

Article

The Heritage Building Information Modeling Methodology for Structural Diagnosis: An Integrated System of Digital Models for the Baptistery of San Giovanni in Pisa

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Abstract: The structural diagnosis of monumental buildings necessitates organizing diverse cross-disciplinary data. The H-BIM procedure employs 3D digital models to create a comprehensive virtual repository, offering advantages in documentation access, interoperability, intervention design, cost evaluation, and maintenance management. This work proposes an approach to combining different models while addressing interoperability challenges by best exploiting their positive characteristics. After evaluating the advantages and limitations of textured-mesh and NURBS-based models, and virtual reality environments based on specific comparison criteria, an integrated system of these models within the H-BIM framework is proposed. The latter is applied to study the relevant case of the Baptistery of San Giovanni in Pisa, Italy. The integrated H-BIM model is designed primarily to facilitate the structural diagnosis of the monument, and illustrates how combining different 3D representations, each providing multiple information with different levels of detail, enhances its capabilities. This integration results in a more effective tool for the multidisciplinary conservation of cultural heritage, accommodating a wide range of data beyond structural aspects, thus fostering collaboration among professionals from various fields of expertise.

Keywords: cultural heritage; historical building; documentation; H-BIM; VR environment; NURBS-based model; textured-mesh model; virtual repository



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1. Introduction

In preventive conservation for historical structures, representative models are essential across all phases, from diagnosis to project implementation and ongoing maintenance of Cultural Heritage (CH) assets. Commonly used models include Building Information Modeling (BIM), Geographical Information System (GIS), and Extended Reality (XR) environments [1]. These models help understand, document, conserve, and digitize heritage-related data, facilitating the storage, manipulation, updating, sharing, and transfer of diverse information. Additionally, any digital representation of a physical object can qualify as a representative model if it retains key features, multidisciplinary aspects, and important properties related to the structure. A historical building, like any physical entity, possesses an almost limitless array of qualities that can be measured, characterized, and collected in a representative model. One of the key strengths of such models is their capacity to retain virtually infinite data. However, not all of the information related to a tangible asset can be displayed simultaneously in the digital replica, which is ultimately a synthesis of the properties deemed relevant based on the purpose of its creation. Although multiple objectives may coexist, the ability to filter information, retrieve data from other fields when necessary, and display it clearly is crucial for enhancing the understanding of specific issues, such as those related to structural diagnosis.

Recently, representative models have seen increasing use in the conservation of built CH, also thanks to significant advancements in digital techniques to capture the geometry of real constructions, and for the continuous progress in information technology, software, and hardware industries to process survey data and transform it into 3D models [2].

Given their capacity to integrate multidisciplinary aspects of historical buildings, representative models are strongly encouraged by governments and public authorities, often supported by specific European-level regulations [3]. This is particularly important to ensure interoperability among specialists, which is crucial to understanding and conserving structures while respecting their heritage values. Additionally, the development of protocols and platforms to systematically collect, visualize, exchange, and manage data related to CH assets and their conservation is frequently promoted in international projects [4,5].

BIM models are among the most widely adopted representative models first emerging in the mid-1970s [6]. They are designed as collaborative processes centered around digital models, using an object-oriented methodology [7] to incorporate various layers of information. These models are saved in standardized exchange formats to ensure improved interoperability among the many specialists involved in building-related processes throughout the entire lifecycle of a structure.

Originally developed for new buildings, BIM models have recently gained ground in documenting CH, including historical structures [8] and archaeological sites [9]. Heritage Building Information Modeling (H-BIM) and Archaeological Building Information Modeling (A-BIM) models offer significant advantages by organizing multidisciplinary data through collaborative input from experts such as architects, engineers, and archaeologists. This systematic approach is vital for existing buildings, where abundant but unstructured data often remains underutilized. H-BIM's ability to systematically archive and visualize data, combined with advancements in digital technologies for easier acquisition of cultural heritage shapes, has significantly progressed its development [10]. However, H-BIM for CH buildings is still less widely adopted than BIM for new constructions, mainly due to the limited availability of reusable parametric object libraries and challenges in modeling unconventional elements like deformed geometries. Despite these issues, H-BIM models have been successfully implemented in various cases [11–15].

Most Heritage Building Information Modeling (H-BIM) models are focused on public use, management, and dissemination of CH structures to raise awareness for their preservation [14]. However, compared to using H-BIM for documentation and conservation, relatively few studies explore its application for damage detection and, more broadly, for structural diagnosis of CH buildings [10]. Integrating different digital models to enhance the virtual representation of historical constructions for diagnostic purposes remains largely unexplored. Notable exceptions include the work of Bruno et al. [16], which integrates databases connected to BIM models with web services, cloud-based applications, and Virtual Reality (VR) and augmented reality models; and Banfi et al. [17], who create novel BIM objects (families designed for Structural health monitoring (SHM)) and use cloud storage solutions to manage large datasets. However, neither study directly integrates different digital models.

Other than H-BIM models, XR technologies are among the most up-to-date tools to reproduce entire real-world contexts or individual objects with variable virtual overlays. These technologies have significantly benefited from advances in real-time graphics hardware, increased computational power, and reduced costs [18]. XR is a collective term for technologies that blend real and digital content to varying degrees, including virtual reality, mixed reality, and augmented reality, in decreasing order of immersion [19]. In particular, VR refers to a fully digital environment that can replicate an existing scene or create a completely new, detached setting.

Initially developed for the video gaming and film industries, XR technologies have gained valuable applications in the Architecture–Engineering–Construction (AEC) sector in recent decades [20]. They enhance structural design, CH conservation, building activities, and structural condition assessments by reducing errors, risks, costs, and time. XR mini-

mizes the need for on-site inspections allowing remote evaluations in VR environments [21] and improves collaboration by enabling stakeholders to annotate and share feedback directly within the same digital model, replacing ineffective paper-based practices [22].

Recently, the CH sector has increasingly adopted XR technologies for engaging and interactive dissemination to scientific and general audiences [23]. However, their use in evaluating structural safety and monitoring historical constructions is still nascent, with few documented examples. One notable case is [24], which presents a remote SHM system based on the Internet of Things in a VR environment, effectively embedding sensor data into detailed site reconstructions.

De Fino et al. [25] highlight the benefits of photorealistic virtual tours of CH buildings created from 360° panoramas, allowing easy asset exploration and access to external resources via “hotspots”. Their study shows that integrating diagnostic data within VR enhances understanding of building characteristics and visible damage. They also note that virtual tours offer faster navigation than Point Clouds (PCs) [25], which require more computational power and time, making them less suitable for in situ inspections.

Overall, adopting XR-based tools is recommended as a valuable aid in diagnosing the conservation state of CH assets and evaluating interventions. However, despite the successful use of XR technologies in SHM of civil and CH structures, challenges remain before they become standard practice in structural diagnosis alongside more rooted techniques.

While individual models have matured, their full potential for CH structural diagnosis deriving from their integration remains underutilized, particularly in providing a comprehensive, up-to-date view [25]. In this sense, efforts have mainly focused on embedding all data within a single environment, limiting the benefits of using different model types. For example, VR environments are more accessible on portable devices than BIM. In addition, model interoperability issues often hinder fully leveraging their strengths.

The combination of different models could be improved; however, the research is already rather established as for the integration of BIM paradigm with GIS technology. The first codes historical constructions in terms of their components, generating parametric descriptions. The second allows embedding of environmental data based on geographical references [26], and the production of digital maps that overlay CH assets while maintaining the information spatial reference (i.e., thematic maps of damage patterns [1]). Numerous effective applications can be found in the literature, both at the territorial/city level [27], and multi-scale level, e.g., for vulnerability assessments [28].

On the other hand, combining BIM with XR technologies, other digital representations, and possibly dedicated platforms, even only for first quick data analyses, is still limited, with only a few documented attempts. In this direction, recent endeavors can be found in [29], where the authors develop a digital-based integrated method for preventive conservation of diverse typologies of built CH assets. They include an H-BIM model and dedicated applications collecting all of the information about the inspected construction to create a reference database hourly updated with environmental data from sensors installed on the building. In this way, they facilitate monitoring activities and support condition-based maintenance actions in an interactive and immersive mixed reality, also leveraging a virtual tour of the palace. Similarly, Matrone et al. [30] created a spatial database based on H-BIM and GIS paradigms to incorporate geometric and alphanumeric entities useful to manage conservative operations and planned maintenance. They develop a custom online dashboard to establish a connection between the BIM model and associated information with 3D multi-scale representations. Additionally, in [31], the author reflects on the evolution of interactivity, immersion, and interoperability in H-BIM, and tests the use of a digital process and the development of virtual and augmented reality environments to enhance a deeper knowledge of built CH if employed along with H-BIM models.

With respect to the latter examples cited, the comprehensive view offered by combining multiple digital representations could be further enhanced, once the strengths and weaknesses of different model types are known. For example, other models could be included to offer a depiction of surfaces visually richer than the virtual tours used in [29,31],

namely textured-mesh models, which are characterized by the stereoscopic geometric accuracy of mesh models along with realistic textures. Moreover, the use of VR representations and custom online platforms for fast data analyses could be systematically embedded within H-BIM properties to streamline consulting different data available for the structural diagnosis of CH structures.

This paper proposes an approach to integrating different models while addressing interoperability challenges by maximizing their positive features. After establishing specific evaluation criteria, the work compares various digital models as virtual repositories. These models are then integrated to enhance their strengths, creating a cohesive system centered around the H-BIM paradigm.

The effectiveness of this integrated model system is validated through the application to the Baptistry of San Giovanni in Pisa, selected for its unique shape, size, and notable structural damage patterns. Indeed, accurately diagnosing its damage requires gathering extensive multidisciplinary data and understanding the geometry and connections of its structures. In this context, digital techniques and models are crucial, as this work demonstrates.

2. Materials and Methods

This section outlines the steps taken to develop a comprehensive digital model that serves as a virtual repository, offering significant advantages in documentation access, interoperability, intervention design, cost evaluation, maintenance management, and structural diagnosis of monumental buildings through well-organized cross-disciplinary data. The first step of this process involves comparing different digital representations, here called first-level models, such as textured-mesh and NURBS-based models, as well as a VR environment. Initially, evaluation criteria are established, which enable the analysis of the strengths and weaknesses of each model. The second step focuses on the development of an integrated system of digital representations, comprising the first-level models, centered around the H-BIM paradigm, namely, a second-level model. Figure 1 outlines the stages from data acquisition to the creation of first-level models and their subsequent integration to build an H-BIM model. The last paragraph presents the case study for which the integrated model is realized.

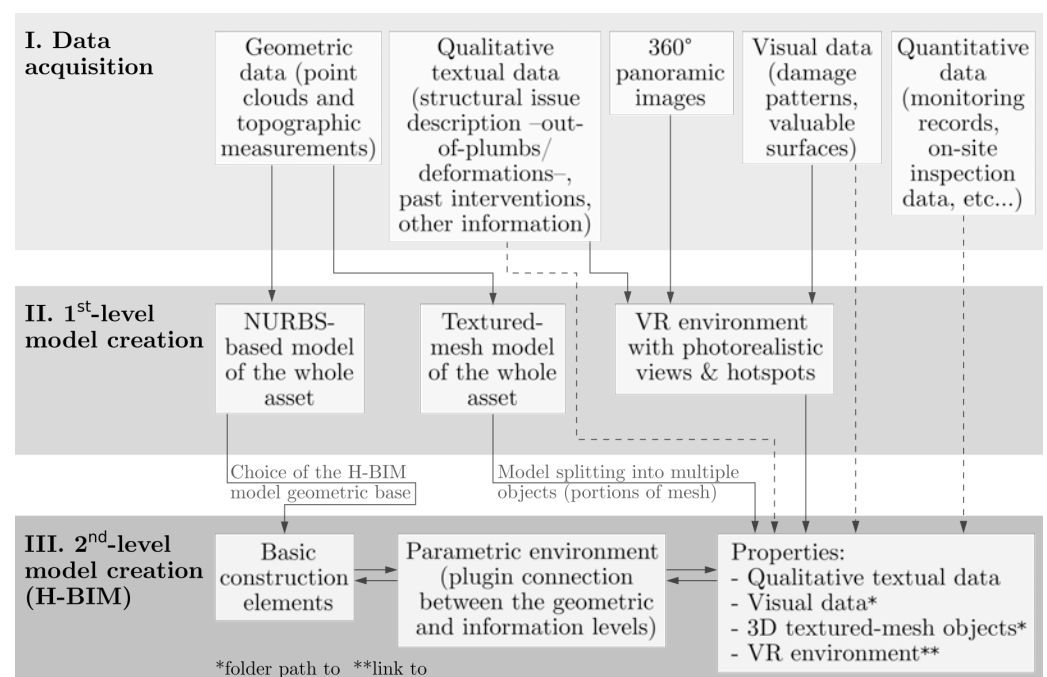


Figure 1. Workflow of the methodology proposed to create an integrated system of digital representations revolving around an H-BIM model.

2.1. Model Comparison Criteria

To evaluate the strengths and limitations of the textured-mesh and NURBS-based models, as well as the VR environment, the following comparison criteria were considered:

- **Ease of model creation:** this means the *automation* of the reconstruction process, as opposed to the need for manual operations; the *computational burden* required to generate a digital model; the need for *skilled operators, specific knowledge, and expensive equipment* to perform basic acquisitions to be further processed for model reconstruction; and the *overall speed* of the model generation process.
- **Output control:** This parameter refers to the ability to control the model geometry generated through a certain process. In a way, it is the opposite of automation, although automatic procedures generally guarantee a certain degree of output customization.
- **Model measurability:** this criterion refers to the ability to determine the geometric dimensions of model elements by querying the model directly, without the need for additional tools.
- **As-built elements uniqueness reproduction:** This feature is connected to the capability of the model to account for the peculiarities making every element different from another. These differences may include artistic details (e.g., the actual shape of a decorative element) or geometric variations (e.g., out-of-plumb vertical elements), among other factors.
- **Surface textures reproduction:** this is related to the capability of models to reproduce the textures of the elements with various levels of realism.
- **Model navigation easiness:** this encompasses how effortlessly users can explore different viewpoints and angles, including rotating, panning, zooming around, moving within the virtual space, and more in general, interacting with the model.
- **Visual inspections assistance:** This refers to the possibility of employing digital models both during on-site and off-site inspections. In the first case, it concerns the capability of models to serve as digital supports to take notes of relevant observed elements. In the second case, the criterion is related to the potential of models to be regarded as virtual replicas reproducing some features of the real building that are always available to be closely examined.
- **Three-dimensional visualization:** This refers to the possibility of users to interact with models to view and inspect each element from any perspective. Unlike flat, 2D representations, 3D visualization enables users to orbit objects, zoom in on details, and examine them from various angles, thus to provide a deeper understanding of the model's structure, proportions, and spatial relationships. This comparative criterion is linked to the nature of the elements constituting the models themselves, namely 3D meshes for the textured-mesh model, closed polysurfaces for the NURBS-based model, and 2D 360° images for the VR environment.

2.2. Software Modules

The generation of the textured-mesh and NURBS-based models, and the VR environment, entailed performing various operations. These can be carried out by adopting a variety of equivalent software. For this reason, and considering that the innovative contribution of this work lies in the integration of different models more than in the deployment of specific software (most of which are well-established), in the following, priority is given to the actions and operations required in the model generation process, with less emphasis on the software used.

PC simplification (cleaning operations for noise removal and point reduction) was performed with Meshlab 2021.10 [32], which allowed the creation of textured-meshes mainly through the already-implemented screened Poisson surface reconstruction algorithm [33].

For 3D editing operations, i.e., putting together different parts of meshes and creating 3D geometries from scratch through basic Boolean operations and complex editing of NURBS curves, surfaces, and solids, Rhinoceros 7 [34] NURBS-based CAD software was employed.

Photo editing, necessary to emphasize some aspects of the real construction, such as cracks, then used to generate VR environments, leveraged Photoshop [35] tools.

Software specifically designed to create interactive virtual tours from 360° views (panoramas) or videos, and floorplans, which also enable the addition of hotspots, and clickable objects, such as 3D Vista Virtual Tour [36], was used to define customized VR environments.

Archicad BIM software [37] was employed to host the H-BIM model while ensuring its saving with the suitable standard exchange format.

Grasshopper [38], a visual programming language and environment running as a Rhinoceros plugin, gave us the possibility of organizing information to enrich the H-BIM model thanks to a specific tool, namely Archicad Live Connection. The latter guaranteed the creation of native Archicad BIM elements in Grasshopper through familiar nodes in an automated and simplified way, and the achievement of a live connection between Archicad and Grasshopper applications.

The following paragraphs report schematic flowcharts, and a brief description of the operations performed to generate the various models mentioned above. Specific reference to the employed software is made to demonstrate the methodology, though similar outcomes could be achieved with other available alternative programs.

2.3. Textured-Mesh Model

Figure 2 illustrates the main steps that can be followed to create a textured-mesh model, namely a 3D digital representation of a specific asset, where the geometric level is provided by surfaces composed of interconnected polygons (triangles or quadrilaterals, i.e., “meshes”), while the color data (patterns and shadings) are given by a texture, namely a 2D image mapped onto the mesh [39].

The starting point to generate a textured-mesh model is the acquisition of a PC. It retains both geometric features and reflectance properties necessary to build a textured-mesh model, and can be obtained through different techniques (Terrestrial Laser Scanner, Time-of-Flight Cameras, Light Detection and Ranging (LiDAR) systems, etc. [2]). Subsequently, subsampling operations consisting of point reduction can be performed to have simplified (i.e., lighter) PCs to be managed more easily during the subsequent steps. Further, the subdivision of the simplified PC into smaller portions may be required to minimize the computational burden of transforming it into textured meshes through various algorithms, such as the Poisson Surface Reconstruction [40]. Then, if multiple meshes are derived by separately processing different parts of the PC, they need to be assembled to create the finalized textured-mesh model.

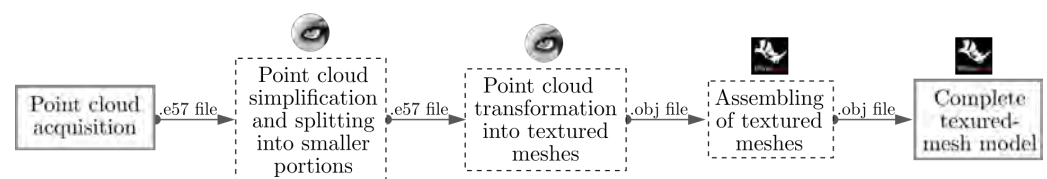


Figure 2. Textured-mesh model generative procedure.

2.4. NURBS-Based Model

The main steps to create a NURBS-based model, namely a 3D model that uses mathematical curves and surfaces to represent complex shapes with smooth, continuous geometries, are reported in Figure 3. In particular, the flowchart makes reference to the case in which a PC of the asset is used as a geometric basis, and manual operations are performed to generate the 3D model. From a PC, automatic procedures can be contemplated as well, but fall out the scope of this paper. In the case of manual operations, no particular simplification of the PC is needed, in that it is only used for a preliminary evaluation of the elements constituting the construction, but not for directly generating the model. Therefore, once the level of detail to reproduce the whole asset is chosen, single construc-

tion elements need to be manually modeled as NURBS-based geometries to create the entire construction.

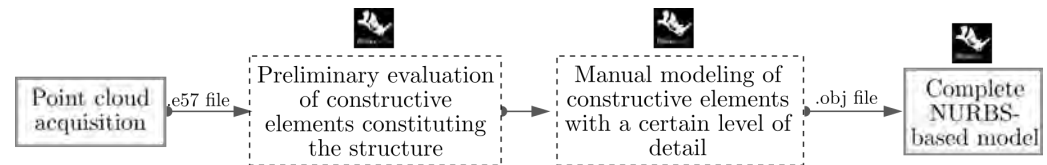


Figure 3. NURBS-based model generative procedure.

2.5. Virtual Reality Environment

Figure 4 shows the few steps required to create a VR environment from 360° images.

Unlike the textured-mesh and NURBS-based models, the transformation process in this case is straightforward and fully automated: once the 360° images are acquired, it is sufficient to use software for 3D virtual tour generation to position hotspots corresponding to the points where the photographs were taken, thus creating customized virtual tours with spherical photorealistic views.

Additionally, some images can be modified to create extra spherical views that specifically highlight certain aspects, such as crack patterns. These views provide alternative visualizations of the basic VR environment that can be accessed by clicking on hotspots strategically placed within the model. Using this approach, other layers of information can be embedded, such as textual data about the length and width of cracks. Further hotspots, represented by various symbols (e.g., an open door), can also be easily created within the software to allow users to navigate within the structure. Finally, reference plans and sections can be included within the VR environment to facilitate orientation while navigating the model.



Figure 4. Virtual reality environment generative procedure.

2.6. H-BIM Model

The integrated system of digital models is thought to be based on an H-BIM environment, which incorporates the other models through links, folder paths, and adequate connections, making full use of the capability of H-BIM models to include several types of data in an organized way (Figure 5), while partially untying the H-BIM model from the specific level of detail of its components. Consequently, the H-BIM model is presented as a type of second-level model that can link first-level models and virtual platforms, integrating data from multiple sources.

As is known, an H-BIM model follows an object-oriented paradigm, and is made of a *geometric level* that describes the geometries of the object under study; a *connection level* that defines the relations existing between the single elements of the model itself; and an *information level* that represents the stored data characterizing model elements. For example, an H-BIM model could be created by bringing together a NURBS-based model (*geometric level*), and many other data types making up the *information level*, namely textual data, images, other models such as (portion of) textured-mesh models, VR environments, and virtually any other model type, comprising web platforms. The geometric and the

information levels can be then connected through any environment interfacing with BIM software and capable of establishing a live connection between them to easily update the model as new data becomes available. Indeed, a prerequisite for any BIM software is to host the geometric entity (a 3D model) and its custom groups of BIM features, which make up the semantic structure of the final H-BIM model.

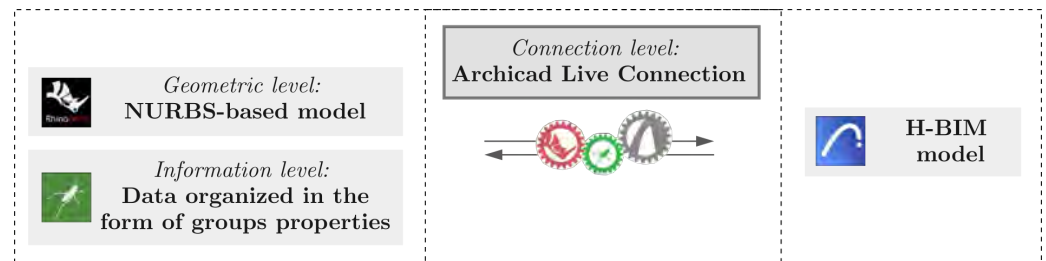


Figure 5. Geometric level, information level, and connection level of the H-BIM model.

As shown in Figure 5, with Archicad 25 chosen as the BIM software, the H-BIM model can be defined starting from data organized with a specific logic in a parametric environment, i.e., Grasshopper, and then finalized in Archicad 25 with the *Options/Property Manager* tool. The latter enables the creation of new properties to be punctually associated with the 3D model elements. In particular, the connection between geometric and information level, with the simultaneous transition to the Archicad model, can be achieved through the *Morph-solid* component with relative *Morph Settings* implemented in Archicad Live Connection. These settings, which are detailed in the Grasshopper environment, can include any customized properties and are also linked to Archicad settings defined within an Archicad file. Consequently, the assignment and compilation of information related to the model elements are conducted directly in Grasshopper. At the end of this procedure, the *Synchronize* tool in Grasshopper allows the import of the geometric level, i.e., the NURBS-based model with its constituting elements and related H-BIM data, into an Archicad file. Additionally, within Archicad, *Graphic Override Combinations* can be set up, along with associated *Graphic Override Rules*, to manage the visualization of different information levels.

2.7. The Baptistery of Pisa

The San Giovanni Baptistery, located in Pisa's Piazza del Duomo, a UNESCO World Heritage Site since 1987, is an outstanding example of medieval architecture (Figure 6). It is a key component of the monumental complex, which also includes the famous Leaning Tower, the Monumental Cemetery, and the Cathedral of Santa Maria Assunta. This masonry structure is renowned for its impressive dimensions and unique covering system, as well as its distinctive blend of Romanesque and Gothic architectural styles, which reflect the evolution of design throughout its construction. The Baptistery was founded in 1152 in the Romanesque style under the supervision of architect Diotisalvi, with construction spanning approximately 250 years. By the early 13th century, after several interruptions, the lower section of the structure up to the arcade was completed. In 1260, significant modifications were made under the direction of sculptor and architect Nicola Pisano, and the external dome was completed in the 14th century after further delays.

With a circular plan, an external diameter of 35.4 m, and a height of approximately 54 m, it is the largest baptistery in Italy, and one of the largest in the world. The limestone masonry structure is topped by two concentric domes: an outer dome that encloses an inner truncated dodecahedral pyramid. The outer dome rests on exterior walls made of San Giuliano marble, which have a thickness of 2.60 m at the base, while the inner dome, spanning about 20 m at its base, is supported by two levels of columns surmounted by arched drums. Inside, the ground floor features a circular colonnade composed of eight granite columns and four stone masonry pillars, forming an ambulatory covered by groin vaults. This arrangement is repeated on the upper level, where an internal colonnade of

12 pillars defines the women's gallery, covered by a toroidal vault. Two non-intersecting helical staircases, carved into the stone walls, connect the two levels. At the women's gallery level, 12 radial masonry arches connect the prismatic dome's drum to the external walls, helping to counteract its horizontal thrust.

Currently, a significant crack pattern affects the structures: at the edges of the inner dome, on the outer walls, and at the intrados surface of the groin vaults covering the ambulatory. This deformation pattern also impacts the pillars of the women's gallery, which exhibits an outward tilt, deviating from plumb. The causes of the current cracks and deformations, potentially stemming from both the inherent mechanical properties of the building materials and the construction sequence should be further investigated to clarify the reasons behind the present situation.

To formulate the diagnosis of the damage state, it is essential to gather a large amount of multidisciplinary data and, above all, to have a clear understanding of the correct geometry of the structures and the connections between the elements. Digital techniques and representative models are therefore of primary importance in this context.

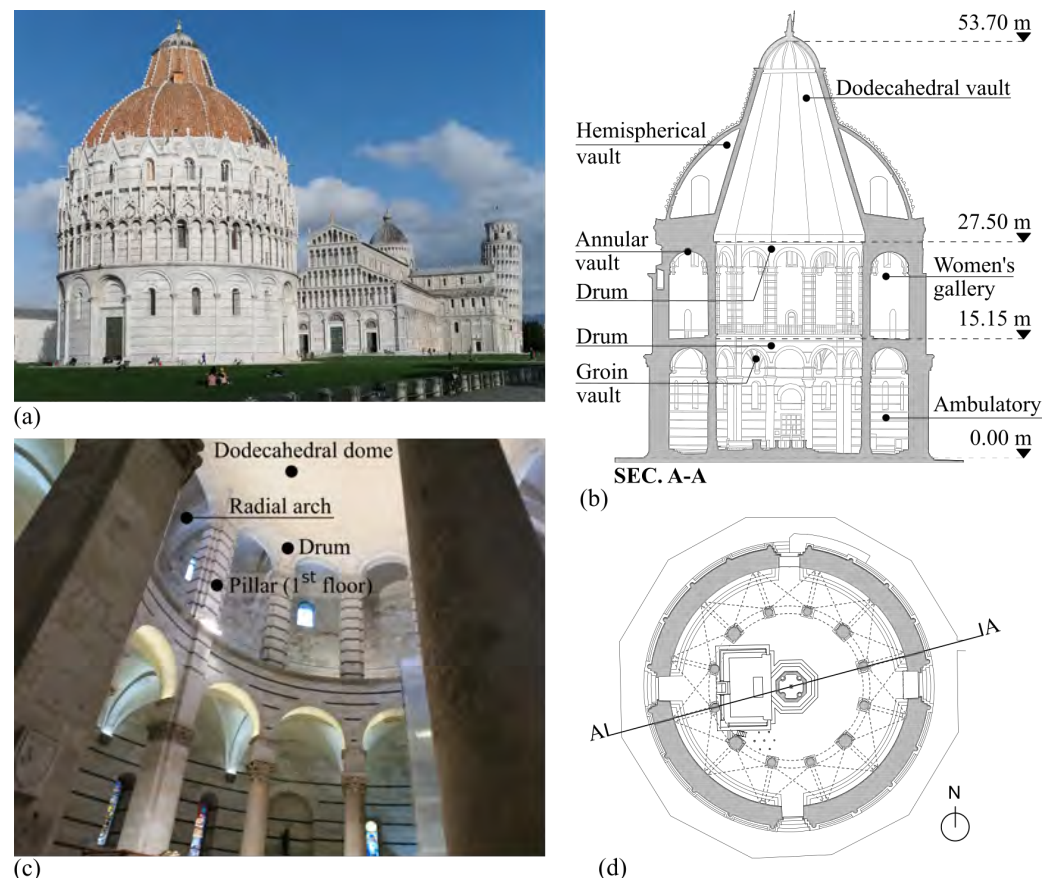


Figure 6. (a) San Giovanni Baptistery in Cathedral Square (Pisa, Italy); (b) vertical section; (c) internal view; (d) ground floor plan view.

3. Results

This section presents the results obtained by following the procedures indicated in Section 2 to create the textured-mesh and NURBS-based models, and the VR environment of the Baptistery of Pisa, as well as to develop the integrated second-level model that combines and integrates the previous ones.

3.1. First-Level Models

Figure 7 illustrates the textured-mesh and NURBS-based models of the Baptistery, both generated from a point cloud acquired through Leica C20 Terrestrial Laser Scanner (TLS)

by EuroTech Pisa SRL, after suitable elaborations illustrated in Figure 7a,b, respectively. In the case of the Baptistery the PC was as accurate as it was heavy.

The textured-mesh model required several manual adjustments before any further processing, including the simplification of the PC. The simplification consisted in the manual removal of useless parts (such as the grass around the monument or internal scaffolding placed at the first level) and in the reduction of points (subsampling) constituting the above-ground structure. Additionally, the simplified PC was segmented to facilitate the transformation into textured meshes using the screened Poisson Surface Reconstruction algorithm implemented in MeshLab. Consequently, the various processed meshes were assembled to create the final model, whose aim was to represent surface textures with a level of detail adequate to spot potential differences in construction materials and identify the diverse characteristics of elements- features that can assist in stylistic dating.

In contrast, the NURBS-based model required no simplification of the PC, which was mainly used to derive the morphology, geometric dimensions, and spatial relationships of the elements. After establishing the level of detail for the construction elements, they were manually modeled, deliberately omitting many details, such as specific decorations, as these were outside the model's primary scope. The chosen level of detail ensured an accurate representation of the articulation and arrangement of the construction elements in space, essential for gaining an intuitive understanding of the overall structural behavior.

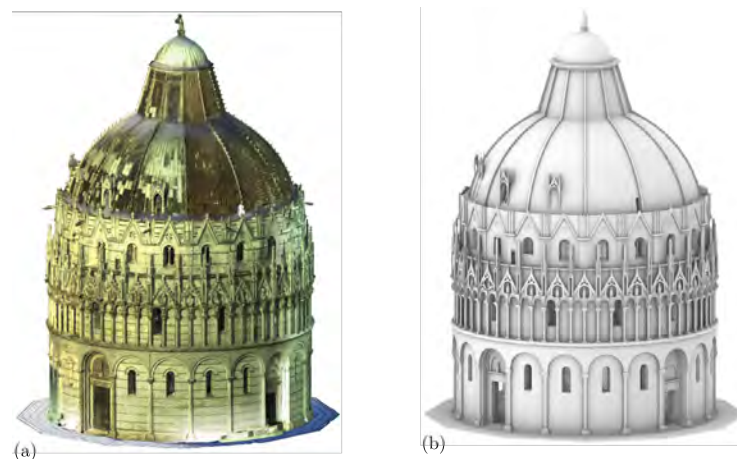


Figure 7. (a) Textured-mesh model; (b) NURBS-based model.

In addition, a VR environment was created in an almost fully automated way in 3D Vista Virtual Tour starting from the acquisition of 360° images of the interior of the Baptistery. They were taken with an Insta360 X3 (72 MP) camera, and were then converted into a VR model. The only manual task involved placing hotspots to mark the image capture points. Additionally, some of the original images were cloned and manually modified in editing software to trace and highlight the surveyed crack patterns. Hotspots were then inserted into the VR environment containing the unmodified images, allowing users to click and access 360° panoramic photographs, which serve as an additional data layer (another 360° virtual tour) where cracks are marked in red (Figure 4). Other hotspots, such as open-door icons, were added to ease navigation across the different floors of the building. Reference plans and sections were also embedded within the VR environment to facilitate orientation while navigating the model. Figures 8 and 9 illustrate some views of the VR environment, showcasing the high level of surface realism achieved with this model type. In particular, Figure 9 illustrates some information incorporated in the VR tour through ad hoc hotspots, exemplifying the benefits of embedding data using this approach.

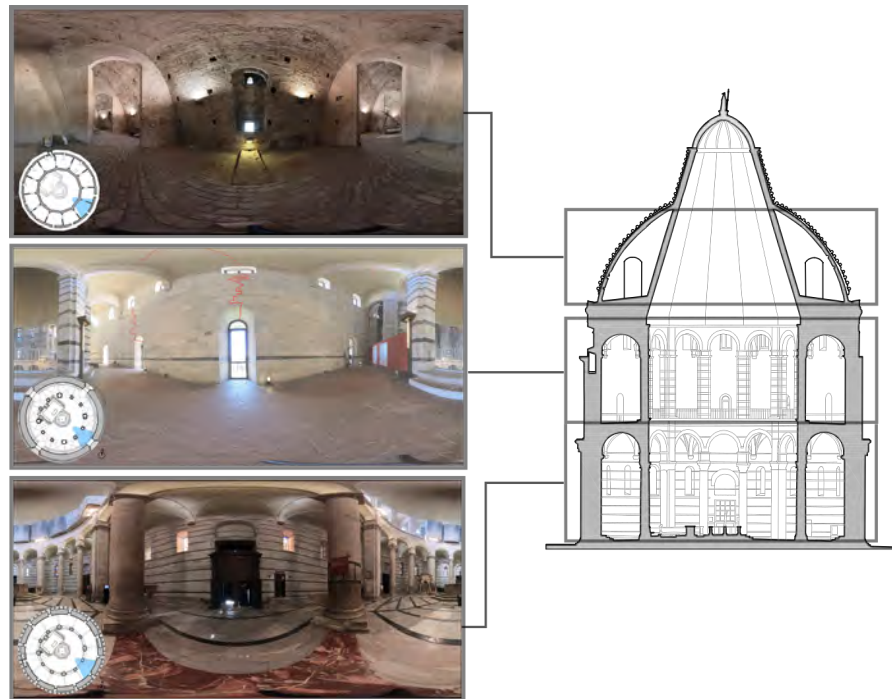


Figure 8. VR environment.

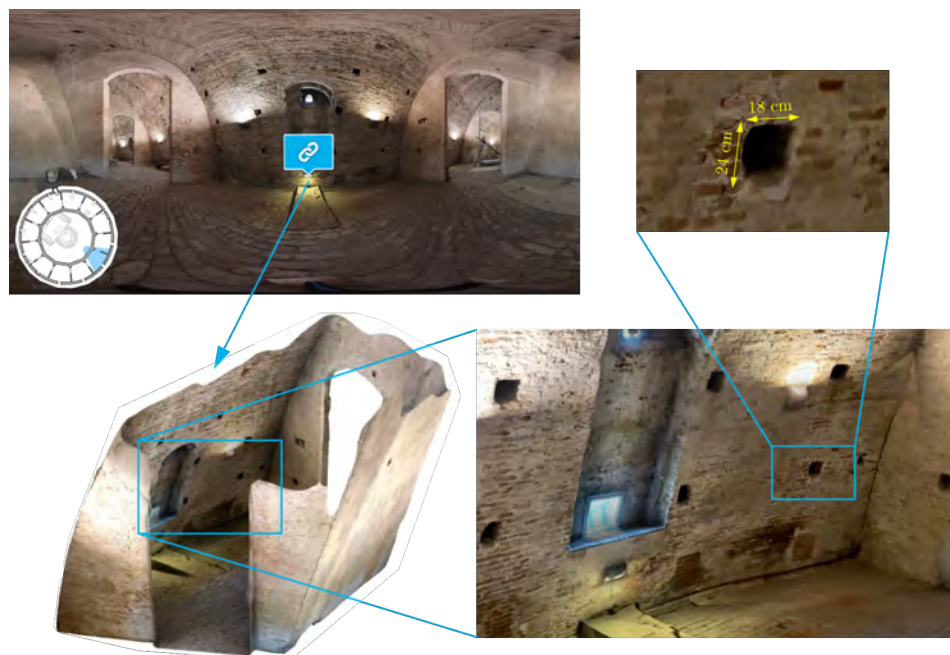


Figure 9. Details of the VR environment.

3.2. Second-Level Model: An Integrated System of First-Level Digital Models Based on the H-BIM Paradigm

The second-level model presented here is the result of the integration of the textured-mesh model, NURBS-based model, and VR environment illustrated in the previous section, according to the logic detailed in Section 2 to establish a live connection between the NURBS-based model and stored data. In this case, the NURBS-based model represents the geometric base of the H-BIM model; the connections of elements and the transformation of the NURBS-based model into a BIM one are realized by means of Archicad Live Connection plugin; the information level is made of data previously collected and elaborated according to its type, and then structured into newly defined property groups. In particular, since the

NURBS-based model was already created and the plugin already existed, in the present case, efforts to finalize the H-BIM model were mainly focused on defining groups of objects and properties. Then, specific model objects and relative properties (i.e., *Morph Settings*) were connected by leveraging the *Morph-solid component*, with the morph entity being selected, as shown in Figure 10.

The properties assigned to the newly created object groups were set to support a multidisciplinary environment capable of storing various data types, relevant for preliminary qualitative analysis and structural diagnosis of the Baptistery. These properties cover the above-ground structure, foundations, and the soil beneath the monument. Although the groups of objects and properties were defined for the diagnosis of the Baptistery, they were chosen general enough to be applicable to other CH assets.

The identified groups of objects, set based on the attribution of the same type of tags, were classified as: *Symbols materializing measuring points*; *Foundations*; *Soil*; *Cracks*; and *Generic H-BIM object*, as shown in Table 1.

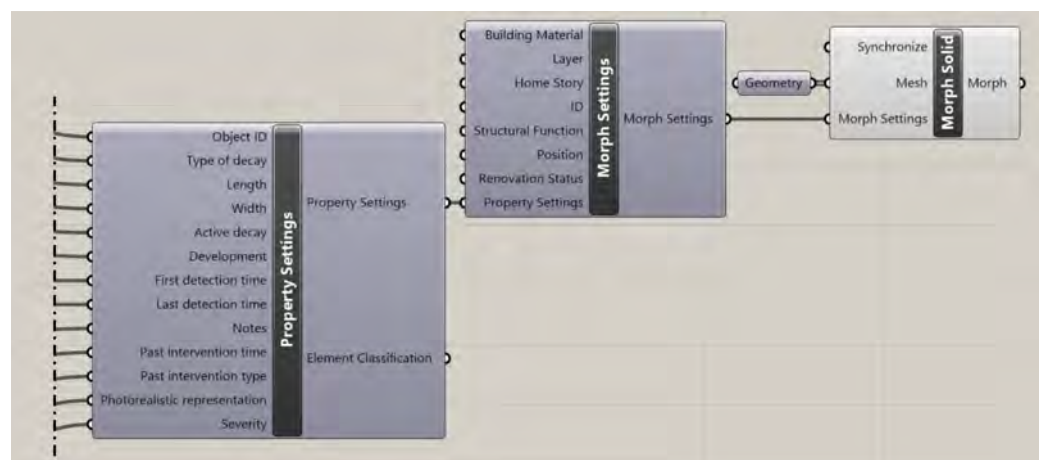


Figure 10. Grasshopper canvas: Morph-solid and Morph-settings.

The object group labeled *Symbols materializing measuring points* (Figure 11) comprises all the small solids used to materialize the various monitoring devices installed within the Baptistery: cubes symbolize the displacement sensors, spheres stand for the leveling staffs, and octahedrons represent the prisms measuring 3D displacements. The new properties defined for this object group are categorized under the *Measurement data* property group, and contain information designed to uniquely identify each measuring point within a specific monitoring system (see Table 1). Key properties include: *Measuring point ID* (a unique code—textual data—identifying the measuring point within the model); *General monitoring system (network) ID* (a code—textual data—identifying the broader monitoring system (network) to which the specific measuring point belongs); *Test type* (textual data specifying the type of instrument used for data acquisition, i.e., displacement sensors); *Instrument model/accuracy/other relevant information* (textual data collecting details about the instrument, including model, accuracy, and other relevant specifications); *Instrument localization* (visual data such as plans and sections indicating the measuring point's coordinates and its location within the building and monitoring system (network)); *Raw data sampling frequency* (textual data of the frequency of measurements acquisition); *Measuring starting/ending date* (textual data indicating the starting and ending date of measurement acquisition); *Interactive plots* (textual data, namely a link to a Github folder with the code and material to use the dashboard with interactive plots from monitoring data; and *Notes* (textual data for recording observations or insights derived from the collected data at the measuring point).

Table 1. Property settings (Morph Settings component) for objects groups of the H-BIM of the Baptistery.

Object Type	New Properties
Symbols materializing measuring points	Measurement data : Measuring point ID; General monitoring system (network) ID; Test type; Instrument model/accuracy/other relevant information; Instrument localization; Raw data sampling frequency; Measuring starting date; Measuring ending date; Interactive plots; Notes
Foundations	Object data : Object ID; Dimensions; Materials Test data : Test ID; Test type; Instrument model/accuracy/other relevant information; Instrument localization; Raw data sampling frequency; Measuring starting date; Measuring end date; Plots; Notes
Soil	Object data : Object ID; Stratigraphy Test data : Test ID; Test type; Instrument model/accuracy/other relevant information; Instrument localization; Raw data sampling frequency; Measuring starting date; Measuring ending date; Plots; Notes
Cracks	Object data : Object ID; Type of decay; Width; Length; Development; Severity; First, detection time; Last detection time; Active decay; Past interventions type; Past intervention time; Notes; Photorealistic representation Monitoring data : General monitoring system (network) ID
Generic H-BIM object	Object data : Object ID; Materials; Construction period; Documentary sources; Past interventions; Photorealistic representation; Three-dimensional representation; Structural issues; Valuable surfaces; Notes Monitoring data : General monitoring system (network) ID Test data : Test ID; Test type; Instrument model/accuracy/other relevant information; Instrument localization; Raw data sampling frequency; Measuring starting date; Measuring ending date; Plots; Notes

This structured property system ensures each measuring point is thoroughly documented, facilitating comprehensive analysis and monitoring of the asset's structural condition.

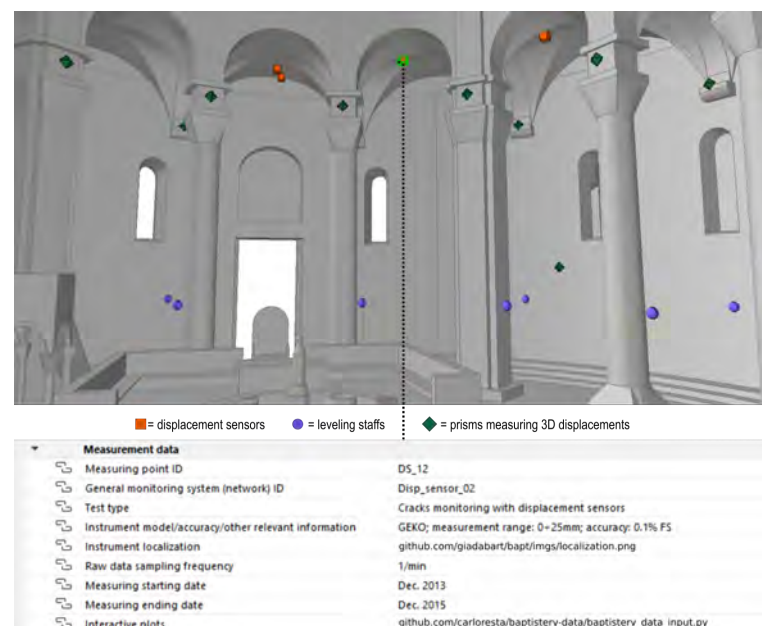


Figure 11. Symbols materializing measuring points. The material is available at github.com/giada bart/bapt (accessed on 9 November 2024) and github.com/carloresta/baptistery-data (accessed on 9 November 2024).

The object type labeled *Foundations* stands for the underground structure, both the internal and external foundation rings. The new properties added for the *Foundations* belong to two property groups: *Object data* and *Test data*. The first group includes data related to the foundations themselves, such as the *Object ID* (a unique code—textual data—identifying the object within the model); *Dimensions* (textual data detailing the foundation’s measurements), and *Materials* (an image showing the different materials of the foundations). The second group of properties, instead, provides specific details about the tests conducted to assess the foundation’s dimensions and materials. These properties roughly correspond to those introduced for *Symbols materializing measuring points* under the group *Measurement data*, except for *Plots*: in the case of the *Foundations*, they are static images rather than interactive plots due to the lack of raw data from the experimental campaigns. The *Test data* properties group currently encompasses data about georadar surveys, geoelectrical tomographies, and core drillings, with the potential to expand as new tests on the foundations are conducted.

The object type labeled *Soil* includes the solid simulating the soil below the Baptistery. Like *Foundations*, two new property groups were set to adequately collect data concerning the soil itself (*Object data*), and tests performed to characterize its stratigraphy (*Test data*), as shown in Figure 12.

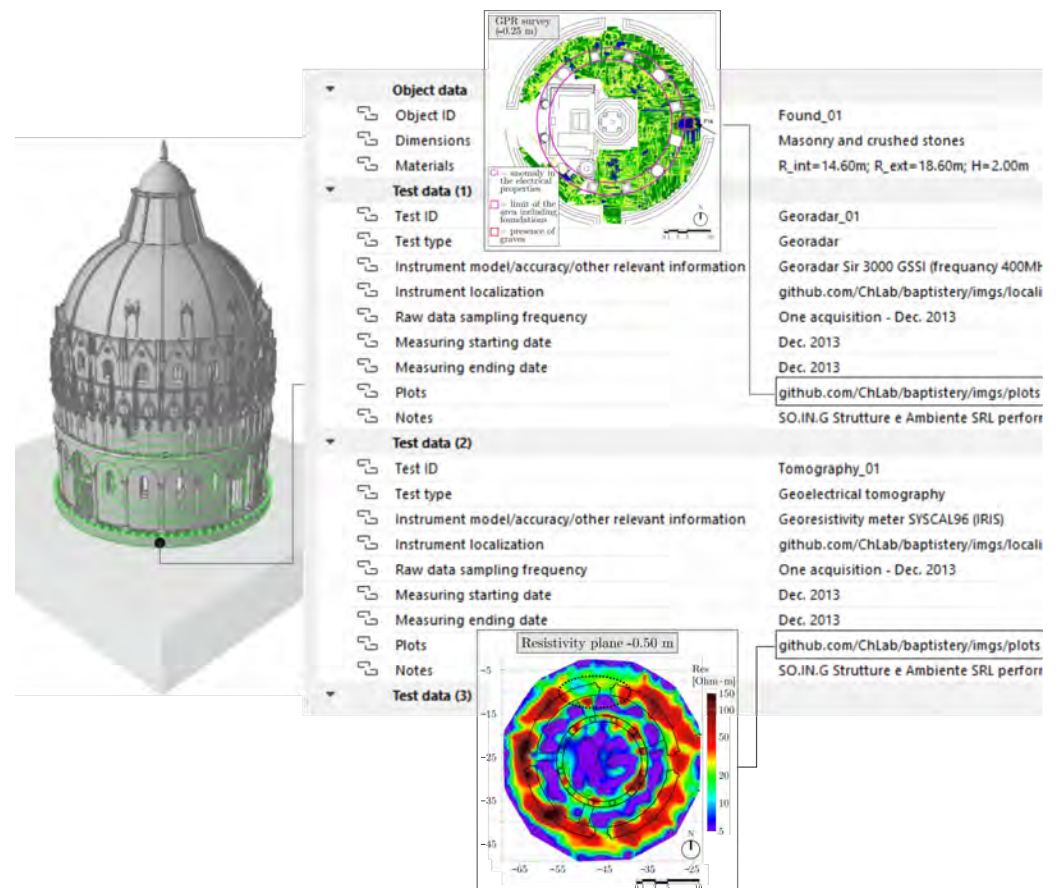


Figure 12. Example of property settings for the object group *Foundations*. The material is available at github.com/giadabart/bapt (accessed on 9 November 2024).

Information such as the *Object ID* (a unique code—textual data—identifying the soil object) and *Stratigraphy* (an image displaying the most likely soil stratigraphy based on the performed tests) goes under the first group, while the second one mirrors the structure of the corresponding group for the *Foundations*, with similar property tags. So far, the *Test data* properties group stores data about penetrometer tests with piezocones, the seismic dilatometer test, and continuous core drillings (with soil samples extraction), encompassing

all the tests performed on the soil below the Baptistery. Any new data can be added following this archival structure.

The object type labeled *Cracks* contains thin pipes simulating the previously surveyed cracks (Figure 13). Like for some of the other objects mentioned above, two custom groups of properties (*Object data* and *Monitoring data*) were added to give a thorough description of the cracks. Apart from the *Object ID* used as an identification code for each object of the model, and the *Type of decay* employed to clarify the decay type considered, the *Object data* properties group incorporates relevant information aiding to portray the crack pattern. Among them, there are *Width* and *Length* (numerical data providing insight into the extent of the damage); *Development* (textual data describing whether the damage advances vertically, horizontally or inclined); *Severity* (textual data classifying the damage level, particularly if cracks appear on both sides of a surface); *First detection time* and *Last detection time* (textual data indicating when the damage has been first and last spotted); *Active decay* (textual data specifying whether the damage is active); *Past interventions type* and *Past interventions time* (textual data providing information on previous actions taken to mitigate or address the source of damage); *Notes* (textual data summarizing key findings from collected data); *Photorealistic representation* (a link to open a VR model with photorealistic images of the cracks). In addition, basic data to identify the monitoring system potentially installed to monitor the evolution of the damage at issue is saved within the entry *General monitoring system (network) ID* (within the *Monitoring data* properties group).

This structure ensures that all relevant details about the cracks, from physical characteristics to monitoring data, are thoroughly documented for further analysis.

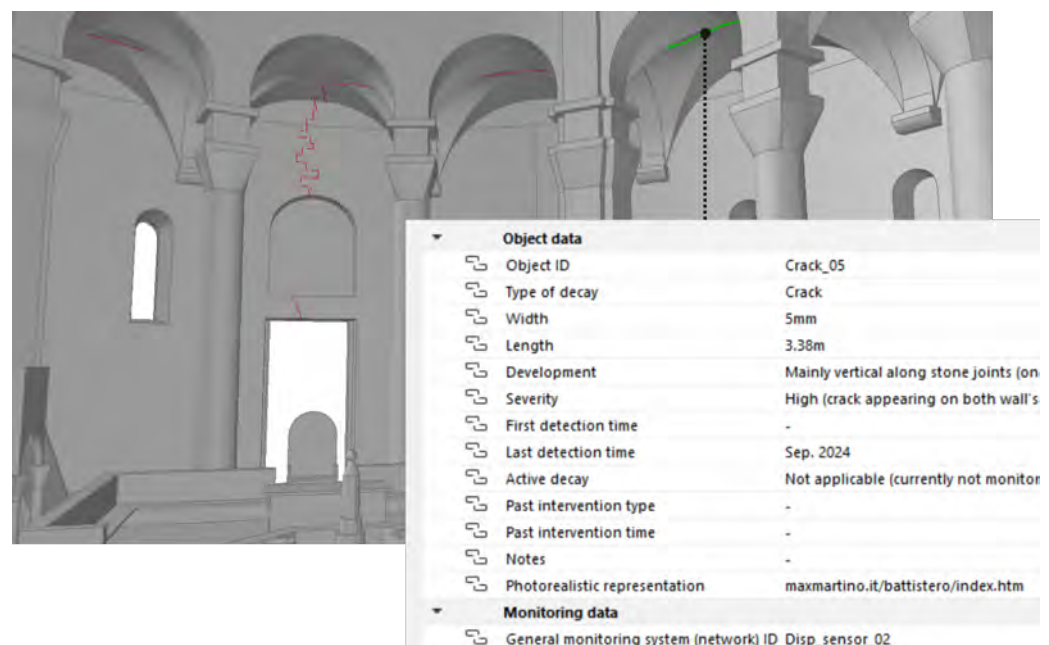


Figure 13. Example of property settings for the object group *Cracks*. The material is available at maxmartino.it/battistero/index.htm (accessed on 9 November 2024).

The object type labeled *Generic H-BIM object* collects all the other objects of the H-BIM model falling into none of the previous object types (Figure 14).

The added property groups for such objects entail a set describing the object itself (*Object data*); a property facilitating the connection between the 3D object and monitoring data of the measurement network it is part of (the link is established through the property group *Monitoring data*, in particular via the *General monitoring system (network) ID*); and another set considering tests carried out on the object (under the properties group named *Test data*). Some properties, such as *Object ID*, *Materials*, *Notes*, and *Photorealistic representation* are identical to those explained for other object types. However, there are additional

properties specific to Generic H-BIM Objects, including *Construction period* (textual data referring to the likely construction period); *Documentary sources* (textual data with a link to a table reporting the available historical records about the construction process, architectural modifications, and renovations); *Past interventions* (a table listing past interventions, including historical events—e.g., earthquakes—that may have impacted the structural condition); *Three-dimensional representation* (textual data of the folder path containing the .obj file of the 3D textured-mesh of the specific object); *Structural issues* (images from computer-generated analyses aimed at identifying potential structural problems, such as vertical elements showing out-of-plumb conditions [41], as seen in Figure 14), and *Valuable surface* (textual data denoting whether the surface is frescoed or features any other valuable surface treatment requiring preservation).

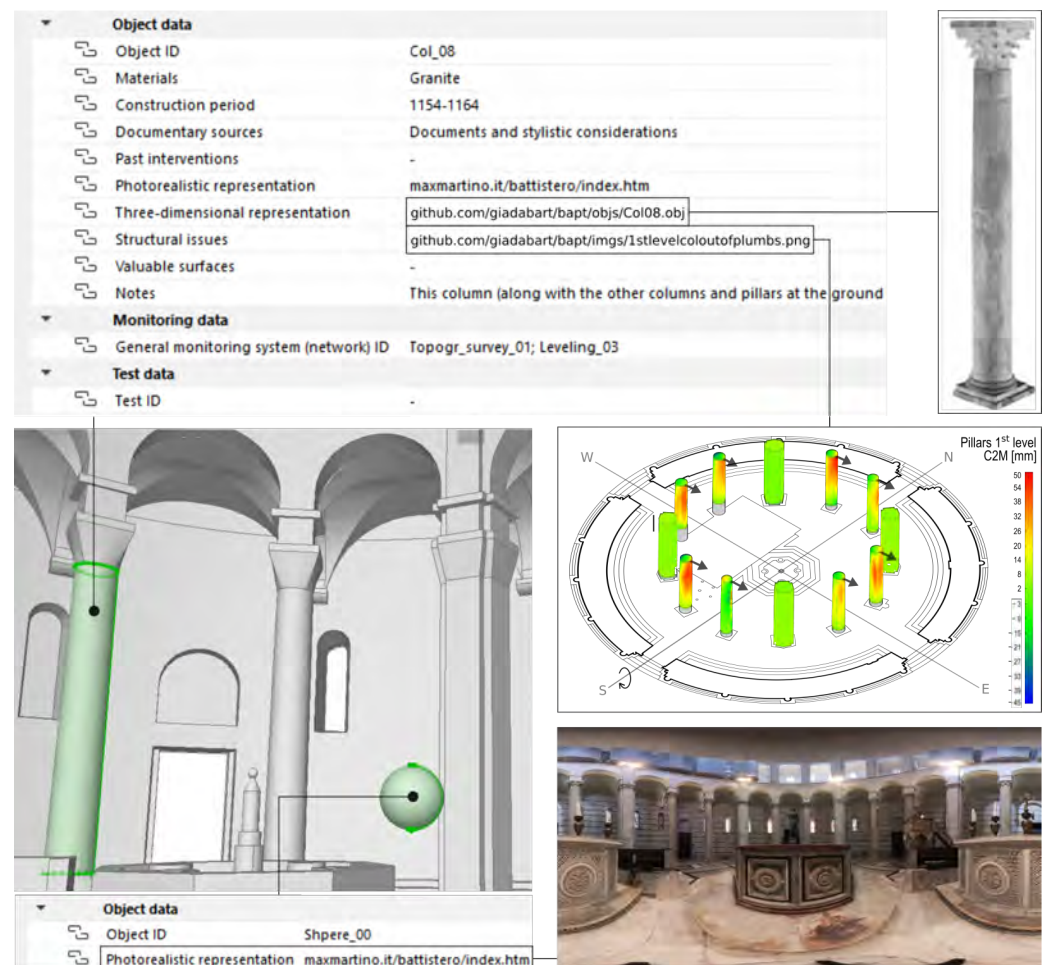


Figure 14. Example of property settings for the object group *Generic H-BIM object*. The material is available at maxmartino.it/battistero/index.htm (accessed on 9 November 2024) and at github.com/giadabart/bapt (accessed on 9 November 2024).

This structured approach ensures that each *Generic H-BIM Object* is thoroughly documented, connecting its physical and historical characteristics to relevant monitoring and test data.

In addition, a dedicated ball-shaped *Generic H-BIM object* was placed in the center of the model for more direct access to the VR environment (Figure 14), serving as an alternative to the property *Photorealistic view* embedded in every *Generic H-BIM object* (and in *Cracks*). This feature is included in all the elements for which consulting the model with its photorealistic view can be useful.

Finally, once all data were stored within the H-BIM model, *Graphic Override Combinations* allowed filtering layers of information, enabling the visualization of specific

information while excluding others. For example, Figure 15 shows the application of the *Graphic Override Rules* of Archicad to selectively visualize the construction sequence of the Baptistery (Figure 16) or the materials constituting the monument (Figure 16).

This functionality enhances the model's versatility, allowing for targeted analysis of different aspects of the monument.

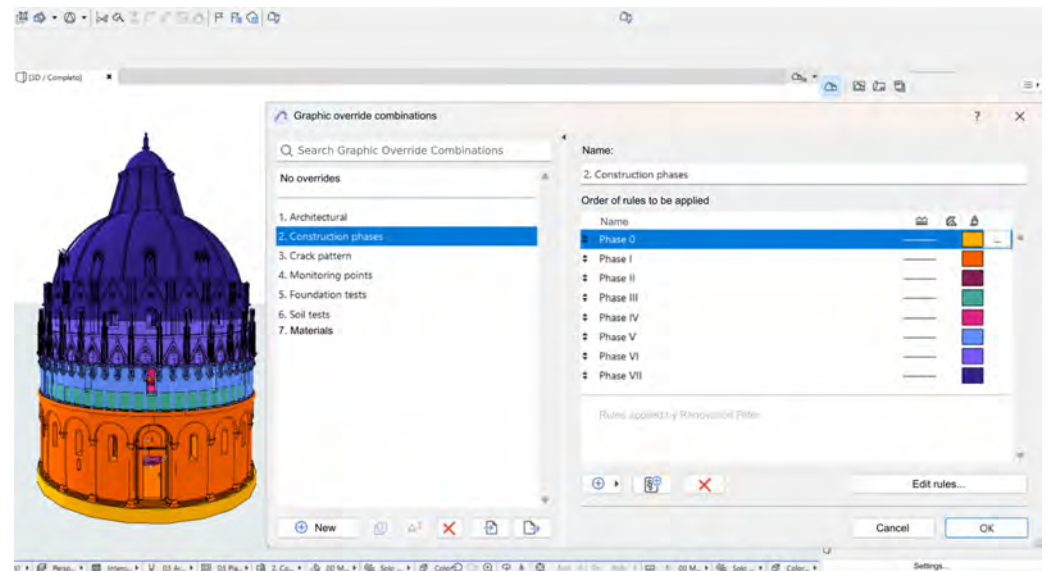


Figure 15. Archicad Graphic override of the construction phases of the Baptistery.

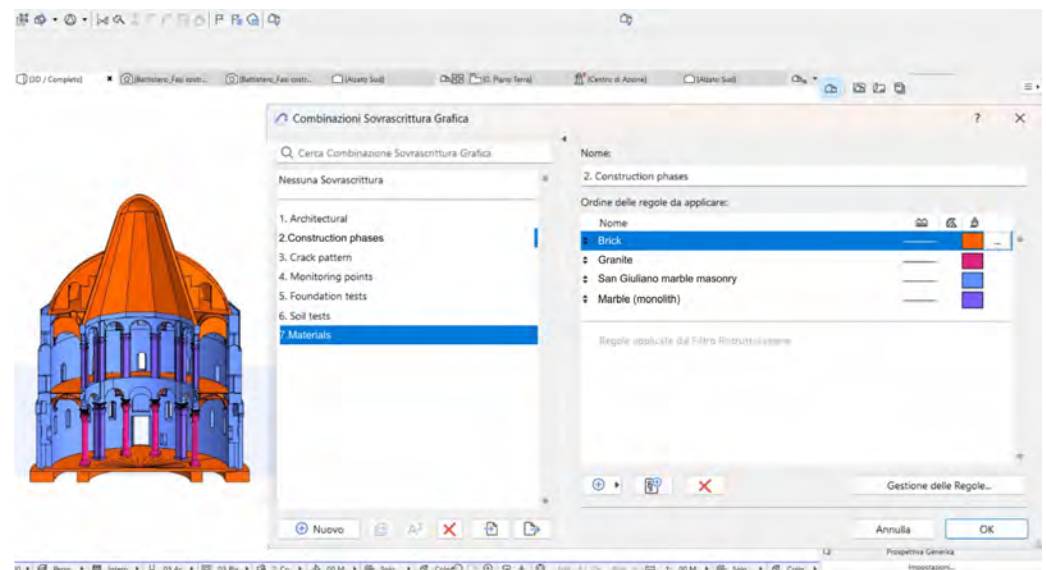


Figure 16. Archicad Graphic override of the building materials of the Baptistery.

4. Discussion

4.1. Strengths and Weaknesses of the First-Level Models According to the Comparison Criteria

This section comments on the results of the textured-mesh and NURBS-based models, and VR environment considering the comparison criteria defined in Section 2.1.

- Ease of model creation:** The realization of the textured-mesh model was quite efficient thanks to the employed reconstruction algorithm that reduced manual operation near to zero, if not for the definition of the initial parameter setting for the transformation of the PC into a textured-mesh [33]. However, the computational burden of the process was high, so much so that the creation of the model required splitting the PC into several portions. In addition, the acquisition of the PC used as a basis for

textured-mesh generation relied on TLS surveys, which involved operators with certain expertise in maneuvering costly instrumentation. Considering such surveys, the required preliminary simplification procedures of the PC (manual removal of extra portions and points reduction), as well as the mesh reconstruction, the process to obtain the textured-mesh model was not the fastest, especially if compared to the creation of the VR environment. In the case at hand, building the NURBS-based model was a cumbersome procedure, because it was carried out manually to choose the proper level of simplification for each element. Despite the manual nature of this process, the computational strain was lower compared to that of the textured-mesh model. The creation of the NURBS-based model could potentially be sped up by employing Scan-to-BIM procedures to automate the transformation of PCs into H-BIM models, but this would increase computational demands and sacrifice control over the simplification of individual elements. Additionally, like for the textured-mesh model, the acquisition of the geometry of the asset to derive the NURBS-based model leveraged TLS surveys. Therefore, the same drawbacks of such an acquisition method recurred. By and large, building the NURBS-based model of the Baptistery was demanding. On the other hand, the VR environment was generated automatically using 360° images captured by specialized cameras and processed with appropriate software. This method did not require significant hardware resources. Unlike TLS-based PCs, getting 360° photographs was rather quick and intuitive: the use of cameras capable of taking such pictures did not require any particular tool or knowledge. Moreover, the cost of 360° cameras is considerably lower than that of TLS instrumentation. All these things considered, the VR model generation process stands out as the most efficient and cost-effective among the three methods discussed.

- **Output control:** The output control of the textured-mesh model is reasonably good, considering that separate elaborations were performed for different parts of the PC, allowing for customized parameters of the Poisson surface reconstruction algorithm to be set as needed for each part. As for the NURBS-based model, the customization of the geometries was almost total. Indeed, manually building single elements permitted the definition of the desired level of detail for each of them, according to the general purpose of the model. For the VR environment, the output control does not refer to the possibility of precisely defying the model geometry, as creating a VR model does not entail reproducing the 3D geometry of single elements, but a 3D representation of entire scenes. Hence, in this context, output control is meant as the possibility of regulating the generation of the 3D virtual environment (views), which is quite limited due to the fully automated process underpinning the transformation of 360° images into VR models.
- **Model measurability:** This feature is supported by default in the textured-mesh and NURBS-based models in that they are made of 3D elements retaining the real mutual geometric relation. Conversely, measuring features are not available in VR environments by default. However, this limitation can be partially overcome by leveraging hotspots that link .obj files, which can be opened in external software equipped with measurement tools. Therefore, while native measurability is limited in VR environments, this feature can still be achieved across all three model types through appropriate workarounds.
- **As-built elements uniqueness reproduction:** The textured-mesh model, as it came directly from the PC of the asset in its current configuration, faithfully reproduces the unique characteristics and specificities of the structure. NURBS-based models can include as-built features, i.e., using Scan-To-BIM procedures for automated model generation. However, in the manually built NURBS-based model of the Baptistery, specific as-built characteristics useful for qualitative analysis and diagnostics, such as geometric deviations or irregularities, were not included in the modeled elements. This was a deliberate choice to maintain a simplified geometric representation, with external information—such as structural issues—linked to the

H-BIM model instead of being directly incorporated into the geometry. For the VR environment, the reproduction of as-built uniqueness is limited to visual aspects. It can only capture specificities from a visual perspective, primarily focusing on textures, colors, and surface appearance through photorealistic rendering. Structural irregularities, such as vertical misalignments or uneven horizontal elements, are not detectable in the VR model unless linked as external textual data via hotspots. Therefore, while the VR environment offers a high degree of visual fidelity, it does not inherently account for geometric uniqueness without additional annotations.

- **Surface textures reproduction:** The textured-mesh model allowed the reproduction of surface textures with a high degree of realism, permitting the detection of different materials. However, this capability is generally associated with heavy files, as in the case at hand, which prevents this type of model from being the optimal solution to visualize real textures. On the other hand, the NURBS-based model is a purely geometric 3D representation of elements constituting the construction and has no pretense to represent textures. Its focus is on geometry rather than the materiality of the asset. Nevertheless, there exists the possibility of projecting real texture meshes on NURBS-based geometries, but it is a viable solution only for regular straight vertical elements or horizontal diaphragms and, as a rule, elements whose NURBS-based geometry closely matches the actual shape. In such cases, the correspondence between the two tends to hinder projection issues from occurring. However, achieving perfect consistency between textures and geometries is generally challenging for all elements in a historical building. However, complex geometries, such as vaults, ornaments, or statues, are often difficult to accurately replicate, leading to mismatches when projecting real texture meshes (which may originate directly from a PC) onto simplified model geometries. Additionally, the addition of textures in the NURBS-based model increases the file size, thus leading to lose the advantage of it being relatively light in comparison to the textured-mesh model. Therefore, other solutions not implying consistency issues might appear more competitive in reproducing realistic textures with fairly light files. In this sense, the VR environment has the highest level of texture realism among the three types of models addressed, by supporting a picture-like visualization of surfaces. Although the level of surface detail depends on the image quality, with modern 360° cameras, it is such as allowing the detection of small details, such as cracks, or different stone processing—key indicators of different restoration periods or the age of construction elements. Consequently, VR environments might be considered powerful tools for the structural diagnosis of historical buildings, especially in light of the recent advancement in acquisition digital techniques and their well-priced availability underpinning the obtainment of 360° photographs to build such environments.
- **Model navigation easiness:** This is closely tied to the file size, which is, in turn, connected to the detail level of the reproduced elements. Due to the differing characteristics of the digital models analyzed, it is challenging to directly compare their navigability at equivalent levels of detail. Thus, the navigability was evaluated according to each model's aim. The textured-mesh model, while offering a high level of detail useful for assessing the geometry and morphology of construction elements, as well as identifying different materials, poses significant challenges in navigation. However, the model navigation is unfeasible due to the great computational capacity and response time required to change views when orbiting. Mesh quality could be reduced, but it would compromise the model's ability to distinguish between different materials—one of its primary purposes. In contrast, the NURBS-based model guaranteed good navigability while satisfying the objective of easily moving around within the model to understand the articulation of the construction. This balance between navigability and functionality makes the NURBS-based model more user-friendly for exploration. The VR environment, designed to support virtual tours through spherical views, effectively ensured optimal fast navigation even from tablets

or smartphones, thus resulting in being the model with the easiest navigation among the three considered.

- **Visual inspection assistance:** Neither the textured-mesh nor the NURBS-based models can be employed during in situ inspections, since they require at least the acquisition and elaboration of a PC for their generation. At any rate, both models can be used for remote inspections. In particular, the textured-mesh model can be navigated to investigate specific issues mainly related to textures, such as identifying different stone processing. In contrast, the NURBS-based model can be profitably utilized to better comprehend relations among different parts of the construction, which may not be immediately fully understood during in situ inspections. The VR model is the most versatile representation, which can be effectively employed both during on-site and off-site inspections even for areas that are difficult to access. During on-site inspections, 360° images can be captured and edited in real-time to highlight important details. Modified images can be directly converted into a VR environment, or indirectly linked to a virtual model made of not edited photographs through customized hotspots, an approach adopted for the Baptistery. Additionally, VR environments can come in handy for off-site inspections by capturing small details in hardly reachable areas that go often unnoticed at a first inspection. Notably, the computational burden required to generate the VR environment of the Baptistery, which is a complex historical construction with many interconnected elements, was not particularly high. Therefore, the creation of models like this could be performed almost simultaneously with the image acquisition, just by employing software for 3D virtual tour generation to position hotspots in correspondence to points from when photographs are taken.
- **Three-dimensional visualization:** While textured-mesh and NURBS-based models allowed a real 3D exploration of elements, the VR environment did not. At any rate, this limitation was overcome by employing suitable hotspots allowing us to embed 3D elements in the VR model to be visualized in different environments (Figure 9).

Table 2 summarizes the comparison elements between the three types of digital models created to represent the Baptistery of Pisa. A check mark indicates that the model fully possesses a particular characteristic, while a cross mark signifies that the model lacks that feature and cannot acquire it. The check mark along with a cross mark means that the model partially retains the given characteristic. A cross mark with a plus sign suggests that the model does not have such an attribute by default, but the limitation can be overcome.

Table 2. Strengths and limitations of the first-level digital models of the Baptistery.

	Textured-Mesh Model	NURBS-Based Model	Virtual Reality Environment
Ease of model creation	✓/✗	✗ ⁺	✓
Output control	✓	✓	✗
Model measurability	✓	✓	✗ ⁺
As-built elements uniqueness reproduction	✓	✗ ⁺	✗ ⁺
Surface textures reproduction	✓	✗ ⁺	✓
Model navigation easiness	✓/✗	✓	✓
Visual inspections assistance	✓/✗	✓/✗	✓
Three-dimensional visualization	✓	✓	✗ ⁺

✓: the model fully has the characteristic indicated; ✗: the model lacks the characteristic indicated; ✓/✗: the model does not have the characteristic indicated by default, but the limitation can be overcome.

On the whole, it can be noted that each model has specific peculiarities that make it more or less suitable for specific aspects of structural diagnosis. However, there is no single model that can be deemed the best choice for supporting the structural assessment of historical buildings; therefore, integrating these models is the most recommended approach. Indeed, by balancing strengths and weaknesses, every model resulted in being more suitable for different aims. The textured-mesh model allows the identification of different construction materials and textures, and the three-dimensional perception of the monument and comprehension of the structural systems, resulting in a file of around 500 MB. Conversely, the NURBS-based model is instrumental in understanding the structural functioning of the monument. The use of simplified, manually generated NURBS-based 3D elements necessitates a thoughtful consideration of the interactions between different structural components prior to modeling, encouraging the modeler to reflect on their structural purposes. Additionally, the NURBS-based model is significantly lighter, approximately 140 MB, making it easier to navigate, even though it does not incorporate texture information. In contrast, the VR environment is functional to interactively explore and experience the internal spaces of the Baptistery in a fully immersive, three-dimensional, and easy way, also in view of its lightness (the .vtp file on 3D Virtual Tour is only 77 kB).

By leveraging the strengths of each model, a comprehensive understanding of the Baptistery can be achieved, enhancing the structural diagnosis and preservation efforts.

4.2. Second-Level Model

The lessons learned from the strengths and weaknesses of the analyzed first-level models were instrumental in realizing an H-BIM model.

In this work, the H-BIM *Property Settings* were specifically designed for the Baptistery: it is a very comprehensive case study with several different data types to consider that required and allowed the definition of a wide range of object types and properties constituting a good grounding from which the study of different monumental structures can actually also benefit. In this sense, delineating *Property Settings* capable of systematically organizing data can contribute to overcoming the limit to the use of BIM models for existing structures highlighted in the literature, which is mainly due to the low efficiency in employing H-BIM models lacking comprehensive sets of properties general enough to be used as a starting point for different assets. To make the rationale behind the definition of new *Object groups* and *Properties* transparent to be easily reused for other cases, it is worth clarifying specific examples. For instance, *Symbols materializing measuring points* were created to provide a comprehensive overview of the monitoring system. The associated properties were designed to be general enough to accommodate additional measuring instruments, which can be represented following the same logic adopted for existing ones (by adding small solid geometries to the Archicad model). In particular, the logic of *Symbols materializing measuring points* is well suited for the cases in which monitoring measurements are at multiple points spread around in the structure and all belong to the same (monitoring) network. In such cases, data interpretation to obtain a comprehensive view of structural behavior can be enhanced by visualizing measuring points in their current locations within the overall structure and the broader measurement network to which they belong.

However, in some cases, attaching data about tests directly to the relevant element is more practical. This is exemplified by the *Foundations*, where data on georadar surveys, tomographies, core drillings, etc. is archived in the *Test data* group, without adding specific objects (*Symbols materializing measuring points*). This method is considered optimal when tests do not belong to a measurement network, allowing results to be more effectively allocated to specific property entries of the virtual replica of the corresponding physical object.

A similar rationale applies to the modeling of specific 3D elements to represent cracks rather than incorporating them as properties of the surfaces (e.g., walls, vaults, etc.) on

which they are located. Other than enabling directly visualizing their distribution in space, physically modeling them provides easier access to specific details such as length, width, first detection time, etc., as these attributes are directly attached to the object of interest. With a 3D object materializing a specific damage, it is also easier to identify the monitoring system potentially installed to evaluate its development over time and access monitoring data by creating a direct link between the object (i.e., *Cracks*) and monitoring data through an ad hoc entry. In the present work, this connection was achieved by creating the *General monitoring system (network) ID*, appearing as a property of both *Cracks* and *Symbols materializing measuring points* (Figures 11 and 13).

Considering that cracks are just one of the many different damage types that can threaten the stability of historical structures, the rationale for data storage applied to cracks can also be extended to other types of damage, such as degraded surfaces. In such cases, thin solids with the shape of the real degraded areas could be easily created and connected to their relative properties, similarly to *Cracks*, as shown in [2].

In addition, the definition of specific *Property Settings* was useful to overcome some limitations belonging to the analyzed first-level models. For example, the insertion of the *Three-dimensional representation* entry for the *Generic H-BIM object* provided an effective solution for visualizing the 3D textured geometry of specific elements without the need to manage the overly large files typically associated with complete textured-mesh models. Indeed, one of the main limitations of this type of model was found to be its reduced navigability, often due to the large file sizes required for high-quality meshes. However, this issue was overcome by externally embedding separate parts of the textured-mesh model, allowing for smoother navigation while still preserving detailed visualization where needed.

What is more, the integration of VR representations within the H-BIM model, linked through the *Photorealistic representation* property of the *Generic H-BIM object*, adds to elements their photorealistic textures, while guaranteeing a full 3D perception of the NURBS-based elements. The as-built 3D geometry of portions of the textured-mesh model complemented with the VR views provide a comprehensive perception of the asset, equaling the experience of on-site visual inspections. The logic of creating an integrated system of digital models linked to the main H-BIM model through adequate connections enables different visualizations of the same asset with various levels of detail and diverse information.

Further, embedding in the H-BIM model external links to additional models other than the textured-mesh one and the VR environment, or to platforms, could be contemplated to improve data merging for 3D digitization of CH assets. Not only could it be seen as a viable strategy to overcome compatibility issues often reported in the literature when merging data from different representations within the same model, it could also foster data integration and exchange, thus collaboration among experts in different fields. The latter is crucial, as each professional brings unique expertise and priorities in preserving different aspects of the structure.

The customization of *Property Settings* defined in this work goes in such a direction: it aims to foster interaction among experts with different skills, enabling each to focus on the strategies more suitable to preserve a specific value or requirement (i.e., structural safety) without compromising others. For this reason, the H-BIM model was designed to include entries facilitating the connection among groups of properties focused on different aspects, which can also be further implemented with the involvement of new technicians. For example, the *Valuable surfaces* entry owned by a *Generic H-BIM object* highlights the importance of a multidisciplinary conservation, alerting structural engineers to the potential existence of other values (artistic, historical, archaeological, etc.), which might be neglected otherwise. In particular, the inclusion of information from the archaeological domain within the H-BIM properties, as proposed here (Table 1), offered an interesting perspective for a thorough diagnosis of CH constructions by providing further insight into history-related aspects often capable of explaining the causes of the current crack and deformation patterns.

Moreover, with reference to the difficulty of filtering information when large amount of data are available, the *Graphic Override Combinations* here employed are a handy workaround to visualize different levels of information relevant to a specific element or groups of elements, once a subdivision of the construction into different components commensurate with its complexity is defined. In particular, a significant advantage of *Graphic Override Combinations* is that they do not require splitting the model into small portions, potentially until creating different BIM elements for every stone ashlar, which would be unsustainable. At the same time, they do not even require considering more elements grouped (i.e., arches along with vaults and pillars), which would be impractical in case different materials are to be attributed as separate information to joint elements (Figure 16). As a result, the obtained H-BIM model serves as a well-organized database to be progressively updated as further data becomes available and new experts engage in the conservation of CH structures, thus facilitating a continuous improvement in knowledge from various perspectives.

H-BIM models with the mentioned features can be considered powerful tools for a first qualitative interpretation of the structural functioning of complex historical constructions thanks to the inner capacity of such models to store many different data types in a well-organized way, and filtering information, as needed. Moreover, H-BIM models can make manifold contributions to realizing computational models. First, they assist in selecting the most suitable numerical models by highlighting available data (e.g., material properties, wall and soil stratigraphy), as different constitutive laws need different mechanical characteristics as input parameters. In addition, BIM models can constitute a geometric basis for numerical models: through some Scan-to-BIM-to-FEM procedure [42], the first can be turned into finite element models, exported into a suitable format, and imported into some structural software with mechanical properties directly attached to the diverse elements [43]. However, these workflows still require streamlining, as manual geometric simplifications and corrections for complex geometries are often necessary [44]. Finally, H-BIM models facilitate a deeper understanding of the asset by integrating multidisciplinary information, which enables more informed hypotheses about potential causes of specific conditions, such as crack and deformation patterns. These hypotheses can then be effectively tested against reality and refined through numerical models, supporting improved structural diagnostics of the asset [45].

For different historical assets, the approach used in this work—with textured-mesh and NURBS-based models, as well as the VR environment linked directly to H-BIM model properties to make up part of its information level—can still be applied. Adaptations may be required based on specific needs influencing each model's relevance in creating the H-BIM. For small and compact buildings, such as standalone chapels, linking the entire textured mesh of the asset could be feasible, and useful to gain a 3D view of surface textures, which is especially valuable if there are extensive frescoed surfaces. Conversely, for more extensive CH complexes, like groups of buildings together forming a culturally significant scene (such as a square or historic street), multiple VR environments (tours) might be preferable over full textured-mesh models, which could be reserved for specific elements to keep the H-BIM model manageable.

5. Conclusions

This paper proposes an approach to accommodate various 3D digital models within the H-BIM paradigm to ease the combination of multiple, cross-disciplinary information. Such an integrated system of 3D representations is applied to study the Baptistery of Pisa by gathering data from many years of past studies and investigations on its behavior, to improve its structural diagnosis so far limited by the lack of a general overview of the asset. First, the strengths and weaknesses of the textured-mesh and NURBS-based models, as well as VR environments, are evaluated considering some chosen comparison criteria. Secondly, the H-BIM paradigm is employed to fruitfully combine such models. Several object types and properties are defined to archive information useful for the main focus of

structural diagnosis methodically. Nevertheless, they can easily be implemented to accommodate different expertise and data related to non-structural aspects, for the all-around conservation of CH assets respecting their structural integrity without compromising other values and vice versa.

In the present case, integrating multiple data types in a well-structured way by defining appropriate property settings, including links to other models, has proven effective in enhancing the understanding of the structural functioning of the construction, thereby providing a comprehensive view useful for a first comprehension of the structural functioning of the asset, and for guiding the subsequent computational models to realize and analysis to perform. The presented integrated system of digital models fosters the traditional capabilities of H-BIM models by integrating multiple representations capable of providing information with different levels of detail from that of the H-BIM model. Furthermore, the creation of the comprehensive sets of objects and properties here defined can also serve as a starting point for the conservation of other historical constructions, thus improving the usability and effectiveness of H-BIM models in the field of cultural heritage. This is a step forward with respect to the limited efficiency of H-BIM often affected by difficulties in reusing existing properties and objects, when not general enough, as highlighted in the literature. However, other than the mentioned opportunities, the integration of digital models of a different nature also presents some challenges related to the combination of various types of data, structures, and methodologies. As a challenge ahead, priority should be given to the creation of collaborative platforms, standardized approaches, and protocols facilitating interoperability and seamless data exchange among diverse professionals. Additionally, creating repositories for sharing parametric scripts (e.g., Grasshopper) with well-organized collections of predefined components and properties across disciplines—such as history, architecture, engineering, and conservation—would significantly enhance H-BIM usability. These repositories could provide accessible, tailored resources for conservation and management projects, supporting professionals and researchers in assessing the condition of historical assets within a multidisciplinary context in which a variety of different values are to be contemplated.

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Abbreviations

The following abbreviations are used in this manuscript:

BIM	Building Information Modeling
CH	Cultural heritage
GIS	Geographical Information System
H-BIM	Heritage Building Information Modeling
IoT	Internet of Things

PC	Point Cloud
SHM	Structural Health Monitoring
TLS	Terrestrial Laser Scanner
VR	Virtual Reality
XR	Extended Reality

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