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DIGITAL MODELS FOR E-CONSERVATION: THE HBrIM OF A BRIDGE ALONG THE ATERNO RIVER

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Abstract

Existing road and railway systems often incorporate bridges, part of the historical heritage, that need careful attention not only for their operational safety and safeguard. For this reason, the approach to the inspection and to the constructional knowledge requires the integration and coordination of phases like the analysis of primary sources to the in-situ characterization of the local and global performance of components and materials. The management of infrastructures has to exploit digital technologies, both in the data collection phase and in the decision-making process. The paper deals with the e-conservation paradigm and discusses the results of an investigation on the potentialities offered by parametric models of historic bridges. It also checks and validates the introduction of the approach advised by recent National regulations in the framework of the Historic Bridge Information Modelling (HBrIM) combining safety and conservation knowledge instances.

Keywords

Historical bridges, E-conservation, Integrated survey, HBrIM, Digital Twin

1. *Introduction*

The running development of Information and Communication Technology (ICT) empowers the use of digital modelling and its integration with information systems. As a consequence, the representation methodologies of architectural and infrastructural heritage are evolving, particularly in the way they interact also with the analysis and management phases. Decision-making processes throughout the life cycle of the asset, indeed, foresee new frontiers particularly in the case of a real and effective interoperability of software and tools involved in the process. Building Information Modelling (BIM) has assumed a central role in recent years because of the potential of parametric models in the several design, operational and management phases. Despite the awareness of the opportunities offered by this technological environment for the existing building, the procedures for building parametric models from the semantic decomposition of the existing building stock are not fully established (Teruggi et al., 2021; Russo & De Luca, 2021; Cera & Campi, 2021; Xia, Yang, & Cheng, 2022).

Among the civil engineering and architecture works, road and railway infrastructures play a prominent role in the development of entire countries, therefore the implementation of the BIM technology to bridges, viaducts and tunnels needs specific and detailed development.

The BIM methodology is consolidated for new constructions, as proved by the several Bridge Information Modelling (BrIM) (McGuire et al., 2016; McKenna et al., 2017; Costin et al., 2018; Mabrich & Hatami, 2019; Conti et al., 2020; Nili, Zahraie & Taghaddos, 2020; Girardet & Boton, 2021), confirming that the process is facilitated in the preliminary feasibility assessment and the subsequent design, construction and operation of the infrastructure through the analysis and control of time and costs. However, a greater effort must be made to adapt it to historical infrastructures that, due to material characteristics and cultural aspects, have problems similar to those found in the parametric modelling of historic built heritage. This circumstance led research to the implementation of Historical Bridge Information Modelling (HBrIM).

Furthermore, the application of digital survey and representation techniques on infrastructures becomes more relevant when operating in territories subject to multiple hazards, both natural and anthropic, which could lead to the loss of this heritage, as demonstrated by the catastrophic events that occurred at National and International level (EC, 2011, ASCe 2017).

The recent events, characterized by collapse and damage, have focused attention on the maintenance and durability of the works, encouraging involved Countries to adapt and define tools and regulatory frameworks aimed at improving their management, health assessment and safety and defining intervention priorities to be implemented in order to reduce the risks, both natural and anthropic, associated with their damage and loss (MIT, 2020). For this reason, according to typological, constructive and material peculiarities, historical bridges deserve special attention. Continuous maintenance has ensured their survival, and today these works are not only functional infrastructures for road traffic and connections but also part of our built cultural heritage. As a consequence, they must be preserved not only in their material aspects but also in their intangible ones, which are related to the historical memory of places (CoE, 2005).

In this context, it is important to understand and assess the artefacts' condition both from a structural point of view, using monitoring systems and visual inspections (Solla et al., 2011; Rainieri et al., 2018; Omer et al., 2019), and from a historical and cultural one, by evaluating the reasons that led to their construction and maintenance. In addition, it is worth noting that the knowledge phase has a key role in the processes related to historical heritage. This phase is preparatory to the implementation of operations aimed at safety and safeguard and, thanks to a joint multidisciplinary effort, it facilitates the analysis of the artefacts and their specificities (ICOMOS, 2003; Lubowiecka et al., 2011). The amount of data provided by a holistic approach during the knowledge phase also emphasises the importance of documenting and managing heterogeneous data, whose complexity is often improved by using digital models enriched in terms of information and semantic content (De Luca, 2011; Messaudi et al., 2018; Garozzo & Santagati, 2021).

In this perspective, and following the research trends currently discussed by the international scientific community, digital replicas of the artefacts have been implemented by identifying and integrating different methods and tools that are able to link the results of multidisciplinary research, document the current state of the structures and carry out remote analysis and visual inspections in order to satisfy the requirements related to the safety and conservation of historic bridges. This digital replica moves toward the development of the Historic Digital Twin (HDT) that permits to connect monitoring of the real system to its virtual representation (Marra, Trizio, & Fabbrocino, 2021; Marra et al., 2021). The orientation towards experimentation of increasingly digital and integrated techniques for representation and data management is also motivated by the massive application of Information and Communications Technology (ICT) to cultural heritage and the digital transition implemented by European strategy (EC, 2020). This has fostered the definition of new paradigms, the e-conservation one, with applications wider than single historical infrastructures (Trizio et al., 2021). Indeed, Public Administrations (PAs) are called to renew their administrative management in order to respond to the principles of e-government, streamlining procedures and ensuring greater access to citizens. Nowadays, the biggest challenge is the management of essential services to citizens, but digital development will have to invest in other fields, such as the management of the PAs' cultural, real estate and infrastructural heritage.

The proposed e-conservation paradigm aims to guarantee the digital preservation of historical memory and data resulting from knowledge analyses, on the one hand, and to provide digital tools oriented to facilitate the analysis and definition of effective practices for safeguarding historical artefacts and infrastructures on the other. In this perspective, an operational procedure is being experimented with to define a Historical Bridge Information Modelling (HBrIM) that can combine the traditional approaches used in the knowledge and data acquisition phases with the innovative ones. The procedure scope is the creation of a parametric model that supports the assessment of the structure's state of conservation in the modelling environment, defining specific families and parameters.

2. *Materials and Methods*

The assessment of Italian infrastructural heritage aimed at safety in terms of human lives and the preservation of the viability with repercussions on the social and economic sphere of entire territories has increased considerably after disastrous events in recent years (Bazzucchi, Restuccia, & Ferro, 2018). The safety of existing infrastructures is related to different risks, both intrinsic, such as those related to the construction period and the life cycle of the materials as demonstrated by the collapse of the Morandi bridge (Invernizzi, Montagnoli, & Carpinteri, 2020), and external, such as the deterioration due to causes that may be environmental (Petrangeli, Lardani, & del Drago, 2019). In addition, the lack of maintenance and monitoring and the changed load conditions compared to the times of construction can affect the safety of these structures. As a consequence, the monitoring activities have been increased, and methods and tools able to ensure the maintenance of the constructions and the management of data in different formats have been considered by the scientific community.

The research presented here, developed within the context of a national project for the investigation and monitoring of infrastructures, is aimed at implementing an operational method for the analysis of bridges by creating digital replicas. The analyses focus on a specific type of historical infrastructure, namely the masonry arch bridges over a waterway. These bridges are subject, in addition to the problems of deterioration of materials and stresses related to changing load conditions, to the force of water and have to cope with floods and the accumulation of debris, overflows and floods. In this perspective, the multi-risk approach for the analysis and assessment of the health state of structures becomes crucial, both through visual inspections, in situ and remote, and through monitoring systems with static and dynamic sensors. The purpose of these analyses is to facilitate maintenance operations, which are generally very costly if related to the fragmented management of the Italian infrastructural heritage, giving priority to specific interventions on certain structures over others. The collected data with a multidisciplinary approach must be linked and reworked in the perspective of documentation and management of the infrastructural heritage. Therefore, one of the research purposes is to evaluate the potential of single digital systems and their integration to define an operational, scalable and replicable procedure for the conservation, protection and management of the assets belonging to the historical infrastructure network (Trizio et al., 2021).

The experts involved in this process move to collect heterogeneous information to complete the defined knowledge framework. Significant information is provided by the building archaeology that allows to highlight the different masonries categorizing them by type, materials and construction techniques (Francovich & Parenti, 1988; Doglioni, 1997; Brogiolo & Cagnana, 2012). The integration of these data with those coming from the geometric and dimensional examination also provides support in identifying the original elements from the following ones and the nature of the irregularities present, as well as the evolution of possible damage and degradation mechanisms (Savini et al., 2021). In addition, the recognition of the existing pathologies, the understanding of the acting causes, the relative mechanisms, as well as the effects that these phenomena have on the built system, represent a crucial phase to identify the actions to be implemented for the conservation and safety of the structure (Fiorani, 1996).

The acquired data must be digitized and computerised to make them accessible to the different actors involved in the analysis and knowledge processes. In this context, the parametric modelling applied to historical infrastructures (HBrIM) play a crucial role since it can link the different thematic interpretations and the information concerning the evolutionary history and the state of conservation and damage.

The HBrIM model structured in this manner is suitable for the drafting of diagnostic investigation and structural monitoring plans and is efficient also for numerical analyses for assessing the behaviour and performance of structures (Abbate, Invernizzi & Spano, 2020; Angjeliu, Coronelli, & Cardani, 2020; Cascardi et al., 2021). It is worth noting that, the implemented HBrIM enables, using specially designed shared families and parameters, the inclusion of the results derived from monitoring to create the Historic Digital Twin (HDT), a tool through which planning the possible remedial actions to be implemented for the conservation and safety of the historic built heritage (Jouan & Hallot, 2020; Boje et al., 2020; Kang, Chung, & Hong, 2021). The HDT, thanks to the interrelation created between the artefact and its digital replica, supports the virtual analysis of the physical system responses to external actions (Mora et al., 2021; Marra, Trizio, & Fabbrocino, 2021). The application to some historical infrastructures located in Abruzzo, in central Italy, and specifically in the area of Aterno river valley (fig.1), has led to test and validate the proposed procedure for the creation of the HBrIM at the base of HDT, and its results are illustrated in the following section.

Fig. 1: Location of analysed area and of historical masonry arch bridge in Abruzzo

3. Results

3.1 The case study and the thematic analyses

Among the arch masonry bridges analysed in the investigated geographical area, the *Ponte delle Tavole* bridge (fig.2) is a historical infrastructure still included in the road route connecting the two Municipalities located in the Subequana Valley, Fontecchio and Tione degli Abruzzi, in the province of L'Aquila. It is a structure long 42 meters and characterized by three segmental arches, with two central piers equipped with circular cutwaters both on upstream and downstream sides of the rivers, which serve to deflect the debris transported by the Aterno, reducing the risk of foundation erosion. The documents attest in the investigated area the presence of an ancient Roman route that intersected the river cross by crossing it (Liberatore, 1839). However, the structure visible today is probably the result of a 19th-century rearrangement. Indeed in this period, the regional road system, such as the national and European ones, changed significantly with the road arrangement, the retrofitting of historical ones, the construction of new bridges and the creation of the railway network (ASAaq; Vittoria, 2016). The thematic analyses performed from the high-resolution orthomosaics of the infrastructure, and correlated with the in situ investigation, led to characterizing the construction material used to build the bridge. It was realized with local limestone worked in squared blocks and laid on regular rows with a good construction technique. The stratigraphic analyses of masonries highlighted the presence of different masonry types, some in phase, such as for the parapet and spandrel wall, others belonging to subsequent phases, as in the case of wing wall. The different masonry textures and the presence of iron tie rods suggest that the artefact was extended and reinforced after its construction.

At the same time, the conservation state and the identification of the pathologies affecting the artefact were assessed, filling in the defect survey forms proposed by the Italian Guidelines (MIT, 2020; Trizio et al., 2021).

Fig. 2: The *Ponte delle Tavole* in Fontecchio (AQ)

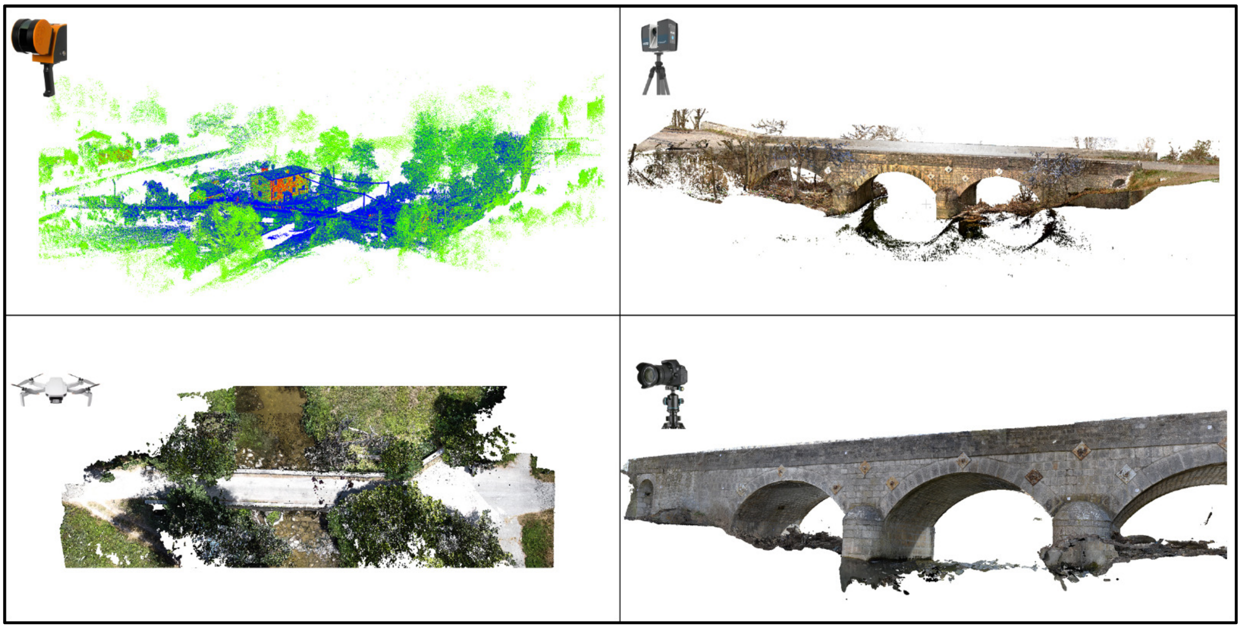

Fig. 3: Survey of the *Ponte delle Tavole* bridge

The structure in its whole is in good condition probably due to the continuous use over time and the maintenance works regularly carried out since past time. The analyses of surfaces degradation phenomena revealed the presence of biological patina caused by the growth of mould, fungi and bacteria, and the widespread infesting vegetation on the wall surfaces. In addition, some flow traces are visible, especially near the tie rod anchors that are oxidised due to their exposure to different weather conditions. Phenomena related to capillary rising damp, efflorescence and different colouring of masonry are still visible. Finally, the presence of debris, consisting of yellow sandy loam soil mixed with trunks and branches, is particularly significant under the north span of the bridge. This defect is related to weather conditions and lack of maintenance in the riverbed and surrounding flora. The debris at the base of the structure not only contribute to the river overflow in particular conditions but can also affect the stability of the foundation.

3.2 The integrated survey and digital representation

The digital survey of the bridge was performed using a consolidated operative procedure for the stereometric survey. Laser scanning (TLS and SLAM) and photogrammetry (terrestrial and aerial) were used and integrated to obtain a reliable survey from a metric point of view and high-quality orthomosaics that support several thematic analyses. The expeditious survey carried out with the Zeb Horizon, an instrument based on the SLAM technology (Simultaneous Localization And Mapping), enabled the investigation of the built landscape deriving from the integration of the infrastructure with the surrounding environment.A UAV (Unmanned Aerial Vehicles) photogrammetric survey, carried out using a DJI Mavic mini quadcopter, was performed both to integrate the survey of the structure and part of the riverbed with the colour data and to evaluate the variation of water flow. During the survey, about 723 photos were acquired and processed within different chunks by using the Agisoft Metashape Professional 1.5.1 software.

The UAV survey was integrated with the terrestrial photogrammetric survey guaranteeing the acquisition of colour data. The 480 photos collected in a single in situ acquisition campaign were processed with the Agisoft Metashape Professional 1.5.1 software.

The high-resolution orthomosaics were created from the photogrammetric model, scaled and textured. They became the support on which mapping the thematic analyses.

A laser scanning survey with a FARO Focus S70 scanner, equipped with an integrated camera with HDR functionality, was performed to obtain a precision survey of the structure. The scanning parameters (definition, quality, HDR) were set in relation to the size of the space surveyed and their complexity. The post-processing of data was carried out with the SCENE 2018 software, proceeding with the automatic registration of the scans and the processing of the entire point cloud.

The final result confirmed that the integration between the laser (TLS and SLAM) and the photogrammetric survey (terrestrial and aerial) allows to obtain a geometrically reliable digital 3D model enriched with the colour data, perfectly functional to the subsequent analysis phase.

Indeed, the integrated survey (fig.3) was functional to the parametric modelling phase of the infrastructure and its pathologies. A procedure previously tested for the elements of liturgical furniture of medieval churches (Trizio et al., in press) was used for modelling some pathologies. This procedure foresees the re-meshing of the photogrammetric model to obtain a solid mesh that can be imported into the parametric environment.

3.3 The HBrIM model for the conservation of infrastructural heritage

The HBrIM model of the *Ponte delle Tavole* bridge is the result of the application to historical infrastructures of procedures already used and tested in the parametric modelling of existing constructions.

Before starting the modelling within the BIM software of the investigated bridge, a semantic decomposition of the structure was carried out based on its constructive, structural, geometric and typological features comparing the information acquired with the ones found within manuals (Torre, 2003). The semantic decomposition of the infrastructure according to its component enabled the preliminary identification of the elements, structural and not. These can be modelled through the system families or creating specific families by using workflows that combine different procedures (Martone, 2018; Allegra et al., 2020; Sampaio et al., 2021). The creation of these families permits the definition of element libraries that can be adapted to the projects' needs, thus making the modelling phase more flexible and faster (Santagati, Lo Turco, & D'Agostino, 2017; Godinho et al., 2020; Guzzetti et al., 2021).

The obtained point cloud was imported into Revit software (Autodesk), defining different levels useful for infrastructure modelling. The single levels correspond to the main planes, namely those of the roadway, vault impost, the lower level of the water surface and the upper one of the parapet. In a second phase, the bridge geometry was modelled using the system families, i.e. wall and floor, to represent the wing walls and the elements of the abutment, haunching and bridge's fill material (fig.4).

Fig. 4: Point cloud imported into BIM environment for the development of the parametric model of the bridge

In this phase, the orthomosaics, obtained from the photogrammetry and mapped with the results of thematic analysis on masonry surfaces, were imported into the project to obtain a three-dimensional model that is representative of the bridge's current state and of the changes that occurred over time. New parameters were associated with each modelled element to enrich the data defined in the model with those collected by multidisciplinary investigation, thus achieving a higher level of information (LoI) (UNI, 2018).

Finally, new families were defined to represent both single structural elements, such as the arches, and combined systems, such as the one made by the pier, cutwater and foundations, which includes both components with structural function and those for supporting the main structures. The arches modelling was performed using solutions already adopted in the literature for the creation of vaults (Allegra et al., 2020). In particular, modelling was based on the 'Generic adaptive metric model' template, which permits adapting the elements to the several design requirements and the dimensions of the environments already created thanks to the identification of 'reference points' and metric design parameters.

The parametric modelling of the pier-cutwater-foundation system was implemented after a critical analysis of the solution adopted both for the *Ponte delle Tavole* bridge and for the other structures in the area, comparing the data acquired from the in-situ inspection with those available in the manual. Therefore, a new family dedicated to the pier-cutwater-foundation system was defined using the 'Generic metric model' template, which permits the creation of all components. Specific geometric parameters were created for the pier model, in addition to the ones descriptive of the elements (*ID* and *Image*) (fig. 5). These parameters enable the change in length and width of the element according to the dimensional characteristics acquired during the metric survey phase. At the same time, they modified the thicknesses of the wall elements, which generally is

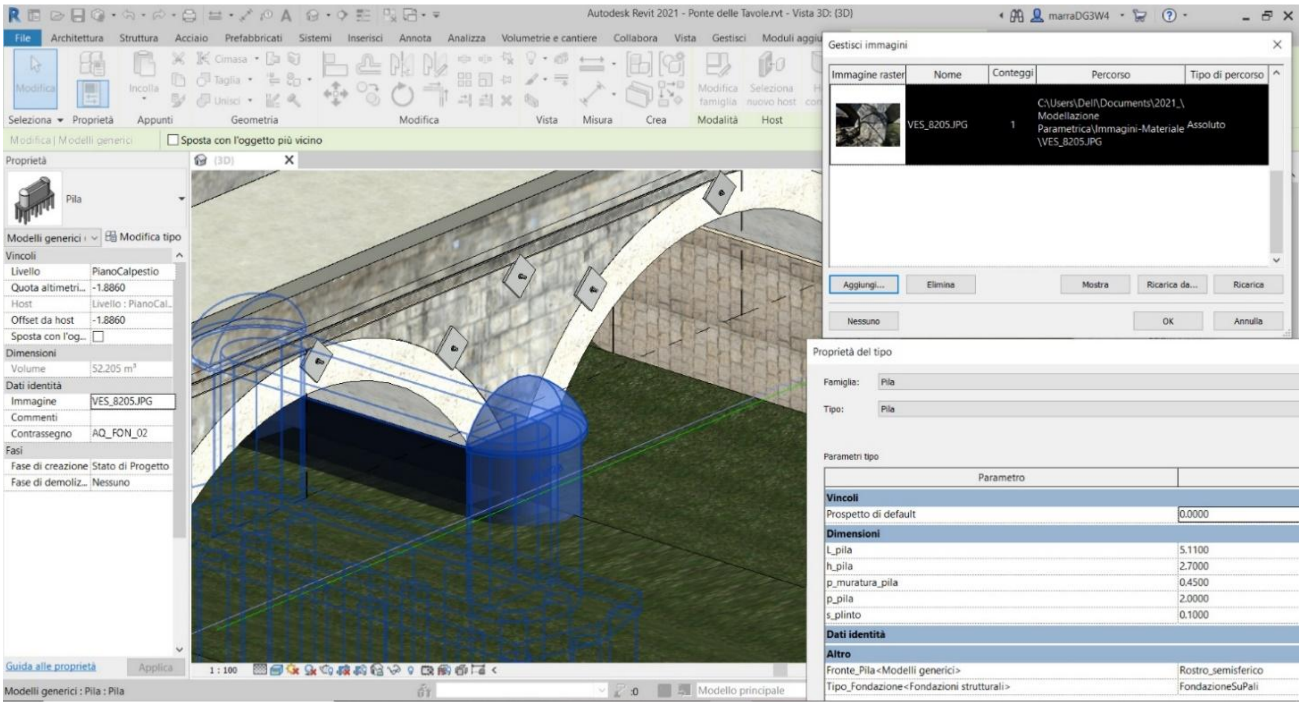

Fig. 5: Creation of new parameters for the pier-cutwater-foundation family and integration of new information within a parametric project of a historical infrastructure

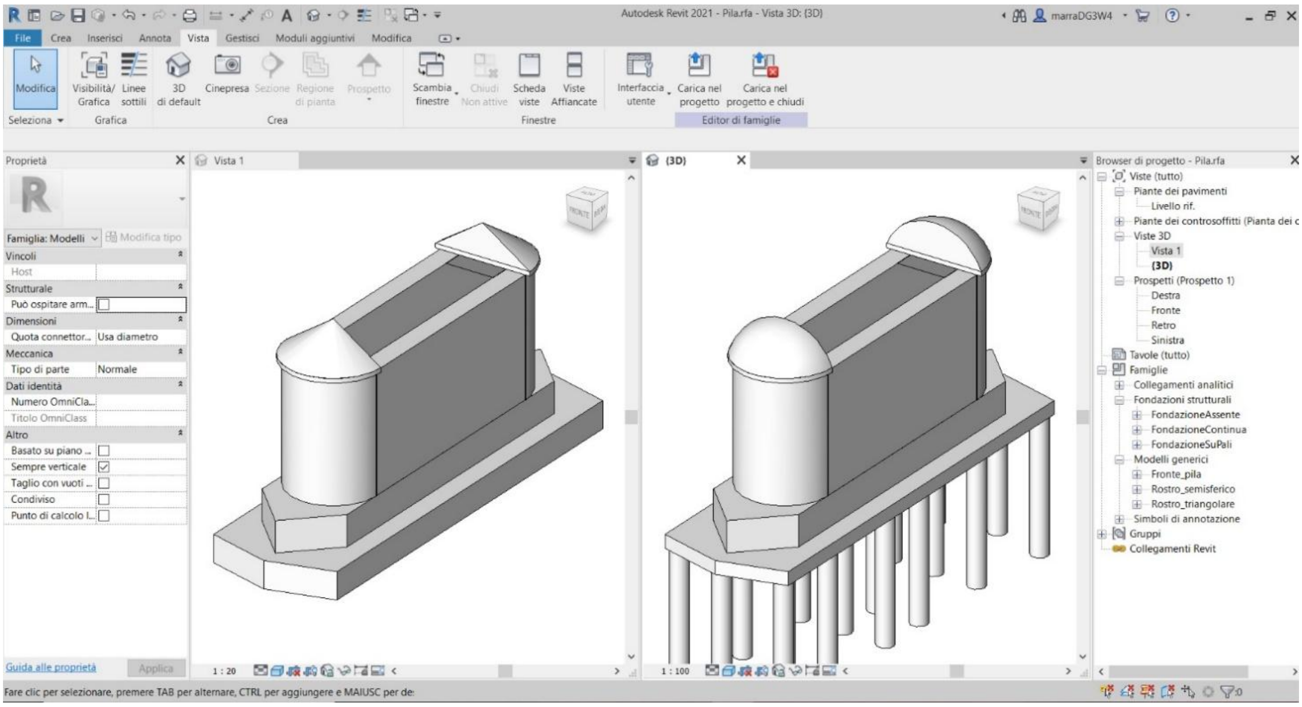

Fig. 6: Modelling of the pier-cutwater-foundation construction system and creation of "labels" and parameters for the development of a parametric library for data management of historical infrastructures

difficult to define given the relationship with different factors. Indeed, the cutwater and foundation structures were included as specific labels within the pier family, with the aim of representing solutions adopted during the construction phase and found both in the examined area and in the manual (fig.6). The single elements characterizing solutions different from the one examined were modelled for each component and appropriately parameterized. Therefore, it is clear that the creation in the family of these two specific labels facilitates the choice of the components to be included, simplifying the modelling and drafting phase of the management and maintenance project of the infrastructure. The same procedure was used in the modelling of the tie rods detected in the structure.
A specific family was created for this structural device, specifying descriptive, geometric and material parameters and including the anchor in a label. This choice is related to the different types of this element that can be detected and associated with the historical and territorial context.

The model was enriched with new parameters related to the families representing the forms of degradation and damage in order to create an HBrIM model of the historical infrastructure that is able to support the management phases of the existing structures and the design of possible interventions for the conservation, according to the Italian Guidelines (MIT, 2020).

In particular, the alteration and degradation phenomena were modelled recurring to a twofold representation. In the first case, the single pathologies afflicting the surfaces were recreated using an adaptive family by importing the orthomosaics edited for the specific issue into the project. A local model obtained from the processing of the photogrammetric mesh was imported into the BIM environment to reproduce the debris transported by the flow and located under the bridge arches or near the piers (fig.7). Instance parameters describing the pathology of degradation detected (*Defect*), the area and the coefficients of extension and intensity (*K1-Extent* and *K2-Intensity*) were defined for the families representing the degradation forms, as already experimented for other infrastructures (Trizio et al., 2021). These parameters were defined according to the Italian Guidelines (MIT, 2020) and are linked to the defect weight parameter (*G-Defect weight*).

The definition of the relative values of these

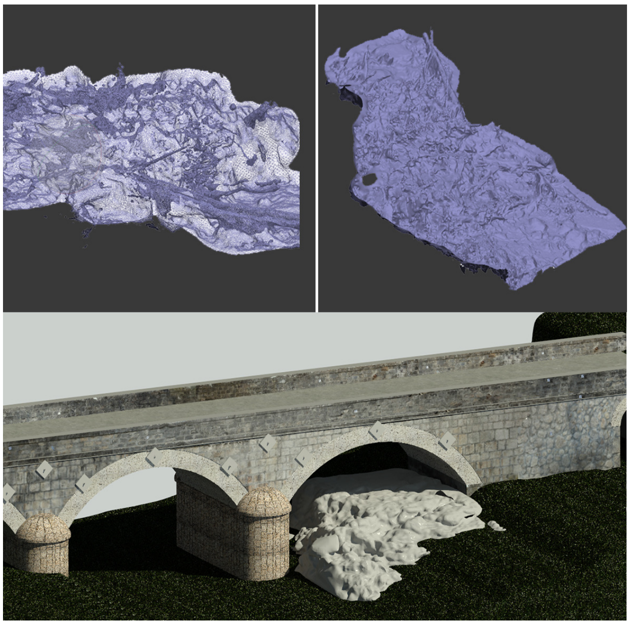

Fig. 7: Mesh model of debris obtained from the photogrammetric survey and then imported into BIM

parameters, in accordance with the defect forms of the Guidelines, allows the Relative and Absolute Defect Index (*DR – Relative Defect Index* and *DA – Absolute Defect Index*) to be assessed directly in the modelling environment, as required by the first-level assessment defined by the same standards (fig.8).

In addition, specific parameters were defined to manage all the information in a coherent and single way and to facilitate the interoperability of the model with relational databases and other existing systems.

The *ID-Bridge* parameter identifies the investigated structure and connects to the numeric identification code available in databases previously created for the census of infrastructures on the Aterno (Savini et al., 2021), creating a biunivocal connection between these and the parametric model (Marra et al., 2021). Other parameters were created to manage information related to visual inspections and structural monitoring in a coherent manner. The first parameter links the parametric model to a module that reworks the forms proposed by the Italian Guidelines.

The form was designed using online modules, which are effective in data management because they synthesize the information from the census and inspection of the historical infrastructures, permitting the data processing in graphs and tables (Fabbrocino et al., 2021).

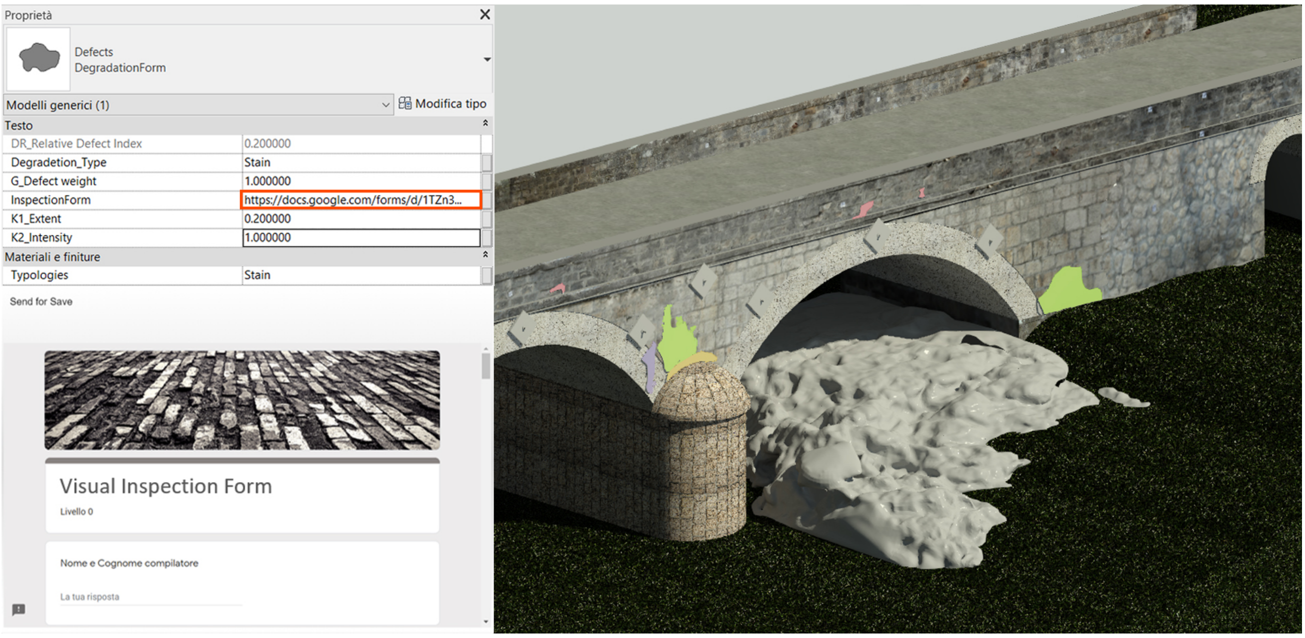

Fig. 8: Modelling of degradation phenomena in BIM environment. Definition of novel parameters according to visual inspection guideline and correlation to forms shared in a storage cloud

The second parameter links the parametric model to the data acquired during the structural monitoring surveys, making them available in an external cloud (Marra, Trizio, & Fabbrocino, 2021).

4. Final remarks

The digital model of the *Ponte delle Tavole* bridge is the result of the data integration obtained from the interdisciplinary investigations and the metric information derived from the integrated instrumental survey. The extensive information acquired relating to the masonry stratigraphy, the materials and construction techniques and the state of preservation permitted the creation of an HBrIM model with a high level of geometric detail (LoG), in line with the standards defined for new buildings. In addition, the digitization of the geometric and formal information, through the creation of specific parameters, has increased the LoI already achieved with the modelling of single elements.

The investigated operational procedure provided an exhaustive and integrated view of the artefact and demonstrated the interoperability of the parametric model with relational databases and other existing systems. Therefore, the HBrIM appears as a hub capable of managing and relating heterogeneous data and, at the same time, as a useful tool for the management of historical infrastructures. This approach is coherent with the idea underlying the Bridge Management System. Indeed, the accuracy achieved in modelling and digitization has led to the creation of an as-built model of the analysed historical artefact, which is suitable for further investigation and to support detailed qualitative and quantitative analyses.

This goal is achieved by creating significant parameters for the preservation, maintenance and management of the historical infrastructure, which allow assessing, in a semi-automatic way, the state of preservation based on visual inspections.

On the other hand, the results herein illustrated confirm that the digital model can act as an effective tool for the assessment of the risk factors affecting the infrastructure. Particularly, it has been shown that the definition of the Classes of Attention (CoA) provided by the Italian Guidelines in the 2nd level of analysis is feasible and can incorporate aspects associated with the preservation of historical infrastructures. Digital tools strengthen the e-conservation paradigm for territorial management by matching the needs of administrators and stakeholders operating in the territory. The virtuous processes of conservation, maintenance, management and control to increase the participation and involvement of the entire community will be possible to implement thanks to e-conservation.

Finally, since the parametric model represents the 'static' component of the HDT, further efforts are needed to integrate dynamic data into the system. These dynamic data will be acquired by a structural health monitoring program and integrated into the HBrIM model.

These are closely related to the virtual system and the way in which the information collected in the physical system is processed and interacts, thanks to Machine or Deep Learning, with the digital models providing significant information for the daily management of the physical system, structuring also the possibilities offered by the IoT.

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Credits

The research presented is the result of the authors' collective work, of continuous comparison and of a common discussion. Adriana Marra wrote sections 3.1 and 3.3, she also implemented the parametric model. Ilaria Trizio wrote section 1 and supervised the paper. Giovanni Fabbrocino supervised the research, reviewed the work and wrote section 4. Francesca Savini wrote sections 2, 3.2 and implemented the photogrammetric model.

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