HR LOD based HBIM to detect influences on geometry and shape by stereotomic construction techniques of brick vaults

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Abstract

The use of construction techniques in cloister vaults in noble buildings, as covering elements for square or rectangular rooms, is widespread across Europe. The geometric continuity at the intrados makes generally possible the execution all over the span of frescoes, stucco and decorations, with a great diffusion of a great variety of solutions. The construction of brick vaults, from the late Middle Age, was sped up by limiting the centring to the wooden planks arches that were instrumental in the profile determination. Starting from laser scanning, photogrammetric and thermographic techniques, the punctual reconstruction of the geometry and construction techniques allowed to recognise and understand the constructive richness, the multiplicity and unicity of each vaulted element, made of recurrent elements and specific features, thus sketching a mixed pattern of workers and highlighting the constructive knowledge of 'stereotomy' applied to the brick block vaults. Nowadays, the availability of several BIM-based modelling procedures and tools based on high detailed surveys allows to identify and reconstruct the shape, drawing reliable assumptions about the construction methods and the execution time. The research methodology here proposed intends to tackle an updatable geographic catalogue, able to transfer the construction richness, inheriting the historic lesson of French 'repertoires' to generate modern HBIM vault libraries (*abaci*). The paper focuses on a well-documented case, the Magio Grasselli palace in Cremona in which the cloister vaults of two main rooms, and others, show different construction systems embodied by the geometry. The methodology has shown how the cloister vault typology can be turned to a dome construction in the same vault, and how 'stereotomy', the capacity of skilled workers to control the space, modified the typical geometry, made by the 'generative' construction process used for the cloister vault (intended as the intersection of 2 barrel vaults), turning it into a dome in the upper part, giving back a sort of morphing, merging the two different generative rules (dome and vault) as described hereafter and creating unexpected scenic effect.

Keywords Cloister vaults · Stereotomy · HBIM · Terrestrial laser scanning · Photogrammetry · Modelling · IRT Infrared · Thermography

Introduction

Considering their importance both architectural and figurative, the construction of vaults is an ever-current theme in European culture, though the intensity and orientation thereof may differ in the various linguistic ambits. Brick vaults in Northern Italy between the 16th and 18th centuries are characterised by a wide variety of types and constructive

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solutions: much more diverse arrangements (*apparecchiatura* in Italian), such as in stereotomy, may correspond to the same shape, though elementary—a cloister vault, a groined vault, a pendentive dome. The use of brick texturing, however, also changes the geometry itself: the difference is not immediately visible, but digital survey techniques quickly highlight it. The arrangement—no less than shape and dimensions—marks the static behaviour of the vaults, as recently underlined by Richard A. Etlin (2015).

Nowadays, the support of the laser scanning technique integrated by 3D photogrammetric orthoimage allows to accurately identify the surface profile and thickness. To understand the whole system, it is mandatory to determine the properties of the binders and the shape and dimensions of the bricks, and to carry out a comparison between the geometry of the intrados surface and the evidences emerging at the extrados. HBIM allows to embody such information within the model object itself made by different components as shown hereafter. All these indications, in turn, are useful, in view of an interpretation of the structural behaviour, to identify weaknesses, and to highlight contributing factors of instability (if any). The paper describes the method adopted in order to generate the complex detailed HBIM with an high-resolution level of detail (LOD500 to LOD600) using the novel grade of generation (GoG) recently introduced (Banfi et al. 2017b).

The paper focuses on a well-documented case, the Magio Grasselli palace in Cremona in which the cloister vaults of two main rooms show apparently similar, but, in the reality differ-ent, construction systems, although they were built almost at the same time (18th, 1770–1785). The laser-scanner survey, photogrammetric techniques and thermographic recordings highlighted the various shapes due to the different arrange-ments used for the two cloister vaults (Fig. 1). In the same palace, we find the same different generative mixed roles also in the beautiful Staircase built one century before (17th) with a more relevant merging of the cloister vault transformed in an apparent dome, as we can find many other rooms covered by the traditional cloister vaults, thus giving back an extraordinary multiplicity characterised by different 'footprint' gener-ated by different constructive protocols, even if coming from the same typological rule.

Literature review: studies on the vaults and a synthetic overview of the European perspective—the stereotomic construction

Stereotomy is a term derived from the association of the two ancient greek words, 'στερεός' solid, spatial, three-dimensional and τέμνω, to cut, meaning the art of cutting in the three-dimensional spatiality. It refers to the set of procedures and rules supported by the descriptive geometry for designing and cutting from the rocks, or other materials, the ashlars, the stones of walls, arcs and vaults, already known in the past, among the Egyptian constructions as shown in some illustrations of the nineteenth century (Fig. 2). In the Gothic period, the art to draw in the 3D space, to trace and cut the single objects (the stone ashlars) in order to ensemble them in the final complex structure has been particularly diffused in the construction of arches, vaults and domes.

In France—thanks to the policy set up by Jean Marie Pérouse de Montclos—the revival of the inventory in 1964 led to a census in the significant realisations of stereotomy and the re-evaluation of the vast and learned writing treatises on the subject from the sixteenth to the nineteenth centuries (Pérouse de Monclos 1982). As in the case of the treaties (Fig. 2) made by '*Philibert De l'Orme architecte du roi 1514-1570*' (Pérouse de Montclos edition 2000) that Pérouse de Montclos contributed to bring to the attention, by diffusing them.

The 'vocabulaire' of architecture reconnects the typology with the lexicon through the graphic and photographic illustration of individual examples (Pérouse de Monclos 1972), but this terminological correspondence is possible insofar as the central administration and its culture have in a certain way 'standardised' language. In Spain, studies carried out are less systematic and more recent, but they have renewed substantially the history of architecture focussing on—in the late Gothic period and in Renaissance construction (Palacios Gonzalo 1990)—the quality of stereotomic construction. In England, as in France, from the first quarter of the nineteenth century (Willis 1842), the classification of vaulted systems represented an essential moment in the re-evaluation of medieval construction, but the scarce diffusion of real vaults in the construction of the Modern Age has circumscribed the theme to its most monumental and ancient heritage, which is

Fig. 1 Magio Grasselli palace in Cremona, the room 3.27, on the left, and the room 3.14 on the right, both painted by Giovanni Manfredini (photo by Giuliano Regis). The plan of piano nobile with room numbering

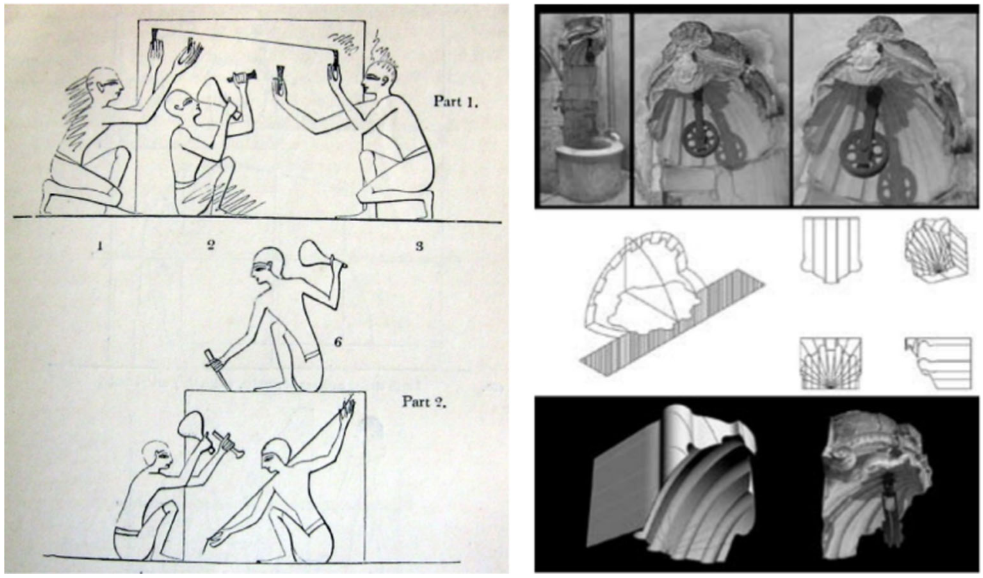

Fig. 2 Examples of the stereotomic knowledge in the centuries, intended as the art of cutting stone ashlars in the 3D space. "Checking and smoothing off a limestone blok, as depicted in the tomb of Rekhmire - Taille d'un bloc de pierre, thebes", Sir John Gardner Wilkinson, 1854 ©, on the left. Baldacchino del pozzo hôtel Bullioud, Lion: previous formal antecedent of the trompe d'Anet © (P. De l'Orme, 1536), on the right

relatively scarce. In Germany, on the other hand, from the Middle Ages to the Baroque period and throughout the nineteenth century, stone vaults, and moreover brick vaults, were very common and the technical literature and drawings increase steadily right up to the Modern Age (Wendland 2008). It is no surprise, therefore, to see the sheer number and quality of the studies and the presence of yearbooks (Erhalten historisch bedeutsamer Bauwerke) in which even experimental archaeology has played an important role (Wendland 2014). Studying the individual examples in great depth, we can see that they are often strongly representative of a heritage that is well documented by exhaustive inventories drawn up from the beginning of the twentieth century.

Piccoli started to highlight the richness of the stereotomic construction technique applied to the brick block vaults especially in the Piedmont region, describing the richness of the composite vaults, as in the case of the so-called Planterian vaults (Piccoli 1999, 2001). Texts on stereotomy suggest that the most difficult solutions were implemented throughout Europe in permeating complex solids. Guarini's *Euclides adauctus* appears a widely shared reference, more than the treatise on architecture published in 1737. In this way, the framework could be over-simplified, reduced to its bare bone consisting of centrings that corresponded to the profile of the arches, and the bricks were then laid by hand in subsequent arches that could be quickly completed. In general, the bricks are soldier-laid; rarely, do we find thicker systems, and while there are many light vaults, the bricks are laid *in folio*. The main curvatures are often indicated by thicker arches, from one to two bricks thick. These also act as reinforcement or permitted the phases of construction to be carried out in order. They are often coordinated with the wall-ribs (the so-called Italian *frenelli*) and with the extrados tie rods to reduce the side thrust and maintain verticality of the side walls during the slow setting of lime mortar.

The Italian treatises—with the significant exception of Guarini—is often elementary and repetitive in describing the vault catalogue. From the mid-seventeenth century, direct reference is made to the French texts (Forni 1993). Contemporary studies therefore lack an overview of reference leading inevitably to an involuntary localism—see the 'Manuali del recupero' of the individual cities—but also in more extensive works the 'geographical' skills of the authors appear to determine the ambit of treatment and the time-space perimeter within which they are studied. Within such rich framework, it is difficult to reconstruct regional specifics: Piedmont stands out for the vast quantity of complex examples and for their success in historiography, way beyond their mere singularity (Piccoli 1999, 2001).

Evolution through time can also only be found in the details, or in the lower frequency of one or another typology. The very same sub-Alpine master builders exported unique typologies—such as framed arches vaults—from Abruzzo (Varagnoli 2009) to Bohemia. When brick is used we find rational methods of construction that spread throughout Europe as evident in the drawings of German handbooks from the late eighteenth and early nineteenth centuries dedicated to the texture of the vaults (Gilly 1797). Stefan M. Holzer (2013) has succeeded in tracing an overview that not only deals with Italian case studies but also pairs them with similar German examples. Viollet-le-Duc, under *Construction* in the fourth volume of the *Dictionnaire* (first edition of the first volumes: 1854–1857), considered groined vaults as characteristic of medieval English construction, in which the ashlars were laid perpendicularly to the diagonal arches (Viollet-le-Duc 1854-1857).

The system is, however, extremely widespread throughout the Modern Age in the brick-manufacturing regions of conti-nental Europe: Holzer illustrates one example—among the many—in Augsburg but there are many cases also south of the Alps.

This paper is part of an ongoing research aimed to gain and document the richness of vaulted systems not yet documented in Lombardy Region (Grimoldi 2009) and Italy, differently from the French repertoires and German tradition, in the modern form of an HBIM catalogue of vaults, starting from the vaults coming from a Palace of Cremona.

There are two series of them from the second half of the seventeenth century in the Cremona building subject to this article (we do not move far…). The case study selected to illustrate the described methodology is the Magio Grasselli palace in Cremona, since it presents a multi-facet variety of different vaults (groined vaults and cloister vaults), where apparently similar vaults (cloister ones), in facts characterised by different construction systems. It is the case of the groined coverings at the underground level and in the porch (Fig. 3).

As reconstructed by the 3D photogrammetric survey, the groined vaulted system of the cellars under the porch is with-out plaster; hence, it allows to well illustrate one of the adopted constructive techniques, where the bricks were laid perpendicularly to the diagonal arches.

This particular construction might have been built without centrings directly on the modelled sands or with small centring portions, thanks to the small diagonal arches realised starting from the 2 orthogonal spring lines of the 2 adjacent perpendicular vertical walls. In this way, the construction of such small courses is very quick, easily supporting the mortar grip. The 3D model highlights the brick block arrangement along a typical diagonal direction adopted to reduce the cost of the centrings, applying the described stereotomic space control by means of brick blocks instead of the stone ashlars coming from the Middle Age stereotomic construction technique.

HR LOD based HBIM modelling to catch construction techniques of different cloister vaults based on stereotomic knowledge: methods and criteria

The paper intends to propose a methodology to survey, understand, recognise and reconstruct the stereotomic construction techniques adopted to cover halls and rooms of the Palaces with a variety of solutions in the realisation of the cloister vault systems, and reusable for the multi-variety of the covering systems. High resolution surveying, integrating laser scanning with the 3D photogrammetric image blocks, have been modelled using advanced modeller (MC Nell Rhinoceros ©) and BIM parametric tools (Autodesk Revit17©) in order to build up an HBIM model object able to embody the acquired richness of the shape, going beyond the surface shape, toward the thickness of the object, till to the texturing of the brick blocks as described in the work flow schema (Table 1).

International debates on the LoD/LoA/LoI (level of detail, of accuracy and of information) approach to BIM when applied to existing and complex building heritage (Fai and Rafeiro 2014) are witnessing the maturity of the thematic and complexity issue characterising the historical heritage, even if the parametric approach is still limited to LOD300 considered as an average compromise. At the same time, the research is progressively moving the attention from the LoD linear sequence ‘simple-to-complex’ (i.e. LOD100-200-400) traditionally applied to the new construction and simpler buildings through the different design steps (preliminary study-executive designas built), toward a ‘mixed approach’ taking in account the understanding process since the starting phase of the analysis: thus requiring to anticipate the knowledge of the morphology, with its complexity, and related behaviour, since the first preliminary stages in order to limit the costs growing of the preservation activities during the construction site (Brumana et al. 2017).

The HBIM model (Autodesk Revit17 ©) of the vault system has been obtained starting from the model of the vault intrados surface derived from the point clouds (Faro Focus3D ©). A NURBS based model has been generated (Autodesk Autocad 2017 © and/or MC Nell Rhinoceros ©), in order to

Fig. 3 Magio Grasselli palace in Cremona: groined vaults in which the bricks were laid perpendicularly to the diagonal arches (3D photogrammetric reconstruction of the model and arrangement)

Table 1 The workflow followed to get the HBIM model starting from the different surveying methods

On site surveying	HBIM modelling	Scale, accuracy *licences*
Laser Scanner Faro Focus © (Scans registry)	3D geometric analysis - Slicing (vertical, horizontal, radial, diagonal in function of the different typologies) - 3D edges (i.e. spring lines/cell web lines/borders) CONSTRAIN: congruent intersection of all the 3D splines and polylines with respect to the cloud points surveyed	Scale 1:20 Accuracy of the cloud points (2÷3 mm)
HBIM	HBIM vault model (intrados surface) - REVIT © LOD500 (GOG 9 and GOG 10) NURBS-based model using: GOG 9 a. 3D edges (discontinuity lines, i.e. spring lines, or borders among the different vault components, as in the case of lunettes, web cells) b. Slices (vertical, radial and horizontal slices in function of the shape) derived from the point clouds GOG 10 a. 3D edges (discontinuity lines, i.e. spring lines, or borders among the different vault components, as in the case of lunettes, web cells) b. Point clouds included within borders and spring lines	*Mc Nell Rhinoceros ©* *Autodesk REVIT17 ©*
3D Photogrammetry Vault Intrados and Extrados (RGB Image Block acquisition)	Digital Camera Nikon D3300 Focal lengths 18-55 mm, sensor dim.15.6 × 23.5 mm (pix. 6000 × 4000) a. Intrados image block: [3.14 Manfredini] scale ~ 1:10 Focal length 18 mm, max distance 8659 m Image block: n.102 taken Terrain (Ground) Pixel resolution 0.84 mm (GCP: Faro Focus Laser Scans) b. Extrados image block [3.14 Manfredini] scale ~ 1:5 Focal length 18 mm, max distance 3,27 m Image block: n. 211 taken (half sector) Terrain (ground) Pixel resolution 0.4 mm Target - tie points	Scale 1:10–1:5 *Photoscan* *AGISOFT©*
3D Photogrammetry Vault Intrados and Vault Extrados Object extraction and 3D reconstruction	3D orthoimages (GeoTIFF and OBJ model) Intrados: 3D model object of the surface from the point clouds and RGB orthoimage of the vault (Rhinoceros ©) Extrados—object element detection from the photogrammetric cloud points and 3D object restitution (OBJ) managed within Rhinoceros ©: a. Arches and vault elements: extraction of generative lines, 3D edges and spring lines. b. Brick block texturing from GeoTIFF: extraction of the 3D generative lines along the brick block arrangements (i.e. courses parallel to the vertical walls, herringbone courses, diagonal courses springing from the corners, conic arches springing from the corners). c. Detection of 3D elements: 'frenelli', tie-roads, roof timber and beams.	*Mc Nell* *Rhinoceros ©* *Autodesk* *REVIT17 ©*
Infrared Red Thermal Image acquisition Vault Intrados Method: active IRT acquisition (room pre-heating)	3D qualitative georeferentiation and projection (qualitative IRT assembling - referenced through natural points viewable on the RGB and IRT images) Integration of further information to better decode the vault texturing Equipment: -IRT InfraRed Thermal Camera AVIO TVS-500, 320 × 240 res, 8 to 14 μm, 22 mm lens - FOV, 1.07mrad spatial resolution and 0.05 C minimum temperature resolution)—DASTU; -FLIR T640 (640 × 480), 8 to 14 μm, 0.0035 C minimum temperature resolution, 45 and 15 lens—DABC, DASTU; -FLIR TAU1 - stand alone equipment and UAV Falcon8 (Ascending Technologies) - DABC	
	HBIM LOD 600 The LOD500 model is embodied by the LOD600 brick block single object texturing a. Integration of Intrados thermal information within the 3D overall 3DBIM model. b. Integration of stratigraphy related to the vault masonry wall family. c. Detection and modelling of the different brick blocks characterising the different constructive portions of the vault: the BIM Object elements have their own different measures and are positioned on the surface following the arrangements as derivable by the extrados 3D orthoimage (*'in folio'* brick block, *'a coltello'* brick block). Thickness detection from the surveying.	*Mc Nell* *Rhinoceros ©* *Autodesk* *REVIT17 ©*

manage the model in the BIM tools as a parametric object following the novel generative Grade of Generation proposed for high resolution BIM modelling (Banfi et al. 2017b, Brumana et al. 2017), particularly GOG 9 (using in the model-ling 3D edges and slices) and GOG 10 (using in the modelling phase 3D edges and point clouds), with a LOD500-LOD600:

it allowed to maintain the richness of the surveying in term of accuracy and of reliability of the shaped objects with respect to the reality. Such approach allows to associate the surveyed (or hypothesised) thickness to the object model within the BIM management tool.

NURBS-based objects allow to be imported and managed within the BIM tools assigning the thickness to the object-surface, thus transforming the surface into a parametric object element, with the possibility to assign family, categories and properties. The classical 'component' functionalities or 'massive' ones does not allow to be managed as BIM object and are not linkable to the property description, being simply surfaces and not fully operational BIM objects.

At this state of the art, the process of BIM vault generation is not working automatically (Banfi 2017a), due to the complexity of the sequences of functionalities and by the multiplicity of the shapes requiring a one-to-one analysis in the NURBS generation to maintain the accuracy, but few enhancement under this point of view are on course within a doctoral research programme (Banfi 2016) by mean of a semi-guided process. In particular: (a) semi-automatic slicing: in the case of GOG 9, the process can be exploited using automatic slicing, selecting a proper number of cloud points for the slices and checking the accuracy of the result obtained according to the surveying accuracy (2 ÷ 4 mm): local cleaning and outlier rejection after the slicing process, by a 2-step iterative process is applied; (b) in the case of GOG 10, the check is made directly on the cloud points selected, same 2-step iterative process to check the model shaped respect to the point clouds.

The experiment on course is based on the possibility to run a semi-guided process acting ADD IN sequences of commands, capable to guide the users on following—step by step—the required processing and checks, addressing their modelling effort with pre-defined functionalities and command sequences in order to check the adherence to the reality with respect to the point clouds and the morphological richness.

In the case of GOG 9, the slicing process has been applied along the horizontal planes every 20 cm, taking in account the 2 different portions identified within the same vault, characterised by different construction techniques, highlighted by the vertical profiles and by the extrados arrangement detection together with the IR thermal images (Manfredini Hall, Fig. 6): (i) the first zone adjacent to the spring vault is realised as a typical intersection of 2 barrel vaults, obtaining the typical cloister shape (rectangular profiles); (ii) the upper zone is characterised by a morphology similar to a dome construction (curved profiles). The NURBS model is constrained to the point clouds thus maintaining the richness of the shape, avoiding typical error generated by spline based models.

In the case of GOG 10 (Vault of the Staircase, Fig. 8), it has been mandatory to constrain the NURBS surface to grip on the cloud points belonging to the 2 different construction portions of the vault: the cloister vault zone along the spring border and the one rising from the cloister vault portion, with the typical mixed dome-vault shape. The borders and the cloud points belonging to the different zones have been man-ually selected in order to constrain the model adherent to the complexity and richness of the morphology, without loss of detail and generalisation respect to the cloud point surveyed and to the shape.

The high-resolution LOD here gained has been reached thanks to the integration of the extrados geometric information coming from the 3D photogrammetry and by the IR thermal images of the intrados. Generally, the widespread use of plastered masonry hides the arrangement that is otherwise visible in cut-stone vaults. The extrados cannot be seen when they are supporting a floor above. In this context, the extensive use of thermography is vital. They are just as many obstacles, but they may become an advantage insofar that the most modern survey techniques integrating a variety of instruments may find herein a significant moment of experimentation. The information coming from the intrados thermal information has been integrated together with all the other information, within the overall 3DBIM model, detailing the 3D texture with the documentation of the brick block arrangements following the thermal evidences and extrados 3D orthoimage.

HBIM procedure has been addressed to boost the genera-tive modelling phase, obtained from the intrados surface, pro-gressively embodying in the model itself the construction technique information gained from the brick block dimension and from the vault thickness. The BIM object model of each vault has been integrated by the 3D brick block object textur-ing adopting a sort of enriched LOD500 toward LOD600 embodying the brick texture modelling: the procedure of BIM object ashlar exploitation has been applied also in the case of the HBIM pillars of the Basilica di Collemaggio addressed to the preservation of authenticity after the earthquake damages (Brumana et al. 2017).

At the end of the process, the stratigraphy related to the vault-masonry-wall-family has been updated together with several information added to the properties, as the knowledge of the construction period, localization, archive documents and references (i.e. chronological construction, phasing, descriptions, dates). The HBIM obtained helped to detect differ-ences among 'apparently similar' vaulted system, classified under the unique typology of 'cloister vaults', evidencing the different geometries registered on the shape by the con-struction due to the different assembling of the brick block and by their texturing techniques, as explained in the following paragraphs.

The methodology applied to the different vaulted rooms of the Palazzo Magio allowed to highlight an unbelievable variety and unsuspected extraordinary richness in the Italian regional framework as well, poorly studied in the past by our treats, respect to the valorisation carried out in the tradition of the French repertoires across the centuries. The surveying and analysis of such vaulted systems made in the last 10 years by the authors together with other experts allow to give back a sample of a field that deserves to be further studied, opening the way toward an open catalogue of such construction systems.

French stereotomy represents the most extended and coher-ent development of this know-how. The treatise writing is known and, in different ways and measures, according to the local conditions, applied throughout Europe in the seven-teenth and eighteenth centuries. A fundamental part of the interpretation is precise inspection but this should be system-atically correlated to the constructive methods, to the laying of the stones or bricks, addressing both the collection of the data as well as their rendering, as here proposed.

Cases of 'cloister' vaults: different shape gives back the different construction techniques

The documentary research on Magio Grasselli palace (Landi 2011) has established the sequence of the constructive phases of the building. By correlating the archive data with surveys and diagnostic investigations, we have been able to date the vaults. Without necessarily sinking into technological deter-minism or mechanical processes of chrono-typological dating, this limited but reliable evidence allows for better understand-ing of the more general processes to constructively refine brick vaults in a medium size city, however attentive to receiv-ing technological updating and ready to export innovative solutions. The most complex vaulted passageway and the con-temporary presence of different constructive outlines could be clearly witnessed in Palazzo Magio Grasselli between 1760 and 1785. In the more general citizen overview, evolution is divided into longer times, and is affected by multiple social, economic and cultural factors that determine the choice of clients, architects and master builders. The in-depth studies undertaken on Palazzo Pallavicino Soldi and Palazzo Raimondi Stauffer, whose dating, with the exception of the famous façade, is different from what reported in existing literature (Visioli 2001), demonstrated the *longue durée* of some constructive techniques, which were first implemented in the sixteenth century and still in use during the first few decades of the nineteenth century. The Magio Grasselli palace, composed by late medieval buildings partially dismantled and transformed into a modern aristocratic palace, was designed by architect Francesco Pescaroli from 1658 until 1681, the year Camillo Magio—client and amateur architect—died: construction was interrupted and, in 1703, a post mortem in-ventory describes a series of noble apartments which were only completed in the main body overlooking the road. The anti-chamber room n. 3.27 (for the numbering room see Fig. 1) is rustic in style, with rough plastered walls, a wooden intermediate floor and a roof. Only around 1760 did Camillo II Magio and his wife Teresa Crivelli resume construction of the interior wing, partly demolishing and partly raising existing buildings (Landi 2011). This partially determined the distribution of the rooms and we can still see the structural joints between the old and the new. The materials resulting from demolition were partially reused as we can see from the re-adapted wooden ceilings as were probably the bricks of the walls and the vaults, cleaned of the earthen bed-fixing mortars. Between 1768 and 1775, all these rooms were covered with cloister vaults, and the main hall was decorated by the painter Giovanni Manfredini as we can see by the writing 'JM 1772'. By 1780, work was completed by Marquis Giuseppe Magio, son of Camillo II: the Magio-Araldi coats of arms allow us to date Manfredini's decoration to around 1780, the year Giuseppe Magio married Ippolita Araldi. On the *piano nobile* overlooking the road to the east of the entrance, the wooden ceilings of the apartment and the anti-chamber hall were re-placed by cloister vaults as we can see by a number of traces in the attics and above the false ceilings: the documents do not clarify if the vaults date back to the work undertaken by Giuseppe Magio around 1785—the year in which Manfredini signed the decoration of the anti-chamber hall [3.14]—or whether they were the result of a previous inter-vention no earlier than mid-century, as Natali decorated the apartment to the west, with wooden ceilings, between 1713 and 1724. The archival, metric and thermographic information concerning the Magio Grasselli palace are abundant and con-siderable and are integrated with the plurality of data, essential to define an elevated standard of documentation, which allows to justify both detailed hypotheses on the construction tech-niques, and classification criteria. It is important, however, to subject the whole to a critical examination, in order to define principles effectively shared and aimed at building a reference system, whose absence was already pointed out. Here are shown two main rooms of the Palazzo Magio that present a shape that can be traced back to the common generic classifi-cation of 'cloister vaults' but realised with 2 different geomet-ric arrangements systems: one with the typical semi-cylindrical intersection of 2 barrel vaults (2 development sur-faces with a simple curvature), one with a double curvature surface obtained with the arrangements of the tiles, thus more similar to a dome system. The final 'visible' effect is a cloister vault but the geometric roles are indeed very different (Fig. 4). Beside the two described Manfredini's halls, many other vaults of the palace have been considered, contributing to give evidence of recurrent techniques, justifying the concept of a catalogue, in order to understand the similarities and differ-ences, the construction techniques and the state of damage of the halls vaults: using the methodology shown in the workflow

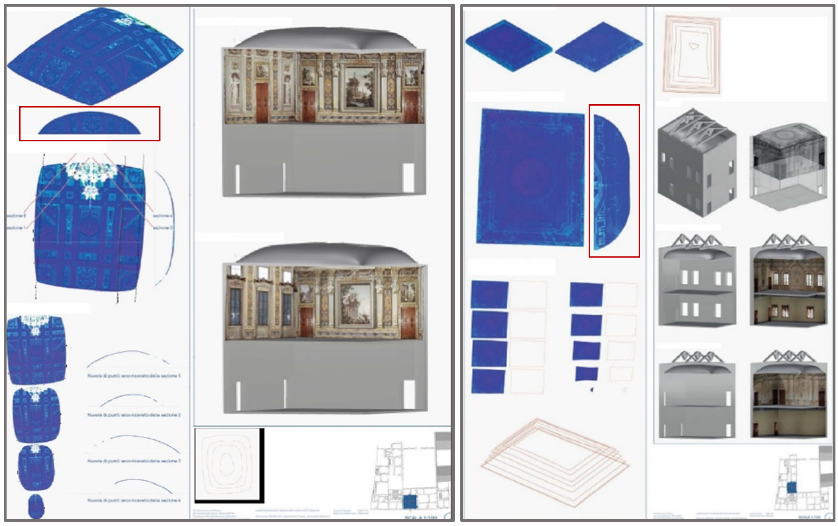

Fig. 4 The different 'recognisable footprint' (blue) registered by the point clouds of the 2 vaults of the two Manfredini Halls apparently similar, but very different as for the geometry highlighting different construction techniques: on the left image [Hall n.3.14] the horizontal slices derived from the laser scans put in evidence the 'rounded' profile and shape of the vault, while on the right image [Hall n.3.27] the laser scans put in evidence the typical rectangular cloister shape deriving from the intersection of 2 cylindrical volumes. The HBIM library of the 2 vaulted Halls (on the right area of the 2 cases) allows to manage the different data derived from the surveying and modelling (© Courtesy of Advanced Surveying Technique Course, labABC- GIcarus, Mattia Previtali - PhD Geomatics Surveying, trainer Riccardo Valente - Archaeologist PhD, and of M.Sc. students F. Moroni et al.)

(Table 1) an integrated survey using laser scanning, photogrammetry and thermographic investigations was carried out. Such a survey allowed understanding the morphology of many vaults and their own masonry pattern, highlighting certain critical aspects of the structural elements, the kind of instability and decay, and the mechanisms (Brumana et al. 2014). The thermographic recordings and laser-scanner surveys highlight the various arrangements used for the cloister vaults.

In the rooms of the subsequent enfilade [3.28, 3.30 and 3.31], the vaults run parallel to the wall, in variable heights, in correspondence with the lowest radius of the curve (and the highest slope) of the polycentric arch that makes up the section. In the lowered central area, the bricks are laid diagonally to form two contrasting herringbones, with a rotation of the direction that resembles, in simplified way, the 'böhmischen Kappen'. The extrados are hidden by flooring but we can make out the presence of metallic tie rods with struts to contrast the side thrust, laid at the same time as the side walls and the vaults themselves. The last room toward the garden also has a cloister vault, the heads of which are formed by bricks in diagonal courses to form a sort of cuff, while in the centre the weft runs parallel to the springers. Dimensions are limited: the main body of the building of which it is part is a later addition. This sequence highlights the variety of the abacus.

The rooms in the apartment overlooking the road [3.15–3.17] e [3.18–3.21] have the same constructive characteristics as those of the large room overlooking the road [3.14] where the bracing arches, visible from the extrados, were the centring outline of the vault profile and enabled it to be built without the support of planks. The extrados arches vary in width from one to two bricks thick in the vaults of the smaller rooms and tie rods with struts and web-ribs are located in correspondence with this ribbing.

In the main hall [3.14], the four arches erected perpendicularly to the walls on which the vault is built are two bricks wide and protrude half a brick above the extrados as ribbing, while the intrados contains a more complex construction. This is visible in thermography only in the keystones where they cross over, marking out the central bay: here we can see parallel courses of brick-on-soldier. At the springer are double header bricks alternating with *in folio* bricks that connect the arches to a continual leaf again in *folio* brick parallel to the springers, which also bend horizontally in quarter-circles in correspondence with the corners, resulting in a kind of cone shape: this solution, in which the arrangement is regular while the geometry is uncertain, allows the realisation of an intrados with no corners, perfect for uninterrupted decoration, mediating with the quadrangular plan of the main halls.

The thickness of the bays—measured in correspondence with the holes for the lamps and verified instrumentally—never exceeds 8 cm, including the topping and plaster.

The investigation of easily detectable extrados parts makes a deeper knowledge of such constructions possible: it allows a better interpretation of recurring situations, even more problematic to be detected. This interpretation, however, cannot be carried out without an accurate survey integrated by the thermography extensively used at the intrados surfaces.

In this specific case, the three-dimensional model of the intrados of the hall of Manfredini [3.14] at the first floor, located over the porch, obtained from the laser scanner clouds, has been integrated with the thermal image of the intrados and the three-dimensional model of the masonry pattern, visible from the extrados, obtained from the elaboration of photogrammetric image block (3D orthoimage) (Fig. 5). This integration allowed to reconstruct the geometry of the structure, characterised by two large and respectively transverse and longitudinal arches, which divide the surface in nine squares and support thinner vaults, made of brick tiles (3–5 cm), widely used since the sixteenth century. The vault is characterised by the arches and by the vault itself:

I. the 4 arches can be considered the components of a 'skeleton', made by mean of the 2 main longitudinal arches (brick block used for the reinforced arches are textured in a vertical position on header), maybe the first elements built up in the sequence, with the 2 tie rods at the extrados embedded in the arches themselves giving stability and rigidity to the arches together with the *frenelli*; the 2 transversal arches complete the structure of the arches;
II. the vault itself is realised texturing the tile-brick block along the 'curved shape' as described in the first part of the paper and here reconstructed from the scans.

The two structures, vaulted elements and arches, are not independent once respect to the other (Fig. 6), in fact the vault portions are gripped to the arches thanks to the interaction of some vertical brick block of the arches interweaved among the tiles in correspondence of the arches as shown by the thermal images of the intrados (Fig. 7). The HBIM model embodies the information coming from the thermal images and from 3D photogrammetry at the extrados: the 3D object model of the single brick has been inserted highlighting the joke of the 'in folio' skin and the interweaved structural arches.

Following the intrados geometry, the HBIM reconstructed the position of the object elements of the tile brick block (thickness ~ 4 cm) used for the vault in order to diminish the weight, obtaining a sustainable very light structure compared with the dimensions of the covered hall.

The modelled elements of all the components of the vault (arches and vaults) have been imported within the HBIM model in order to manage the abacus of the different elements. A in *folio* cloister vault from the same period in courses parallel to the springers covers the loggia toward the courtyard, but the span is relatively limited (3 m) and the section is semicircular. It is the thinnest wall overlooking the courtyard (three bricks thick, 45 cm) which suggested lesser thickness of the vault.

The construction is lighter than the vaults of the interior wing, and stability is favoured by a larger rise. The larger height of the street-side façade corresponds to a higher volume of the attic area where the vaults have ample space. The

Fig. 5 The shape of the intrados and extrados: the 3D orthoimages of the intrados obtained using the laser scans GCPs of the vault (upper); the 3D orthoimage of the extrados (bottom) has been obtained from the image block acquired along the arches, due to the thin fragile vault elements (© Courtesy of labABC- GIcarus, trainers PhD Geomatics Mattia Previtali, PhD Archaeologist Riccardo Valente, and M.Sc. thesis student Dario Attico)

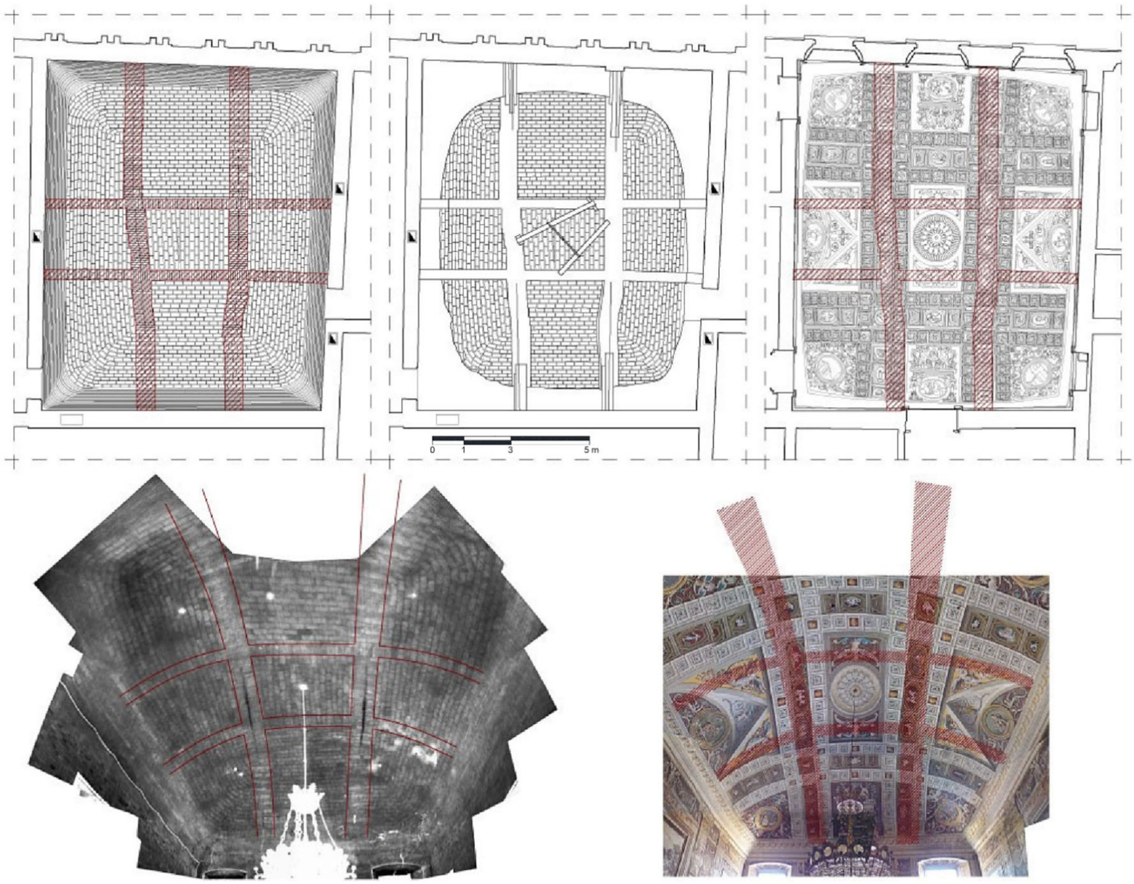

Fig. 6 The information on the texturing have been read from the thermal mosaic (not-metric) of the intrados by mean of the grey tones thermal image mosaic (© courtesy of DASTU, IRT images, Luca Valisi) and from the metric orthoimage of the extrados from the 3D orthoimage, with the structural arches represented in the 3D model (obj), obtained from the cloud points derived from the 3D orthoimage of the extrados (© Courtesy of labABC- GIcarus, trainers PhD Geomatics Mattia Previtali, PhD Archaeologist Riccardo Valente, and M.Sc. student Dario Attico)

sample illustrates how the deeper integration of both the IR survey at the intrados and of photogrammetric survey at the extrados allowed to add more information on the connections, otherwise not comprehensible.

From the lesson of 'repertoires' toward HBIM vault libraries: an updatable geographic catalogue (*abaci*)

The patient reconstruction of the geometry and construction techniques allowed to understand the constructive richness, made of recurrent elements and specific features, sketching a mixed pattern of the workers employed and their constructive knowledge spanning from regional domain across Europe.

This process may result into current geographical updatable *abaci*, inheriting the tradition of the French repertoires that can be nowadays supported by HBIM: the BIM modelling process could lead to BIM libraries of vaulted elements that should be, however, not aimed at flattening and oversimplifying these valuable items to a unique parametric matrix for 'copy-and-paste' operations at will, with mere changes of dimensions. Unfortunately, an oversimplification of complex elements (such as vaults) is often the rule in the application of BIM to the cultural heritage. This oversimplification is the demonstration of incomplete knowledge and deviate interpretation of BIM that could be used, on the contrary, to better handle differences and peculiarities (Volk et al. 2014; Fai and Sydor 2013). Protocols approach handling with the complexity of the architectural heritage and its components are working in this direction to overcome the simplification of the construction elements populating the product catalogues used for the new constructions (AEC 2014; AIA 2015; NBS 2016). Through the concept itself of BIM *instances* the families of the vaulted elements are enriched by the richness of unique and complex elements, assigning to each object the added value of the multiplicity, by distinguishing 'hic et nunc' of each vault (Figs. 8 and 9). What is different is the point of view that should be aimed not at unifying, but at the comprehension of the acquired knowledge.

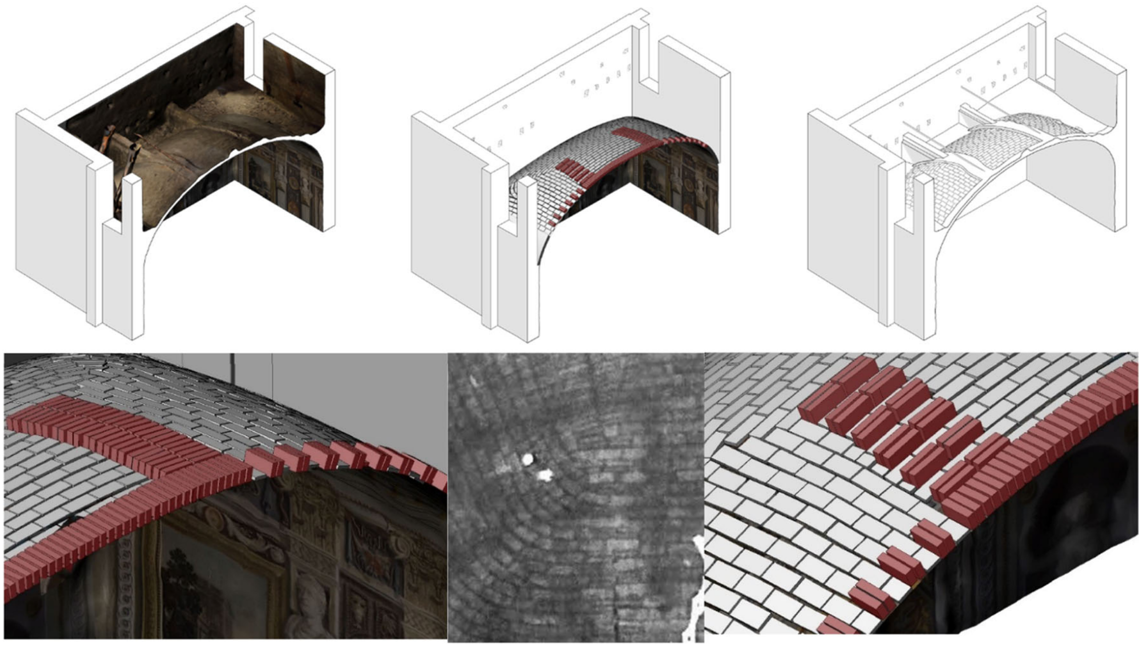

Fig. 7 The integration of the 3D orthoimages at the extrados and intrados, together with the thermal image (intrados), allowed to understand the detail of the integration of the interweaved structure obtained from the skeleton of the arches (3D 'a coltello' bricks in red) with the continuous thin structure of the vault in correspondence of the arch itself (3D 'in folio' bricks in white). In fact, in correspondence of the arches are viewable both the brick block of the arches and the tiles of the vault hold on to the arches. The result is a perfect curved surface as highlighted by the laser scans (©dABC GIcarus, Preservation lab, M.Sc. thesis student Dario Attico courtesy)

As testified by some recent experiences, BIM models support this different approach to complex surfaces modelling and NURBS (Piegl and Tiller 1997; Banfi2016). The management of such multiplicity can be accessed inside the BIM

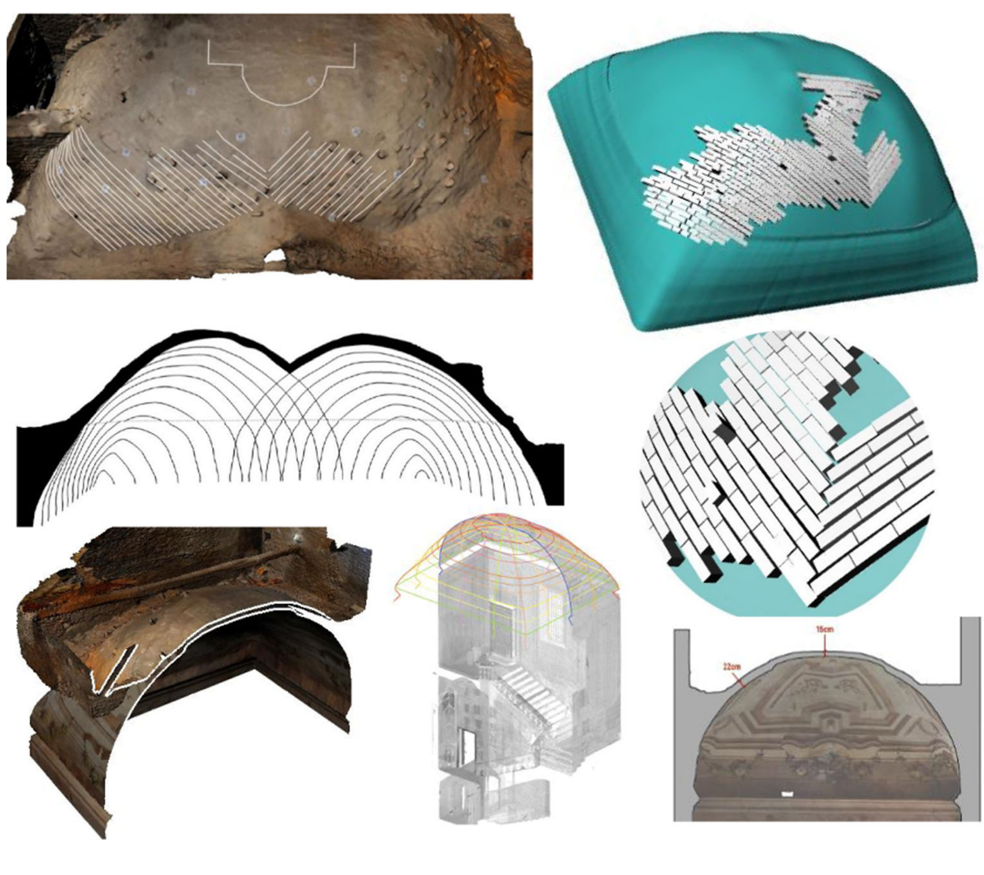

Fig. 8 The great vault of the Staircase Hall (Palazzo Magio Grasselli). The shape of the extrados obtained by the 3D orthoimages and their integration with the 3D orthoimage of the intrados (bottom left). The HBIM model obtained by the Rhino surface, integrated by the single brick object texturing (© Courtesy of labABC- GIcarus, trainers PhD Geomatics Mattia Previtali, PhD Archaeologist Riccardo Valente, and M.Sc. students Raimondi, Stefanina, Tomasoni)

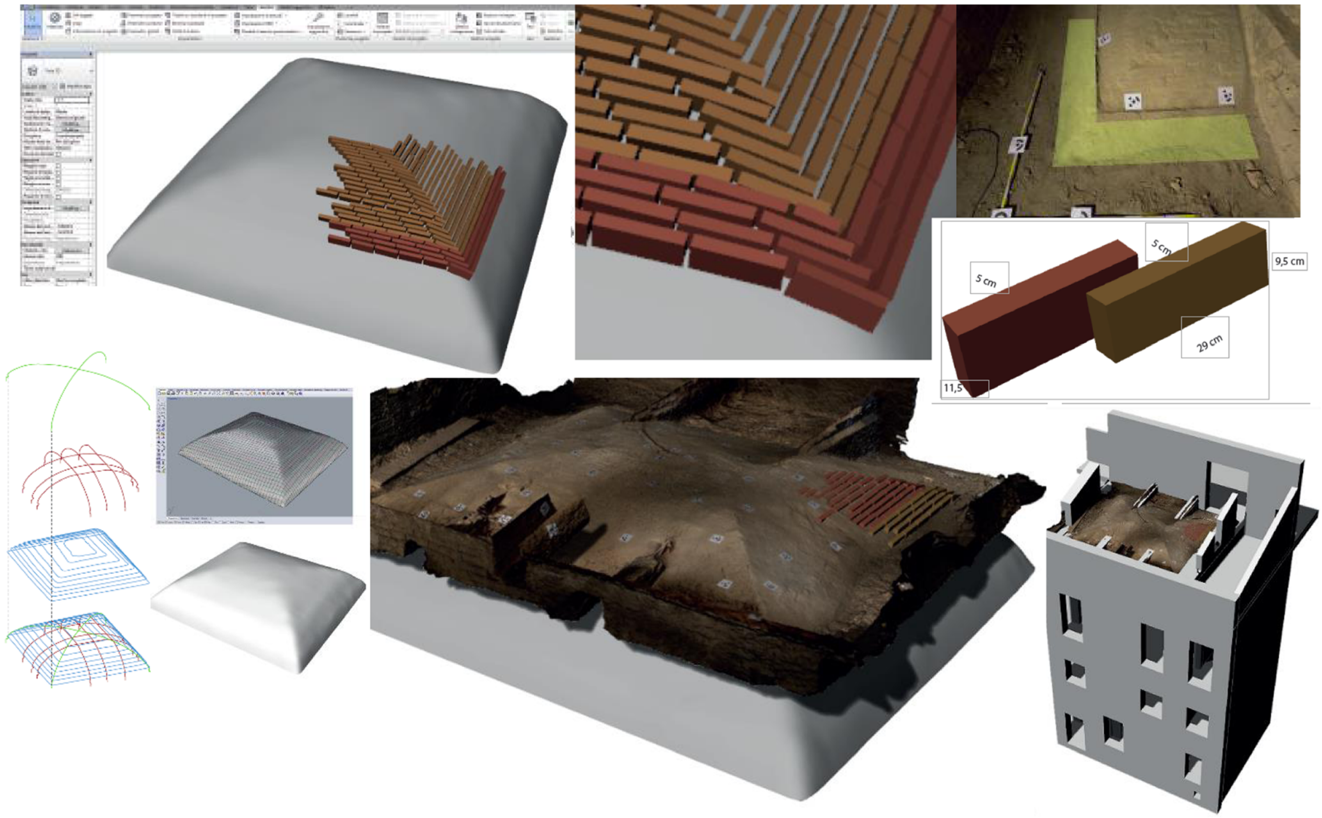

Fig. 9 Toward HBIM library of vaulted systems: the HBIM model of a room characterised by a typical cloister vault with the courses of brick block arrangement along the walls direction. The diagonal discontinuity lines belonging to the web cells are evident at the intrados and extrados, as well as the 2 different portions with different brick dimension, with the perimeter band maybe often realised without centrings and the central one lighter with smaller brick block (© Courtesy of labABC- GIcarus, trainers PhD Geomatics Mattia Previtali, PhD Archaeologist Riccardo Valente, and M.Sc. students Bassani, Bianchi, Zohar)

tools by the users, but also outside the BIM tools thanks to the remote cloud management, in the form of catalogue and object libraries, accessible in the form of Virtual Reality via I-devices (i.e. smartphone) for touristic purposes and among professionals contributing to the knowledge transfer and building capacity for the on site management and decision making (Barazzetti et al. 2015a).

An updatable catalogue can be populated by the single HBIM vaulted models and accessed by the different users. The Abacus can be implemented by other vaulted rooms modelled by the BIM logic as here described, starting popu-lating the 2 different families of cloister vaults in the Palace. It was the case of the Staircase Hall, realised in the seventeenth century, about one century before the Manfredini Hall [3.14]: the Staircase Hall was aimed to underline and celebrate the palace, and was covered by a typical cloister vaults 'tuned' to a dome shape, emphasising the slender effect upwards rising up respect to the cloister vault. The laser scans radial profile highlighted the arched profiles characterising the case of the families of cloister vaults degenerating toward an evident dome (Fig. 8).

The diagonal vertical profiles extracted in correspondence of the 4 corners along the diagonals illustrates the different geometry respect to the classic intersection of two cylindrical barrel vaults: the lack of edges and discontinuities lines in the diagonals is representative of the different construction technology here adopted. While the 'conic' profiles—derived following the textured model of the extrados—highlighted a sort of conic-to spherical shape of the building construction arrangement, different from the parallel horizontal courses used in other domes. The scenic complex vault has been modelled and inserted within BIM environment, populating the library of objects collected and documented in the Palazzo Magio Grasselli.

The information to build the HBIM has been derived just from the scans and 3D photogrammetry of the intrados and extrados. To model the complex vault the model has been split in 2 portion following the information given by the vertical profile geometries in correspondence of the middle of the vault: (a) the springing portion characterised by a cloister rectangular shape and construction technique and (b) the 'dome' portion itself. Given the height of the Staircase Hall and the climate-exposure condition, it wasn't possible to acquire the thermal images nor with the passive thermal image acquisition, nor with the 'active' method heating the Hall, as carried out in the other vaulted halls of the Palazzo Magio Grasselli. They would have been very useful to solve some doubts on the springing zone, covered at the extrados level by incoherent material to give stability, thus hiding the junction to the walls. Open questions that could be integrated and updated in the future in case of restoration and interventions in a never endless process.

The different portions characterised by different arrangements has been reconstructed in the HBIM model of another room characterised by a typical cloister vault with the courses of brick block arrangement along the walls direction (Fig. 9). Another case of mixed solutions, testifying the granular richness recorded by the HBIMs in an open updatable archive.

Toward deeper enriched structural analysis using the HR LOD HBIM modelling

Determining the (at times extremely complex) geometry of the vaults is an essential phase of construction (Oreni et al. 2013). Ensuring the stability of the springers, the shape, both that of the overall structure as well as that of the arrangement, and also that of the ashlars, is essential to guaranteeing the static equilibrium. Its knowledge can be improved by a deeper modelling phase using the resolution of the surveying to better understand the state of conservation for the preservation and maintenance plans.

The potentials and advantages of the LOD500 toward LOD600 HBIM modelling methodology on limiting unexpected activities in the cost computation and on site delays are quite evident, even if it is not yet commonly adopted as a standard procedure: lack of modelling skills and of deeper diffused knowledge of the construction system of the vaults contribute to rise the costs of BIM modelling and many times it is a barrier to the exploitation of BIM adoption in the historical buildings. Guidelines, protocols and specifications as described can contribute to lowering such gaps, using some samples as study cases to transfer the lesson learnt building capacity among professionals.

The spatial representation of the vault BIM model related to the walls and other object elements makes it possible to draw some conclusions as regards the structural behaviour of the particular structure of some vaults. In the case of the Manfredini Hall (n. 3.14, Fig. 1), the four arches thrust on the masonry walls, whereas the openings (doors and windows), above which no lunettes are pres-ent, support the very light in folio portion. The fact that no cracks are visible on the surfaces allows assuming that the vault does not give structural problems to the lower parts. From the structural point of view, it is clear that the behaviour of such a vault is completely different from that of ordinary cloister vaults (as highlighted also in the case of the Manfredini Hall n. 3.27, Fig. 1), where the weight is distributed on all perimeter walls, with a peak at the centre of the single wall. The arches compose a framework carrying the majority of the loads, despite the presence of ties. The curvature of the vault at the corners makes it more similar to a dome, whereas the remaining in folio portions is similar to barrel vaults.

A deeper analysis of the structural behaviour taking in account the richness of the geometry entailed by the arrangements is nowadays needed to investigate if it can be used to enhance the level of comprehension of the structural behav-iour. Study cases of cloud-to-BIM-to-FEM have been applied to structural simulation with accurate historic BIM from laser scans. Under the interoperability point of view, it has been demonstrated by the research group (Barazzetti et al. 2015b) that the HBIM NURBS-based model objects in the case of the Masegra Castle (Sondrio, IT), about 30.000mc HBIM, can be directly managed within recurrent Finite Element Analysis tools (as Midas ©, or others). A FEM analysis (Martinelli et al. 2018) has been carried out bearing capacity assessment of the fourteenth century historic bridge (Ponte Azzone Visonti, Lecco, IT) to check the structural potentials and sustainability of the infrastructure daily crossed by heavy vehicles with respect to its preservation: a typical structural model based on linear approach has been applied, but loosing the geometric and stratigraphic richness obtained by the HBIM model (Barazzetti et al. 2016), with a lack of information in the simplified model interpretations.

In order to overcome such limits, a research has been started by the authors of this paper together with structural engineers to cope with the obtained geometric information. The research is at the very beginning to be reported, but the way is opened. Considering the continuous updating of commercial software for the numerical model during the last years, it would be interesting to systematically introduce the avail-able integrated information within BIM (understood as written above), in order to obtain results taking into account the multi-faceted constructive complexity of real structures. Even if scan to BIM to FEA process is fully interoperable, what we lack is to carry on robust researches on the cross cutting edge area represented by a structural simulation able to consider the richness coming from the information documented so far, about arrangement and course texturing, from the knowledge of the used material (brick block, mortar), and so on. A further development toward this direction is be undertaken by the research group by mean of customised code implementation.

In addition, the availability of a detailed three-dimensional model allows a backward knowledge of the construction technique, maybe not in its entirety, but sufficient enough to explain and highlight that the provision and use of centrings in the constructive phase, as previously mentioned, ‘changes’ the geometric shape by creating multiple variations. This information could be a useful means to improve the understanding of the structural behaviour of vaults. Although the new modelling strategies allow to introduce the types of vaults and the materials in the numerical models, in comparison to the past, often an oversimplification of the structure remains, which can lead to an incomplete understanding of the structural behaviour.

In Italy, the national standard helps by emphasising the importance of taking into account the historical knowledge of the building, the construction techniques and, among other things, the state of damage, when setting up a numerical model. Considering the case of vaults, in particular, the structural behaviour can be adequately captured through a suitable reduction to its generator arc. Moreover, the analysis of the three-dimensional geometry of the structure should be aimed at identifying possible symmetries, in order to bring in further simplifications.

Conclusions

The great variety of cases—as regards geometry and arrangement, of the Palazzo Magio Grasselli, but also deformation and crack pattern—has been analysed, in the same building, in the same period, in the same city, showing the poor foundation of any generalisation, but the rapidity and reliability of results that guarantee detection techniques today—metric and quantitative—and thermography, essentially qualitative, should favour their adoption, and also substantially change the quality of the strengthening project, especially if integrated within the laser-scanning, IRT and 3D photogrammetric techniques. The methodology of a high-resolution LOD-based BIM here adopted demonstrated to support the richness of the variety of the construction techniques, helping to recognise the effect of arrangements on the shape, in general unknown to the professionals and public, contributing to enhance the knowledge and comprehension of stereotomic capacity of the different skilled workers.

The geometric and thematic survey supported by the historic analysis and object-based representation by mean of HR LOD HBIM contributed to highlight the richness of the construction sites in the same Palace and of the construction techniques: in summary, it seems that the different constructive outlines used in the wing overlooking the road and the interior wing have been chosen as they best respond to the—differing—work conditions. Two completely different construction sites could be hypothesised, with completely different master builders, in the two wings, which can be recognised by the different thicknesses (*in folio* brick, *brick-on-soldier* technique), but the various chronological hypotheses already discussed exclude a gap between the two of any more than 20 years, at the same time, there are also recurrent elements (as in the case of reinforced arches integrated in the cloister vault system). Numerous examples of contemporary in folio vaults can be found in the city—just think of those by Faustino Rodi in the Town Hall (Jean 1998) and Palazzo Cattaneo built from 1788 (Grimoldi 2005), but there are some that date even further back in Palazzo Ariguzzi Pallavicino (Grimoldi and Landi 2012). Examples of the brick-on-soldier technique can be found in the vaults of the 'piano nobile' of Palazzo Raimondi (between 1828 and 1836) and the vaults of the ground floor in the same building, hardly beyond the first half of the seventeenth century.

The HBIM library of the vaulted systems of the Palazzo Magio Grasselli has been undertaken in the form of an open catalogue and it is on course of population, it will allow to articulate the different typologies, the groined vaults and the cloister vault variety spanning the last ones from the pure cloister vaults to a mixed vault-dome technique. The HBIM model is now ready to be used for deeper structural analysis. The possibility to elaborate a catalogue reporting out of plumbs and crack patterns, allowing to co-relate the structural objects in a spatial domain, makes it possible to gather the necessary information for the abaci related to damages, which may allow defining the most frequent damage mechanisms. This knowledge, currently fragmentary, might orient a more conscious and more suitable approach to the consolidation project for this particular kind of dome-vaulted structures, which, as previously mentioned, is fairly different from classical cloister vaults. The research need to be further developed in the field of structural analysis in order to embody the HBIM geo-information on the arrangements.

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