

3D MODEL FOR THE DOCUMENTATION OF CULTURAL HERITAGE: THE WOODEN DOMES OF ST. MARK'S BASILICA IN VENICE

Luigi Fregonese, Laura Taffurelli

Politecnico di Milano, BEST, ITALY
luigi.fregonese@polimi.it; laura.taffurelli@polimi.it

KEY WORDS: Cultural Heritage, Survey, 3D Laser Scanning and modelling, Georeferenced Database

ABSTRACT:

The survey of the wooden domed structures surmounting St. Mark's Basilica in Venice is part of a project of documentation, analysis and representation that the E-Lab laboratory of the Politecnico di Milano has been involved in for several years in conjunction with the Procuratoria di Venezia. Three-dimensional modelling and representation through laser scanner acquisition is the method that best lends itself to gathering information on the conformation and state of conservation of the beams that make up the roof of St. Mark's Basilica, which expresses its enormous architectural character chiefly in its five domes. The database obtained from the survey and processing of the topographical data represents a support on which to georeference the information and valuations of the heritage, directly in a 3D environment.

1. INTRODUCTION

Three-dimensional modelling and representation through laser scanner acquisition is a widely used method in the survey of architecture and cultural heritage. In addition to providing information about the geometry of the object of study, this technique makes it possible to extrapolate information on the state of conservation directly in a 3D environment.

Creation of models whose objective is defined in the framework of geometric, spatial, and temporal knowledge implies taking a complex approach to the analysis and organization of the information, which frequently are left out of the normal survey applications. Knowledge also proceeds by subsequent accumulations of information which are built up in a unique container that must make it possible to use them, analyze them and provide interrelationships that can be traced, plus an opportunity to extract the appropriate knowledge.

The database offered by the georeferenced point clouds represents the Spatial Information System for architecture (Gianninetta et al. 2006) which can be used to base important assessments for classifying structural elements or determining the state of decay or conservation of every element that makes up the object of study.

This work of research has involved a "hidden" part of the St. Mark's Basilica in Venice, whose monumental façade, sculptures, and wall and floor mosaics surprise and enchant admirers and whose architectural space is topped by its great, majestic domes. The form and function of the superstructures present in these domes is the focus of investigation of the architectural space that ties the interior of the domes of the Basilica with the volume perceived on the exterior.

Our study closely analyzed the domes and the contiguous areas, more specifically, the "Pentecoste" and "Profeti" domes, with their underlying wooden "skeleton" structure which is covered and which rises up to dominate St. Mark's Square and the lagoon.

In the case of survey of the roof of St. Mark's Basilica in Venice, and the domes in particular, realization of a 3D model of the complex, multiple-part load-bearing structure of the

domes, achieved using semi-automatic and manual techniques, makes it possible to understand the form and composition of the beams and represents the basis for creating a 3D database on which to georeference the information.

It is then possible to identify the wood species used, the state of conservation of the beams, as well as the static function in the typological and structural classification. In addition, it was possible to distinguish the poorly preserved parts in need of rehabilitation from the more recent sections, which were added as replacements for other parts in restoration and maintenance, in order to date the entire load-bearing structure.

Modern needs of systems management (electrical, plumbing and fire extinguishing systems) and maintenance of this historic heritage also require planning based on a survey that is appropriate to these areas, which considers the 3D quality of the structure.

The model realized demonstrates the advantages of laser scanning techniques to obtain a solid 3D representation thanks to the accuracy and completeness of the data, the speed of acquisition and processing (after making a necessary cleaning and vetting of the point clouds), the capacity to supplement the data from other sensors and at different scales.

Interactive visualization and navigation of the model also provide access to information about the form and dimensions of this architectural heritage, in addition to the history and all types of information that can be georeferenced in it, for operators who work on its conservation and for the thousands and tourists and art lovers that can pay a "virtual visit" to the site, which would otherwise be inaccessible.

1.1 The 3D model of the roof of St. Mark's Basilica in Venice

Survey of the general framework of the ceilings and acquisition of the wooden beams of the roof began with an initial campaign of acquisition in 2003-2004.

Before this, the area between the roof and the extrados of the dome and vaults of the Basilica was characterized by the absence of documentation of the complex wooden system. This

is why all the spaces had been surveyed, except for the five main domes.

This study has included application of traditional survey methods, conducted with the TCRM1101 total station and direct survey, with integrations of high density laser scanning survey only in some areas. The sensor used in these cases was the HDS3000, time-of-flight laser scanners by Leica Geosystem.

This was necessary due to the type of spaces - often denoted by difficult access, small size and narrow or on several levels - and due to the objectives of representation. The model resulting from this survey was executed entirely in a CAD environment and simplified as regards the real form of the beams for the purpose of a 3D hierarchical representation of the wooden elements and to promote system engineering and fire-prevention safety, adapted to a 1:50 scale.

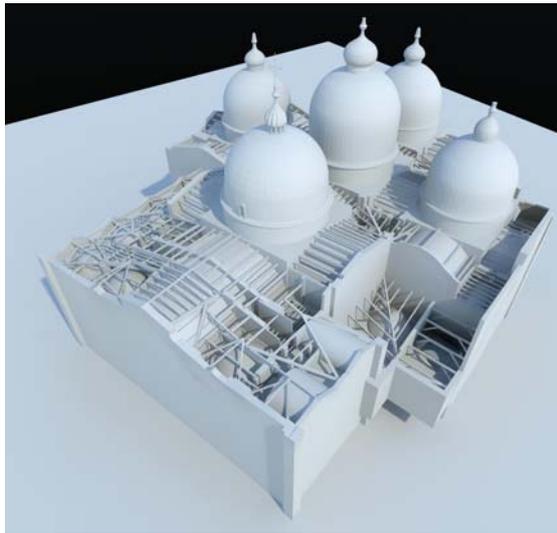


Figure 1. The 3D model of the roof of St. Marc's Basilica in Venice

The second survey campaign, carried out in May 2008, in a single day of acquisition involved the spaces inside two of the five main domes of the St. Mark's Basilica.

1.2 Remarks on the history

St. Mark's Basilica, the structure that stands before us today after many centuries, is the third *reconstruction* of the original foundation built between 827 and 829 AD. Built at the behest of Doge Domenico Contarini, it was initiated in 1063 and completed in 1072 by Doge Vitale Faliero and its design was inspired by the Twelve Apostles Church in Constantinople. It was inaugurated only two decades later, however, when they found reliquaries of the saint, which had been lost during the fire in 976 that destroyed the previous basilica. Historic documents refer to this period, using the term *Fundata*, as if Contarini's Basilica had been a radical work of reconstruction, beginning with the foundation plans, contrary to the philosophy of recovery and restoration of the buildings and safeguarding human resources and materials, typical and characteristic of that historic period.

More recent analyses, however found that this process was not defined by an interruption, but rather through a construction practice that did not evolve by extemporaneous accelerations, but rather by a single structural body in continuous change and reuse.

The writings, the analyses made of the documents and innovative survey techniques have since made it possible to identify pieces of the walls of the previous basilicas, incorporated into the present-day building, which clearly prove that the previous architecture was used rather than the old church of the Particiaci having been demolished to build a new one from the ground up, more or less in the place of the previous church, to give a sign of power and to leave an indelible sign of Doge Contarini's legacy. Therefore, the massive job of structural reorganization owes to Contarini's period, which radically changed the appearance of the basilica and its distribution. The entire structure of the building was renovated, from the foundation to the roof.

1.2.1 The domes of the Basilica

At the current state, documents and sources do not demonstrate with certainty the construction system of the domes, namely, whether they were generated by curves or complete self-supporting domes. Their installation in the 13th century is proven by various sources and by analyses of the construction materials: the fake drums covered on the exterior with stone present a layer of filling with stones to create the continuous supporting surface of the crown by means of the wooden superstructure. Certain iconographic sources identify a span of time of between 1210 and 1270 AD for construction of the raised portions.

Constructing the domes was indispensable to make them visible from the lagoon beyond the Doge's Palace, which in its reconstruction after the fire in 976 had hidden from view.

Construction can be dated from between 1210 and 1270, estimated by the presence of two mosaic images inside and outside the basilica that describe the form in different time periods.



Figures 2 - 3. The St. Marc's domes before and after the built of superstructures in wood and lead

Image no. 01, located on the western wall of the south transept, represents the basilica with the Romanesque roof: in this case, the mosaic was dated at 1210 AD. Image no. 02, located on the façade of the great archway to the left, represents the church with the Byzantine domes, surmounted by the wood and lead structure: the mosaic is dated at circa 1270 AD.

The practice in use at the Basilica involved conservation of the wood superstructures: this is intended to affirm that the maintenance and conservation processes of the individual wooden elements also involved the portions of the domes in our investigation. At the present time, the Pentecoste dome has been submitted to numerous, major renovations over the years, some done recently, with have not changed the type or characteristics of the elements from a structural perspective. Another case is manifested in the Profeti dome, whose present-day appearance dates back to the early 19th century and is in need of a complete renovation intervention. There are evident signs of structural decay due especially to water seepage. To preclude any further damage, safety scaffolding was installed on the dome. The Procuratoria di San Marco is currently designing a general plan

of action for this structure, which includes a piecemeal dismantling and reconstruction/replacement of the load-bearing elements where necessary and renovation and conservation of the remaining parts.

This is the background of the research for the 3D survey of all the elements of these parts.



Figure 4. The 2D representation of *Pentecoste* wooden beams into the Basilica longitudinal section

2. THE SURVEY

The survey of these fascinating areas was done using the phase differential TLS HDS6000 sensor by Leica Geosystems and with the support of the TCRM1101 total station for the topographical placement of the Basilica in the general reference system.

Approximately 18 scans were acquired per dome, at three different levels, in order to appropriately cover the areas of interest.

In the first level, the laser was mounted on a tripod and set on the brick and mortar dome; in the second level, the laser was mounted on the tripod set on the wooden beams; and on the third level, the laser was located directly on the beams for the reduced dimension in height, at the top of the dome.

The acquisition resolution selected for this type of intervention (super-high resolution with point spacing of 3.1x3.1mm at 10 meters of distance with panoramic acquisition of 360x310°) has led to the use of rapid scanning times (approximately 7 minutes per scan) for a total of 65 million points each.

The body of data obtained was very dense and highly detailed, albeit quite heavy in terms of hardware management.



Figures 5. The survey was done using TLS HDS6000 (Leica) approximately with 18 scans per dome at three level

The response of the sensor with respect to the wooden material surveyed was as the instrument manufacturer's claims. The

wood species present in the documents have given an excellent albedo surface (this wood is dried and seasoned, with a low water content), therefore ensuring a surface with a ± 2 mm precision.

3. DATA PROCESSING

The noise present in the scans done was generated by elements inside the domes of various material; the temporary safety scaffolding installed on the Profeti dome and the stainless steel pipes of the old fire-prevention system present in both domes have generated a datum in proximity to these elements and in the tangential points with respect to the scanning center with a higher than expected noise.

The first step in processing the data acquired was reduction of these outliers present in these outliers in these unstructured scans. Subsequently, the plan proceeded with a process of segmentation and filtering to eliminate redundant and superfluous data.

The results of the scans were aligned by combining features, vertices and making use of area-based matching algorithms. For example, figure 06 shows the alignment data of a pair of scans (Cup1-23 and Cup1-24) done in the Pentecoste dome in which we see that the high density of the acquisitions enables precision in this process of a maximum of 2 mm in the three components.

Control ID	Scanfield	Scanfield	Type	Status	Weight	Error	Error Vector
sc Target: 12	C1_23	C1_24	Control: Vertex/Vertex	On	1.0000	0.001 m	(0.000, 0.000, 0.001) m
sc Target: 14	C1_23	C1_24	Control: Vertex/Vertex	On	1.0000	0.001 m	(-0.001, 0.001, 0.000) m
sc Target: 2	C1_23	C1_24	Control: Vertex/Vertex	On	1.0000	0.002 m	(0.000, 0.000, -0.002) m
sc Target: 200	C1_23	C1_24	Control: Vertex/Vertex	On	1.0000	0.002 m	(0.001, -0.001, 0.000) m
sc Target: 204	C1_23	C1_24	Control: Vertex/Vertex	On	1.0000	0.002 m	(0.001, 0.001, -0.002) m
sc Target: 5	C1_23	C1_24	Control: Vertex/Vertex	On	1.0000	0.001 m	(-0.001, 0.000, 0.001) m
sc Target: 8	C1_23	C1_24	Control: Vertex/Vertex	On	1.0000	0.001 m	(-0.001, 0.000, 0.000) m
sc Target: 9	C1_23	C1_24	Control: Vertex/Vertex	On	1.0000	0.001 m	(0.000, 0.001, 0.001) m

Figures 6. An example of alignment results

The next phase of georeferencing the point clouds with respect to the general reference system of the St. Mark's Basilica, was done on the basis of targets, acquired with the total station, after the scans were aligned with each.

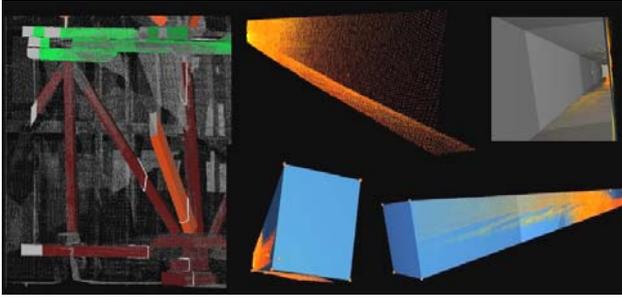
In this case, the values of the absolute transformation have provided residuals of approximately ± 3 mm, slightly more than the previous one. The data expected and verified demonstrate how it supplies a similar accuracy of the control points (± 3 mm) even the use of forced centering systems in the topographical placement done using traditional instruments and typical operating techniques (total station and prisms set on tripods).

Cyclone 6.0 software was used to elaborate the acquisitions done on three levels for a total of 380 million point clouds.

4. MODELLING

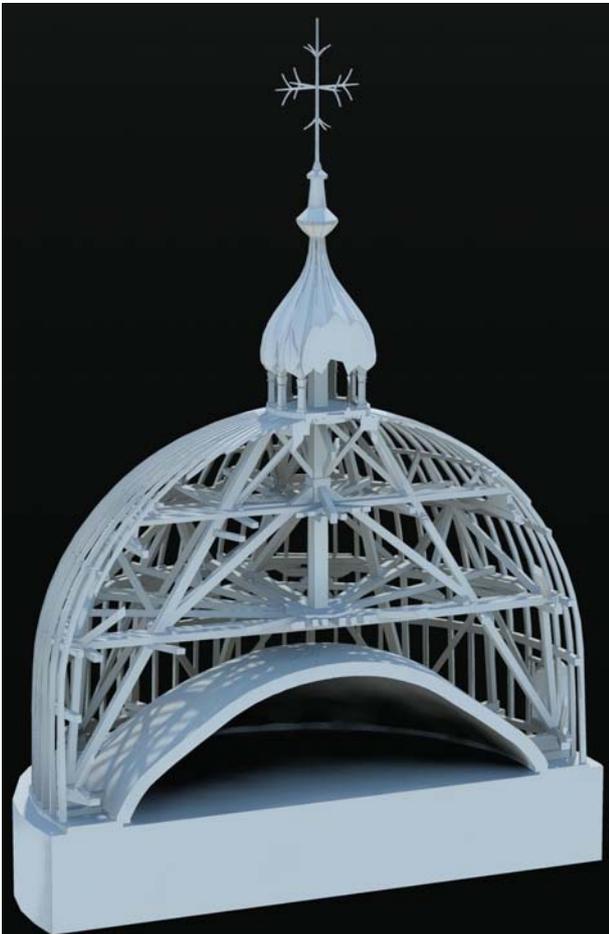
The 3D reconstruction of the space under the wooden domes atop St. Mark's Basilica was adapted to the type of final model required by the project, which has a different nature depending on which dome is being studied.

As regards the Pentecoste's dome, the first visible dome from the main façade of the church, the purpose of the survey was to document the structure in its entirety in order to understand the



Figures 7. Automatic generation of solids from laser data

construction methods and static situation, to realize a 3D database on which to georeference multiple types of information. The primary and secondary wooden beams were realized through the use of primitives, with automatic generation of solids or patches of the point cloud, thanks to the use of best fitting algorithms of the spatial surfaces.



Figures 8. Visualization and rendering using 3DStudioMax 2009

This procedure has inevitably led to simplification of the complexities that characterize these elements, made up of a "living" material such as wood, distinguished by defects or deformations and twisting induced by the static behaviour of the structure as a whole.

Where the deviations of the real geometry of the surface were considered acceptable, the process was conducted in the semi-

automatic mode, working in the Cyclone environment, while in the other cases, modelling was done in CAD (Autocad 2008 – Cloudworx 3.2), through the use of cross-section profiles along the directions chosen.

Visualization and rendering of the final model was executed using 3DStudioMax 2009 software by Autodesk.

5. REPRESENTATION AND USABILITY OF THE DATA

Representing the object through the use of models makes it possible to simulate very faithfully three-dimensional images that the human eye is unable to distinguish from perspective photographic representations. In our case, the models for representing the hidden parts, which up to now have been considered empty or devoid of architectural definition due to the lack of information, take shape and can be studied, analyzed and interrogated through product repertoires.

A cognitive model in the architectonic environment can be described as a collection of structured objects, identified through a precise vocabulary that diversifies the meaning, building an abacus of the 3D entity or an abacus of the types.

The concept of intrinsic usability meets the principle of efficiency; the more simple the structure of the model is, the more usable it will be. It would be wrong to confuse simplicity with a lack of information or superficiality, in which not all things can be explained using simple words.

This efficiency is reached by classifying the elements through a division into levels:

- a. the general level, for example the dome, vault, skirts, connections, etc, in the case of architectural representations;

In particular, the space under the roof and the domes are divided onto levels of environments and in each one are subsequently classified the objects contained in it. For example the Pentecoste dome is split into three levels, with a hierarchical structure that starts from the connecting ring of the circular beam, to the central post at the top.
- b. the topographical level, which involves the way in which the various parts are divided and connected to each other; this category includes a division of the elements associated with the general class level, according to a distinction that can concern the behaviour in the structural case. The first level of the Pentecoste dome is divided according to the structural behaviour in: the structural support beam, trestles to divide and unload the tension on the support walls, connecting beams used as windbrace tension members, support brackets located up high for the second level
- c. the metric level, or the way that the objects occupy the space, with what shape and what dimensions. In this level are the geometric characteristics of the form and the properties associated with it (deformation, decay, others).

In this way, even complex models can be known and analyzed.

6. CONCLUSION

The modelling process, still in progress for the Profeti's dome at this release date, will fulfil the geometrical component of wooden roof database of the st'Marc Basilica and will be able the georefereration of all information about it.

The acquired process of knowledge, and that will derive from the realization of this database, will be able to satisfy the documentation and representation requirements, that fits well

with it's made in rest of Basilica, and it will be able to promote greater control and planning of conservative operation. The measurement and diagram types of covering elements may facilitate the study of the involving of the static over time. The possibility to interface to virtually model by several types of users, also make possible the access to places not visible to the non- experts, but of great interest and fascination.

7. REFERENCES

ROBERTO CECCHI, La basilica di San Marco, la costruzione bizantina del IX secolo. Permanenze e trasformazioni, ed.Marsilio, Venezia 2003.

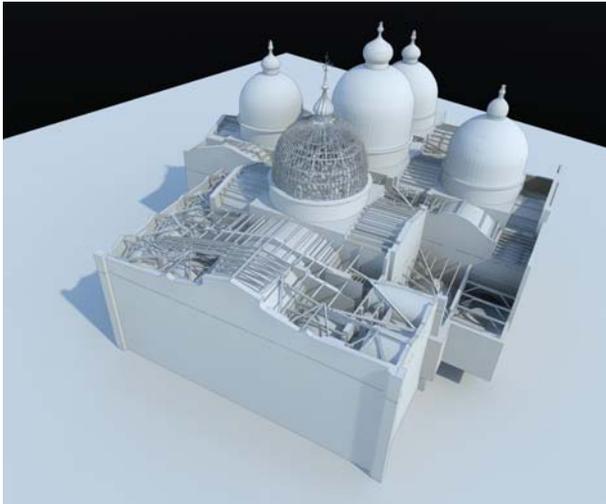
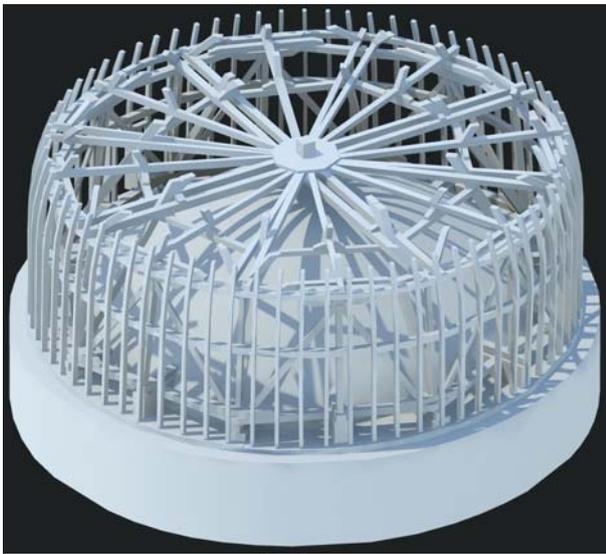
RENATO POLACCO, San Marco. La Basilica D'oro, Milano 1991.

VIO E., LEPSCHY A., Scienza e tecnica del restauro della basilica di San Marco, Atti del convegno Internazionale di Studi – Venezia 1995 , Istituto di Scienze, Lettere ed arti, Venezia 1999.

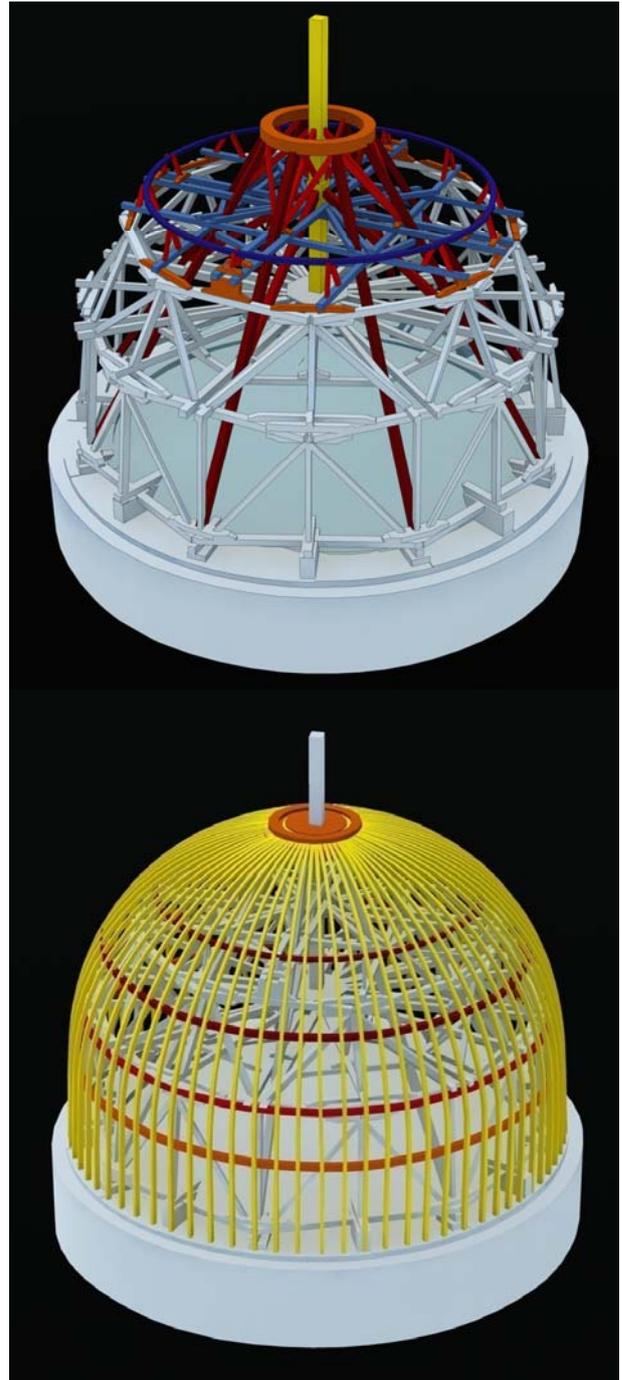
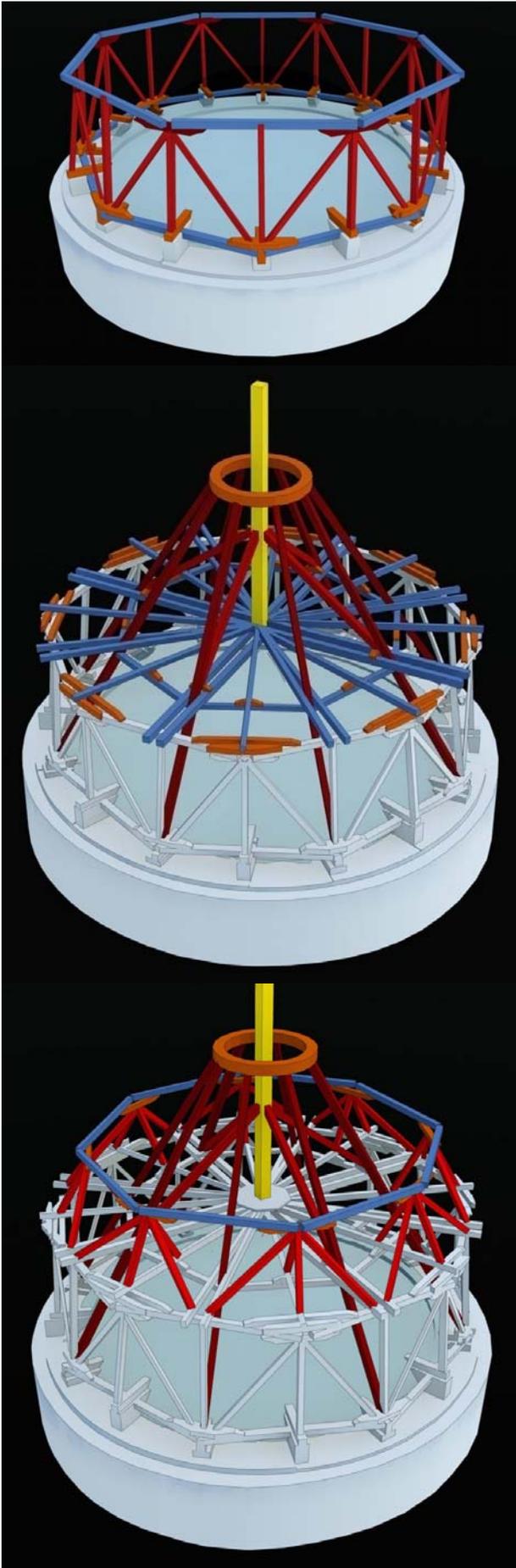
GIANNINETTO M., GIUSSANI A., RONCORONI F., SCAIONI M, Integrazione di differenti tecniche di acquisizione dati per l'analisi diagnostica 3D di un oggetto architettonico, VIII Conferenza Asita, Rome , Italy

7.1 Acknowledgements

We thank arch. Ettore Vio and Ing. Davide Beltrame for their cooperation and willingness to allow us to work in the St.Marc's Basilica places; we thank Roberto Picelli for his work in this research context.



Figures 9-10-11. Visualization and rendering using 3DStudioMax 2009



Figures 12-13. The classification of beams in according to the structural behaviour