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Laser modeling and Structural assessment of a XVIIth century wooden dome

Modelowanie laserowe i ocena konstrukcyjna XVII-wiecznej drewnianej kopuły

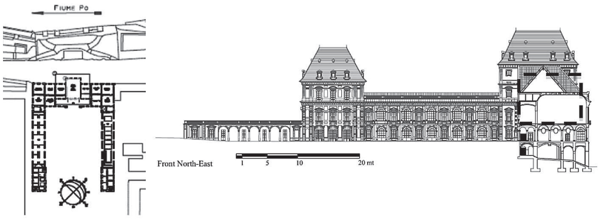
Keywords: Cultural heritage, Wood dome, Structural assessment, Digital photogrammetry, Laser surveying, Orthophotography

Słowa kluczowe: dziedzictwo kulturowe, drewniana kopuła, ocena konstrukcyjna, cyfrowa fotogrametria, pomiar laserowy, ortofotografia

1. INTRODUCTION

The Valentino Castle is placed on the north side of the river Po, and is nowadays fully included in the city of Turin, Italy. The Castle has a very ancient origin, though the first official reference to it dates only 1543 [1]. The Duke of Savoy acquired the asset composed of a palace with garden and, starting from 1620, Christine of France charged the architect Carlo di Castellamonte with some main extension works, including the doubling of the central body and the realization of the towers. In the nineteenth Century the destination of use of the Castle changed several times (Veterinary school, barrack, Royal School of Application for Engineers), and the structure of the Castle was each time modified consequently.

Nowadays, the Castle hosts the Faculty of Architecture of the Politecnico di Torino. The U shaped plan of the Castle is covered with a valuable roof in Vallone's Dark Stone tiles, supported by wooden tables connected to an elaborated wooden frame [2]. A scheme of the plan and longitudinal section of the Castle is shown in Fig. 1.



(a) (b)

Fig. 1. Plan (a) and longitudinal section (b) of the Castle

The Hall of Honor, located at the first floor of the main body, is now the aula magna of the faculty of Architecture. The Hall has a rectangular shape 16 m long and 11 m wide. The Hall is covered by a pavilion vault, and is fully decorated with frescoes and stuccos.

The vault has been damaged by water infiltration in the past, especially during the last world conflict, due to the fact that the roof was largely damaged. For this reason, the fresco in the central region of the vault is interrupted, and replaced in the past with uniformly colored stucco.

The dome of the Hall is a so-called "fake vault" or "camorcanna" realized with plaster applied on reed mats, which are hanging on a rib wood frame. The typology of the vault can be referred to the Philibert Delorme technique [3].

The principal structure is the above wood rib frame (Fig. 2a) that rules the curved shape of the dome. Each rib is obtained joining together two or more shaped planks with steel nails. The wood planks are 3-6 cm thick, 20-40 cm wide, and usually 2-3 m long. The rib spacing is around 0.7 m. The ribs are connected with steel nails to the underlying orthogonal wood joists. Joist section is 5 cm wide and 2 cm height. The joist spacing is around 25 cm. The continuous reed mat is hanging on the joists, and realizes the surface for the subsequent layers of plaster and stucco for the frescoes.

Since the dome suffered from degradation during the years, a series of interventions were put into place. Among the most relevant, at the end of the XIXth century

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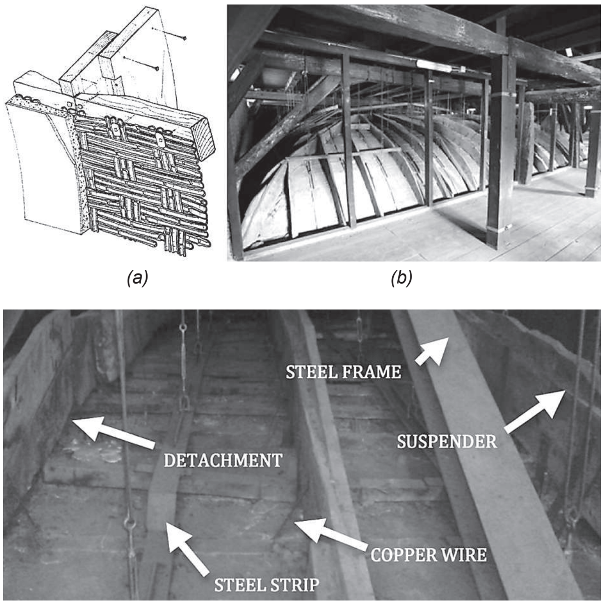
A. d'Andrade provided to fill the space between the joists with additional plaster, reinforced with steel nets, connected to the ribs by copper wires. The aim was to contrast the detachment of the vault from the rib structure. Unfortunately, the majority of those interventions added weights to the original structure.



(a) (b)

(c)

Fig. 2. Scheme of "camorcanna" layers [4] (a), extrados of the Hall of Honor (b) of the Valentino Castle

More recently, in occasion of the celebrations of the first Century of the Italian Republic, the roof structure was renewed and a steel frame structure was placed above the dome, and connected, with vertical suspender cables, to iron strips that were screwed to the little wood carpentry. An overview of the extrados of the dome, with the steel frame structure and the suspenders is shown in Fig. 2b, while some details are shown in Fig. 2c.

Nowadays, a survey revealed that the suspender cables above the vault in the region close to the abutments have lost their tension. This may indicate an increase of the vault deformation; therefore a structural assessment of the dome is mandatory.

The present paper illustrates the results of the structural survey and of the numerical simulation of the dome. In addition, some non-destructive acquisitions are described, which were carried out to support the structural analysis. Finally, possible intervention techniques are discussed, accounting for the restoration criteria of reversibility, minimum intervention, sustainability and compatibility.

2. LASER SURVEY AND MODEL GENERATION

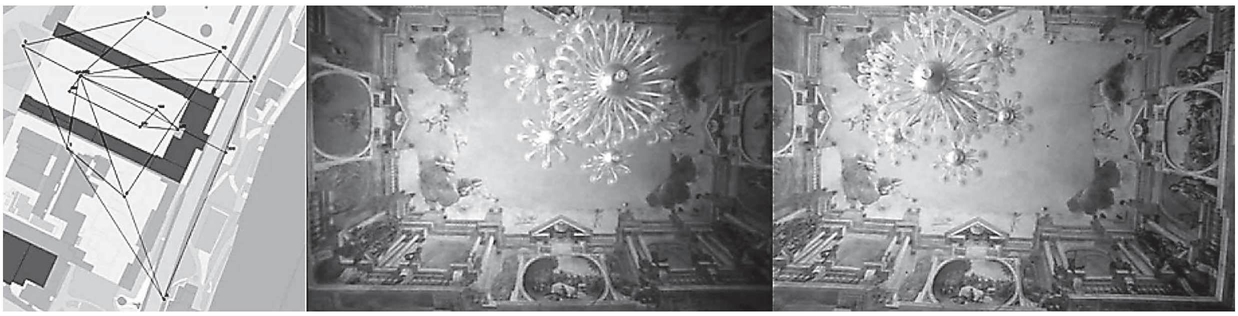
Laser scanning techniques, which enable the generation of 3D models, even with high details level, can properly provide the metric survey of non-planar architectural structures and elements, featured by high complexity of general composition and decoration [5].

Despite a large number of commercial systems are equipped by digital cameras, coaxial with laser distance ray, when a high photographic resolution and precision is needed, integrated systems combining digital photogrammetry and laser clouds acquisition are preferred. [6]

The harmonization and the perfect matching of laser survey and connected models with photogrammetical products are ensured by a set of control points; laser clouds alignment and photogrammetical processes in fact are based on these points that are measured by high precision topographical methods. The topographical networks ensure the single reference system for each surveyed portion of the building, and the control of random blunders diffusion (Fig. 3). In cultural heritage documentation, traditional or innovative 3D types, the main reference system can be local or global; in the study case of Valentino castle, some topographical networks just fixed during other metric documentation activities ensure that every survey updating can be related to the main coordinate systems, which is connected to the regional and urban technical maps (UTM WGS84 reference system).

The vault of the Hall of Honor is featured by a clearly knowable revolution surface, constituted by a cylinder surface based on a polycentric translating arc; there is a rich frescos decoration but not plastic ornamental elements, such as in other lounges, so the laser survey acquisition performed by LEICA HDS6100 phase based scanner has been fulfilled easily with the only encumbrance of the huge chandelier (Fig. 3). 360° points clouds have been acquired in three different position just to front the chandelier shadow cone; they have been registered by control points signalized by reflective target, and results are featured by sub-centimetrical accuracy.

After the complete cloud clearing (clearing of furniture and filtering cloud in order to remove noise) we obtained the points model describing the only interesting surfaces (floor, walls and vault). A large number of revealing section planes have been detected with the aim of analyzing the curves trends

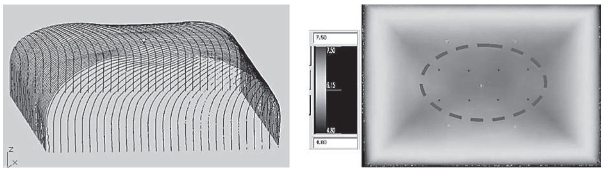


(a) (b)

Fig. 3. The first order GPS network fixed for the Valentino castle survey (a), Stereoscopic photograms showing the encumbrance of the chandelier (b)

and spotting the anomalies (horizontal and vertical planes, containing straight lines or generatrix polycentric arcs). After a model shape optimization, several sets of the vaults profiles have been extracted using the commercial tool 3D Reshaper-by Technodigit (Fig. 4a).

The digital elevation model (DEM – Fig. 4b), in which radiometric code of each pixel represent the distance from a plane, in this case horizontal, have been obtained by a cloud decimation until 5% of raw data (from 20 to 100 million points). This surface representation reveals a probable loss of the original geometrical shape: we can estimate a subsiding area near to the central portion of the vault (red dots oval in Fig. 4b). The loggia vault, located close to the main lounge, presents some more precise geometries; the second DEM, derived from another laser model similar to the one we are discussing [7], shows different clarity of intersection bends; we need to consider that such structure has been under restoration during 1980s. The Dem is also used for the correct photogrammetical projection of images on a plane, in order to obtain orthophotos or textured models [8].



(a) (b)

Fig. 4. A laser profile model for visual control of subsidence (a); The Hall of Honor DEM: the red oval identify the subsidence zone, caps shaped, while the light points are fire detectors and the blue points are the computed locations of photograms projection centers (b)

2.1. Digital photogrammetry and orthophotography

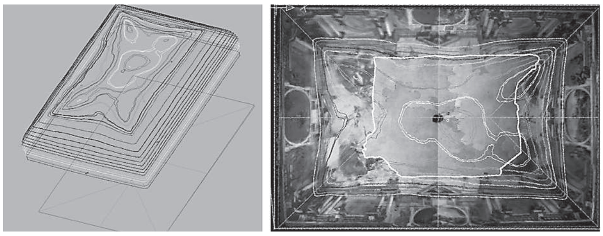
The photogrammetrical survey has been planned in order to generate an orthophoto of the dome [8]. The non metric camera (Canon EOS 1Ds mark II, sensor CMOS 24 × 36 mm 4992 × 3328 pixels) with the calibrated objective (focal length 20.42 mm) has acquired photograms from the floor; since the max shot distance is about 9 m, the embracement is about 16.2 × 10.8 m, i.e. close to the Hall size.

The presence of the chandelier required the acquisition of redundant data. Therefore, 8 photograms, set in two stripes with a high overlapping percentage (80%), have been collected with the pixel size equal to 3 mm (Ground Sampling Distance – GSD). The orientation solution, performed by a single block processing (bundle block method) has provided very good results, with round minus square on measured points equal to few millimeters.

The analysis of section profiles, set in the horizontal or vertical planes and compared with the hypothetical original bending arcs, has enabled the chance to ascertain several localized deformation of the vault, in the order of few centimeters. The surface contours of the vault, computed with a equidistance of 5 cm, presents an high level of geometrical aberration (Fig. 6a), that must be considered in the structural assessment of the vault.

The location of height anomalies obtained from the laser model, and the shape of the frescos abruption outlined in the orthophoto, are in good agreement when results are reported to the same reference system (Fig. 6b).

The asymmetrical trends of contours seems to be connected with the ambit of the vault restoration, and the careful examination of discards measuring the distance in selected points of the actual profiles from the expected ones.

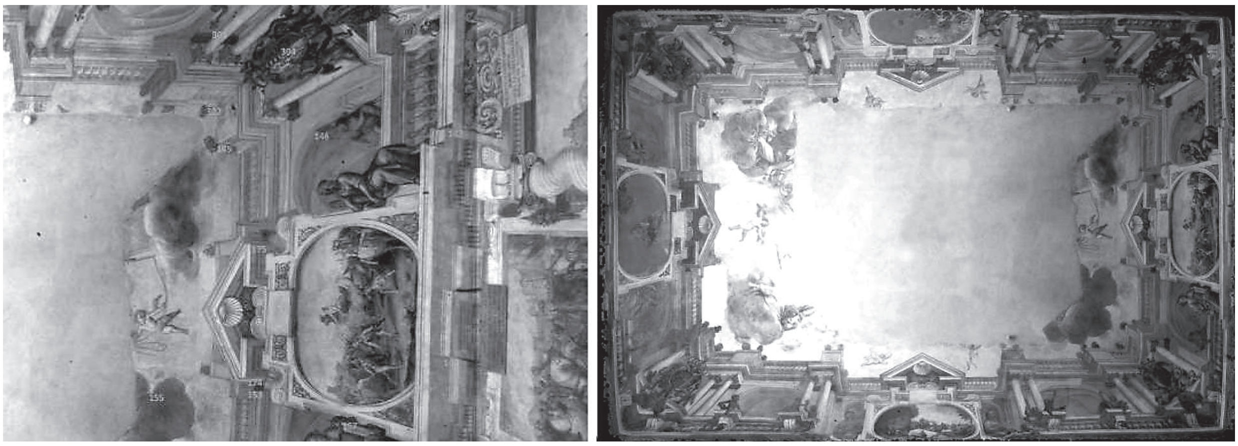


(a) (b)

Fig. 6. Superimposition of the referenced orthophoto with the section profiles (a); final orthophoto of the dome, obtained by a mosaic of projected photograms (b)

3. MATERIALS CHARACTERIZATION

For historic structures, quality assessments of members allow for the maximum retention of original material. The preservation of original structural fabric and associated construction conserves both the cultural significance of the building including architectural qualities and building techniques and the historic and socially important aspects associated with the structure. Furthermore, gaining additional understanding of building material durability, capacity, behavior and



(a) (b)

Fig. 5 Control points for the computing of photogrammetric solution are natural points on the frescos (a); final orthophoto of the dome, obtained by a mosaic of projected photograms (b)

(a) (b) (c)

Fig. 7. Sampling of the wooden structure for identification: from the joist (a); from the rib (b); from the reed mat (c)

use, as well as building techniques and craftsmanship from existing structures provides knowledge that can be applied to present-day construction. A quality assessment begins with the assessment of the members and components that make up the structure as a whole. Samples for the identification of species concerning the main structural elements of the vault are shown in Fig. 7.

The wood ribs of the vault are made of poplar (*Populus sp*.). In order to assess the quality of the wood, a semi-destructive campaign has been performed with resistographic drilling.

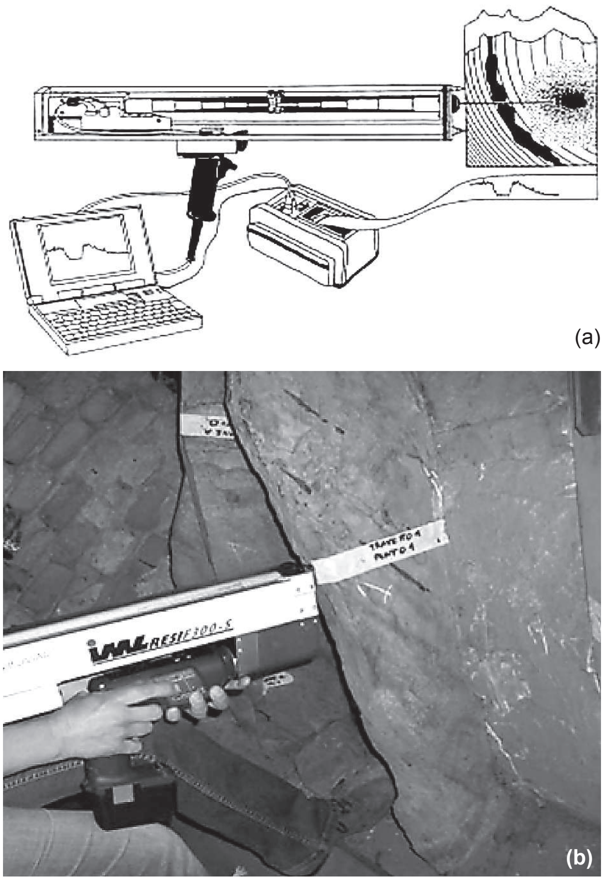
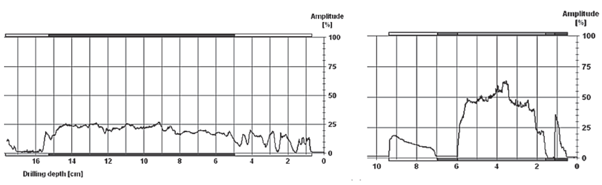


Fig. 8. Sampling of the wooden structure for identification: from the joist (a); from the rib (b); and from the reed mat (c)

Resistance drilling offers a non-destructive means of analyzing the quality of the interior material in wood members. Resistance drills use small diameter (1.5-3.0 mm [0.6-0.12 in]) needle-like drills to bore into timber members and measures the resistance the drill bit encounters as a function of the penetrated depth. Resistance drills have electric motors and are battery operated, offering portability for field investigations. Drill bits are flexible, tungsten steel-tipped needles that will vary in length depending on manufacturer. The needle has to be replaced after 50 to 100 drillings, depending on manufacturer and use.

The drill bit is advanced and rotated at a constant speed throughout the drilling. The torque required to maintain the constant cutting speed corresponds to resistance and is recorded and graphed with respect to the penetration depth. Graphing of resistance data can be done with paper strips, wax paper, or recorded and stored electronically on computer (Fig. 7). Peaks in drilling plots correspond to higher resistance or density, while dips and low points are associated with lower resistance and density.

The resistographic drilling sampling was performed on some of the ribs of the vault, drilling in the two directions perpendicular to the rib longitudinal axis, respectively along the rib height and along the rib thickness (Fig. 9). When drilling is performed along the thickness (Fig. 9b) of a rib composed by three planks, the two discontinuities are clearly recognizable.



(a) (b)

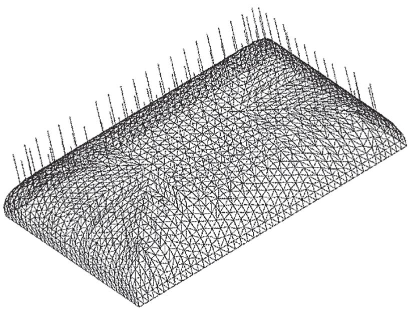
Fig. 9 Resistographic drilling diagrams: along the rib height (a); along the rib thickness (b)

The amplitude in the resistograph diagrams reveals a wood quality ranging from good to very good. It is worth noting that such values are hardly ever encountered when testing nowadays poplar samples. In fact, historical poplar, grown without intense cultivation program, and in a quite colder environment with respect to nowadays, is a much tougher material.

On the contrary, the efficiency of the connections is very hard to assess, although each rib is composed by two or more planks, and head joints are not overlapping.

4. PRELIMINARY FINITE ELEMENT MODEL

A preliminary Finite Element model has been set up in order to understand the structural behaviour of the vault. The model accounts for the exact geometry of the vault, according to the laser survey and the corresponding initial geometry extrapolation. In addition, all the main structural components are considered: the shell and the rib frame, as well as the iron strips and the suspenders. The shell represents the behaviour of the plaster, of the reed mat and of the wood joists in a single equivalent layer. The linear analysis has been carried out with the finite element program DIANA [9]. The overall mash of the model is shown in Fig. 10a, while the table in Fig. 10b reports the basic mechanical assumption.



(a)

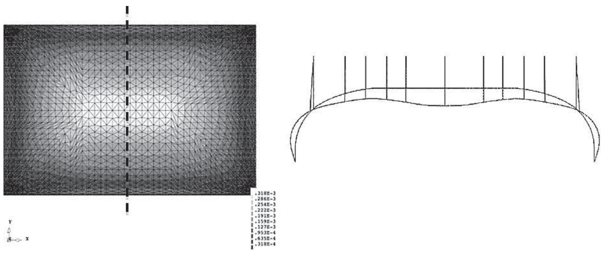
	E [Pa]	ν	ρ [kg/m^3]	type
Suspenders	2.1E+11	0.3	7850	truss
Ribs	8E+9	0.2	510	beam
Strips	2.1E+11	0.3	7850	beam
Vault	13E+9	0.3	1500	shell

(b)

Fig. 10. Mesh of the model (a); mechanical parameters of the model (b)

The model is subjected to the only action of dead load due to gravity. At the present stage, the nonlinear behaviour of the materials has not been considered yet. Therefore, the model can provide only preliminary information about the structural behaviour of the dome.

Nevertheless, the obtained deformed shape, shown in Fig. 11, is in agreement with the anomalies measured by the laser-scannig survey. In particular, the annular region around the big chandelier appears to be the most prone to displacements. On the other side, the suspenders, which are located in the outer region of the vault, are not elongated at all. This corresponds well with the evidence of the survey, which reveals that many of them have actually lost their tension.



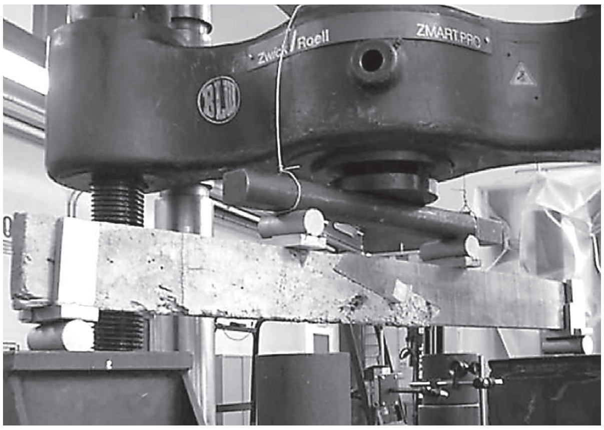
(a) *(b)*

Fig. 11. Contour plot of vertical displacements (a); transverse section with vertical displacements (b)

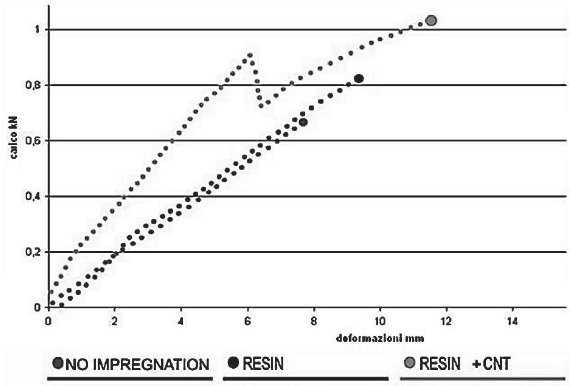
5. CONCLUSIONS

The case study of the Hall of Honor of the Valentino Castle in Torino, Itlay, is presented. The detailed laser survey, and ortophotography allowed for an accurate modelization of the vault geometry at the present state, and the localization of the main geometrical anomalies.

This information is combined with some non-destructive analyses and with the structural survey of the extrados of the vault. The preliminary finite element model is confirmed as far as the deformed shape is concerned, and also the loosen suspenders can be localized.



(a)



(b)

Fig. 12. Bending tests and scheme for the mechanical resistance on timber "Jupiter" joints (a); load displacement diagram: positive effect of the reinforcement (b)

The extraordinary maintenance of the vault has to be carried out adopting very low invasive, but very innovative techniques. This is the subject of the project M.A.N. for the consolidation and reinforcement of historical wood structures with nanoreinforced composites. Such techniques have been already tested on historical samples, characterized by the classical "Jupiter" joint connection [10]. The first results obtained from the laboratory tests are quite promising, as can be see by Fig. 12b; therefore the technique will be applied in the described case study.

ACKNOWLEDGEMENTS

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Abstract

The main room of the Valentino Castle in Torino, the "Salone delle Feste", was conceived and realised in the XVIIth century under the guidance of Carlo di Castellamonte. The beautiful frescos and stuccoes of the domical vault are sustained by a typical Delorne carpentry, whose span is among the largest of their kind. The dome suffered from degradation during the years, and a series of interventions were put into place.

Nowadays, a survey revealed that the suspender cables above the vault in the region close to the abutments have lost their tension. This may indicate an increase of the vault deformation; therefore a structural assessment of the dome is mandatory.

In order to reinforce the structural hypothesis of damages and to reveal the deformation effects, a high detailed metric survey have been carried out with integrated laser scanning and digital close range photogrammetry. The photogrammetrical survey of frescos, with the re-projection of images on vault surface model (texture mapping), is purposed to exactly localize formers restoration and their signs on frescos continuity.

The present paper illustrates the generation of the 3D high-resolution model and its relations with the results of the structural survey; both of them support the Finite Element numerical simulation of the dome.

Finally, possible intervention techniques are mentioned, accounting for the restoration criteria of reversibility, minimum intervention, sustainability and compatibility.

Streszczenie

Główna sala na zamku Valentino w Turynie, zwana "Salone delle Feste", została zaprojektowana i zrealizowana w XVII wieku przez zespół pod kierunkiem Carlo di Castellamonte. Piękne freski i stiuki na sklepieniu są wykonane na konstrukcji ciesielskiej typu Delorne, której rozpiętość jest jedną z największych pośród konstrukcji tego typu. Przez lata kopuła systematycznie niszczała, w związku z tym podjęto serię prac interwencyjnych.

Obecnie badania ujawniły, że ściągi umieszczone powyżej sklepienia, w pobliżu przypór, straciły napięcie. Może to wskazywać na wzrastającą deformację sklepienia, dlatego niezbędne jest przeprowadzenie oceny konstrukcyjnej kopuły.

W celu potwierdzenia oceny stanu konstrukcji dotyczącej zniszczeń oraz wykrycia skutków deformacji, została przeprowadzona bardzo szczegółowa ekspertyza metryczna przy użyciu zintegrowanego skanowania laserowego i cyfrowej fotogrametrii bliskiego zasięgu. Badania fotogrametryczne fresków, oraz ponowna projekcja obrazów na modelu powierzchni sklepienia (mapowanie tekstury), miały na celu dokładną lokalizację wcześniejszych działań restauratorskich i ich śladów w ciągłości fresków.

Niniejsza praca ilustruje proces tworzenia modelu 3D o wysokiej rozdzielczości, oraz jego odniesienie do rezultatów ekspertyzy konstrukcyjnej, oparte na numerycznej symulacji kopuły metodą elementów skończonych.

Na koniec wymieniono działania, które można podjąć w celu ratowania obiektu, uwzględniające restauratorskie kryteria odwracalności, minimalnej interwencji, trwałości i zgodności z pierwowzorem.