Terrestrial Laser Scanning and settled techniques: a support to detect pathologies and safety conditions of timber structures

Terrestrial Laser Scanning and Settled Techniques: a Support to Detect Pathologies and Safety Conditions of Timber Structures

Clara Bertolini-Cestari[1, a], Filiberto Chiabrando[1,b], Stefano Invernizzi[2,c], Tanja Marzi[1,d] and Antonia Spanò[1,e]

[1]Politecnico di Torino, Dipartimento di Architettura e Design, Viale Mattioli 39, 10125, Torino, Italy.

[2]Politecnico di Torino, Dipartimento di Ingegneria Strutturale, Edile e Geotecnica, Corso Duca degli Abruzzi 24, 10129 Torino, Italy.

[a]clara.bertolini@polito.it, [b]filiberto.chiabrando@polito.it, [c]stefano.invernizzi@polito.it, [d]tanja.marzi@polito.it, [e]antonia.spano@polito.it

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Abstract. Nowadays, there is an increasing demand for detailed geometrical representation of the existing cultural heritage, in particular to improve the comprehension of interactions between different phenomena and to allow a better decisional and planning process. The LiDAR technology (Light Detection and Ranging) can be adopted in different fields, ranging from aerial applications to mobile and terrestrial mapping systems.

One of the main target of this study is to propose an integration of innovative and settled inquiring techniques, ranging from the reading of the technological system, to non-destructive tools for diagnosis and 3D metric modeling of buildings heritage. Many inquiring techniques, including Terrestrial Laser Scanner (TLS) method, have been exploited to study the main room of the Valentino Castle in Torino. The so-called "Salone delle Feste" (Hall of Honor), conceived in the XVIIth century under the guidance of Carlo di Castellamonte, has been selected as a test area. The beautiful frescos and stuccoes of the domical vault are sustained by a typical Delorme 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.

A survey has 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 high detailed metric survey, carried out with integrated laser scanning and digital close range photogrammetry, reinforced the structural hypothesis of damages and revealed the deformation effects. In addition, the correlation between the survey-model of the intrados and of the extrados allowed a non-destructive and extensive determination of the dome thickness. The photogrammetrical survey of frescos, with the re-projection of images on vault surface model (texture mapping), is purposed to exactly localize former restorations and their signs on fresco 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.

Introduction

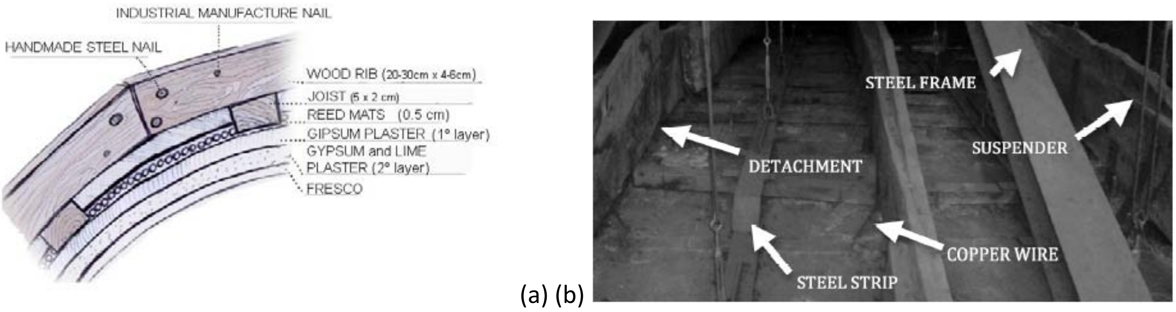
Objectives of the research.

The main target of this study is to propose an integration of innovative and settled inquiring techniques, ranging from the reading of the technological system, to non-destructive tools for diagnosis and 3D metric modeling of buildings heritage. More and more specialized methods of analysis are required to detect a correct knowledge of pathologies and/or the state of safeness of buildings and their components. Compared inquiries have to address proper decision in order to preserve strengthened stabilities. Such consideration is more stringent in case of stratified restoration suffered by buildings, so it is necessary to identify alterations and blemishes with the best accuracy.

A test area has been selected to evaluate the effectiveness and the informative potential of a metric and thematic archive, gained from processes and comparisons of data acquired by different sensors, This area correspond to the main timber structure of the Valentino castle. Many control activities have been just performed [1] and other renewed and recent are going to be presented. Eventually we are going to refer some novelties concerning the case study, and some considerations about the repeatability of the analyses. Basically we are going to point out the efficiency of the next sequence of techniques applications, their acquiring speed, the non-contact nature of most of them, their suitability for historical structures.

The Test Case.

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 [2]. 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 [3]. The Hall of Honor of the Valentino Castle is located at the first floor of the main body, and it has a rectangular shape 16 m long and 11 m wide. The Hall is covered by a pavilion vault, which 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 [4].



(a) (b)

Figure 1: Scheme of "camorcanna" layers [5] (a), extrados of the Hall of Honor (b) of the Valentino Castle.

The principal structure is the above wood rib frame (Fig. 1a) 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 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. More recently 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. (Fig. 1b) 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.

Settled and Innovative Inquiring Techniques

Laser Survey, Model and Orthophoto Generation of intrados of vault.

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 [6].

For the clear pavilion surface of the Hall of Honor, which is decorated by rich frescos and not by plastic ornamental elements, we performed the laser survey acquisition using a phase based scanner (LEICA HDS6100 [7] The points model, after processes that fulfilled the complete cleaning and optimization of surface accuracy, describes the only interesting surfaces: floor, walls and vault. From laser model a large number of revealing profiles belonging to multiple section planes have been detected with the aim of analyzing the curves trends and spotting the anomalies and subsidence of the vault. Some irregularities are visually observable in the mesh model. (Fig 2a)

Furthermore the points model have been used to derive a Digital Elevation Model (DEM) useful for the orthophoto generation. In fact, the metric image texturing has been faced by a digital photogrammetry project; 8 images organized in two stripes have been acquired by self calibrated camera (Canon EOS 1Ds), then they have been oriented using a bundle adjustment process and projected using the DEM. In this way we obtained the complete removal of the huge chandelier encumbrance. The final orthophoto enable to detect the exact location and extension of restoration signs on vault frescos. The surface contours of the vault are computed with an equidistance of 5 cm and pertain horizontal planes: they present an high level of geometrical aberration. 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; it is observable because results are reported to the same reference system (Fig. 2b).

We can estimate the greater loss of the original geometrical shape in the subsiding area near eastern point of intersection of the cylinders of pavilion (red spot in Fig. 3a). Adding to the XXth restorations, this asymmetric subsidence may be related to a general rotation of eastern perimeter wall, that we observed and measured by means of the section profiles on walls (Fig. 2c and 3b). The rotation of about half degree, coincide with 8 cm measured in the centre line, near the impost plane.

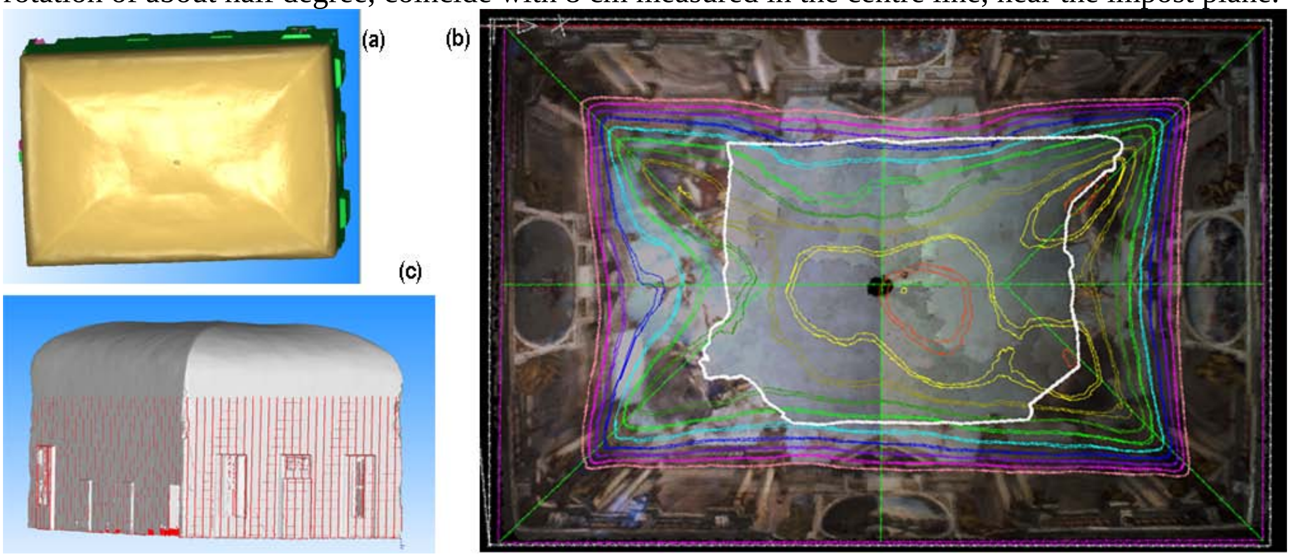


Figure 2: A nadiral view of the mesh model of dome for visual control of subsidence (a); the final orthophoto of the dome intradox, obtained by a mosaic of projected photograms with the superimposition of the section profiles and the signs of prior restorations (b) Total mesh model and sections profiles on walls.(c)

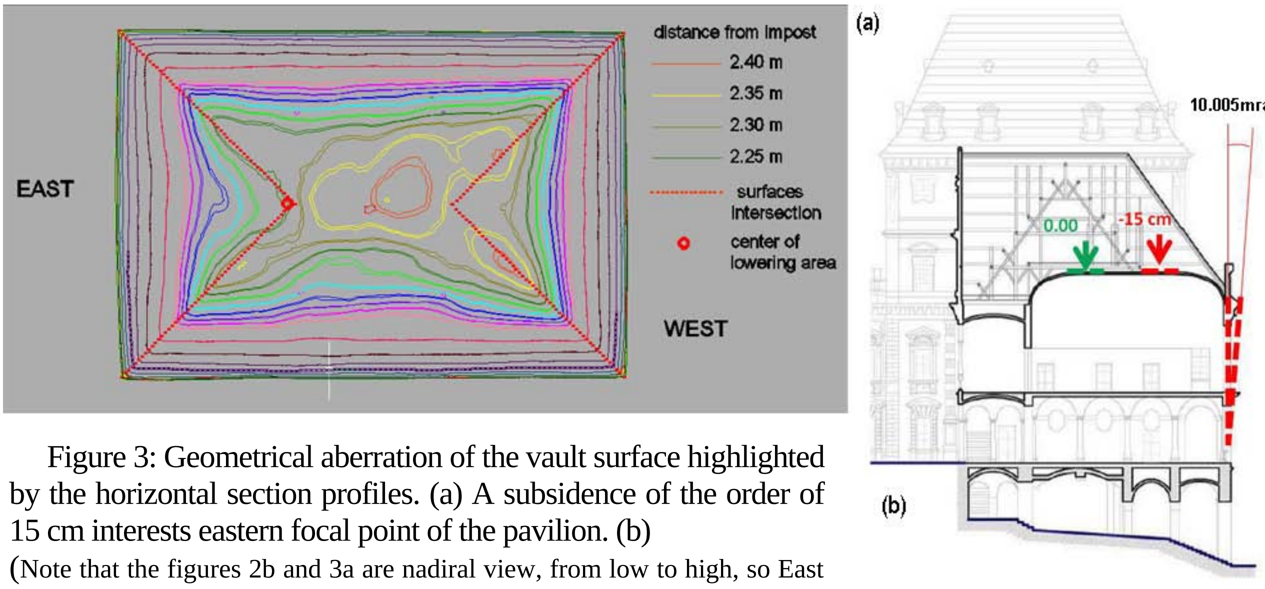


Figure 3: Geometrical aberration of the vault surface highlighted by the horizontal section profiles. (a) A subsidence of the order of 15 cm interests eastern focal point of the pavilion. (b)
(Note that the figures 2b and 3a are nadiral view, from low to high, so East is in the left and west is on the right).

Laser Survey, Model of Extrados and Topographical Measures for mutual Reference

The laser survey of vault extrados has been more complex than the lower, because of the encumbrances of the roof carpentry and since a wooden planking is placed over the vault (Fig. 4a)

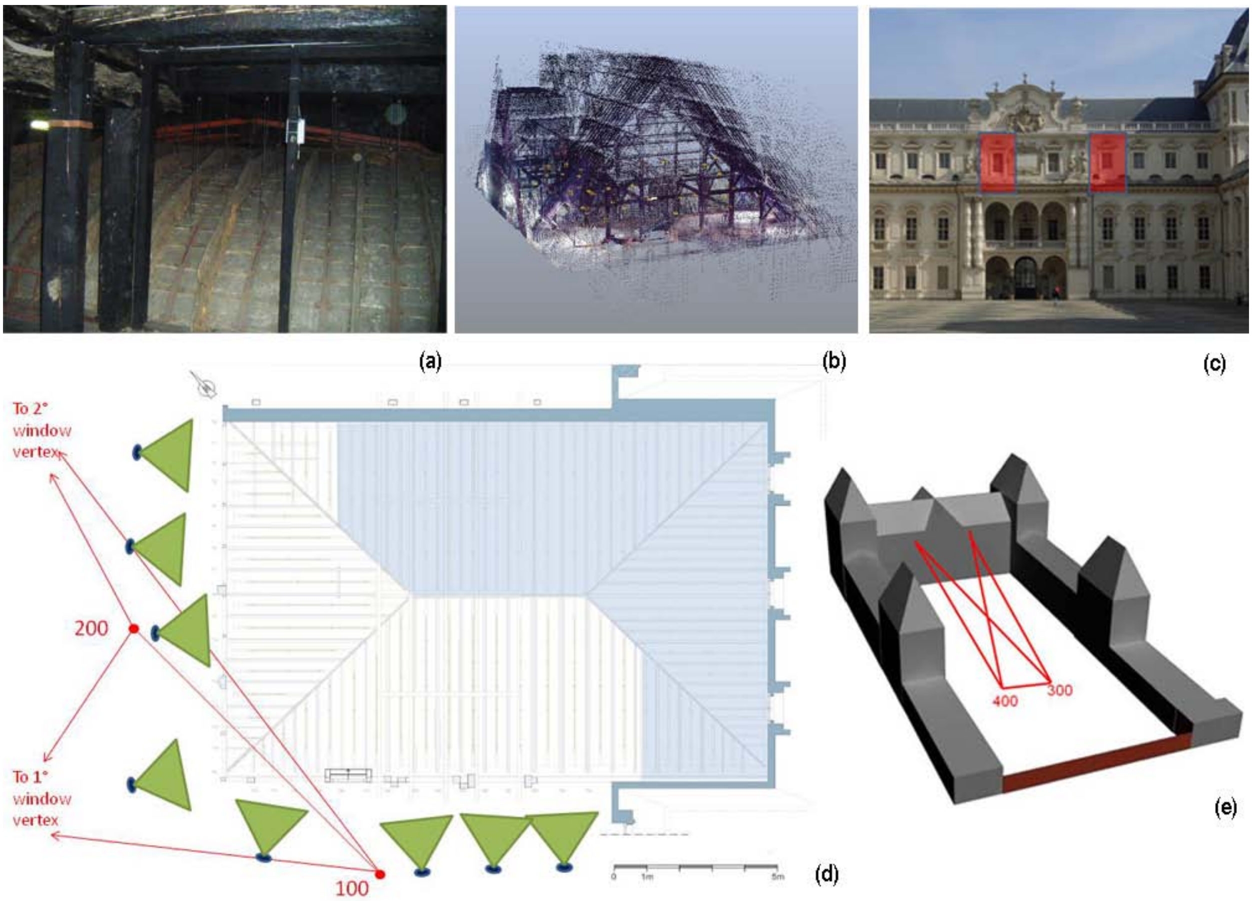


Figure 4: A view of the extrados with the wooden planking over it (a); a view of the registered points cloud (b); the position of windows enabling topographical intersections (c); a plan of the extrados with the scheme of scan positions and topographical measured directions (in red) on vertexes located on attic floor (n° 100 and 200) and near the windows (d), the scheme of topographical intersections connecting the vertexes in the attic, with the ones in the honor court(e).

Moreover the northen side is unreachable for the presence of a bearing wall, and obviously the curvature makes the measurable portion very reduced (in the Fig. 4d, the light blue points out the unmeasurable portion of the vault).
8 scans have been acquired (green triangle in Fig. 4d) and they have been registered with the support of about 25 plane targets, measured by topographical method. For the estrados survey we used the Focus 3D scanner (Faro Cam2) with portable and handy characteristics. The range of scan distances is variable from 0.6 to 120 m for reflective surfaces (> 90%), the error in linear distances is equal to ± 2 mm at 10 m and 25 m for reflectivity of 10% and 90%. [8] The results of registration are excellent (about half a centimeter for each residual) and obviously the cloud cleaning had to be totally manually managed in order to remove carpentry. Even the topographical measures performed with the aim to connect lower and upper models had been hard-working. Many portions of the castle have been surveyed by topographical, photogrammetrical and by TLS method, so a georeferenced topographical network (UTM WGS84 system) stands near the castle. [9]
Three sets of topographical intersections have been fulfilled in order to mutually reference the intrados and extrados models. (from the hall of honour vertexes to the ones placed in the honor court, from the honor court to the attic windows; from the vertexes located near the window to the ones used for detailed measures on vault extrados). We can consider that the mutual reference between the two models of the vault is featured by an accuracy of 1-1.5 centimeters, which is the accuracy that marks out the vault thickness.

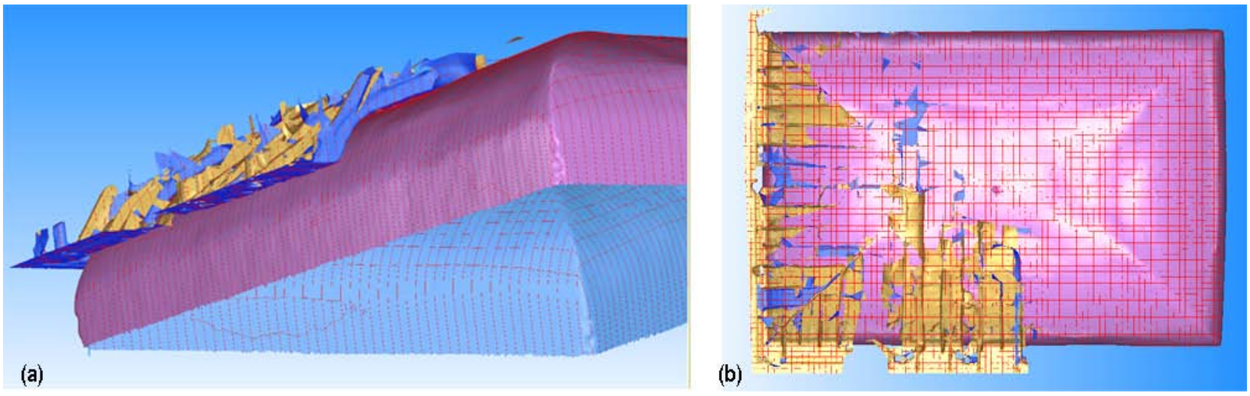


Figure 5: Two views of the combination of the upper and lower mesh models for the determination of the thickness of the vault. (a) (b).

Thickness and Profile Analysis. By means of the combined study of the extrados and intrados laser models (Fig. 5), it is possible to obtain an extensive mapping of the dome thickness and a precise analysis of local deformations. 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 some centimeters, that must be considered in the structural assessment of the vault. (A study on geometrical scheme of dome generation has been performed and we recognized that the hypothetical original bending arcs are very close to the constructive principles concerning the "*Cherche r'alongée*" recommended by P. Delorme in his essay:"Le Premier Tome de l'Architecture". [10])

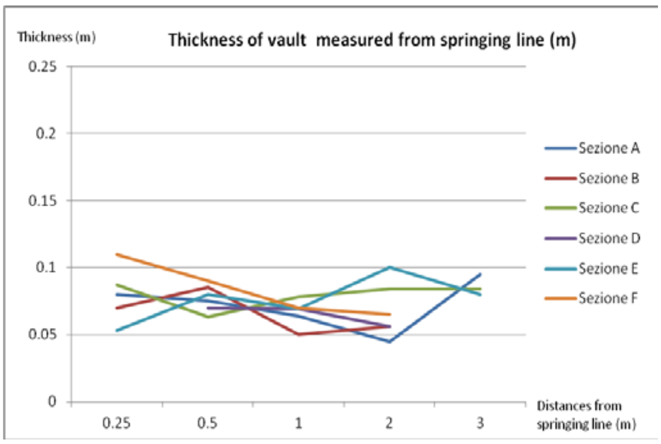


Figure 6: The thickness has been measured along some radiuses, interpolating arcs derived from Delorme geometrical scheme. Some sample vertical sections (A, B, C, D, E, F, about 1.5 m distant from each other) have been located in the measurable portion of

upper model, and they have been inspected and measured.

The maximum thickness is 0.22 m at the springing line. At the range distance between 0.5 m to 1m in plan from the walls, the average thickness decreases and becomes rather equal to 0.10 m. At the reins the thickness is minimum, and rather equal to only 0.06 m. In the central part of the dome the thickness is about 0.11 m, probably due to restorations and material additions. (Fig. 6-7)

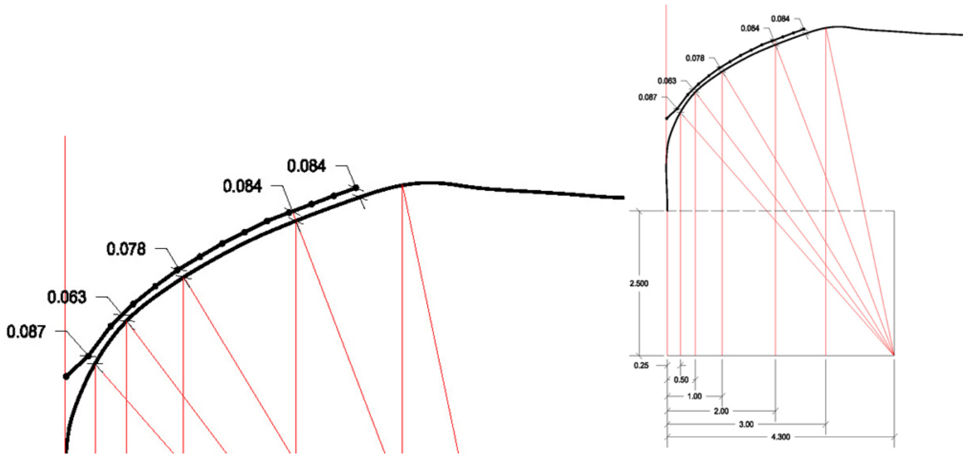


Figure 7: A sample section derived with the aim to examine the thickness of the vault.

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 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. 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.

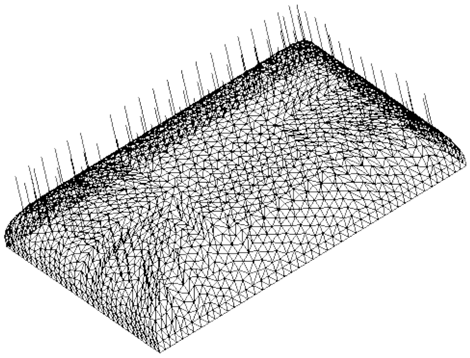
Resistance drilling offers non-destructive means of analyzing the quality of the interior material in wood members. Resistance drills use small diameter (1.5-3.0 mm [0.6-0.12 in]) needle-like drills to bore into timber members and measures the resistance the drill bit encounters as a function of the penetrated depth. 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. 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. When drilling is performed along the thickness of a rib composed by three planks, the two discontinuities are clearly recognizable.

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.

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.



	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

Figure 8: Mesh of the model (*above*); mechanical parameters of the model (*below*).

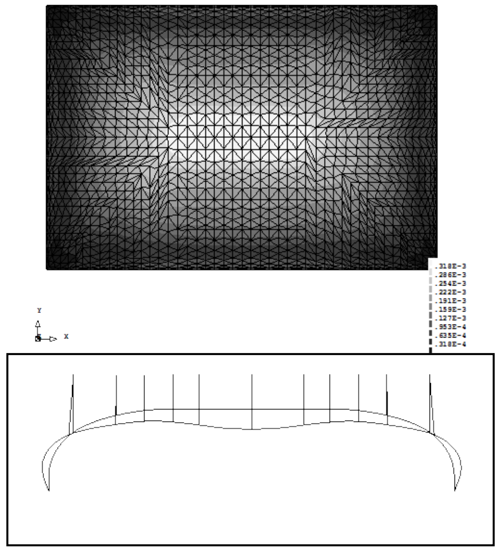


Figure 9: Contour plot of vertical displacements (*above*); transverse section with vertical displacements (*below*).

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 [11]. The overall mash of the model is shown in Fig. 8a, while the table in Fig. 8b reports the basic mechanical assumption. 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 figure 9, 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 (Fig. 10).

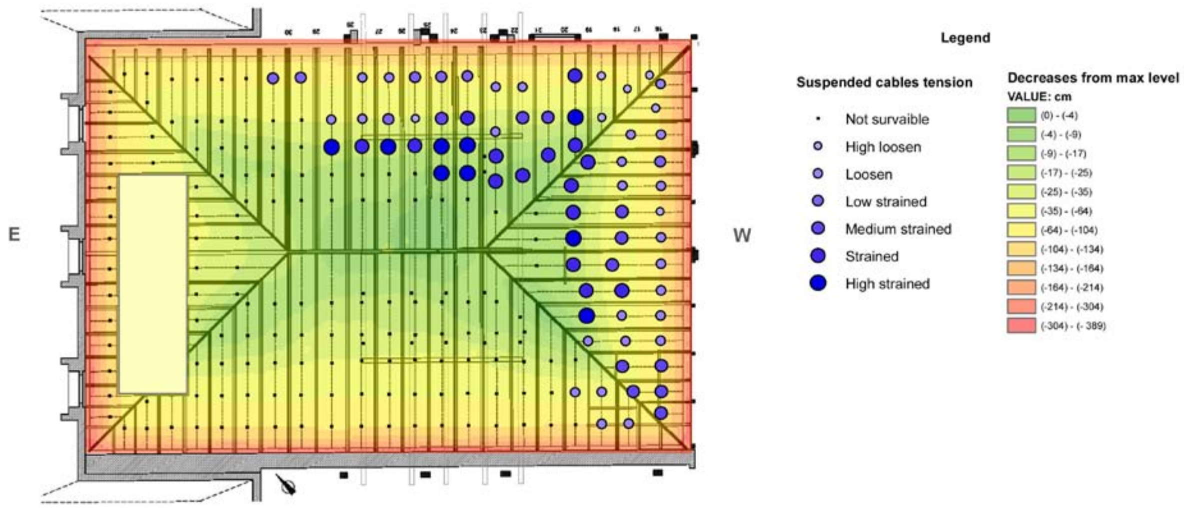


Figure 10: The survey representation of the state of tension in the suspenders is metrically referenced to the intrados Dem by GIS tools. The nadiral view is from low to high.

Conclusions

The LiDAR technology (Light Detection and Ranging) is applied to the case study of the Hall of Honor of the Valentino Castle in Torino, Italy. The detailed laser survey, and ortophotography allowed for an accurate modelisation 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 and laser survey of the intrados and extrados of the vault, allowing also for an extensive mapping of the dome thickness.

The preliminary finite element model is confirmed as far as the deformed shape is concerned, and also the loosen suspenders can be localized. The suggestion is not to provide tightening to the loosen suspenders [1, 12].

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The metric documentation project of the vault has involved graduate students attending the internship of the master degree in Architecture and Engineering at the Politecnico di Torino; Andrea Gallo has cooperated in the orthophoto generation and Cristina Cartella, Elisabetta Donadio and Giulia Ecclesia has cooperated in profiles extraction and laser model managing.

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