The Vaults of Villa Reale in Monza

A 3D Virtual Model for the Accurate Understanding of their Genesis and Construction Techniques

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The survey campaigns of the interiors of the Villa Reale in Monza, which have been conducted from 2002 to 2012, have enabled the creation of a virtual three-dimensional model of the building using both photogrammetric and laser scanner techniques. During the measurements the geometry of the principal rooms, all covered by brick or wooden vaults, was accurately investigated. Analysis and cross-checking of dimensional constructive data with information obtained from direct inspection of the extrados of the vaults led to important observations about the genesis and construction method of the vaults. Moreover, when compared with architect Giuseppe Piermarini's original drawings and with contemporary construction manuals, this information sheds light also on the shape of the wooden centrings that were used for the construction and the arrangement of the bricks.

The geometrical and structural 3D model built for the Villa has both a scientific and a practical value. On the one hand, it can provide support for future conservation programmes; on the other, it can be used to disseminate specific thematic knowledge to the public via an online platform.

Villa Reale in Monza: Historical Notes

Maria Theresa of Austria (1717–1780) decided to build the Villa in Monza for her son, Archduke Ferdinand of Austria-Este, when he was appointed Governor General of Austrian Lombardy. The Villa was planned in 1777 by the imperial architect Giuseppe Piermarini and built in only three years, on a crossroad between Milan and Vienna, the imperial capital.

Less than a century later, during the French government in Lombardy, the Viceroy of the new Italian Kingdom established his main residence in the Villa and the building took the name of Villa Reale (Royal Villa). The Austrians returned to the Villa only after the fall of Napoleon and they

remained there until the Second War of Independence, in 1859, when the Villa was definitively left to the House of Savoy. Due to the murder of the King of Italy Umberto I in the Villa on 29 July 1900, while he was attending a sporting event, the building was closed and the King's son, the new King Victor Emmanuel III of Savoy, moved most of the furniture to other royal residences in Italy. In 1934 the whole complex of the Villa Reale, with the exception of the south wing, was given as a present to the municipalities of Milan and Monza. After the Second World War the buildings were first occupied by military troops and then largely abandoned, leading to severe degradation of the monument. After a long period of neglect, also due to the fragmentation of the current government's properties, a process of restoration of the Villa has only recently started.

Despite these unfortunate historical events and the successive changes of ownership, the Villa Reale has maintained until today the original plan drawn by Piermarini. The transformation of the building in the nineteenth century concerned only limited portions of the structures, leaving intact the spaces and volumes of the *piano nobile* and the main rooms of the central part. Later modifications focused on the furnishings and rich decorations, in order to comply with the changing needs of the court. New ways of court life led to different uses of the spaces and to new functions for each room, but without modifying the original structures.

Instruments and Survey Methods for 2D Representation and 3D Modelling of the Complex

Interior and exterior survey campaigns of the Villa Reale have been conducted between 2002 and 2012. The initial purpose of the surveys was to supply preliminary information on the complex in view of the restoration and reuse of the central building, which was awarded in an international competition in 2004.

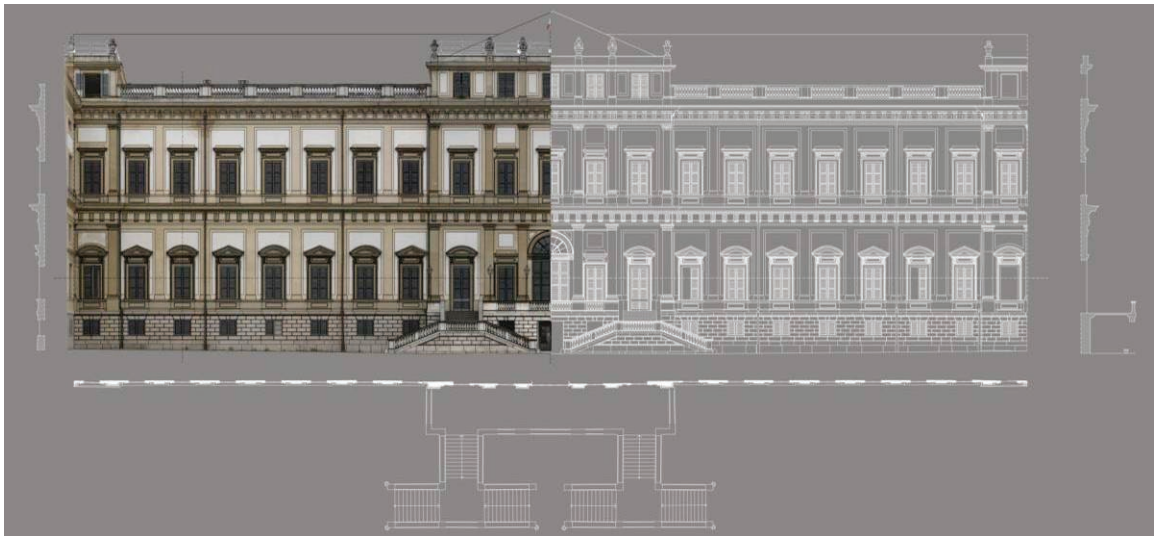

Fig. 1 Drawing of the main front of the Villa Reale, with rectified image, vertical and horizontal section of the building.

During the phase of survey planning, it was decided to use different scales for measurement and representation, according to the various requirements of analysis of the structures and surfaces. This led to the integration of different instruments, technologies and methods: manual survey, topographic, photogrammetric, laser scanner and GPS survey (fig. 1). In particular, 355 rooms were surveyed in detail, geometrically representing the inner surfaces, fine decorations and wooden elements, using 2D 'box system' representations and texturing them with rectified images (fig. 11). Based on this survey virtual 3D detail models were made for 71 rooms (until March 2012), using both photogrammetric and laser scanner survey products, integrating orthophotos and 3D CAD models.

The limited use of handy scan and reverse engineering (fig. 2) was adopted to reproduce particular decorative elements with the aim of documenting their state of conservation and enabling the work of restoration professionals at a great level of detail (scale 1:1, 2:1).

Fig. 2 On the left two drawings by Piermarini (c. 1780), useful to build the decoration template of the interior doors. On the right, the process of reverse engineering to reproduce the same decorative element.

All the survey data were geo-referenced in a unique geographic reference system and were published in the web-portal of the *Virtual Museum of Villa Reale,* where it is also possible to navigate the 3D virtual models of all the rooms. The web-portal is at the moment a prototype and the property of the Region of Lombardy, the authority supervising the project. It is expected that the web-portal will become public in the near future, offering the functions of view, discovery and download to professionals and the wider public.

Finally, for didactic purposes, and in keeping with the use of virtual models to tell stories about the past (adopted also by other famous monuments such as Schönbrunn and the Louvre), a few short movies illustrating the life in the Villa over the centuries were made and published at the portal (fig. 3).

Fig. 3 Still of a short movie illustrating the past life in the main room of the Villa Reale: the Ballroom. The 3D model of the room was created using topographic, photogrammetric and laser scanner data.

Survey and Virtual Models for the Analysis and Comprehension of Structural Elements and Techniques: the Vaults of the Central Part of the Villa

The aim of this part of the work was to identify a methodology of survey, documentation and 3D representation for complex vaulted structures, using both advanced instruments and survey technologies, and to compare these data with the original drawings and the technological information provided by construction manuals from the time of the building's creation.

The dimensional and geometrical data on the shape of the cloister vaults were analysed from a constructive and structural point of view, comparing information obtained from the survey with direct observation of the extrados of the vaults. At the same time, an attempt was made to cross this technological information with information derived from the analysis of the original section drawings by Piermarini, which were used as a guide to build up the cover structures of the rooms (fig. 4). In order to reconstruct the building process we used instructions from manuals supposedly known by the architect. In particular, we tried to understand how the ancient builders drew and built the wooden centrings to obtain the exact shape of the vaults planned by Piermarini, starting from the shape of the room in plane and from the height of the vault (figs. 5, 6, 7).

This method of investigation of the old structures and their constructive techniques represents a reverse knowledge process, starting from observing what exists to virtually reconstructing

hypothetical building phases, considering not only the geometry and the thickness of the walls, but also the materials and the actual disposition of the constructive elements (fig. 8). In this way it was possible to examine the constructive genesis of the vaults and to identify anomalies in their shape with respect to the ideal one, which is useful also for subsequent diagnostic analysis. The final result of this inverse process was the creation of a 3D virtual model of the cloister vaults, mapped with orthophotos obtained as one of the products of the photogrammetric survey (fig. 10).

The following examples illustrate this kind of geometrical and structural research on the cloister vaults of the Sala degli Uccelli ('Birds room') and the Sala da Bigliardo ('Billiard room') on the *piano nobile* of the central block of the Villa.

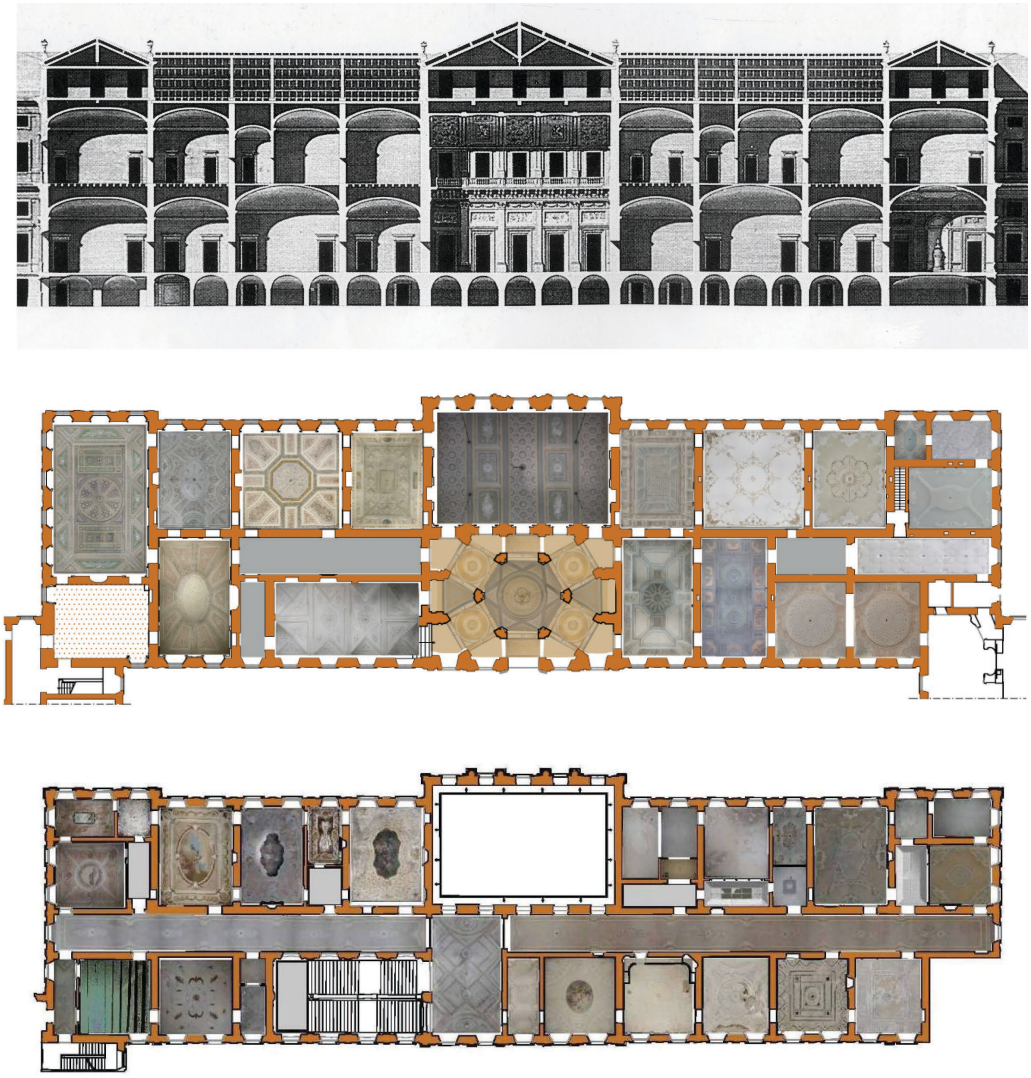

Fig. 4 Above, original longitudinal section (south-north) and the central part of the building, drawn by architect Giuseppe Piermarini in 1780. Centre and below, the surveyed plans of the building (first and second floor) with the orthophotos of the vaults of the rooms.

Example of Analysis of Traditional Method of Cloister Vault Construction

The reconstruction of the precise geometry of the cloister vault started from the drawings with longitudinal and transversal sections of the square room, obtained from the laser scanner point cloud. The aim was to identify the arches of the two barrel vaults, which is useful at the end of the process to compare the *real* shape with the *ideal* shape.

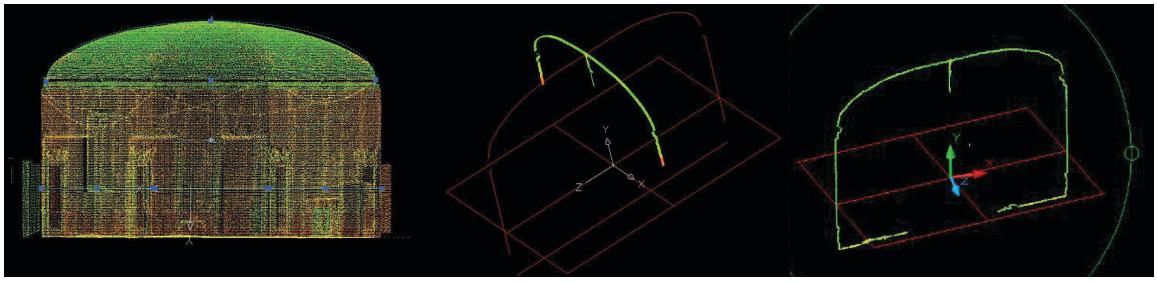

Fig. 5 Process of extraction from the laser scanner point clouds of the transversal and longitudinal sections of the room.

The second step of our process consisted in the reconstruction of the ideal geometry of the sections of the cloister vault, starting from the surveyed plan of the Sala degli Uccelli, using the projective method explained in the manual written in 1737 by the Italian architect Guarino Guarini. Assuming that a cloister vault is geometrically the result of the intersection of two orthogonal barrel vaults, to build the vault it was first necessary to know the two generative curved lines of the two barrel vaults. So the method explained by Guarini consisted in the drawing of the second curved line, for example the longitudinal one, starting from the rectangular shape of the plan of the room and from the curved line of the vertical section. This transversal curved line could be drawn knowing the dimension of the room and the height of the vault, as represented in the CAD sequence below (in blue). Using the diagonal of the rectangular plane it is possible to transfer the height of the transversal section (in red) onto the long side of the rectangular, in order to draw the curve line of the longitudinal section.

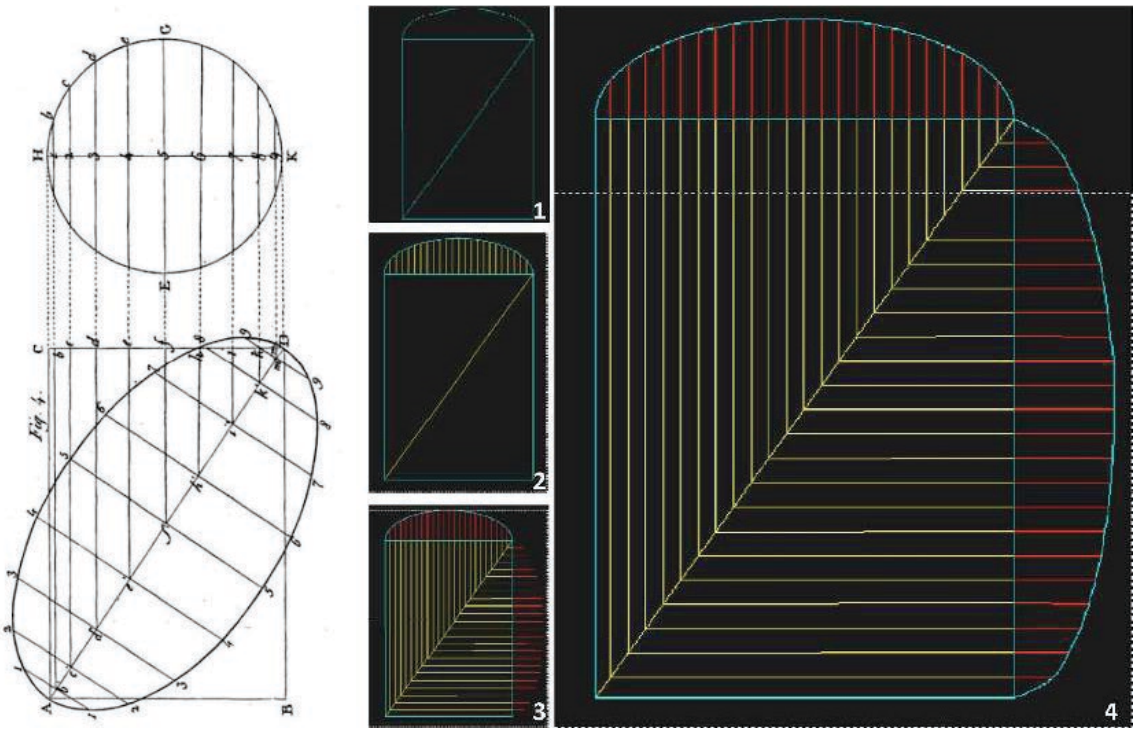

Fig. 6 On the left, construction of the curved lines of the vault by the projection method of Guarino Guarini. On the right, the process of drawing of the two curve lines of the two barrel vaults.

At this point it was possible to make a comparison between the ideal section of the cloister vault, reconstructed with the projective method (blue line) and the actual shape derived from laser scanner survey (red line). This step was useful to identify structural anomalies, such as crushing and implosion areas. This information, which must be constantly monitored and updated, could be essential to identify areas in which to perform additional diagnostic tests.

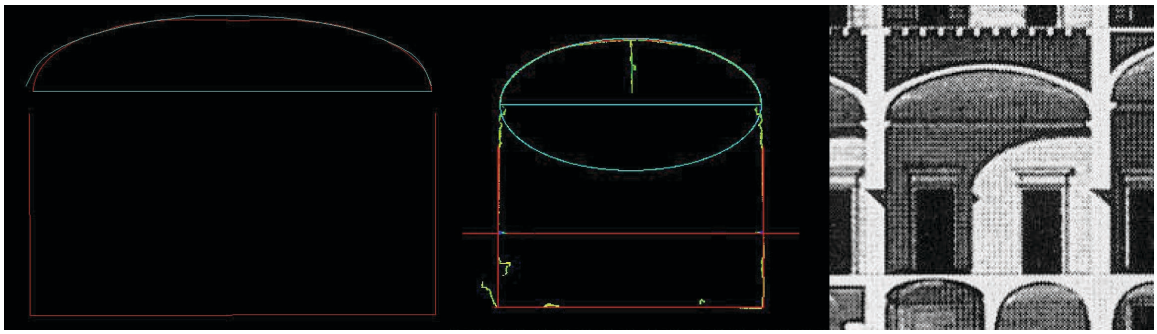

Fig. 7 Left and middle, comparison between the ideal (blue) and real (red) shape of the vault. On the right, detail of Piermarini's longitudinal section (Sala degli Uccelli).

Once the geometrical genesis of the vault was detailed, its actual construction was investigated, analysing the extrados to identify the texture and the arrangement of the bricks. When possible, thicknesses, materials, textures of masonry, and metal or wooden tie-beams were always accurately observed. This provided useful points of comparison also for those areas in which information was not directly obtainable. In this case the nineteenth-century construction manual of Gustav Adolf Breymann was used, with a focus on the different pattern arrangements in the volume on stone building and wall structures. Like many other ancient manuals, Breymann explains the disposition of the bricks in the cloister vaults (fig. 8, centre) and the shape of the wooden elements of the centrings (fig. 9, above right).

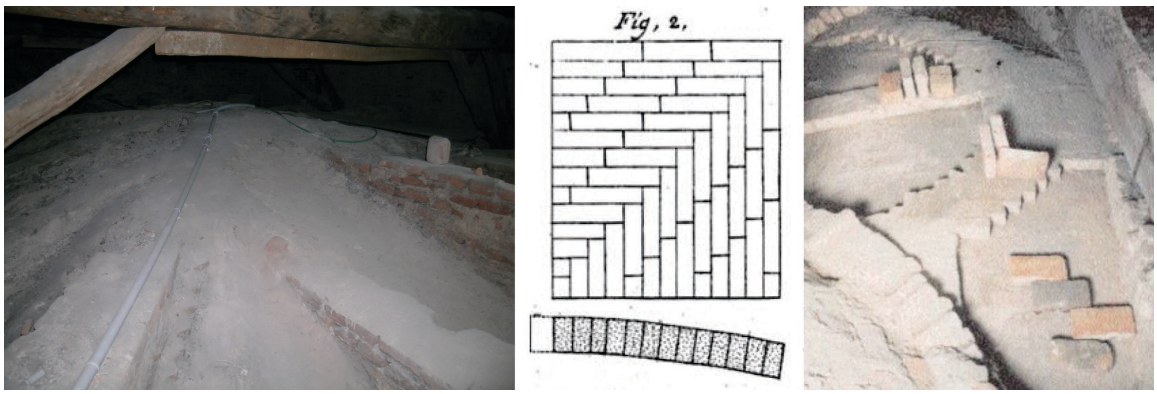

Fig. 8 On the left, image of the extrados of the vault of the Sala dei Quadri ('Paintings room'). Middle and right, example of herringbone pattern of bricks in the cloister vault.

Starting from Breymann's drawings and text, we simulated in 3D the different elements that plausibly composed the wooden centrings used to build the cloister vault of the Sala da Bigliardo ('Billiard room'), in a process of 3D virtual reconstruction. In particular Breymann gave instructions on the disposition of the wooden vertical elements, in function of the dimensions of the room and the quality of the wood (fig. 9). After the virtual construction of the centrings, a wooden frame following the exact shape of the underside of the vault was built. The boards were laid on the frame until the vault was complete and self-supporting (fig. 10).

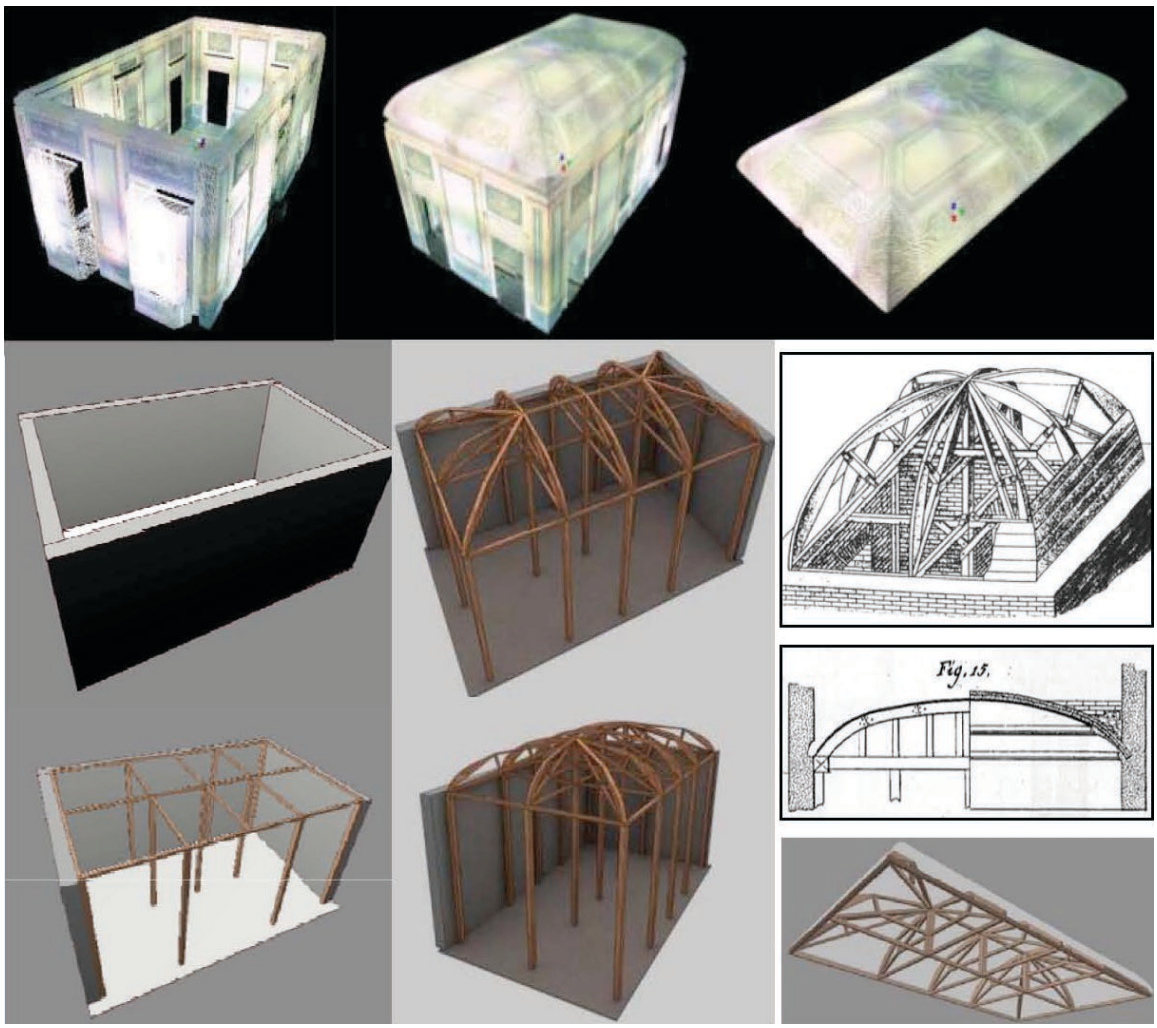

Fig. 9 Simulation of the building process of the vault, starting with the disposition of the wooden centrings. The drawings on the right were extracted from Giovanni Carbonara, *Trattato di restauro architettonico*. The precise shape of the room is derived from laser scanner survey.

The last step in the simulation of the construction of the vault consisted of the 3D virtual reconstruction of the masonry, starting from the arrangement of the bricks oriented along diagonal axes (fig. 10). For the room in which it was not possible to analyse directly the extrados, the virtual reconstruction of the thickness of the vault was drawn in analogy with the surveyed vaults. This was possible because the building was built in a single construction phase, following a unitary plan.

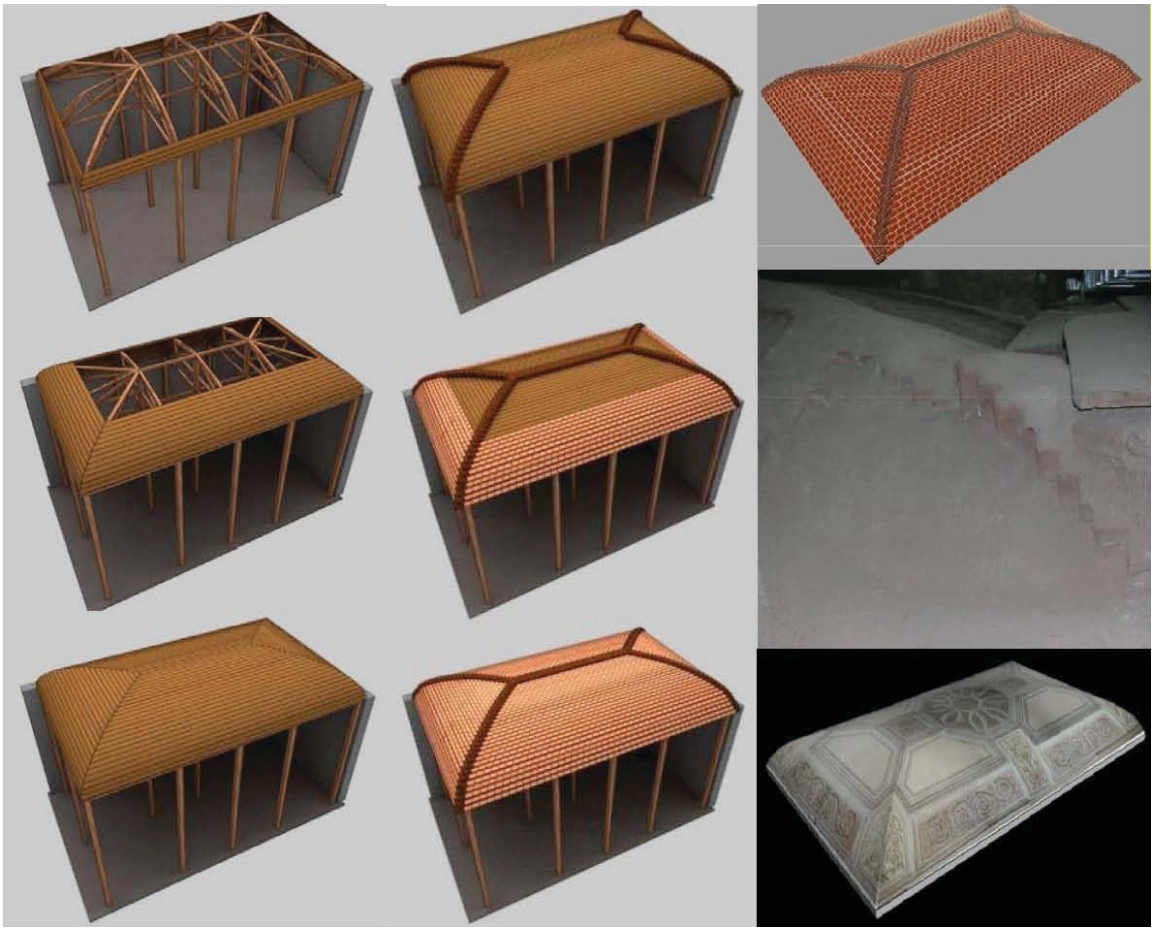

Fig. 10 Simulation of the construction of the cloister vault of the Sala da Bigliardo, with the arrangement of the bricks, as observed in the extrados of the vault. At last the 3D model of the vault was textured with orthophotos.

3D Virtual Model for Preventive Conservation and for Simulation of Reuse

The 3D detailed virtual models of the Villa, useful for improving remote access of 3D data, can in the future provide support for advanced programmes of preventive conservation, in order to guarantee sustainable interventions and maintenance over time. In particular, the 'box-system' (fig. 11) – which is similar to the traditional mode of architectural representation combining plan, section and elevation – makes it possible to represent technological elements not as single but as interconnected units. The open source software and tools that were used to create the infrastructure, which can host both geometrical and historical survey data and models, can be useful for analyses of materials and their degradation across the whole complex.

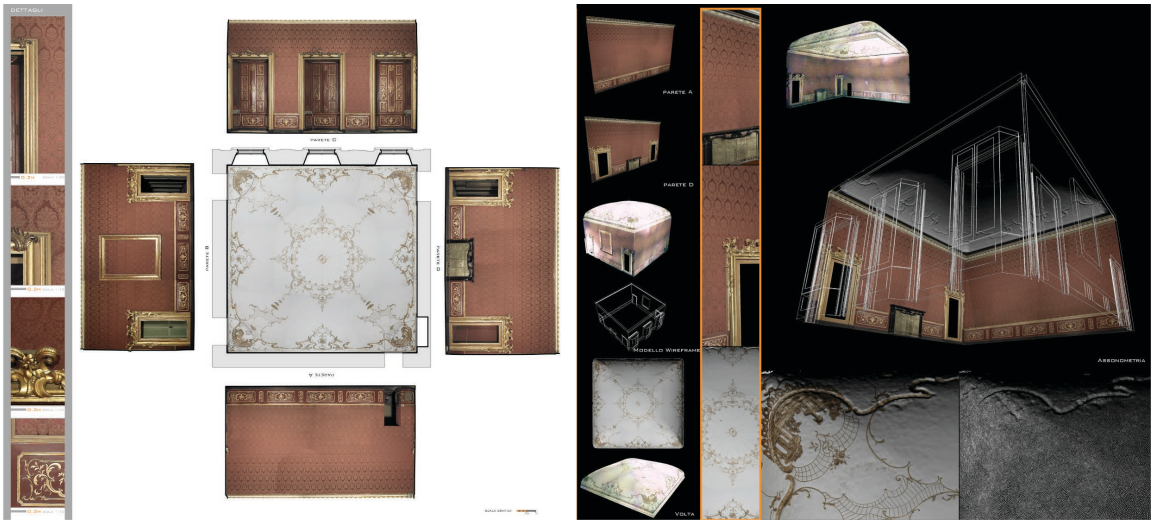

Fig. 11 Left: 'Box system' representation of the Salotto: plan, sections and fronts of the four walls. Right: Three-dimensional model of the room, textured with rectified images. The high resolution of the model enables the user to navigate the rectified images up to a scale of 1:20.

Thus, 3D models of ancient vaults of high geometric precision and incorporating also the exact thickness of the walls, the materials and the disposition of the elements, may support complex analyses on the state of preservation of the buildings and the stability of their structures. In fact, the proposed method shows that through an accurate 3D survey of the structures it is possible also to get all the basic geometric data needed to derive information on the structural genesis of the elements and on the construction methods used in the past. These basic data are useful also to evaluate the structural behaviour of the vaults and to identify geometrical anomalies in the structures.

At the same time, the complex survey and models of the structures and the decorative elements can facilitate the planning of restoration of different parts of the building. The extrados of the vaults and the rooms were surveyed and modelled in a single system. Thus the walls, floors, vaults and their connections can be analysed as one structural whole and each single room can be treated as a sub-unit in a larger system. This can be particularly useful when the structures are fragile and need to be monitored, for example the wooden hanging vaults in the central part of the building (fig. 12).

Fig. 12 Above, images of the extrados of the wooden vault of the Ballroom. Below, 3D model of the vault.

Finally, the high-resolution rectified images, textured on 3D models, make it possible to plan and simulate future uses of the rooms, including the disposition of the furnishings (fig. 13). This is a useful tool for conservation professionals but also for the public administration, as it enables them to make informed decisions about the preventive maintenance of the monument.

Fig. 13 Simulation of future use of the rooms, using the detailed 3D model of the rooms.

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Illustrations

Fig. 1, 3, 5, 10, 11, 13 Drawings by authors.

Fig. 2 On the left *Giuseppe Piermarini* (Milan, 1998). On the right, drawings and photos by authors.

Fig. 4 Above, De Giacomi, *La Villa Reale di Monza* (Milan, 1984). Centre and below, drawings by authors.

Fig. 6 On the left, Guarini, *L'Architettura civile* (Turin, 1737). On the right, drawings by authors.

Fig. 7 Left and middle, drawings by authors. On the right, De Giacomi, *La Villa Reale di Monza* (Milan, 1984).

Fig. 8 On the right, photograph by authors. Right, Breymann, *Allgemeine Bau-Constructions-Lehre* (Stuttgart, 1849-1854); Italian translation Vallardi, *Trattato generale di costruzioni civili* (Milan, 1884), vol. I.

Fig. 9 Drawings by authors. On the right, Carbonara, *Trattato di restauro architettonico* (Turin, 1996), vol. II.

Fig. 12 Photographs and drawings by authors.