studies, and data processing algorithms for damage detection [6].

In Italy, to standardize bridge surveillance processes across the national network, the Italian government issued official guidelines in 2020 for bridge risk evaluation, classification, and monitoring [7]. These guidelines were developed in response to the lack of standardized national regulations and growing concerns about infrastructure monitoring practices. This concern was amplified by the significant number of bridges exceeding their service life and a series of tragic incidents that heightened public awareness of the issue [8].

The guidelines introduce a multilevel approach for risk classification of existing bridges and a decision-making tool for maintenance based on fundamental principles: risk evaluation, safety assessment, and inspection/monitoring activities. The multilevel approach allows up to six different levels of analysis, with the depth of assessment and information recovery increasing with each level. A complete explanation of the level of analysis can be seen in Table 1 while the decision-making process proposed by the guidelines can be seen in Fig. 1. All bridges in the Italian network are subject to levels 0, 1, and 2; however, the complexity of further analyses depends on the bridge classification—termed "Attention Class"—assigned at level 2. Notably, as demonstrated in Fig. 1, the sequence of analyses after classification at level 2 is not necessarily linear. For example, a bridge may advance directly from level 2 to level 4 without undergoing the intermediate levels of analysis.

Given the substantial amount of information to be gathered by the guidelines, several critical aspects may affect their correct application. The classification process begins with data collected through recollection and visual inspections at levels 0 and 1, respectively. Level 0 focuses on general information about the bridge characteristics while level 1 emphasizes defect identification through visual inspection (see Table 1). For both levels, specific data sheets must be compiled and regularly updated. In the case of level 1, visual inspections must provide sufficient detail to compile an inspection sheet for each individual bridge element. This sheet should include information on the type, intensity, and extent of defects, as well as whether the defect affects the structural behavior of the bridge. Furthermore, each defect recorded in the inspection sheet should be supported by imagery. An example of level 1 inspection sheet is provided in Fig. 2.

In Italy, visual inspections are typically performed using under-bridge inspection units. These inspections require significant logistical effort, impacting traffic flow and potentially putting operators in dangerous situations [9, 10]. Moreover, although the vehicle crane can reach the bridge's intrados, certain parts may not be fully covered by the crane's range, making it challenging to inspect with the necessary level of detail [11]. Inability to visually inspect all bridge elements poses a major challenge for the application of the guidelines, as this process forms the basis for all subsequent levels of analysis.

Another challenge in applying the guidelines arises from information management. A unified, easily updatable database to consolidate information from different analysis levels would greatly enhance management and classification decisions. In this regard, BIM methodology is advantageous, as it allows for the digital representation of project data within a single database, facilitating the storage and updating of information throughout the bridge's service life [12]. While BIM is a well-established methodology that has seen significant success in the construction industry, its application for the maintenance of existing structures is more complex than for new builds.

For existing structures, a comprehensive record is essential for BIM modeling with conservation and maintenance purposes. However, issues such as lack of information, discrepancies between design and construction, and the inability to model aging defects are common in the field of HBIM (Heritage or Historical Building Information Modeling) [13]. This approach is often described as reverse engineering, as it aims to create a reliable model of the structure in its current condition, starting from data surveys rather than from idealized project designs [14]. The database should include not only coherent geometric modeling of reality but also non-graphical information regarding element descriptions, site characteristics, material properties, maintenance plans, and more.

HBIM can either recreate existing structures based on available documentation (such as building descriptions and design documents) or perform surveys to map the volume of objects to be modeled. Traditionally, survey procedures for existing structures involved manual and instrumental measurement systems (e.g., tapes, levels, theodolites). However, with the increasing support for 3D point clouds on BIM platforms, remote sensing technologies—such as laser scanning and photogrammetry—have become the predominant survey techniques in this field [15, 16]. These technologies represent a significant advancement in HBIM, providing a

Scheda Ispezione Ponti di Livello 1

6 | **Appoggi** N ____ Strada di appartenenza: ____________ Progressiva km: ____________
Tecnico rilevatore: ____________ Data ispezione: __/__/___

N°	Descrizione difetto	visto	G	Estensione K1			Intensità K2			N° foto	PS	NA	NR	NP	Note
				0,2	0,5	1	0,2	0,5	1						
App_1	Piastra di base deformata	☐	2			☐	☐	☐	☐			☐	☐	☐	
App_2	Ossidazione	☐	2	☐	☐	☐	☐	☐	☐			☐	☐	☐	
App_3	Bloccaggio	☐	4			☐	☐	☐	☐		☐	☐	☐	☐	
App_4	Preregolazione sbagliata	☐	4			☐	☐	☐	☐		☐	☐	☐	☐	
App_5	Presenza di detriti	☐	2			☐			☐			☐	☐	☐	
App_6	Schiacciamento/Fuoriuscita lastre piombo	☐	4			☐	☐	☐	☐		☐	☐	☐	☐	
Difetti d'appoggio in neoprene															
App_7	Invecchiamento neoprene	☐	3			☐	☐	☐	☐			☐	☐	☐	
App_8	Deformazione orizzontale eccessiva	☐	4			☐	☐	☐	☐		☐	☐	☐	☐	
App_9	Schiacciamento/Fuoriuscita neoprene	☐	4			☐	☐	☐	☐		☐	☐	☐	☐	
Difetti pendoli															
App_10	Ammoloramento pendoli in c.a.	☐	4			☐	☐	☐	☐		☐	☐	☐	☐	
App_11	Fuori piombo permanente	☐	4			☐	☐	☐	☐		☐	☐	☐	☐	
Difetti carrelli (metallici)															
App_12	Ovalizzazione rulli metallici	☐	4			☐	☐	☐	☐		☐	☐	☐	☐	
App_13	Fuori sede rulli metallici	☐	4			☐	☐	☐	☐		☐	☐	☐	☐	
Difetti di appoggio generici															
App_14	Deterioramento Teflon	☐	3			☐	☐	☐	☐			☐	☐	☐	
Eventuali note															

Fig. 2 Example of level 1 inspection sheet for bridge supports. Possible defects for this typology of element are listed in the inspection sheet and prompted possibilities for defect characterization are provided

fast survey procedure that yields highly accurate records of all geometrical and color details.

Determining the appropriate methodology, the accurate level of detail required, and the most effective modelling practice remains challenging when using remote sensing technologies with HBIM [17]. Currently, the irregular shapes and model details in HBIM are mostly addressed with a modeling procedure called Scan-To-BIM. This methodology involves performing a remote sense survey to the desired asset and applying processing operations to the produced point cloud. The filtered point cloud is then used as a reference to edit or model BIM elements from scratch [18]. However, maintaining the accuracy of geometric details and irregularities during the transition from point cloud to BIM object poses significant challenges. The modeling process in BIM software typically relies on basic operations derived from a 2D plane (e.g., extrusion, sweep). Additionally, color and texture information often consists of a single image repeated across all faces of an element, making it nearly impossible to recreate real details, colors, and irregularities in BIM objects [19].

To overcome these challenges, some authors have explored a preliminary step prior to modeling, involving the creation of a triangulated mesh from the point cloud for use in HBIM modeling via a Mesh-To-BIM procedure. This process attempts either to import the mesh directly into BIM software or to use mathematical functions to recreate the mesh lines within the BIM object [20]. However, significant difficulties arise because mesh formats are generally not compatible with or easily managed by BIM software.

Various approaches to the Scan-To-BIM process can be found in the literature. These studies either aim to create BIM objects for comparison with surveyed 3D point clouds to refine geometry [21, 22], or directly create BIM elements based on point clouds in a manual or semi-automatic manner [23–26]. Similarly, novel strategies for the Mesh-To-BIM procedure are also documented [27–29]. The most common technique for this methodology involves transforming the triangulated mesh into primitive NURBS (Non-Uniform Rational Basis Splines) for integration into the BIM environment [30, 31]. Other methods, such as importing the 3D mesh into BIM platforms via CAD formats and programming tools, have also been explored [32, 33].

On the other hand, for bridge maintenance and monitoring, the field of SHM has emerged as a vital framework for enhancing knowledge of in-service structures, enabling continuous monitoring and effective management of existing assets [34]. When combined with BIM methodology, most advancements in this field stem from the use of sensors for structural monitoring and the application of BIM methodologies for facility management. Specific analyses have explored interoperability channels and the integration of real instrumented measurements into BIM databases [35, 36] as well as optimized sensor deployment in real-case studies [37]. Additional BIM applications in facility management and monitoring include creating maintenance orders for mechanical equipment [38], conducting energy simulations for buildings [39], and utilizing augmented reality [40]. Furthermore, sustainability has emerged as a significant area of research in the digitalization of aging infrastructure, with studies examining the relationship between infrastructure assessment, digital transition and concepts such as circular economy and environmentally friendly practices [41, 42].

Nonetheless, in the context of bridge monitoring, some of the most significant advancements have been made through inspection and survey procedures with technological equipment, such as Unmanned Aerial Vehicles (UAVs) and laser scanners [43, 44]. These innovations have paved the way for new inspection and monitoring techniques, ensuring safety of inspectors and targeting monitoring of specific bridge elements over time rather than the entire structure's geometry [45]. However, despite these technological advances, few studies have successfully integrated the outputs from these techniques within a BIM framework, while also ensuring adherence to normative standards for damage identification and classification in a unified platform.

Objectives of the present work and applications

The primary objective of this work is to compare and evaluate two BIM methodologies —parametric modeling and Mesh-To-BIM—for creating a database to support infrastructure management operations, while also exploring novel techniques to enhance bridge inspection processes and its integration with BIM methodology.

First, the two methodologies are tested in a case study involving two dismantled prestressed concrete bridge elements. Both methodologies are assessed, and the most suitable approach is refined and implemented for an in-service bridge in a second case study. A special procedure is developed to incorporate the requirements for bridge inspection, as outlined in the Italian guidelines, directly within the software. The modeling process utilizes Autodesk Revit® as the BIM software.

The overall workflow of the applied methodology is illustrated in Fig. 3, while detailed descriptions of the two case studies and the processes used are provided in Sect. 3.1 and 3.2.

This research stands out with respect to existing studies by providing a clear comparison between two commonly used methods in the HBIM modelling process, but given them a context for bridge inspections activities, which has

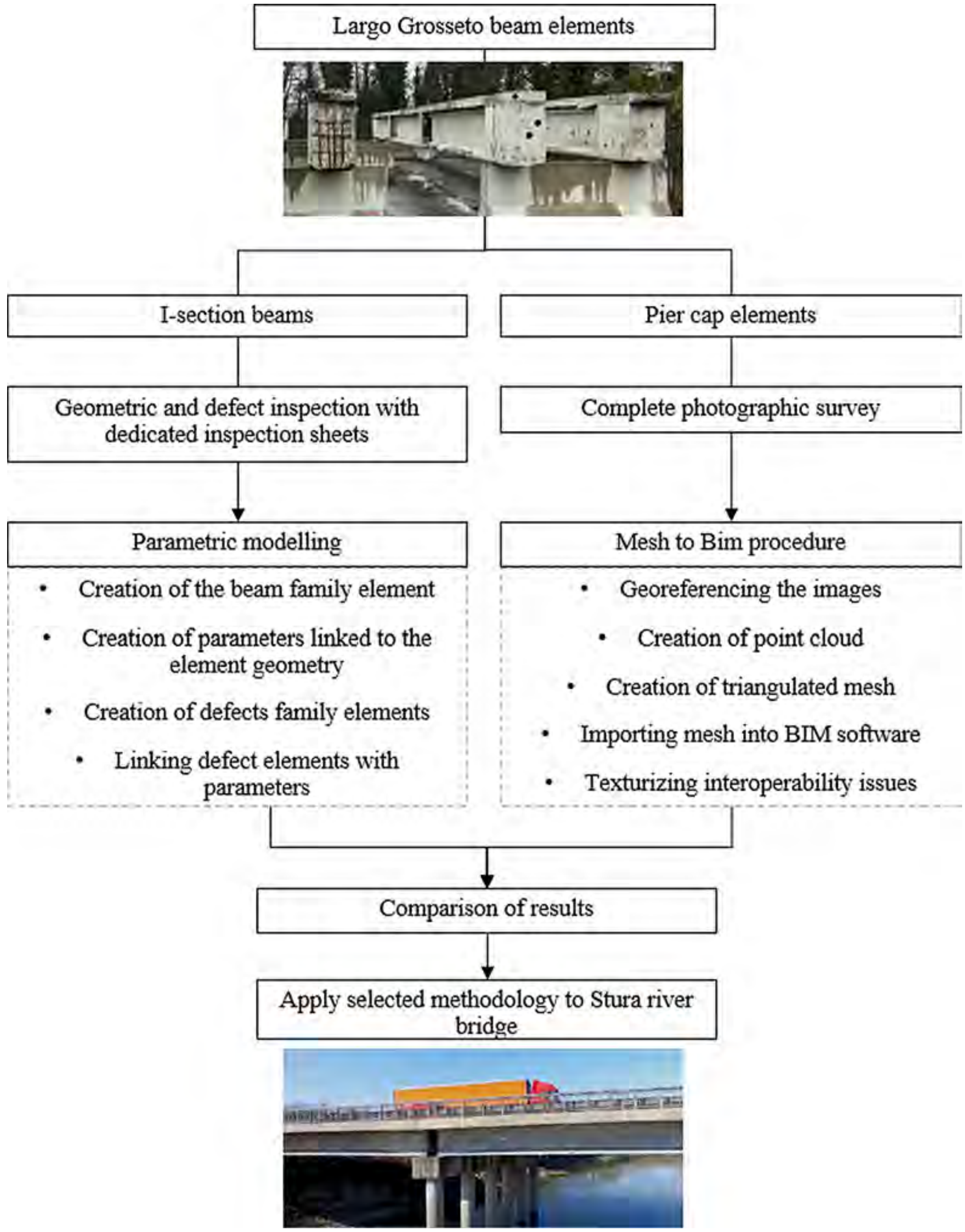

Fig. 3 Workflow illustrating the application of parametric modeling and Mesh-To-BIM methodologies in the first case study for then selecting the correct methodology in the second case study

not been widely explored. The feasibility of both methods for these activities is evaluated, and the most appropriate approach is determined. Although the methodology incorporates various innovative elements (laser scanner survey, UAV inspection, convolutional network for defect inspection) the key innovation lies in the use of the generated mesh for defect inspections, in accordance with normative standards and its integration in a BIM database. By developing a procedure to include defect characterization based on a remote sensing output directly within the BIM model, this study introduces a novel approach to defect inspection that minimize risk for inspectors and optimize both inspection and data collection processes.

Case study 1: largo grosseto viaduct

The Largo Grosseto viaduct was an urban bridge in the city of Turin, Italy built in 1970. It had a total length of 1400 m consisting of 81 spans of variable length from 16 m to 24 m. With the purpose of building a new infrastructure system and considering that the overpass presented severe damage, it was demolished in 2019. In the context of the research project BRIGE|50 a group of beams were dismantled and moved to a storing site to be examined [46]. A total of 25 I-shape precast prestressed concrete beams, 4 edge precast pre-stressed box beams and 2 prestressed pier-caps coming from four decks of the viaduct are used for the project. A photograph of a group of I-shape beams in the storing site can be seen in Fig. 4a. The BIM methodologies tested in this work focus on a single I-shaped beam and a single pier cap beam.

An initial inspection phase was conducted for all elements, resulting in a unique damage sheet for each beam. This damage sheet includes photographs and a CAD drawing of each planar face of the beam, with the respective damage accurately marked. The defects surveyed during this inspection for the selected I-shaped beam are detailed in Table 2, while an example of the damage sheets produced during the inspection phase is shown in Fig. 4b.

The parametric modelling procedure is applied to the I-shaped beam, using the inspection sheet as input information, while the Mesh-To-BIM procedure is implemented for one of the available pier caps. At the conclusion of this analysis, both methodologies are evaluated, examining their respective advantages and disadvantages to determine the most suitable approach for application to a complete in-service bridge.

Case study 2: stura bridge

The Stura Bridge consists of two separate structures adjacent to one another, spanning the Stura di Lanzo River along the RA10 motorway, which connects the city of Turin to the Turin-Caselle International Airport. Each bridge structure serves one direction of travel and features a simply supported structural scheme with a total length of 215 m, divided into six spans of 35.7 m each. All spans share the same structural configuration, comprising three prestressed I-section concrete beams and three transverse beams that support a

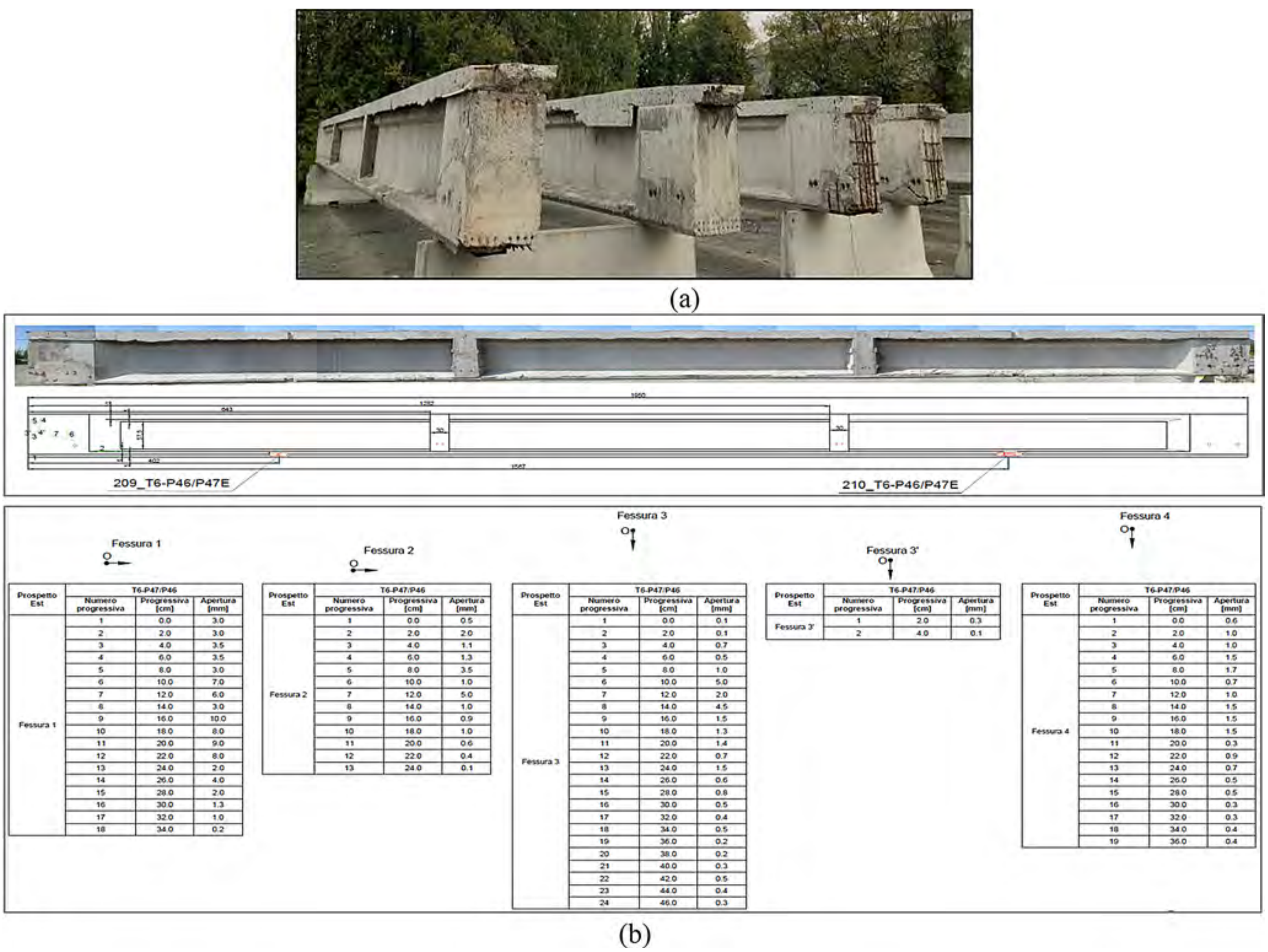

Fig. 4 (**a**) Dismantled beams collected in the inspection site. (**b**) Example of inspection sheet produced after the inspection procedure in an I-shaped beam element

Table 2 Defects surveyed during the initial visual inspection phase for the I-shaped beam analyzed

Bam elevation	Defects surveyed
East elevation	-Horizontal cracks (×7)
	-Vertical cracks (×2)
	-Diagonal cracks (×2)
	-Concrete detachment due to demolition process (×2)
South elevation	-Horizontal cracks (×4)
	-Vertical cracks (×1)
	-Diagonal cracks (×2)
	-Concrete detachment due to demolition process (×2)
Top elevation	- Diagonal cracks (×2)
Bottom elevation	-Horizontal cracks (×1)
North end	-Horizontal cracks (×3)
	-Vertical cracks (×5)
	-Spalling (×1)
West end	-Horizontal cracks (×2)
	-Diagonal cracks (×3)
	-Vertical cracks (×3)
	-Spalling (×2)

Fig. 5 Photograph of the first 3 spans of the Stura river bridge (Turin-Caselle direction)

0.175 m concrete deck. The longitudinal beams rest on rubber supports above prestressed pier caps located atop three piers of variable height. The superstructure of each bridge features a cross-section accommodating a double lane for a single direction of travel, equipped with a barrier system at the ends corresponding to a steel parapet (Fig. 5).

The working procedure for this case study begins with a complete survey of the bridge using laser scanning, UAV photogrammetry, and topographic measurements. Following the survey, the selected methodology for BIM modelling is executed, resulting in the creation of the bridge model. A digitalization process for levels 0 and 1 of the Italian guidelines is subsequently completed within the BIM platform. Utilizing the visual programming tool Dynamo, all non-graphical information required by the guidelines is integrated into the model. Finally, a damage inspection of the bridge's intrados, aligned with the guidelines' requirements, is performed aided with an algorithm for automatic classification of damage.

Experimental application

Largo Grosseto beams

Parametric modelling

The modeling process in Revit for a unique BIM element is facilitated by the creation of families (groups of elements with common properties and similar graphical representations). Using the family editor, a new family for a longitudinal beam was created within the "Structural Frame" category. The modeling process began with the creation of several editable parameters—common properties that can vary depending on the specific element type. These parameters are linked to the geometric measurements of the element, so the graphical and non-graphical information changes according to the selected "element type." The parameters established correspond to the general information of the individual beam and the geometric measurements documented on the inspection sheet -see Table 3.

To incorporate the information regarding defects identified during the in-situ inspection, new families were created in the "Generic Model" category. Utilizing the 2D CAD drawings and the damage extent information from the damage sheet, the 3D geometry of each defect was modelled (Fig. 6). Multiple parameters were included and assigned to the "element types" to encompass the non-graphical information related to the defects. All data regarding defect information is displayed in Table 3. During the damage modelling procedure, geometries corresponding to fictitious defects were also created, with different colours and values assigned to the parameter "Data of Modelling." This fictitious damage serves as a useful tool for testing the

Table 3 BIM family information in the model as parameters. On the left information regarding the beam element, on the right information regarding the defect elements

Beam family parameters	Parameter Type	Damage family parameters	Parameter Type
Beam ID	Text	Data of modelling	Data
Width	Geometric length	Operator ID	Text
Length	Geometric length	Damage ID	Integer
Height 1 - I profile	Geometric length	Damage type	Text
Height 2 - I profile	Geometric length	Damage length (cm)	List: Double
…	…	Damage depth (mm)	Double
…	…	Damage opening (mm)	List: Double
		Damage origin	Image
		Note	Text

model's ability to update over time according to the actual changes that the beam experiences.

Each defect in the damage family was precisely positioned within the beam family to generate a unique nested structure, which was then uploaded into a project interface. A time scale, based on future inspection dates, was developed using "phase filter" tools. Each phase of the project was linked to the "Date of Modeling" parameter within the damage family. As a result, navigating through the different project phases allows the model to automatically update with the latest damage information.

Mesh-To-BIM

The Mesh-to-BIM process began with a comprehensive photographic survey of the pier caps consisting of a total of 86 pictures. These images were processed using specialized software to generate a dense point cloud. When the dense point cloud was obtained, further operations were applied to create a 3D object. The Poisson reconstruction tool was used as a methodology to create the triangulated 3D mesh. Poisson reconstruction is an algorithm that generates surfaces from oriented point samples by solving for a scalar function that matches the vector field of the points. Consequently, the distribution of points in the model directly influences the quality of the resulting mesh. Areas with a higher density of points produce finer mesh details, whereas regions with lower point density result in less refined mesh details [47]. At this stage, the texture of the geometric model is automatically generated through orthographic projections, utilizing the color data from the points. A crucial step before creating the mesh involves cleaning the point cloud to remove "digital noise," thereby preventing inconsistencies in the geometry of the final model. Once the mesh is created, several mesh-processing operations are carried out to enhance the level of detail and address problematic areas. These operations include separating model components, filling surface voids, and eliminating unconnected particles. Optimization and simplification procedures are also applied to improve mesh manageability and ensure its compatibility with BIM software.

To import the triangulated mesh into the BIM software the CAD format .DXF was used. This file format facilitates straightforward interoperative communication without

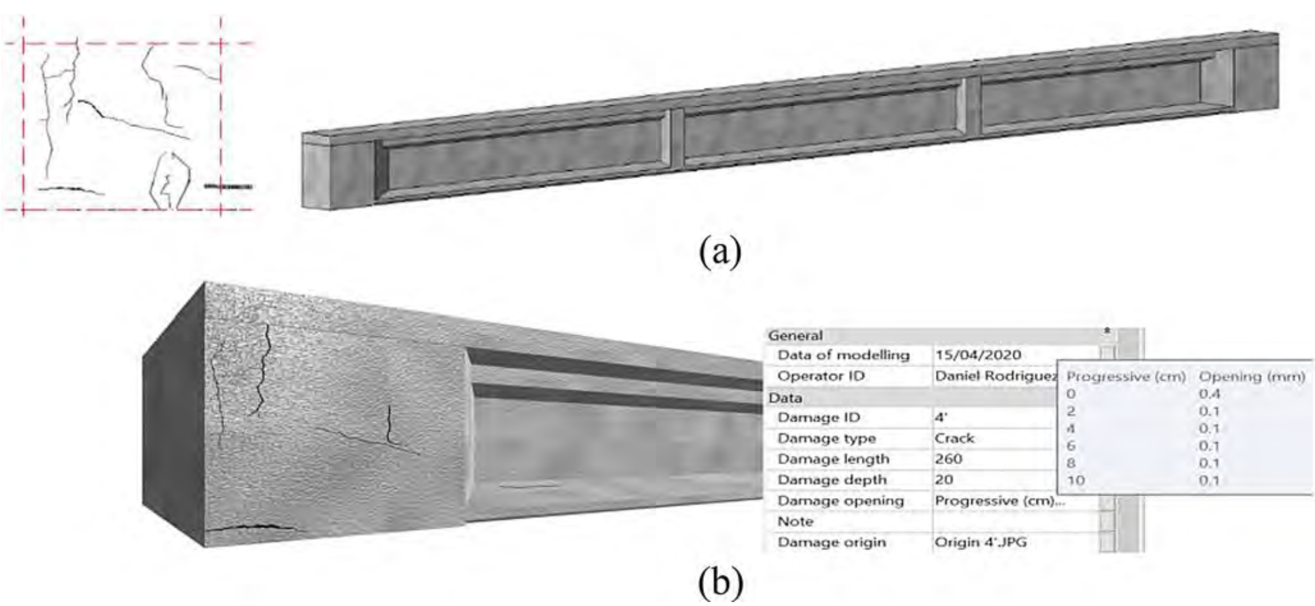

Fig. 6 (**a**) Damage BIM family and beam BIM family. (**b**) Nested family and information displayed as parameters in the model

requiring additional conversion of the mesh object or usage of external plug-ins. When an external CAD element is inserted into Revit, it results in a non-editable solid block within the BIM platform. While this non-editable block may be problematic if further modeling is required, it poses no issue for visualization purposes. Nonetheless, some interoperability challenges remain as the .DXF format does not support texture information, rendering the imported element colorless in the BIM environment. This lack of texture is a significant issue for damage recognition, as detailed color data is crucial for accurate inspection. To address this issue, the triangulated mesh was divided into layers based on its planar faces before importing it into the BIM software (Fig. 7). Once inside the BIM platform, the element was recolored by assigning different material textures to each layer, corresponding to frontal images of the beam perspectives, following a similar approach as described by Pocobelli et al. [23]. The frontal images came from photographs of each face of the beam that were edited to eliminate background information and set the correct scale factor.

Results comparison

Both methodologies explored in this first case study demonstrated strengths and drawbacks when applied to an existing bridge. The parametric modeling approach was more straightforward, as all elements were modeled directly within the BIM environment and information controlled by parameters. One advantage of this methodology is the relatively low computational demand, making it accessible for computers already predisposed for BIM modelling. According to Autodesk Revit specifications [48], a balanced configuration of CPU, GPU and RAM is sufficient, without the need of high-end components (e.g. a moderate RAM capacity of 8gb can handle this sort of operations). However, the model's accuracy in terms of color and geometric details was limited by the basic modeling tools available in BIM, making it impossible to accurately recreate complex, specific details. Additionally, the most significant disadvantage of this approach was its time-intensive nature and the limitations on the volume of information that could be effectively modeled within the database. In this case study, only a single beam element was inspected, resulting in a relatively small number of defects to model and document within the BIM framework. Furthermore, all sides of the beam were easily accessible for inspection, enabling precise defect measurements. However, replicating this process for an entire bridge would be impractical due to limited accessibility for inspecting defects in such detail and the extensive time required to manually model each defect.

On the other hand, the Mesh-to-BIM process through the CAD format involved external modeling of all objects, which were then imported into the BIM software. While this methodology required several additional steps, the resulting model was superior in terms of detail and quality. The geometry and texture of the beam's surface were accurately preserved, producing a highly precise, unique, and reliable model. However, challenges arise when applying this

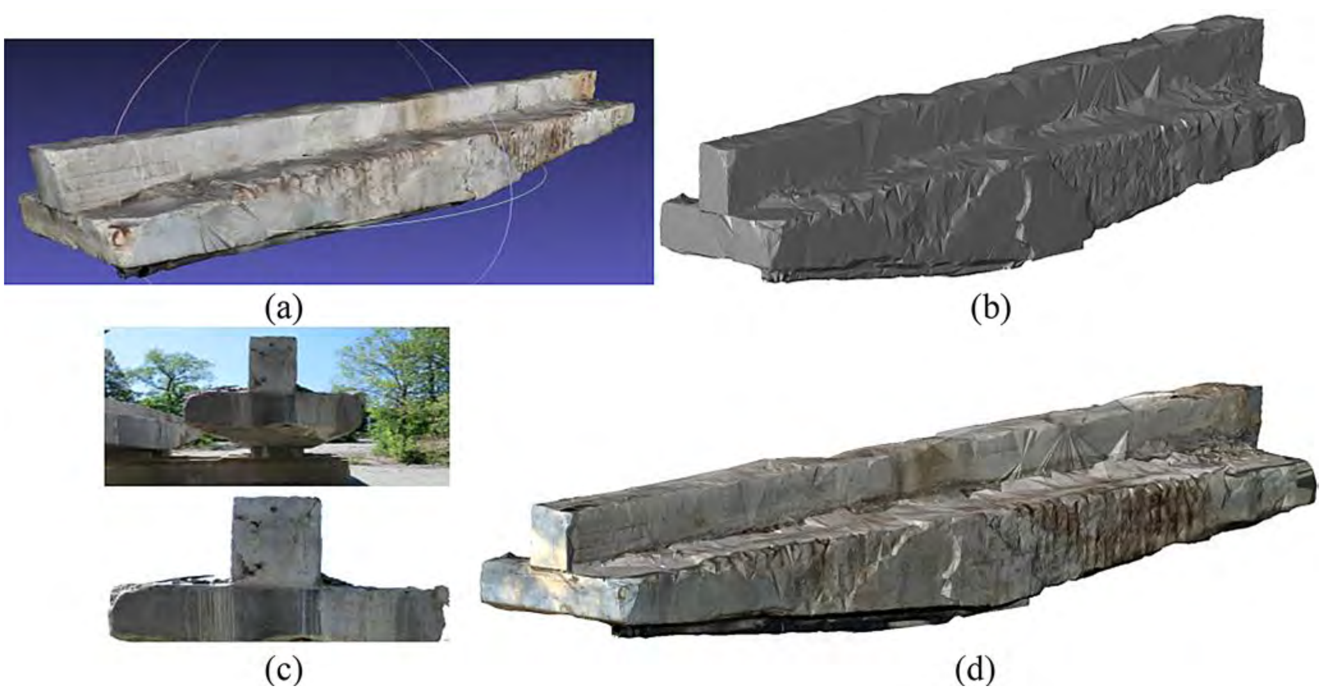

Fig. 7 (**a**) Pier cap mesh reconstruction after photogrammetric process. (**b**) Colorless mesh when imported into BIM environment. (**c**) Image editing process. (**d**) Mesh in BIM platform after re-coloring procedure

methodology to a full bridge, such as the survey method, the computational resources and interoperability issues during data transfer. From a computational perspective, this approach demands significantly more GPU resources, with respect to the parametric modelling approach. Image processing operations, such as point cloud generation and subsequent mesh processing, require substantial computational power and could present a bottleneck for more extensive surveys involving larger datasets [49].

Regarding survey methodology, while this process also requires extended fieldwork, it enables remote inspection of bridge elements, providing safer and faster access to hard-to-reach sections. Alternate survey techniques, such as laser scanning or UAV photogrammetry, offer potential for performing comprehensive surveys of existing bridges. Despite these advantages, interoperability issues remain a significant obstacle in integrating outputs into a BIM database.

In this case study, the availability of a dismantled pier cap allowed for direct photography of all planar faces, enabling the re-coloring process. In contrast, for an in-service bridge, not all surfaces would be planar or accessible for frontal photography, making the resulting colorless mesh in the BIM environment a major problem. Nonetheless, given the significantly higher quality of the mesh model in terms of graphical details and the possibility to inspect various angles of the geometry remotely, this modeling approach was chosen for the second case study. This decision is motivated by its potential to enhance bridge inspection processes by reducing costs, minimizing equipment requirements, and improving safety, while simultaneously delivering a more detailed and accurate representation of the structure at a given time.

The computational resources available for the second case study—an Intel Core i7-10700 K processor, NVIDIA GeForce RTX 3060 GPU, and 32 GB of RAM— are considered sufficient to manage the processing operations effectively, eliminating the risk of performance bottlenecks.

On the other hand, to overcome interoperability challenges between remote sensing output and BIM modelling software, an alternative strategy will be explored. This strategy aims to preserve the mesh's rich graphical detail while fully utilizing BIM's robust capabilities for information management, ensuring seamless integration and enhanced usability for infrastructure management.

Stura river bridge

On site survey

The on-site survey consisted of three distinct procedures: laser scanning, UAV photogrammetry, and the creation of a topographic network. For the laser scanning, a Faro Cam2 instrument was used, performing a total of 12 scans beneath the first and second spans of the bridge. In a second stage, 19 additional scans were carried out beneath the fifth and sixth spans, along the Turin-Caselle direction. These scans were supplemented by a topographic network, which was established using a Leica GPS System 1200 to determine the coordinates of an initial reference point, and a Leica MS50 total station to measure natural points and rectangular markers previously positioned around the bridge. A large number of points (over 40 points) around the bridge were measured to minimize errors during the georeferencing process. Georeferencing the model to its actual coordinates not only ensures the correct orientation of the scans but also makes the model retrievable and updatable. This allows various stakeholders to consult and update the model information through a known reference system.

The UAV photogrammetric survey was conducted using a Parrot Anafi-Work drone, equipped with a 4 K HDR camera capable of rotating 180°, making it an ideal tool for inspecting the bridge's intrados. Four separate drone flights were made to survey the intermediate spans of the bridge (second, third, fourth, and fifth spans in the Turin-Caselle direction). Each flight covered the deck spans by dividing them into four longitudinal strips. During each flight, a video of the intrados was recorded, and photographs were subsequently extracted at a ratio of 1 frame per 30 (one photo every 30 frames). This resulted in 498, 382, 858, and 377 photographs for the second, third, fourth, and fifth spans, respectively.

Data processing

The data processing workflow was divided into three categories based on the type of data: GPS/GNSS data, laser scans, and UAV photographs. For the topographic network, initial triangulation operations were performed using specialized software, generating a text file containing the names and coordinates of all registered points. All points were recorded according to the global reference system UTM/ETRF2000 - WGS84 32 N.

To process the laser scan data, the Faro Scene software was used. All scans were manually uploaded, and a procedure was followed to convert from a local coordinate system to the global reference system. The spatial position of each scan was determined using a two-step approach. First, a location-by-shape process automatically positioned the scans based on the recognition of common shapes. Then, a location-by-target procedure was employed, in which the coordinate file was uploaded to the software, and recognizable natural points or markers on the scans were manually assigned their corresponding coordinates. Once the scans were georeferenced, they automatically rotated and translated to their correct positions within the workspace. After georeferencing, the laser scans had an average error of 1.8 cm.

For UAV photograph data processing, the photographs were divided into four files, one for each flight, resulting in a separate point cloud for each. The photographs from each span were uploaded and aligned using Agisoft Metashape software. This initial alignment produced a sparse point cloud, representing the software's automatic recognition of homologous points between images. An example of this sparse point cloud can be seen in Fig. 8a. Next, the point clouds were georeferenced using the coordinates file from the topographic network. This process involved either manually selecting all photographs where a marker was visible to assign its coordinates or using a guided approach where the software automatically detected and assigned coordinates to photos containing unique markers. Both methods were used, yielding an average error of 1.2 cm. Finally, dense point clouds were created using a high-resolution setting for the densification process.

The point clouds from the laser scans and UAV photogrammetry were then uploaded into CloudCompare software, where digital noise was removed. Once all point clouds were cleaned, they were merged to create a complete point cloud of the bridge - Fig. 8b-. While the final cloud showed a high level of detail, some areas of the bridge's intrados and piles contained voids. Considering this situation, it was decided to proceed with mesh creation for only the fourth span of the bridge (Turin-Caselle direction), which had the most detailed point cloud. For the mesh creation, the normal vector field of the points was calculated, and the Poisson reconstruction algorithm was applied using the software tools.

To avoid the interoperability issues of having a no-colored block in the BIM platform it was decided to avoid the mesh passage to BIM software and produce a double model for the bridge database: One for visualization purposes (the mesh-model) and one for data collection (BIM model). This decision implies that the damage inspection is performed directly in *CloudCompare* software, and it is later transferred into a BIM model (a simple parametric model of the bridge created on a previous work). *CloudCompare* allows the insertion of points and polylines that can only be assigned ID information; therefore, the characterization of the defect in terms of extension, intensity and criticality is not possible. Consequently, this type of information needs to be added in the BIM platform during the communication phase between software. The intrados of the bridge was visually inspected supported by the application of a convolutional neural network (CNN) for automatic classification of damage developed by Savino and Tondolo [50] (Fig. 9).

CNNs offer advantages in the damage recognition process, by learning features directly from training data through interconnected 2D layers, eliminating the need for manual feature extraction. These networks can scale to hundreds of layers, each specializing in detecting specific features from input images [51]. The CNN used in this research was implemented using the deep learning toolbox in MATLAB,

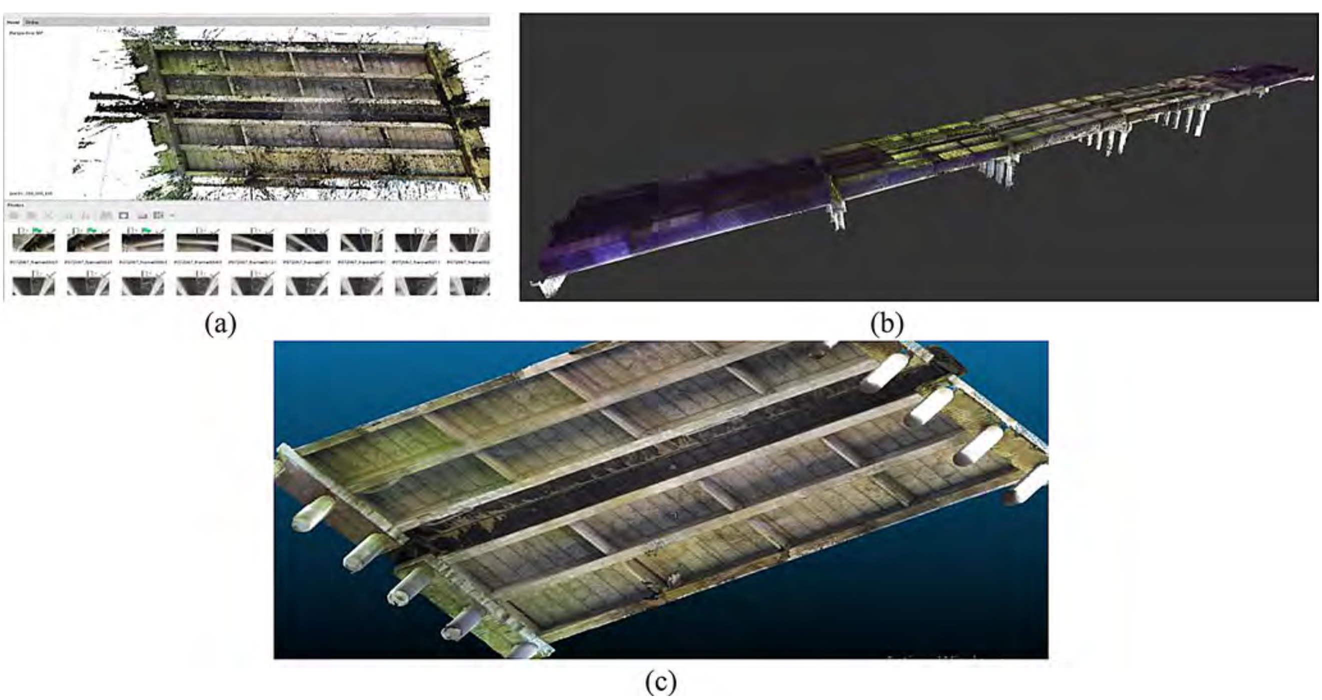

Fig. 8 (**a**) Point cloud processing operations for UAV data in Agisoft Metashape Software. (**b**) Full point cloud of Stura Bridge after merging laser scanner output and photogrammetry output. (**c**) Triangulated mesh of the 4th span of the Stura Bridge in CloudCompare enviroment

Fig. 9 (**a**) Example of an input image used for CNN analysis, along with the defect classification scores generated by the network. (**b**) Mesh model during the visual inspection process, showing isolated defects and areas of defect marked for defects of greater extent

Table 4 Defects surveyed in the mesh model through the CNN network for automatic defect inspection and through the visual inspection of the mesh

Bam elevation	Defects surveyed
Surveyed through CNNs	-Cracks (×6)
	-Delamination/Spalling (×2)
Surveyed through mesh visual inspection	-Passive moisture stains (×3)
	-Active moisture stains (×1)
	-Concrete detachment (×1)
	-Washed-out/deteriorated concrete (×1)

where a pretrained GoogLeNet network was used to classify the model images into three classes: "undamaged", "cracked", and "delaminated". As an output, the network generates a score for each image, indicating the probability the image belongs to a particular class. Details concerning the network training parameters (learning rate, batch size, number of epochs, accuracy) are found in the original publication [50].

The network analyzed the drone and 360 laser scanner images used to create the mesh model, validating defect recognition and minimizing potential human errors. For other defect types not addressed by the CNN, a visual inspection of the model was performed. Markers were added to the model using *point picking* tool for single insolated defects, while the *polyline* tool was used to delineate defects spanning larger areas. A summary of the identified defects is shown in Table 4. Additionally, a text file including the defect name as well as its coordinates (area coordinates for the defects of large extent) was also obtained as an output.

Implementation of Italian guideline in BIM environment

A parametric *Revit* model of the Stura bridge was used for the BIM operations. As indicated in Chap. 4.3, the decision to maintain a BIM model as a data collector and a separate mesh model for visual support means that the BIM model does not require an extremely high level of geometric detail (LoG). Instead, simple parametric geometry is sufficient for the BIM model, as the higher level of graphical detail is achieved through the external mesh model connected to it.

The first step in the parametric BIM model was to adjust the coordinate system and orientation to align with the mesh model. Following this, a decimated point cloud of the full bridge was uploaded into the BIM platform to provide a real colour reference for the BIM model. To recreate Levels 0 and 1 of the Italian guidelines within the BIM platform, Dynamo—a programming tool that accesses the Revit application programming interface—was employed. This tool facilitated the creation of a user interface that allows an operator to input all necessary information as specified by the guidelines directly into the model. Various information-only Revit families were created corresponding to the information groups outlined in Level 0 of the guidelines. The information within these families was managed using text, data, and numerical parameters. Examples of these families can be found in Table 5. Subsequently, different scripts were written in Dynamo to develop the user interface, enabling the operator to load the information families and populate their parameters with relevant data. The interface consists of a series of windows that can be accessed from the main Revit platform. These windows display the information required by the guideline sheets, providing either a list of predefined options or a blank space for entering any type of text, numerical, or yes/no data. All information included in the database can be easily queried, analyzed or edited in a tabular way from the main Revit window.

A second type of programming operation involved creating a link between the mesh model and the BIM model. The defect data in the mesh model included only the defect name and its coordinates. Therefore, the link established between CloudCompare and Autodesk Revit needed to transfer this

Table 5 Information included in the BIM model as BIM families, corresponding to the level 0 of the Italian guidelines for bridge damage assessment

Information-family	Family parameters
General data	Bridge name
	Bridge code
	Belonging road
	Road classification
	Bridge operability state
	….
Design and construction data	Owner
	Supervisor
	Designer
	Design code used
	Design year
	Construction year
	……
	….
Previous interventions /monitoring systems	Maintenance plan
	Maintenance works performed
	Type of structural intervention
	Description of the structural intervention
	Date of intervention
	Intervention results
	…
	…

information while also prompting the operator to classify the defects according to Level 1 of the guidelines. To represent the defect information in the BIM environment, a spherical label family was created. This label family includes parameters related to defect characteristics, such as defect code, weight, risk, extent, and severity, in accordance with the guidelines. These parameters are linked to the geometric characteristics of the label—such as radius and colour—so that when the label is positioned within the bridge model, it allows for easy recognition of the most damaged areas and provides an initial overview of the damage characteristics from a global perspective. The programming operation included developing a second user interface that retrieves data from the mesh model's text file and prompts the operator to select which defect to upload to the BIM platform. Once the operator selects a defect, additional information about its characteristics is requested. A single label family is then placed in the correct position based on the defect's coordinates, and its name is set to correspond with the defect name from the mesh model (Fig. 10). The parameters within the label family are populated according to the information provided by the operator in the user interface, and additional polylines are automatically drawn for defects of significant extent. To provide a clearer understanding of the complete operations presented in this case study, refer to Fig. 11.

Results discussion

From the first case study the results indicated that parametric modeling approach offered simplicity of bridge defects implementation within the BIM environment and moderate computational demand but fell short in terms of geometric and textural detail. This approach relied heavily on manual input for modeling each defect element and assigning its information, limiting the fidelity of the model and resulting in a time-consuming modelling task. Consequently, parametric modelling of defects is suitable for smaller-scale inspections or when structural details are not critical, but its scalability to larger structures, such as an entire bridge, is limited.

In contrast, the Mesh-to-BIM methodology demonstrated superior performance in representing the geometry and texture of the inspected bridge element but at the expense of higher computational demands and workflow complexity. Several data transfer steps between photogrammetry software and BIM tools were needed for the applicability of the workflow, creating potential interoperability challenges. Nonetheless, from a bridge inspection approach, the ability to inspect and analyze defects remotely on a high-fidelity digital representation of the bridge opens the door to safer inspection activities, minimizing risk for operators while maintaining a reliable copy of the bridge state at a given time. Therefore, for the second case study, it was decided to continue with the mesh-to-Bim methodology with some modifications to avoid interoperability issues.

Results from the second case study confirm the feasibility of combining UAV photogrammetry and laser scanning to produce an output with sufficient detail for structural inspection, consisting with fundings from similar studies [52, 53]. This result is a key advantage in terms of safety for the operators with respect to traditional inspection procedures. By enabling remote data collection and subsequent inspection on the generated mesh and images, the need for personnel to physically access potentially hazardous areas is greatly reduced. This is also beneficial in terms of inspection costs as special vehicles or scaffolding systems would not be needed.

Nonetheless, the scalability of the process to large-scale bridge monitoring operations can be limited due to the big amount of data-processing operation required and the computational demand of such operations. In this case study, three different specialized software was required to manage each data type, and several time-consuming operations (geo-rereferring, noise cleaning, point cloud optimization, point cloud merging, mesh producing) were performed until obtaining the desired output for bridge inspection. This level of complexity limits the replicability of the procedure for routine inspections of multiple bridges. Nevertheless,

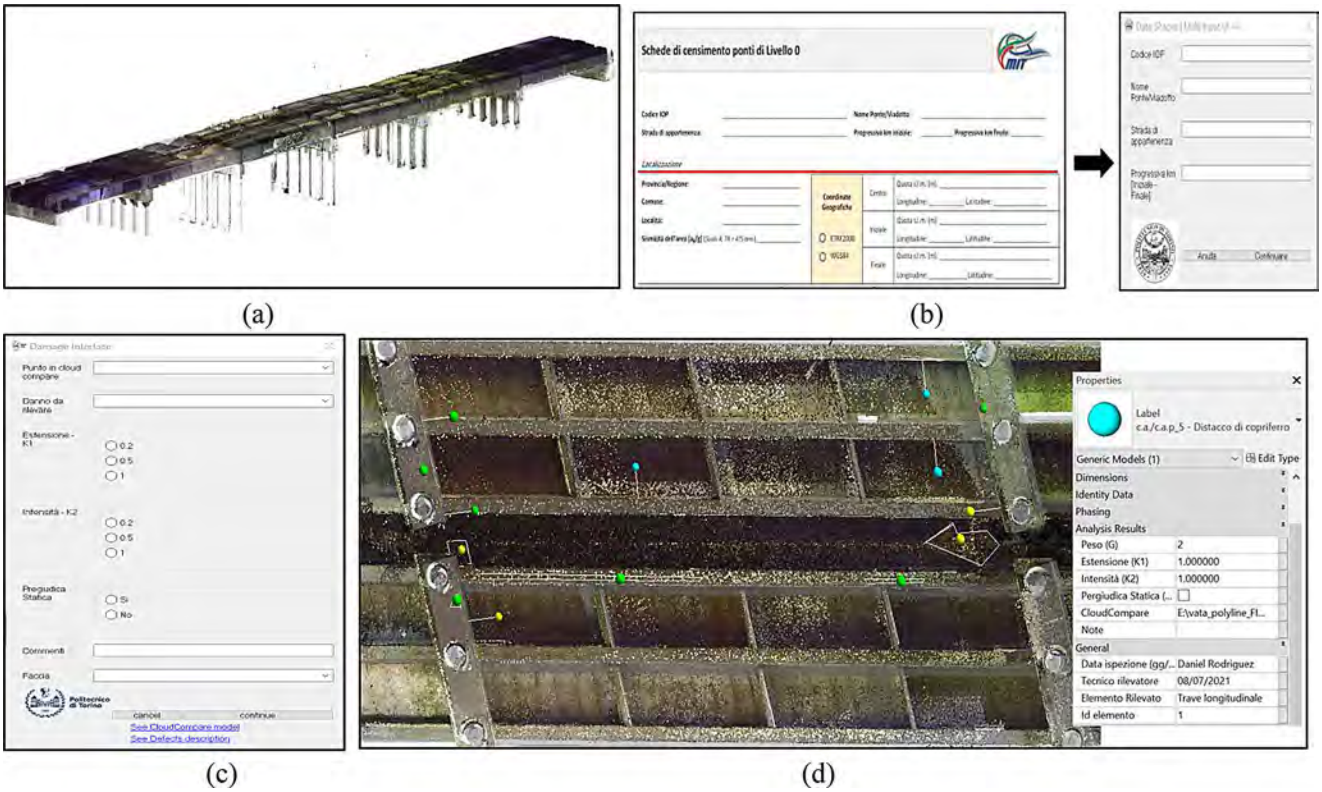

Fig. 10 (**a**) BIM model of Stura Bridge with point cloud for color reference (**b**) Digitalization process for guidelines inspection forms. (**c**) User-interface created to link remote sensing data from CloudCompare with Autodesk Revit. (**d**) BIM model with defects surveyed

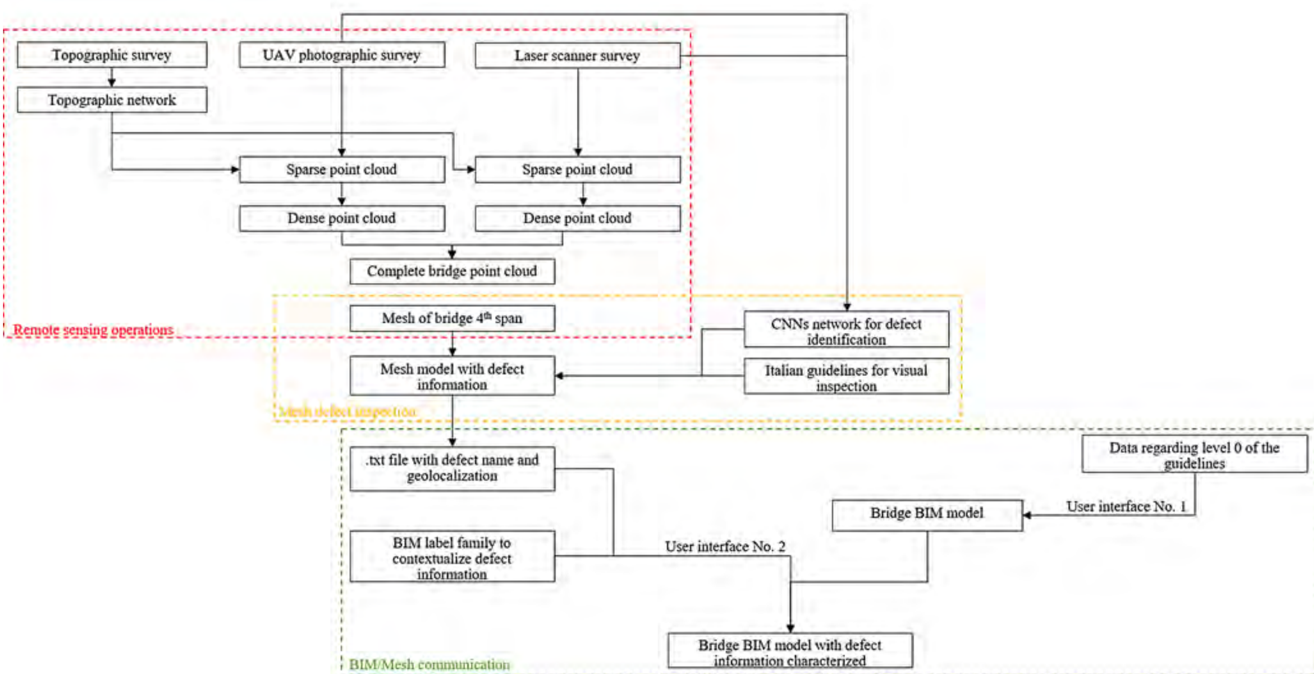

Fig. 11 Complete workout of the methodology applied in the second case study

the facility of using UAVs to inspect difficult-to-reach areas and the possibility to automatize flight plans, can open the possibility to potential targeted inspections, focusing on predefined specific structural elements rather than entire bridge components. In this way, the level of analysis would be greater for specific bridge elements in which the operator retains fundamental to keep an accurate replica during a specific time, while minimizing unnecessary data collection for not critical elements.

From the data processing of both the laser scanner and UAV photogrammetry approach a spatial precision of 1.2 cm was obtained in the dense point cloud. This precision is within acceptable limits for structural inspection but falls short of capturing very fine details. Defects of greater extension such as major cracks, delamination or humidity stains were easily visible, whereas smaller, subtle defects were not reconstructed with sufficient fidelity. This limitation highlights the balance that needs to be considered between computational efficiency and precision. Improved precision could be achieved with higher-resolution imagery or supplementary scanning techniques, at the cost of increased processing time and computational resources.

From the complete bridge point cloud, it was decided to proceed with the mesh creation and subsequent inspection of only the fourth span (Turin-Caselle direction), due to the obtention of some inaccurate details and voids in some other areas of the bridge's intrados and piles. This situation highlights an important limitation in the replicability of the methodology as it is highly sensible to the quality of data acquisition. Optimal survey conditions, including adequate lighting, minimal obstructions, and appropriate UAV flight paths are necessary to produce an output with sufficient detail for defect inspection. However, in typical inspection scenarios, such factors are difficultly guaranteed, compromising the quality of the collected data and, consequently, the precision of the final mesh.

On the other hand, if a less precise model is considered acceptable, defect inspection can be significantly improved through the introduction of neural networks for automatic detection of damage, as demonstrated in this case study. Neural networks can directly analyze the images used for mesh reconstruction, allowing the operator to focus on inspecting the mesh model itself. This dual approach not only enhances the inspection process in scenarios where achieving perfect data acquisition conditions is challenging but also reduces manual workload of inspectors. Additionally, the usage of CNN minimizes inspection variability due to human interpretation and provides a validation tool for a more standardized and reliable defect inspection.

The CNN used in this case study was trained to identify only two defect classes: cracks and delamination; nonetheless, incorporating additional defect categories into the CNN training dataset could enhance its applicability for a broader range of structural issues, opening the possibility of not only identifying but also aiding the characterization of defects. This step-forward would provide a significant improvement in the inspection methodology, nonetheless, requires significant investment in data collection and model development.

Finally, the ease in the integration of the inspection performed to the mesh model with the BIM database proved to be a significant step forward in managing and utilizing structural inspection information. Thanks to programming tools like Dynamo, a user-friendly interface was created to reproduces the Italian code standards within the BIM environment and facilitate the linking of information. This interface allows operators to add and manage information in the model from the main Revit interface in a simplified manner, without requiring advanced knowledge of BIM methodologies or programming procedures. The ability to pass all defect information to the information database, while also classifying the defect according to normative standards represents a notable improvement in the management of inspection data. The BIM model facilitates the application of filters, establishment of correlations, and real-time updates, making it a valuable tool for long-term structural health monitoring and informed decision-making. This enables easy retrieval and analysis of data for effective maintenance planning.

Although this case study addressed the interoperability challenges through a dual-model system and programming tools, the ideal solution would be a unique platform where mesh models can be inspected and characterized according to normative standards. Achieving such improvements requires significant efforts by software developers to enhance usability and enable broader integration of commonly used software for both remote sensing and BIM applications.

Conclusions

In the present paper two case studies were exhibited to integrate bridge inspection data into a BIM framework. In the first case study, two methodologies -Parametric modelling and Mesh-To-BIM- were tested to create a damage database for two bridge elements. Subsequently, the most suitable procedure, with necessary adaptations, was applied in the second case study - an existing bridge-.

The results from the first case study indicated that parametric modelling offered the simplest and most intuitive workflow among the methodologies studied; however, the methodology was time-consuming, and the graphical detail achieved was very limited, relying heavily on basic BIM geometry and texture tools. In contrast, the Mesh-to-BIM procedure significantly enhanced graphical details but incremented computational demand, workflow operations and interoperability issues.

A key conclusion from this first case study is that parametric modelling of defects is not recommendable for a complete bridge but for smaller-scale inspections (or when textures or details are not fundamental), as the procedure is of a significant time-intensive nature and highly limited to software modelling tools. On the other hand, the mesh-to-Bim procedure demonstrated technical feasibility of using high-fidelity meshes for inspection and the potential to address supplementary inspection challenges such as operators risk during inspection.

The second case study involved surveying an in-service bridge using three methodologies: topographic survey, laser scanning, and UAV photogrammetry. With the obtained data several operations were performed to produce a dense point cloud of the bridge and a triangulated mesh of the fourth bridge span. The produced mesh presented a high-fidelity replica of the intrados, making it suitable to be visibly inspected for major damages. For smaller damages it was used a CNN for damage identification, that analysed the images that were used to produce the mesh model.

Then, to guarantee the correct management of information in BIM environment a modification was made with respect to the first case study, as it was decided to avoid importing the 3D object into the BIM environment but creating a communication link between BIM-Photogrammetry software with programming tools. This procedure created a graphic-friendly UI that allowed the inspector to import defect information in the BIM model in its exact position while categorizing the defects according to the Italian normative standards.

The conclusions of the second case study confirm the possibility of using remote sensing output for inspections activities. This possibility represents a major advantage for the safety for the operators that would avoid accessing high-risk spaces and therefore high-risk work situations. The effectiveness of the survey procedure and the output produced contrasted with the numerous operations and computational requirements necessary for data processing. This drawback reduces the scalability of the procedure for common bridge inspections, but opens the possibility of targeted inspections, focusing on predefined specific structural elements (e.g. through automated UAV flight plans) rather than entire bridge components.

Another found limitation of the methodology is the dependence on the quality of data acquisition in the produced output. This problematic could be treated by exploring different data acquisition strategies such as higher-resolution imaging, alternative scanning methods, or hybrid approaches but would likely increase costs and complexity.

Regarding the usage of CNN for defect identification, its usage in this study demonstrated a promising advancement to enhance the monitoring procedure and reduce potential human errors with a low-cost, labour-efficient method. Nonetheless, to broaden the applicability of this tools several efforts are needed to improve the model, which means significant investment in data collection and model adjustment.

Finally, this study stands out as it demonstrated the possibility of using programming tools to connect BIM and remote sensing software in a facilitated manner, while also respecting normative standards to characterize defect information. This possibility represents a great advantage for information storage an analysis as the BIM model acts as a data gatherer platform to analyse bridge defect information through its lifecycle in an optimized manner. The easiness provided by the developed UI, ensures that the methodology can be adapted by operators with varying levels of technical expertise, broadening its applicability in the field.

Nonetheless, if a standardized workflow or a unique platform for both photogrammetry management and BIM management is wanted, additional efforts from software developers are essential to overcome existing challenges and ensure he reliability of the integrated models. The vision of a single model where every defect information is georeferenced and classified may reduce errors or inconsistencies inherent in the dual-model solution, ultimately facilitating a more efficient planning of future inspections and the decision-making procedure for maintenance actions.

In conclusion, the overall methodology demonstrated to be a valid workflow to combine several technologies within a unique BIM framework. While challenges remain, future improvements in software, technologies and algorithms have the potential to develop new inspection procedures. By leveraging innovative tools, these advancements could become transformative for infrastructure management.

Acknowledgements Special thanks are extended to all participants of the BRIDGE|50 research project for their cooperation in facilitating the inspection, data acquisition, and publication of all data related to the beam elements of the first case study. Additionally, we express our gratitude to Engineer Domenico Petruzzelli of ANAS S.p.A. for providing essential support and access during the survey of the Stura River Bridge.

Funding Open access funding provided by Politecnico di Torino within the CRUI-CARE Agreement.

Declarations

Competing interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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