SCAN to HBIM-Post Earthquake Preservation: Informative Model as Sentinel at the Crossroads of Present, Past, and Future

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Abstract. In the last years it has been progressively invested many efforts in the cultural heritage digitization: surveying, modeling activities, diagnostic analysis and historic data collection of architectural heritage. Such actions have been mainly acquired for the preservation process, during the restoration and construction site. Unfortunately, many of them are left abandoned in a latent status without any connection with the long life cycle of the historic architectures or connection to the dissemination. The paper presents the case of an informative model for the Basilica di Collemaggio generated on high resolution surveying (laser scanning, photogrammetric point clouds and IRT Infrared Thermography) to manage the knowledge acquired on the geometry and the collected information on materials, construction technology and decay analysis for the design and conservation after the earthquake occurred at L'Aquila. The paper illustrates the HBIM (Heritage Building Information Model) achieved to support the restoration process funded by EniServizi within the project 'Restart from Collemaggio'. It is described the generative modelling process implemented to embody the complexity and specificity of the morphology related to the collected information on the state of the art, the sum of the current damages and transformations during the centuries, for the preservation plan of the monument. Many damaged structures as in the case of the north wall with the Holy Door and of the arched naves with the ancient pillars have been restored preserving the maximum level of authenticity of the materials and construction techniques. The HBIM of the Basilica, re-opened to the public on December 2017, is ready to a sentinel role among past present and future.

Keywords: HBIM · Informative models · Preservation · Generative modelling Authenticity · Conservation plan · Materials · Open access · NURBS DB · LOD · LOG · LOA · LOI

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1 Introduction

EniServizi (the Italian multi-national energy agency operating in many countries), after the earthquake that occurred at L'Aquila in April 2009, in December 2012 funded - with around 14 million euro - the project 'Ricominciare da Collemaggio' ('Restart from Collemaggio') to restore the Basilica di Collemaggio. On April 6th, 2009 at 3:32 a.m. an Earthquake (Richter Magnitude 5.9) struck L'Aquila (Central Italy). More than 10 billion euro of estimated damage, about 100 churches uninhabitable for the major collapses, along with thousands of historic buildings in the old town and surrounding hamlets. Among them, the Basilica di Collemaggio was significantly stricken (Fig. 1): the dome, the transept and triumphal arches collapsed with their pillars, and great damage occurred to the apses, to the pillars of the arched walls of the nave, and to the longitudinal north front with the 'Holy Door' [1]. EniServizi required an advanced HBIM based on "SCANtoBIM" process to address decision-making processes among the different actors involved in the preservation process, conscious of the potential role in the complex building and infrastructure.

The Basilica di Collemaggio is a famous medieval Romanesque masterpiece characterized by a dense history dating back on 1275-87 with many stratified interventions across the centuries. The project 'Restarting from Collemaggio'[1] has been undertaken and funded by EniServizi with the aim of giving new hope to the L'Aquila community: the project of restoration and preservation has been carried out together with the Superintendence Office of L'Aquila and a large scientific team of universities. The HBIM [2] has been carried on by integrating the laser scanning[2] [3] with the hands-on survey of the pillar ashlar[3] [4] and the support of the historical research[4]. The diagnostic phase with the material, construction technology and decay analysis has been carried on by the Conservation Plan[5]. The Basilica of Collemaggio has been re-opened to the public on December 2017 after the restoration undertaken between 2015-2017.

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1 The Superintendence Office carried on the restoration project with the scientific support of the Università degli Studi de L'Aquila, the Università La Sapienza di Roma, under the coordination of the Politecnico di Milano (Scientific Responsible Prof. Stefano Della Torre).

2 The geometric surveying, HBIM and LOG/GOG contribution has been carried out by the Politecnico di Milano (Prof. R. Brumana) - Geomatics surveying research team (L. Barazzetti, F. Roncoroni, M. Previtali, B. Cuca), HBIM (F. Banfi) - ABClab GIcarus http://www.gicarus.polimi.it.

3 The pillar ashlars surveying, interpretation and HBIM data integration, plan and section interpretation, has been carried out by Daniela Oreni (Politecnico di Milano), feeding the LOG F and G proposal.

4 The historical research by the team of the Università La Sapienza Roma (Prof. G. Carbonara). The structural analysis under Polimi and the Università degli Studi de L'Aquila.

5 The analysis of materials, decay and construction technologies for the Conservation Plan have been carried on by Lorenzo Cantini (Polimi) feeding the HBIM LOI, LOG F&G.

Fig. 1. The area stricken by the earthquake at L'Aquila and the Basilica di Collemaggio.

2 HBIM from Surveying: Geometries as Sentinels of the Past Transformation and Current Assets After the Earthquake

The surveys of the Basilica, started on February 2013, have been addressed to document the geometric and morphologic state of the art of the whole complex and its components (external walls, internal arched walls and the pillars, vaulted systems, trusses, wooden secondary order of the roof), as a result of the earthquake damages and transformation occurred across the centuries, enlargements, restorations, including the ones carried out after the past earthquakes. The objective of the survey was: (i) to support informed decision making devoted to guarantee the maximum level of material preservation, the structural functionality of the single elements and of the dynamic relations among themselves; (ii) to support a cooperative multi-disciplinary interaction through reliable geometric information, punctually surveyed, and geospatially correlated, with an high Level of Accuracy (LOA) comparable to a 1:20 scale. The geodetic network allowed to obtain a robust co-registration of the laser scanning point clouds integrated by the photogrammetric image blocks acquired along the surfaces, including the UAV RGB & IRT flight. The result is a rigorous reading of the out of plumbs starting from the external and internal sections, the different thickness of the vertical walls (Fig. 2).

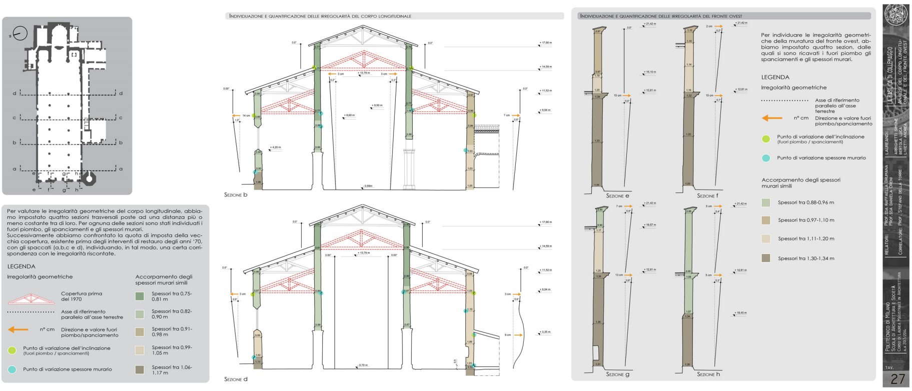

Fig. 2. The vertical sections of the Basilica highlighting the complex geometry of the damaged walls, punctually represented with the different out of plumbs and thickness ranges.

This approach represented the ‘guide line’ followed in the restitution phases, with a rich description of the anomalies and irregularities detecting the shapes of each object, the superimposition of the plans at the different levels evidencing the fragile structures standing on empty zones of the crypt in corresponding of the cracked apses. The surveying geometries can be considered as sentinels of the past transformation and current assets after the earthquake, of the history enriched by precious physical traces that can be at the disposal of the different actors to improve the comprehension for the present and future intervention and uses.

3 Conservation Plan: The Classification of the Traces of Masonry Structures and Construction Technologies

Given the main aim, which was to preserve the maximum level of material authenticity, functional behavior and construction techniques, HBIM generation of the Basilica needed to take into account the whole complex monument with all the structural components relating one to the others. The Conservation Plan has been developed to answer to the following issues: (i) an architectural design project supporting a decision-making process devoted to preservation aims, (ii) the management of critical issues regarding the preservation of authenticity of materials and construction techniques, and (iii) to guarantee safety in case of other earthquakes more severe with respect to the last occurred, at least equal to it. The classification of the traces of masonry structures, construction technologies, and the related decay analysis, are crucial for the design proposal [5]. The Basilica conserved several interventions characterizing its masonry structures, realized with a technological system based on roughly shaped stone blocks, revealing both minor and also profound changing during the long history of the building. All the traces of the repairing techniques applied to the damaged walls, performed on occasion of the frequent seismic events occurred to the church, are visible on its lateral elevations. The north façade shows different masonry textures, presenting a palimpsest of the main phases of construction, repair interventions and integrations experienced by the building. The role of the conservation plan was set for studying and classify these traces, with the aim to structure a parametric database, collecting information on the materials, their characteristics and their state of conservation, integrated with the advanced survey, particularly orthophotos. The model obtained by the application of BIM technology had to support the contributions developed through the conservation plan. From an operative point of view, the integration of the various analysis developed by the conservation plan started from a high level of knowledge produced by previous studies on the dynamic behavior of the Basilica [6] considering both historical information and the results of experimental campaigns. The challenge was to adapt BIM tools, which are designed for existing buildings [7] toward Built Heritage Conservation deploying shaping tools [8]: the goal is to obtain HBIM combining the complexity of the geometrical shape, the design purposes and preservation aims.

3.1 The Holy Door and the North Wall: The Database and the Materials Analysis Integrated to the HBIM

The damaged north wall with the Holy Door represents an important symbol to be preserved for the future. The analysis and the intervention aimed to guarantee its preservation. The Basilica attracts about 30,000 people for the Forgiveness Feast Day (Festa della Perdonanza) on 28-29th August (Fig. 3) established every year by the Pope Celestino V (before the Jubilee - 'Giubileum' - set up by Pope Bonifacio VIII nowadays recurring in the world every 25 years). The Feast is celebrated with the procession ceremony transferring the original Bull from the Municipality to the Holy Door of the Basilica. The result is an extraordinary mix of tangible and intangible values; the design and the intervention intended to preserve and transfer them to the future.

Fig. 3. The opening of the Holy Door during the Forgiveness Feast procession: the provisional structure to put in safety people during the restoration (August 2017).

The metric surveying highlighted the geometry of external walls and arched internal wall. The punctual out of plumbs and profiles have been extracted from the scans. The detailed categorization of each masonry texture constituted the base for recognizing the values collected on this part of the church. The stratifications of different masonry textures, visible on the north wall, testify the changings and the new additions occurred to the building during the time. If the traces of closed large windows are clearly recognizable, a precise representation of the various masonry typologies was realized on the 3D orthophotos thanks to the level of details (pixel resolution 1 mm) with the materials analysis, decays mapping and the intervention subdivided into specific actions (cleaning, sealing and protection phases). To this aim a database containing all the masonry textures classified, with an ID code, a short description, their dating, the material components, dimensions and main proportions, the surface finishing, the picture documentation and the masonry layout was structured (Fig. 4). The geometrical mapping of the Basilica has been integrated together with the DB within the HBIM (Fig. 5). The material decays and the analysis of the crack pattern of the north façade supported the further research on the correct interventions. The advanced survey provided important results for peculiar aspects, like the analysis of the out of plumb of the masonry walls, which are considered another important index of the vulnerability in seismic conditions.

The positive response offered by the masonry structures to the seismic actions indicated that the modifications occurred to the church during the time, after other earthquakes, gave origin to a reliable structural system, able to face the dynamic deformations imposed by the ground acceleration. According to this statement, supported by further evaluations of the dynamic behaviour of the building realized by integrating the 3D model with qualitative and quantitative results obtained by various analysis, the conservative intervention for the north façade and the Holy door was organized. The lack of connection between the decorative elements and the load bearing walls was reinforced by limited interventions (like the introduction of metal connectors) and the vulnerability between some parts repaired in the past was corrected by implementing the monolithic behaviour of the entire walls through local injections and metal bars strengthening.

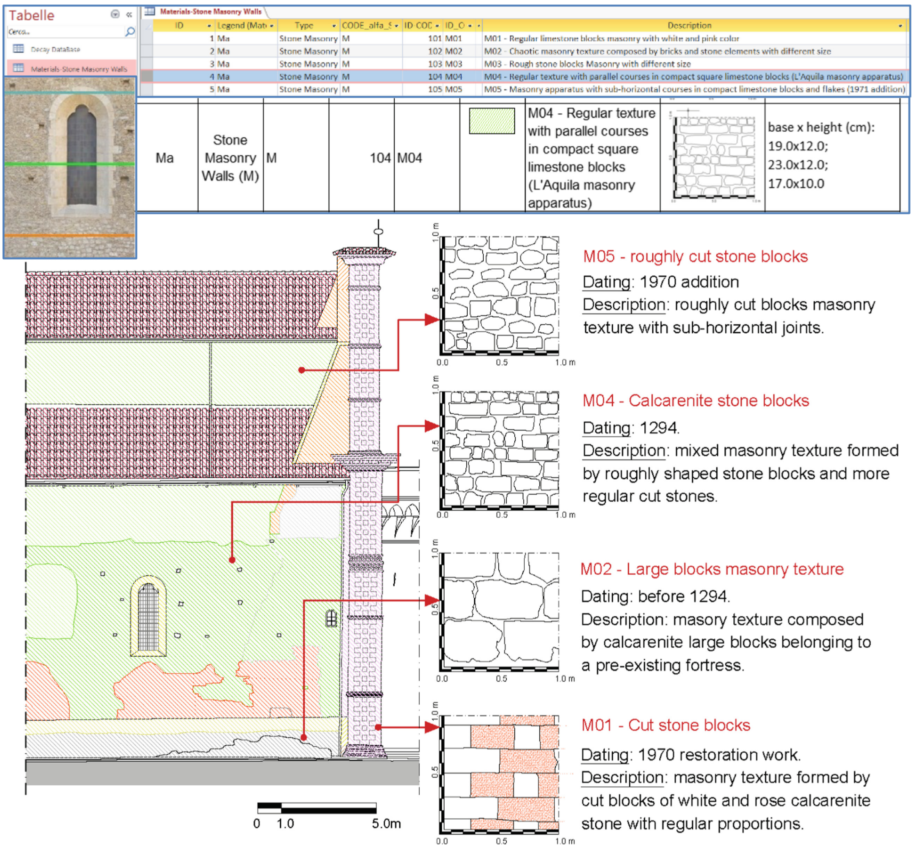

Fig. 4. The database of the materials: a portion of the north façade, with the material mapping drawing obtained on the 3D orthophoto, and the detailed description of some masonry textures according to the historical analysis of the building.

4 HBIM Generative Modelling: LOD (LOG + LOI) for Preservation Purposes

It is nowadays recognized by different researches carried out in the last years that BIM can take a rule in a holistic organization of models and information, needing to define a framework for the HBIM, considering the 'specific' case of documentation of architectural heritage [9] and its preservation [4]. BIM adoption required to be turned to the preservation aims, with a deeper level of knowledge since the starting phase of the design [8], restoration and management process, developing a coherent level of accuracy model matching the complexity [2] of the architectural heritage. The concept of the Level of Development (LOD) has been applied to the BIM management in the case of new construction, thus based on a linear process progressively enriching both the model and the information across the different phases (AIA, AEC, NBS): LOD100 (conceptual a-dimensional model), LOD 300 (three-dimensional model in the design phases), LOD350-400 (the model implemented for the construction site), LOD500 (the as-built updating, thus oriented to manage all the information useful for the maintenance process of the building in the time, including the layers stratigraphy). Such linear approach cannot be automatically applied to the restoration-preservation-management process: it risks to delay the knowledge of the geometry, the state of the art and behavior of the structures with high cost increasing during the process due to unexpected framework; also, lack of information limits the possibility to undertaking design solutions coherent with the state of the art, and the preservation actions.

The Level of Geometry (LOG) and the Level of Information (LOI) – part of the LOD concept (UNI 11337-4/2016)- have been further defined in the HBIM specification criteria in order to match the preservation aims. The research undertaken developed a mixed and reverse LOD approach [10], based on the accurate 3D surveys [3] feeding the HBIM since the first architectural design phases (Fig. 5). In particular, a high resolution Level of Geometry model was generated and enriched by 3D arrangement texturing and by the information on the stratigraphic layers (materials, decay, chronological phasing). The concept of GOGs (Grade of Generation) [10] protocols have been introduced to describe different modelling requirements (Level of Geometry), in function of the geometry detected by the scans. Mainly, for the damaged walls, pillars and vaults, a NURBS based GOG 9 (edge border detection and internal dense slicing from the cloud) and GOG 10 (edge border and point clouds) has been generated for each element, gaining a morphological accuracy of the model (Level of Accuracy - LOA of the model) coherent with the surveying LOA. Hereafter a summary of the HBIM phases (Fig. 5) in the generative modeling workflow:

- Phase 1: Geometric primitives determination.
- Phase 2: Level of Geometry (LOG) – GOG 1-8 vs. GOG 9-10. The analysis of the geometrical irregularities detected by the survey lead to the selection of the proper GOG. For example, vertical walls with a standard deviation respect to the planarity check $\geq$ 25 mm (the tolerance of the survey), or out of plumb $\geq$ 25 mm; and pillars, vault elements or others component with a standard deviation respect to the generative conceptual solids $\geq$ 20 mm, needs GOG 9-10 and NURBS based

objects modelling. GOG 1-8 have been adopted for a standard deviation of the clouds respect to the conceptual solids < 2.0÷2.5 cm.

- Phase 3: Automatic Verification System (AVS). The verification of the accuracy of the modelled object concerning the point cloud. With NURBS modelling a final standard deviation concerning the cloud points $\leq$ 2 mm was achieved
- Phase 4: BIM parameterization of the NURBS model and Database (DB) generation integrating the LOI gained by the material and decay analysis.

The HBIM obtained is the sum of each element (Fig. 5) modelled in function of its geometry. It is interoperable with the construction site management (CO.SI.M), with the finite element analysis (BIM-to-FEA) [11], Design Tools, and Conservation Plan purposes, thus contributing lowering the impact cost of the HBIM generation (Fig. 6).

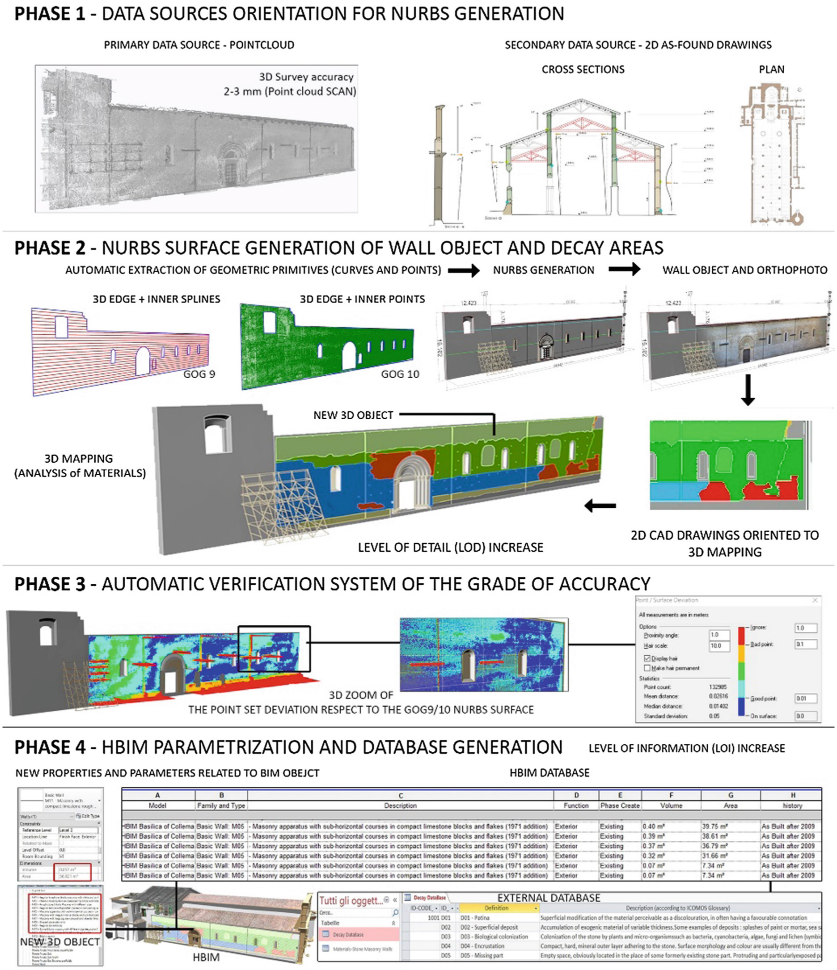

Fig. 5. SCANtoBIM phases: (the north wall). The HBIM model (GOGs 9-10) and DB.

5 The Preservation of the Damaged Pillars of the Arched Nave

The main damages observed on the building were concentrated on the pillars of the naves and the walls of the apses. The transept, completely collapsed, conserved only a portion of the lateral walls with their Baroque style altars. The philosophy of the intervention was based on this main assumption: conservation could be applied to the survived damaged structures, whereas the no-more existing transept had to be integrated by the realization of the missing volumes of the building. The juxtaposition of new architectural bodies to existing ones is always a controverted issue, involving discussion on the preservation of the authenticity of a historic building and its safety response.

The introduction of an integration for connecting the naves body of the Basilica with the apse was used here as a strategic design for providing a new resistant element, able to reinforce the global dynamic behavior of the building to seismic actions. This sort of strong backdrop is realized by a contemporary reinforced concrete technology and shaped according to the geometrical information collected by the historical analysis. The analysis applied to the pillars consisted in a first classification of the materials, distinguished in structural blocks and integrations added during the last restoration designed by Mario Moretti in the second half of the previous century. The analysis of

WALL	INTERNAL SPACE VOLUME m³	WALL VOLUME m³	GROSS FLOOR AREA m²	TIME REQUIRED BIM GENERATION BY GOG 2013 (GOG 9-GOI 1-2) & 2017 (GOG 10-GOI 1-2) (Hours - h)	TIME REQUIRED BIM GENERATION BY TRADITIONAL PROCESS (GOG 9) (Hours- h)	LEVEL OF DETAIL (LOD)	REF. HBIM OBJECTS
MAIN FACADE	/	1274	/	30h, 2013 & 15h, 2017	35-40	300	
TOWER	929	190	LEV.01+02=140	6h, 2013 & 2h ,2017	10-12	300	
NORTH WALL	/	1141	/	20h, 2013 & 3h ,2017	30-35	500	
SOUTH WALL	/	941	/	8h, 2013 & 3h ,2017	12-15	500	
INTERNAL NORTH WALL ARCHES	/	537	/	20h, 2013 & 3h ,2017	12-15	500	
INTERNAL SOUTH WALL ARCHES	/	460	/	15h, 2013 & 6h ,2017	20-25	500	
BELL TOWER	437	180	LEV.01+02=25	20h, 2013 & 15h ,2017	25-30	400	
APSE WALLS	11491	1790	LEV.01=823	60h, 2013 & 25h ,2017	70-80	500	
APSE VAULTS	/	160-190	/	50h, 2013 & 20h ,2017	60-70	500	
CRYPT	977	250	LEV.00=336 LEV.01=280	60h, 2013 & 20h ,2017	50-60	400	
ROOF	36987	7244	LEV.01=2194	120h, 2013 & 50h ,2017	130-140	500	
TOT.	51 000~	14 000 ~	3798 ~	409h~, 2013 162h~ ,2017	522~		

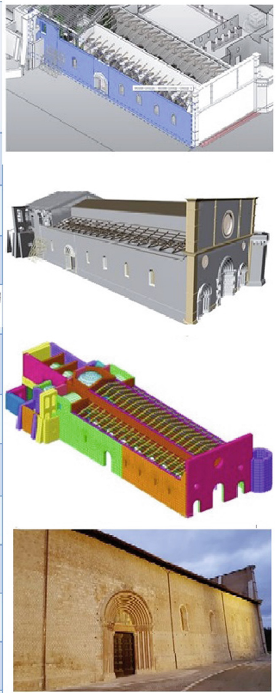

Fig. 6. The HBIM NURBS based model objects (volumes and hours effort). On the right, the case of restored north wall with the BIM to FEA (Finite Element Analysis).

the diffused crack pattern characterizing the pillars received fundamental support by the detailed analysis of the out of plumb of each structure, combined with the manual measurements of each stone component that allows recognizing the masonry section characteristics. This approach drove to an in-depth knowledge of the real extension of the damage of each pillar and drove to the final decision: conservation with local repairing interventions for almost all the pillars and reconstruction limited to two pillars, due to their damage condition. Unfortunately, it was not possible to analyze the inner core of the pillars directly, due to the reduced safety of the structure. The ultrasonic investigation had been performed in a first phase, but these tests did not give a significant response on the nature of the inner core, because of the diffused cracks influencing the velocity of the signals and its distribution maps in the plane sections. Thanks to an hands-on survey of all the pillar ashlars it was hypothesized an average of 35% of damaged ashlars (yellow) to be necessarily substituted during the intervention, in the consciousness that this percentage would undoubtedly increase during the works (Fig. 7). The analysis of the compressive strengths required a careful choice of the new stones. The hypothesis was to substitute damaged ashlars with new ones, with the same external shape and dimensions but prolonged to replace all the angle of the central core, there-fore strengthening the section anyway. The HBIM LOD500 obtained embodies out of plumbs, geometry with the 3D ashlars elements (Fig. 7). The careful survey aimed at enabling the control of local repair works, avoiding or minimizing the total dismantle of pillars. In the design step the decision, based on the lack of confidence on the quality of the inner core, was to disassemble only the most damaged pillars, also exposed to the highest actions in case of an earthquake.

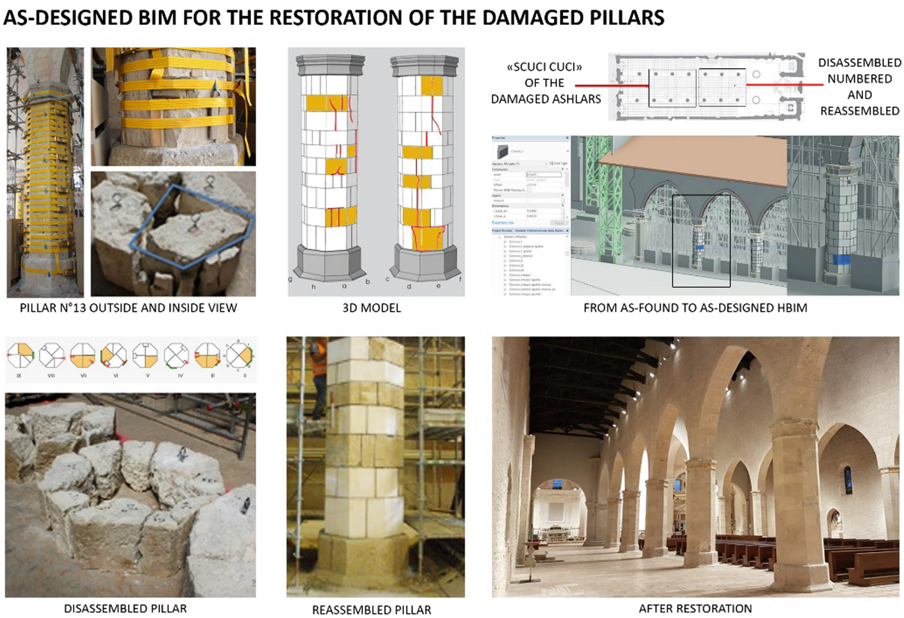

Fig. 7. The hypothesized HBIM design and the restoration of the most damaged pillars. (Color figure online)

6 HBIM for ALL: AS-FOUND to aS-BUILT, and Beyond

The detailed surveying of the plan of the Basilica highlighted different alignments within the Basilica (Fig. 8), particularly among the portion represented by the apse and the crashed domes with the first pillars and the part of the naves with the 12 pillars. The historical research report carried out [12] together with the geometric analysis contributed to reconstruct the different transformation occurred in the different chronological phases. Such analysis have been taken into account in the various design solutions for the HBIM design simulation (Fig. 8):

1. a solution with the reconstruction of the crashed dome (built in the seventies by Moretti during the restoration);
2. a solutions with the rebuilding of a dome on pendentives and a groined vault;
3. a solution with the wooden trusses and coverage of the naves and transept. The final decision of the wooden coverage solution remembers the first implant of the Basilica dating back to the 'Angevin' period.

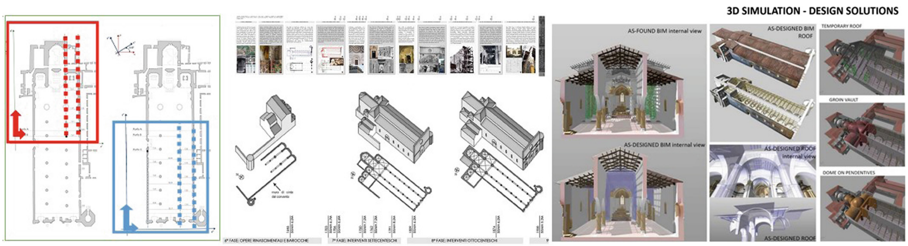

Fig. 8. The AS-FOUND BIM with the different geometric alignments of two portions highlighting the transformations occurred (left): the historical research (G. Carbonara ©) with concept model and timeline (centre); the AS-DESIGNED BIM coverage solutions (right).

Fig. 9. BIM OUT for ALL: MR enriched by BIM open access information

7 Conclusions

On the lesson learnt, the current Codification criteria (UNI11337-2009) has been updated with the UNI11337-4-2016: for HBIM adoption a draft proposal is on course of definition with the new LOG-LOI F&G levels (UNI11337-3-2017) on the restoration and maintenance domain, requiring morphologic complexity in the HBIM models (besides the conceptual structural models), as-built updating, and the monitoring during the times. Transferring the HBIM richness into the Life Cycle Management process will contribute to lower the initial HBIM model costs spreading its usability after the restoration process, taking in account the knowledge and information gained. An Open Access HBIM can represent a bridge toward Mixed Reality (Fig. 9): historical transformations, DBs, documents, the different materials and masonry texture in the past intervention and recent restorations (i.e. the façade after the earthquake of 1915). Memory of the past through the present toward the future.

The HBIM delivered is now at the crossroads of entering into the phase of forgetfulness, or it can play the critical role of a precious witness into the future being, transferring the richness of such virtual informed model to the people, tourists, citizens and future actors involved in the maintenance management. HBIM Open access is ready to be tested and to be harvested within Europeana networks in order to enhance the portability of the information gained and to share them with other case studies within a space-temporal framework: this will allow the comparison of masonry texture, history of material finishing and skilled workers across space and time.

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