

Terrestrial laser-scanning point clouds for modeling masonry vaults

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Abstract –The paper addresses some issues related to the acquisition of points clouds by Terrestrial Laser-Scanning, TLS and their elaboration with the aim to create structural models of masonry vaults. This structural system, existing in several artifacts and historical buildings, presents the advantage of having a good static and functional behavior, reduced weight and good requisites of insulation and aesthetic quality.

TLS technique is well suited for the survey of geometric forms of monumental complexes, often realized with very irregular materials and forms.

As case-study we illustrate a geometric model of an ancient masonry church, having naves characterized by cross vaults, and its use as input values for a structural analysis based on the Thrust Network Analysis, TNA technique, a recently formulated methodology for studying the limit equilibrium of masonry vaults. As the numerical results show, the actual "geometry" of these structures significantly influences their safety degree.

I. INTRODUCTION

The most frequently employed survey techniques, applied also to Cultural Heritage preservation, are both terrestrial and remote photogrammetry and TLS (Terrestrial Laser Scanning). Approaches based on the acquisition of images, with the aim of 3D modeling, are object of significant studies and researches in different areas. In particular, TLS is non-contact and non-intrusive technique that digitally acquires the shape of objects in a very rapid and accurate way. Thus, it is possible to reduce the acquisition time and, moreover, 3D laser devices are now available on the market with different features that can be easily tailored for each application. The literature provides several examples of 3D point clouds acquired for detailed

structural digital models, what represents a particularly relevant issue in the case of masonry structures where geometry plays a meaningful role [1]. Nowadays, starting from an accurate three-dimensional model derived from laser scanning measures, it is possible to implement a BIM model, which allows one to manage the whole project in a consistent and optimal way. In fact, the laser scan techniques, such as TLS, that embody Scan to BIM among other processes, are a precious approach for BIM modeling, since they can support geometric and spatial data which can be acquired, organized and managed to fulfil the required project scale. One single database provides the quality of the results thanks to a direct link among shapes, information and the project documentation [2]. In particular 3D modeling becomes important when these models are adopted for structural engineering.

II. THEORETICAL BACKGROUND

The static model of cross vaults is quite simple; the two diagonal arcs provide the bearing structure which distributes the loads on the four pillars at the vertexes. The four columns support the four ribs of a barrel vault as a succession of increasingly smaller arcs from the external perimeter towards the centre. Each arch transmits its thrust connected to the diagonal arcs; in this way the diagonal arcs are loaded from the combination of the forces they sustain.

Nowadays the finite element analysis can be considered, the most performing numerical technique for structural analysis, since, if compared to the traditional static analysis, allows one to:

- provide a 3D model of geometrically complex structures;
- manage the characteristic parameters of the materials employed in the model;
- perform different analyses (linear, non-linear,

dynamical, etc.) on the same geometry. However, in the case of masonry historical and monumental masonry structures, FEM analysis doesn't represent the best choice since it is difficult to know the characteristics of the materials and the effects provided by the interventions previously performed on the structure.

An alternative effective approach to FEM is represented by the "Thrust Network Analysis (TNA)", a quite recent methodology that is briefly described in the sequel [3]. The method can be considered as an automated and computerized variant of the Mery method used for hand calculations of masonry arches. In particular TNA models masonry vaults as a discrete network of branches, subjected only to compressive forces in equilibrium with the gravitational loads.

Originally provided by O'Dwyer [4] and later developed by Block [5] and his coworkers, the evolution of this method represents one of the first rational approaches to the stability of masonry buildings and takes its steps from the analogy between the equilibrated shape of masonry arches and that of tensile suspended cables.

This analogy, called the "catenary principle", is that of an arc which reminds of a long chain retained at its ends and allowed to dangle. Heyman mixed this principle with the limit theorems of plasticity, in particular with the static one, so as to evaluate the safety of the masonry structures, predicting the ultimate mechanism of arches or 3D framed structures. A first extension to domes and vaults was suggested by O'Dwyer by fictitiously deconstructing the structure in discrete equilibrated arches, what means seeking networks of forces inside the structure, according to what has been denominated Thrust Network Analysis (TNA).

The equilibrium of vaults can be studied taking into account the thrusts, i. e. compression forces which balance the applied loads inside the structure. This network, from now on called thrust network, is described by N_n nodes and N_b branches which connect couples of nodes. The i -th node of the network is defined by its position $(x_n; y_n; z_n)$, in a 3D Cartesian reference system, where z is the vertical direction.

The force concentrated at each node is indicated by

$$f^n = (t_x^n; t_y^n; t_z^n) \quad (1)$$

The generic network branch b is identified by the two ending nodes and by the corresponding thrust value

$$T^{(b)} = (t_x^{(b)}; t_y^{(b)}; t_z^{(b)}) \quad (2)$$

The horizontal position of the internal and external

nodes

$$p^{(n)} = (x^n; y^n) \quad (3)$$

is assigned while their height is unknown. The vertical position of the nodes is assessed in such a way that the free nodes height is contained in the vault width. In particular, the maximum height of the nodes is associated with the minimum thrusts and viceversa.

Equilibrium conditions are adopted to evaluate the thrusts in the branches, the heights of the internal and external nodes and the position, in the horizontal plane, of the nodes belonging to the free edges of the vault.

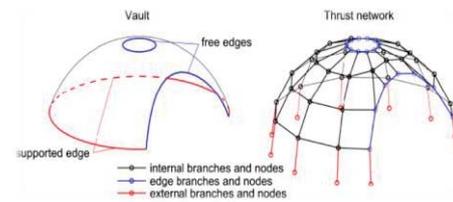


Fig. 1. Modeling of the vaults

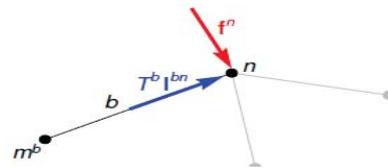


Fig. 2. Equilibrium of a node

The balance equation of the generic node of the vault is provided by the relationship:

$$\sum_{b \in B} T^b I^{bn} + f^n = 0 \quad (4)$$

where T^b is the thrust of the b branch and I^{bn} is the unit vector parallel to b and pointing towards n :

$$I^{bn} = \frac{i^{bn}}{l^b} = \frac{p^n - p^{mb}}{|p^n - p^{mb}|} \quad (5)$$

III. CASE STUDY

The present case study concerns the laser scanning survey of the "Santa Maria della Libera" Church in

the municipality of Aquino, in order to perform structural analysis for the static verification of the church's cross vaults.

The church, dating from the year 1000-1100 A.D. in pure Romanic-Benedictine style, was built with the typical "local soft" travertine, fragmentary material of the remains of Roman buildings surrounding the place where it was erected.

The amazing and austere interior, having dimensions of 17,00 m x 38,0 m, consists of three aisles divided by square pillars with three semi-circular absids. An imposing triumphal arch, also resting on pillars culminating with fragments of Roman cornice that act as capitals, introduces to the transept. The main altar, consisting of a Roman marble sarcophagus, is placed in the centre. The center aisle has a wooden roof, while the side aisles have cross vaults.



Fig.3. Image of central nave

The campaign of measurements has concerned the interior and exterior of the masonry complex having geometries and external projections that made the survey complex and cumbersome. In particular the vaults in the interior aisles of the church have been the subject of a detailed study.

First of all an accurate topographical survey of the historic artifact's site was carried out by the TOPCON GLS-2000 laser scanner station. In a period of four hour 16 scans were performed at different station points in order to get an extremely high density of scan points, approximately 5 million points with measured coordinates having millimeter accuracy.

The survey was divided into several phases after careful planning of the campaign and identification operations of the station points: design of the survey using maps from Google Maps with on-site identification; cloud capture scans of points detected by a laser beam with 360° horizontal and 270° vertical range of action; scanning alignment

in pairs; global alignment; filtering; modeling; editing towards the subroutine which the TNA code is connected to.

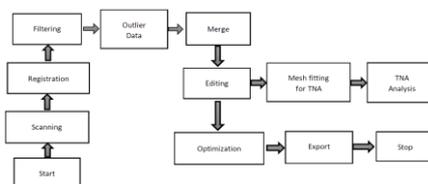


Fig.4. Flowchart of the Scant to BIM process

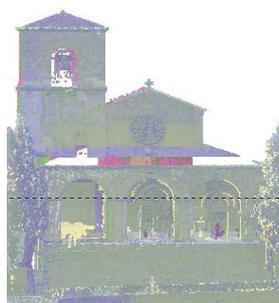


Fig.5. South prospectus of the S. Maria della Libera Church elaborated through Revit software



Fig.6. External 3D digital model of the S. Maria della Libera Church



Fig.7. Image of lateral left nave with view the masonry cross vaults

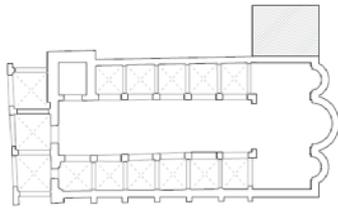


Fig.8. Internal plan 1:100

Point cloud models obtained by surveying with high-precision laser scanning instruments have particular limitations from a computational point of view. Actually, it is not possible to directly associate the physical behavior of the model derived from a point cloud with a computer-based calculation software. The transition from a point cloud to a polygonal surface model can be defined in all respects as a "re-topology" operation since a quantitative and qualitative information of the point's model is translated and adapted to obtain a triangular or quadrangular representation that better represents the polygonal surface.

The structural analysis software uses an algorithm that requires, as input data, the geometric dimensions of the masonry object.

The laser scanning survey consists in assigning to each point a triplet of xyz coordinates, which are first relative and then become absolute with a georeferencing operation. In order to extrapolate the coordinates of the points, the "Cloud Compare" software offers us both the possibility to query the single point or to select a number of n points and export the list in .txt formats.

Once the data has been extrapolated and processed exported to an Excel table. Actually the masonry elements are typically not regular and not continuous, do not have a homogeneous surface and are made of masonry ashlar that are not perfectly squared. Accordingly, geometric data obtained from the survey need to be properly smoothed to get more regular surfaces, i.e. surfaces with no kinks, unrealistic holes or superposition patches.

In order to solve this problem and obtain coordinates that allowed us to provide correct geometric data for making the structural algorithm run, an interpolating function was built. Specifically, the following polynomial formula has been chosen to interpolate in the best way the curve drawn with the coordinates of the surveyed points. The equation of the polynomial formula is:

$$y = -0.0236x^6 + 0.023x^5 + 0.0677x^4 - 0.0597x^3 - 0.3024x^2 + 0.1172x + 12.871$$

The regression line represents a good fit of the points as the index of variance of the line proves with a value $R^2 = 0.9974$, very close to one.

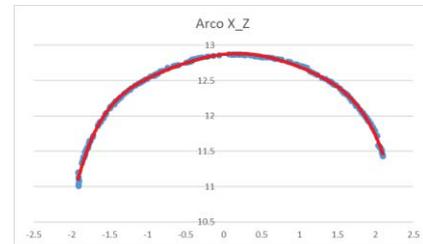


Fig.9. Diagram of the polynomial interpolating function

IV. RESULTS

The application of the TNA method, illustrated here for a single cross vault of the roof, has been extended to the static and structural verification of all the masonry vaults which are present in the S. Maria della Libera Church in Aquino.

Each of the church's cross vaults of the roof in the church's aisles has a square base of 4 mt side, is two meters high, has a thickness of 0.45 m, is made of soft travertine with a specific weight of 2.72 t/m^3 .

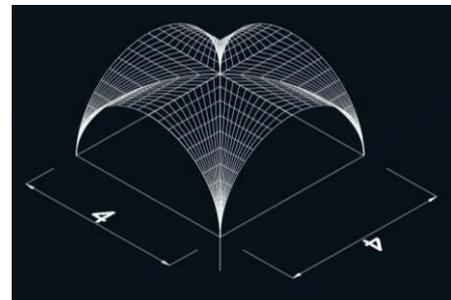


Fig.10. Vault geometry

The application of the TNA method to a single church's cross vault has provided, as it can be seen from the following figures, the minimum and maximum thrust values of each of the 389 branches of the cross vaults and the corresponding minimum and maximum values of the height of each of the 222 nodes of the roof associated with the minimum and maximum thrust values. The maximum height of the network nodes that characterizes the deepest limit configuration, i.e. the one associated with the minimum thrust is equal to 2.48 m.

Conversely the shallowest limit configuration, associated with the maximum thrust, has a value of 1.38 m as minimum node heights.

V. CONCLUSIONS

The Terrestrial Laser Scanner's survey carried out on the monumental complex of the Church of Santa Maria della Libera in Aquino provided a point cloud required to perform a structural modeling of its masonry vaults by the TNA approach. The geometric and geo-referenced 3D model obtained by processing laser-scanning measurements is a model built on a congruent geometric basis, which contemplates the methodological complexities of the detected object.

The paper shows how the interdisciplinarity between a geometric model, built with the innovative techniques typical of the "geomatic" survey, and a structural model can represent a useful support to the structural verification for the safety and conservation of a complex structures, such as those typically belonging to the monumental heritage.

Within this reference context, in the future the research will analyze HBIM models, the latter being a semi-automated method that allows one to switch from point cloud to an advanced three-dimensional model, able to contain all the geometrical and mechanical characteristics of the built object.

Acknowledgments

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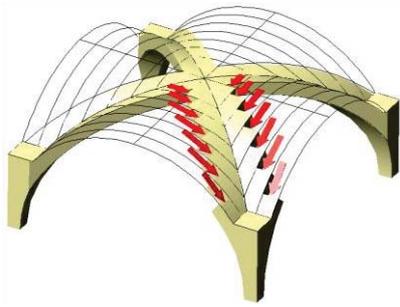


Fig.11. Thrusts diagram

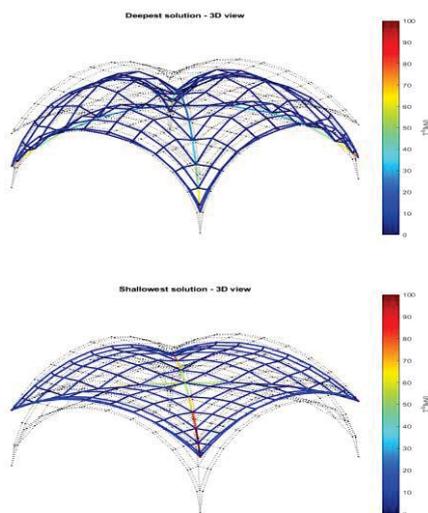


FIG.12. Distribution of max and min thrust

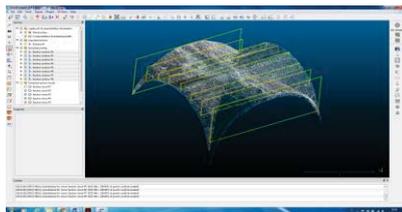


Fig.13. Export sections from Cloud Compare

