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DISPLACEMENT AND DEFORMATION ASSESSMENT OF TIMBER ROOF TRUSSES THROUGH PARAMETRIC MODELLING. THE CASE OF SAN SALVATORE'S CHURCH IN BOLOGNA

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Highlights

Presentation of the research protocol and identification of the case study, the Church of the Santissimo Salvatore in Bologna. Identification of the criteria and procedures to generate the models starting from the three-dimensional geometric survey. Analysis of displacements comparing the point cloud and the 3D models. Interpretation of the collected data coming from the comparison to assess the condition of the wooden trusses of the church. Comparison with previous case studies.

Abstract

The article investigates wooden trusses and their evolution over time, through the re-elaboration and interpretation of the data obtained through a laser scanner survey. From the point cloud of the entire roof, 3D models of the individual trusses are obtained through reverse engineering software and parametric modeling. Each model is rendered by setting robust constructive and evolutionary hypotheses to which these structures must respond and represents a regression over time of the truss from the "current" to the "original" condition. 3D models, therefore, become a reasonable representation of the original condition. Therefore, by comparing the models with the point cloud, it is possible to analyze these trusses in detail, highlight their movements and deformations, obtain precise and comparative information on their behavior and draw global considerations on the health of the entire roof.

Keywords

Building heritage, Terrestrial Laser Scanning, Generative algorithms, Structural systems reverse engineering, Cloud to 3D model comparison.

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1. INTRODUCTION

This work is the development of an extensive research protocol applied to the study of wide span wooden trusses, located in some of the most famous churches in Bologna [1]. This project aims to deepen the knowledge of these complex construction systems and their evolution over time, through the wise use of Terrestrial Laser Scanning (TLS) and the reworking and interpretation of the collected point cloud data. The use of the laser scanner is certainly not new in the architectural survey of the built heritage, and it is increasingly used in the restoration field [2–4], while it is rarely or not yet used in the study of hidden three-dimensional structures such as wooden roofs [5–8]. The large number of geometric data deduced from the acquired point cloud by the TLS tool can be used to draw trusses in detail, derive precise and comparative information on their static behavior, and make assessments on the health of the whole roofing system [9, 10]. This method has been applied in several case studies and developed by making continuous approximations. Based on the feedback, it is continuously evolving, while maintaining well-defined operational steps and protocols.

The research assumes that digital survey technologies allow the extrapolation of a series of considerations that would be almost impossible following traditional methods of investigation based on direct observation or simplified architectural survey. By exploiting the data contained in a point cloud, trusses can be read three-dimensionally, and local and global information on their behavior can be captured [11]. Finally, three-dimensional surveying, if carried out at regular intervals, becomes a valid diagnostic tool for monitoring the evolution of the health state of these structures, in combination with documentary and photographic information. The development of the research protocol has led to the automatic generation of a 3D model with parametric modeling software, adopting the cross-sections of the truss elements near the joints as input parameters. Two different models are created for each truss: a “survey model”, which is the model of the current state, and an “ideal model”, which is the model that best represents the undeformed configuration at the time of construction, obtained through projection and translation operations of the cross-sections themselves.

Then, both models are compared with the segmented trusses extracted from the point cloud. This procedure allows knowing at least the order of magnitude of displacements and deformations from the reference undeformed configurations [12].

2. THE CASE STUDY

The Church of San Salvatore is placed in Bologna on the corner of “via IV Novembre” and “via Cesare Battisti”. The current configuration dates to the year 1623. Inside this religious building, the famous painter Giovan Francesco Barbieri, known as Guercino, is buried. The current rectors of the church are the Regular Lateranensi Canons. The project of the roof has been attributed to Giovanni Ambrogio Mazenta (Milan, 1565 - Rome, December 23rd, 1635), who was an Italian architect and a religious figure. He carried out design projects in the military, spiritual, and civil fields, and he was involved in the construction of the Church of St. Paul and St. Peter’s Cathedral in Bologna [13, 14].

The roofing of the church is supported by ten wooden trusses, built of spruce wood. These structures, which can be traced back to the classic Palladian queen posts configuration, have a span of almost 18 meters. These are open joint trusses, with rafters interrupted by queen posts. All rods have a variable cross-section profile in the range between 20x20 cm for the struts and 30x30 cm for the rafters. The tie-beam is divided into two main timber elements connected to a central beam, which is part of a trestle, the first structure to be put in place, used to support their dead load, and shorten the free span.

The entire TLS survey of the church’s roof has been conducted with a FARO CAM2 FOCUS 3D® laser scanner using a target-less approach. The survey campaign took two working days, and it was necessary to shoot more than 60 scans with a resolution of 7.67 mm/10 m and a quality filter of 3x to get the whole roof system. The scans alignment has been performed with the FARO SCENE 2019® software using an interactive Cloud to Cloud registration, adopting 4 cm of subsampling average distance along with 1 m searching radius. With a minimum overlapping of 17% between the scans, it has been possible to achieve an extremely accurate alignment with an average standard deviation between corresponding points of 2.4 mm and a maximum deviation of 4.3 mm [15].

3. THE SURVEY 3D MODEL GENERATION

After the survey and alignment phase, the protocol requires each truss to be segmented from the point cloud and individually modeled and analyzed (Fig. 1).

3.1. CROSS-SECTION SPLINES CREATION

The individual trusses obtained from point cloud segmentation have been imported into Geomagic Control, an application created for reverse engineering, which is usually adopted to study, and digitize the shape of small objects in the field of mechanical design or proto-

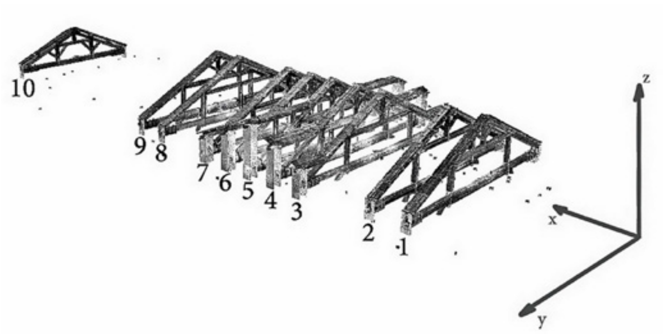

Fig. 1. *Segmentation of the roofing of the Church of San Salvatore. Each truss is numbered from the façade towards the apse along the x-axis positive direction in the chosen reference system.*

typing. The software allows editing the point cloud and performing dimensional comparisons between a test object and the reference object as well as exporting data in structured numerical reports. The cross-sections of each wooden beam element must be neatly identified and extracted. The curves can be automatically vectorized within Geomagic and then edited with the 3D modeling program Rhinoceros. Once these operations are completed, it is possible to go ahead with the 3D modeling using generative algorithms.

3.2. SURVEY 3D MODEL

As mentioned above, the software used for 3D model rendering is Grasshopper, a Rhinoceros plug-in, which is one of the most effective algorithmic modeling tools for the creation and management of complex shapes at any scale, from design objects to large architectures. The software builds an algorithm that receives the cross-sections of every single truss in input and provides a 3D model in output (Fig. 2).

Once the model is generated, Geomagic Control compares the point cloud (imported as "test object") with the survey model (imported as "reference model"). The software then evaluates the deviations by calculating for each point of the test model its distance to the surface of the reference model and graphically returns the results in a chromatic scale. The first model has been created using only three cross-sections per element, and it has shown significant deviations above the threshold set at ± 5 mm; therefore it has been decided to increase the number of cross-section splines required for modeling by raising them to 5, considering the significant deviations of the central portion of the tie-beam (Fig. 3).

After the first tentative 3D model, the detailed analysis of the timber rods used to make the tie-beams and the supporting trestles has clearly highlighted the presence of irregularities derived from the craftsmanship. Confronting the area of the sections with the minimum rectangular shape that circumscribes it, it has been noticed that this parameter is very variable both along the single tie-beam and on the different tie-beams in the corresponding positions. Particular attention has been dedicated to the tie-beam number 9, which has shown the most anomalous values: cross-sections about 17 cm higher than the average, larger net areas, and a visible notch in the three

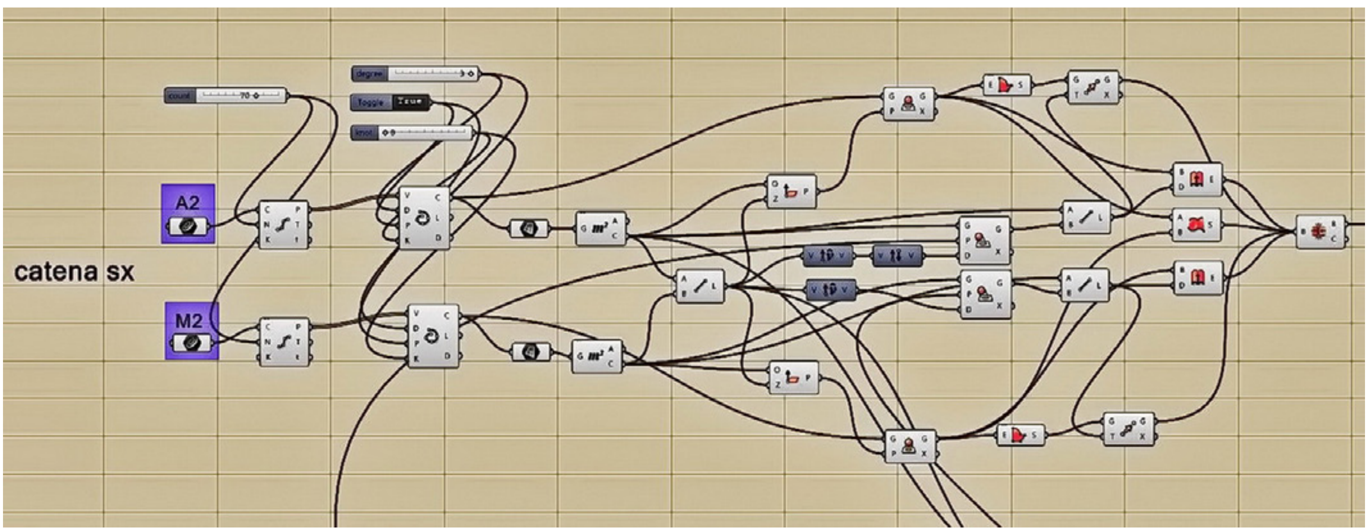

Fig. 2. *Generative algorithm for automatic tie-beam creation from digitized cross-sections.*

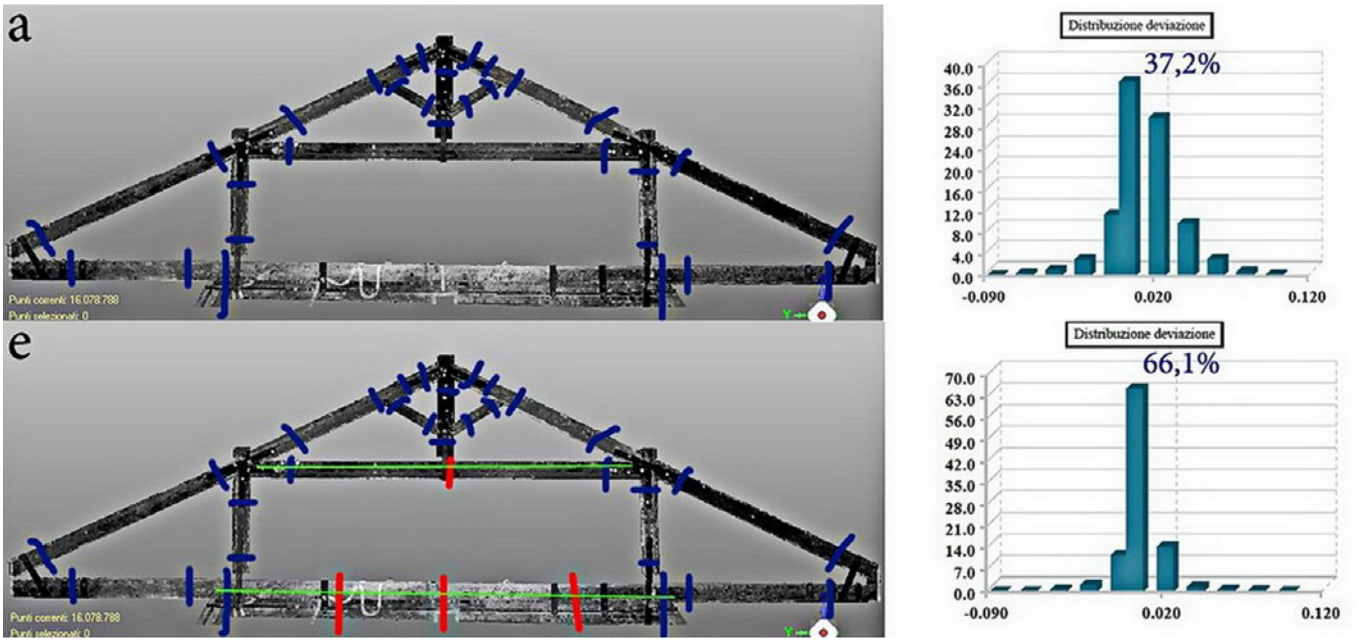

Fig. 3. *Above: cross-section extraction as first tentative 3D modeling and gaussian distribution of points inside the ± 5 mm threshold. Below: cross-section used for the final 3D modeling and gaussian distribution of points inside the ± 5 mm threshold.*

central sections. By carefully observing the point cloud, it could be highlighted that the central trestle is composed of 2 overlapping timber elements instead of one as in other trusses. This closer observation confirmed the greater height of the tie-beam cross-section.

Therefore, by using five cross-sections, the mean squared distance between 3D model surfaces and the truss point cloud has been kept inside the nominal threshold of ± 5 mm for approximately 70% of the analyzed points. This result has been considered acceptable given the execution speed, as well as the presence of sudden section changes along almost all the timber beams axes. Moreover, the presence of metal connectors, which are hard to be modeled, frequently generates areas with more significant deviations. To perform a more detailed model would have been operationally challenging. By applying the upgraded algorithm to the sections of all nine trusses, the 3D model of the entire roofing can be finally obtained.

4. FROM THE SURVEY 3D MODEL TO THE IDEAL 3D MODEL

The next step has been the creation of an "ideal 3D model", which is the model that best approximates the truss at the time of its assembly, created following some simplifying assumptions and hypotheses:

- position of the truss supports as fixed points (orange in Fig. 4);

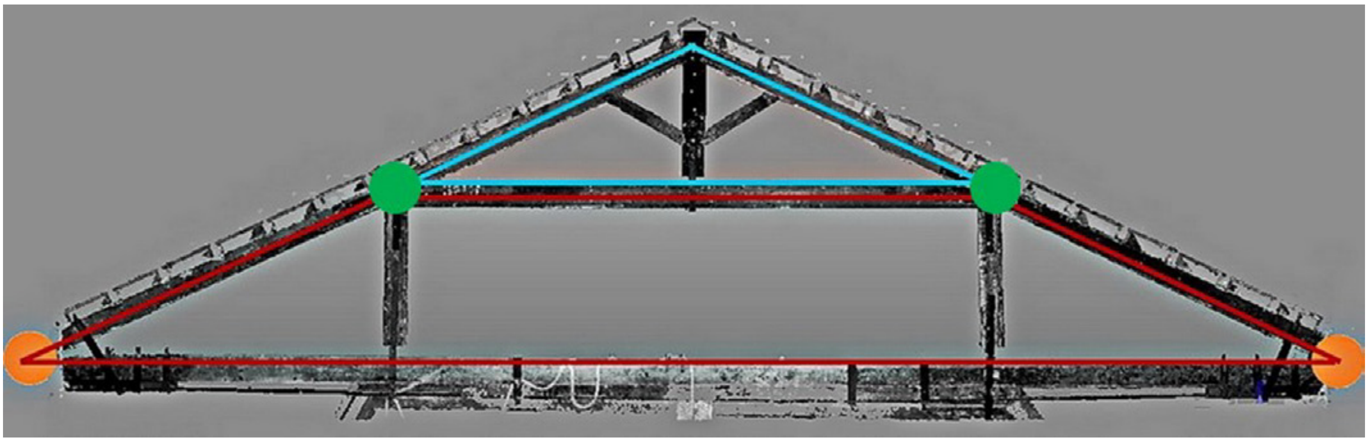

Fig. 4. *Simplifying assumption hypotheses used for the generation of the ideal 3D model.*

- the higher stiffness of the tie-beam and sub-rafter joint compared to the sub-rafter and queen post joint;
- the lower deformability of the upper triangle (cyan in Fig. 4), composed by the top-rafter and the straining beam, compared to the lower trapezoid (red in Fig. 4).

Using the listed assumptions and hypothesis on the characteristic structural elements of the timber truss (Fig. 4), the most plausible movements that the truss may have undergone over time have been hypothesized, and an attempt has been made to transform them into regression algorithms to model the original state.

The first step has been the creation of the "projection algorithm". It, firstly, creates the vertical plane belonging to the sheaf of planes built on the tie-beams' axis, then moves onto it the centroid of the splines made from the cross-sections. The second step has been the creation of an algorithm that regains the flexural deformations of the rods, and the lowering of the ridge through the restoration and rectification of the external triangle formed by rafters and tie-beam (Fig. 5). The "Projection" and "rectification" algorithms have to be applied to the cross-sections of all the trusses and help to define each ideal truss model, which is the one that best approximates the truss configuration at the time of its installation.

5. DISPLACEMENTS ANALYSIS

By using the "ideal 3D model" approach, it has been possible to make comparisons with the surveyed point cloud to highlight the deviations that occurred over time from the original condition. Through the "3D analysis" feature of the Geomagic Control software, it has also been possible to set appropriate comparison parameters in terms of minimum and maximum nominal error and minimum and maximum critical error. The "nominal error" represents the minimum deviation value between cloud and model for which the exact overlap is considered, and it is fixed in ± 5 mm. The "critical error" is the maximum deviation value found between cloud and model for which the point is deemed to be non-significant for comparison, and it is fixed in ± 100 mm.

The 3D comparison has allowed obtaining a representation of the deviations in an appropriate chromatic scale (Fig. 6). Once the three-dimensional comparisons have been carried out, the real analysis of the displacements suffered by the truss elements is made using 2D comparisons between the point cloud and the ideal model. Appropriate cross-section planes are then defined in which the software allows annotating the most significant points, highlighting the values of the displacement vector at that point (Fig. 6). The analyzed positions have been:

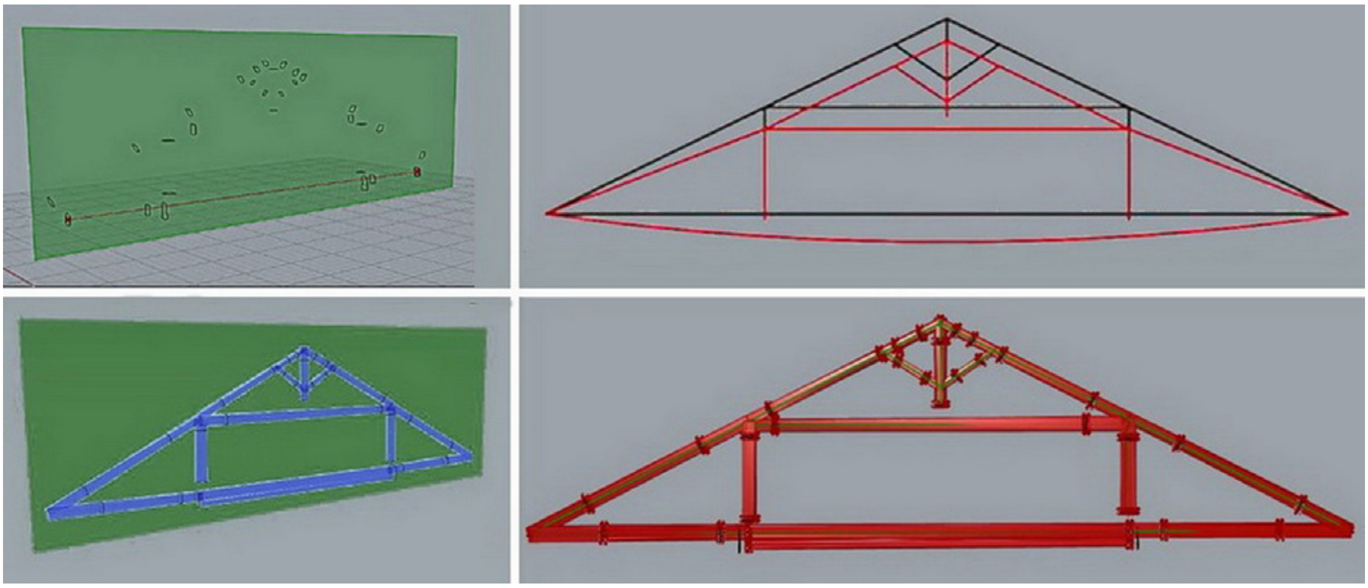

Fig. 5. *Left: "projection algorithm" - All splines moved on the vertical plane passing on the tie-beam axis Right: "rectification algorithm" - All splines moved up to restore the bending of the rafters and the tie-beam.*

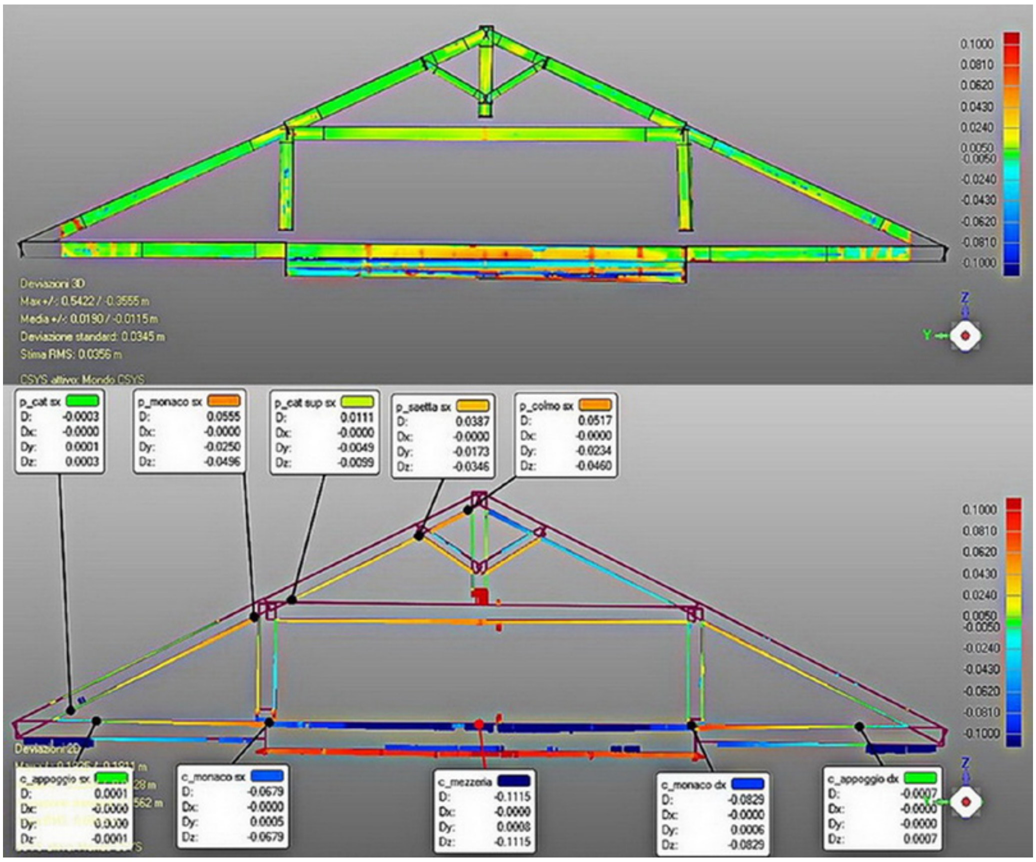

Fig. 6. *Above: 3D comparison with a chromatic scale Below: 2D comparison in the truss' vertical plane with a chromatic scale.*

- mean vertical plane of the truss,
- inclined planes along the rafter axes,
- vertical planes along the king and queen posts' axes,
- horizontal plane on the tie-beam axis.

Setting the ideal model as "reference", and the point cloud as "test", the annotation callout shows the measured distance (D) between the point cloud and the surface of the 3D model, as well as its components along the x, y, z axes (dx, dy, dz). All the annotations values placed on the control points are collected in a spreadsheet. By analyzing the obtained values, it is possible to evaluate precisely the deviations that occurred both for the single truss and for the whole roofing.

5.1. THE EXTERNAL TRIANGLE

The side chapels are located beyond the second span of the church, so their two-pitched roof is inserted into the two-pitched roof of the central nave forming a triangular surface where purlins lean on trusses number 3, 4, 5, 6, and 7. These trusses present the more evident lowering of the ridge and posts. Truss number 5 has the maximum lowering of 6 cm. Because of its position, right in the middle of the roof pitch, it receives a higher concentrated load on the rafters due to the higher number of purlins to be supported (Fig. 7).

The analysis of the rafters' movements outside the truss plane, showed much lower displacements. At first glance, the load-bearing beams of the side pitch and the hip rafters, which are grafted onto the trusses' principal rafter, stabilize their movements outside the plane, almost acting as bracing elements (Fig. 8). It has also been observed that, since the rafter is interrupted, the upper triangle, formed by the top-rafter, struts, and king post, can rotate out of plane around the straining beam independently. An example of this behavior is evident in the displacements of trusses number 2, 3, 6, 7, which clearly show the out of the plane rotation of the upper non-deformable triangle. A twofold behavior therefore emerges; the upper triangle can rotate around the straining beam while the lower trap-

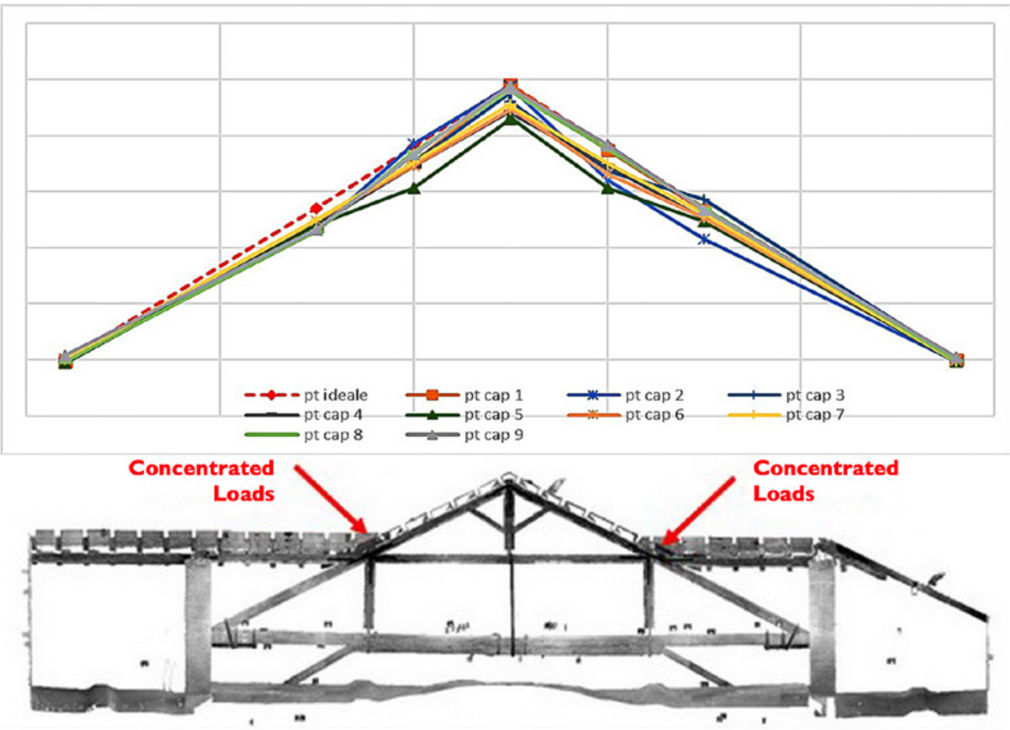

Fig. 7. *Graph of the lowering of the rafters and truss number 5 orthophoto showing the application of the concentrated loads given by the side pitches.*

ezoid can turn around the tie-beam and translate following the movement of the side supports.

5.2. STRAINING BEAM

Trusses numbers 4, 5, and 6 also show a more significant flexural deformation of the straining beam than the others. It can be assumed that the load concentrated on these trusses, which bear the side pitch purlins load, as mentioned above, has increased the compression stress in the straining beam, also causing its higher deformation with a consequent symmetrical lowering of its two joints. Trusses number 4 and 6 support the side purlin right in the rafter-queen post joint, in fact presenting the most considerable flexural deformations.

5.3. KING AND QUEEN POSTS

Looking at the graph (Fig. 8), it is clear the clockwise rotation of the left queen posts and counterclockwise rotation in those on the right. In this way, both queen posts rotate around their upper joints symmetrically with respect to the king post, which on the other hand, undergoes less significant displacements. A combination of two factors can cause these rotations: the rigid connection between the queen posts and the straining beam, which causes these two elements to maintain a right angle, and the imperfect alignment of the forces reaching the rafter-post joint, which tends to induce a rotation on the queen post that is the only element free to rotate around its upper hinge.

5.4. TIE-BEAM

The trusses whose tie-beams have a higher inflection are numbers 4, 5, and 6, where there is bending of more than 10 cm in the center point. These trusses are precisely the ones whose top-rafters are connected to the beams bearing the side pitches, as shown above. Since only the top-rafter is loaded, the tension in the tie-beam is lower than in those trusses where the whole rafter is used to bear purlins. The lower load means that the tie-beam must withstand less lateral thrust from the rafters and is therefore subject to less tensile stress. Probably

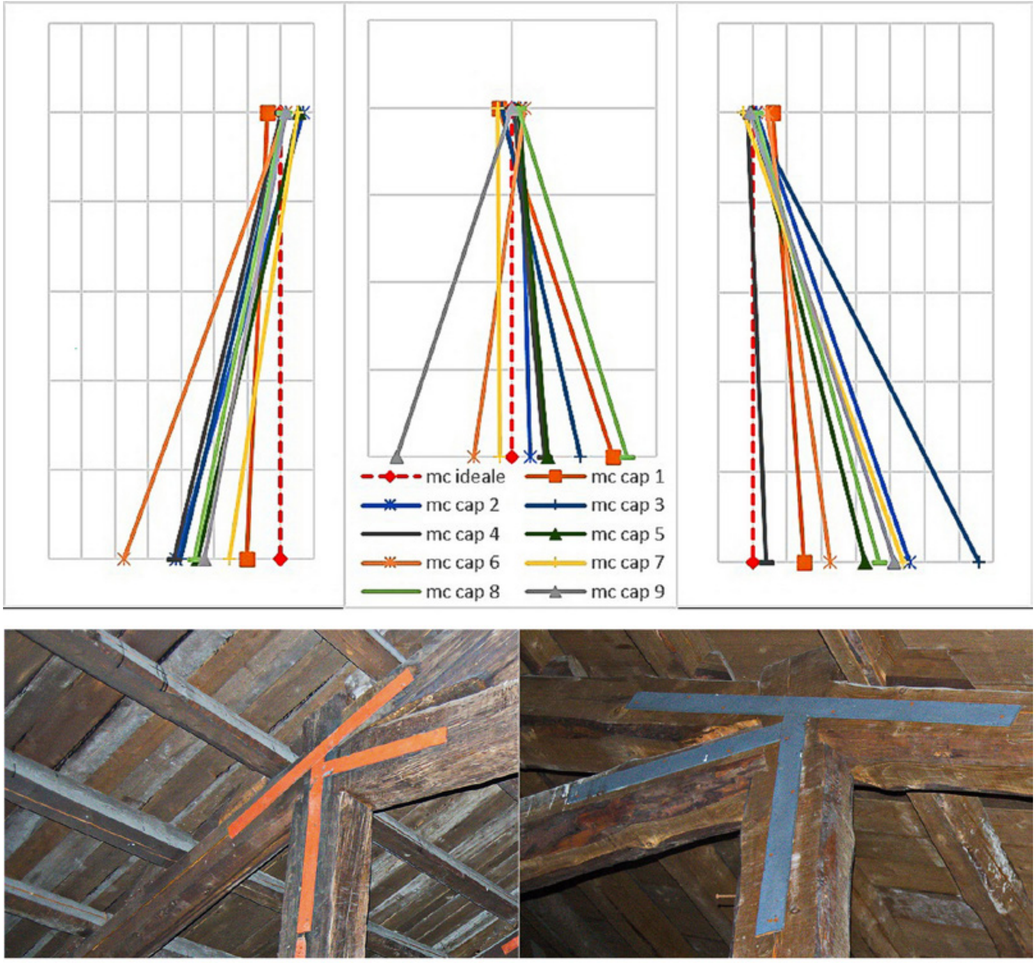

Fig. 8. *Above: Graph of the posts' rotations. Below: metal brackets retention systems added in the '80s to control the stiffness and rotation of post-rafter joints.*

because the lower tension the effect due to its weight is higher, and so the centerline bending effect. Moreover, a closer look at the point cloud reveals the presence of a disconnection in the flute-beak union between the two beams that form the tie-beam of truss number 5, the most inflected. The two parts of the tie-beam appear to be disconnected, held together only by the metal bracket that ties these wooden elements together with the assembly stand below (Fig. 9).

6. FINAL CONSIDERATIONS AND COMPARISON WITH PREVIOUS CASE STUDIES

After the survey, trusses' modeling, and analysis of San Salvatore's Church, the effectiveness and efficiency of the protocol can be evaluated, comparing the results with another case study, the Basilica of San Domenico. Its trusses have been analyzed by applying the same protocol. San Domenico is the patriarchal church of the Dominican order, and the construction of the wooden roofing by architect Carlo Francesco Dotti (Bologna, 1670 - Bologna, 1759) can be dated back to the year 1730. His most famous work is the Sanctuary of the Madonna di San Luca, also in Bologna, where he worked in the first half of the eighteenth century on the University Library and in several noble buildings.

The analysis method used has been the same, although specific adaptations were made to consider the differences in the structural scheme of the timber trusses. While in the Church of San Salvatore, nine trusses over the central nave have been analyzed, in the Basilica of San Domenico, the analysis has been carried out on the five trusses over the choir [7]. Both types of wooden trusses belong to the queen posts truss family and are often used to cover large spans up to 18/20 meters.

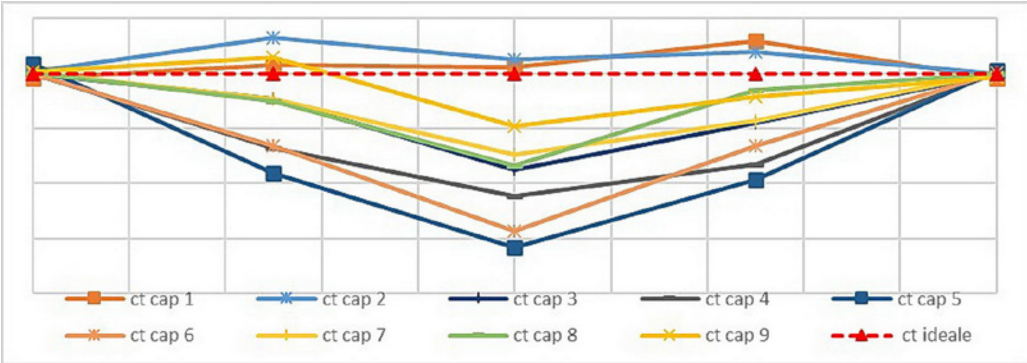

Fig. 9. *Above: Graph of tie-beams deformation. Below: Flute-beak disconnection in truss number 5 joint.*

The trusses of both case studies cover almost the same span and are repeated with very similar spacing. For the trusses of San Salvatore, the average span is 18 m, and the average spacing is 2.9 m. For San Domenico's trusses, the average span is 17 m, with an average spacing of 3.1 m. Both trusses are made of spruce wood, and the only main difference is that each San Domenico's timber element comes from a single trunk while San Salvatore's elements are joined to form the tie-beams. San Salvatore's tie-beam, therefore, consists of a single element of 17 m, while for San Salvatore, the maximum length of the elements is 9 m, and two elements form the tie-beam joined with brackets and metal pins.

Another significant difference is in the structure of the rafters: in San Salvatore, there is a composed rafter formed by two beams of 5 m, joined at the top of the queen post, while in San Domenico there is a single timber, more than 9 m long, supported up to the ridge joint with the king post by a sub-rafter that increases the resistance to bending. Finally, the truss of San Salvatore has diagonal struts loading the king post (Fig. 10).

By analyzing the displacements on the trusses' vertical plane, similar behavior can be observed, bending rafters, lowering and rotation of the queen posts, and bending of the tie-beams. The deformations extent varies according to the different types of connections between the timber elements and the loads involved. In the trusses of San Salvatore, the interrupted rafter lets the joint to rotate and the queen posts to lower and raise depending on the loads changing and movements of the supporting walls. This joint rotation and its lower rigidity explain the asymmetrical behavior of the queen posts. The San Salvatore's truss scheme can be defined as "almost unstable" and comes into play for asymmetrical loads, such as foundation subsidence or snow loading on the pitch facing north, thus allowing movements and rotations without excessively increasing the roofing stress state. Bologna is crossed by underground water canals and has significant subsidence phenomena. These must have been already known empirically by the builders, who adopted different roofing structural systems' configurations according to these characteristics.

The tie-beams are the elements that show, in both cases, the most significant dimensional cross-sections variation. In the Church of San Salvatore, the non-monolithic tie-beams show considerable dimensional variability

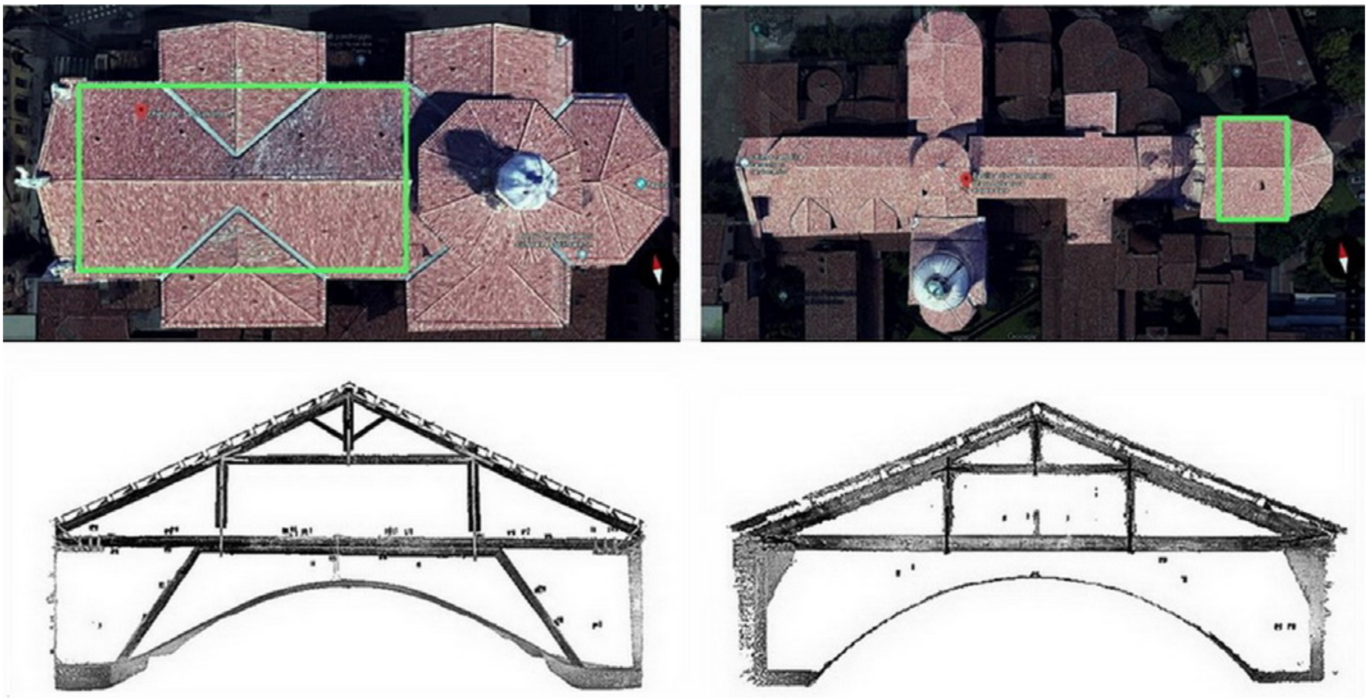

Fig. 10. *Parts of the roofing analyzed Left: Church of San Salvatore and its truss type Right: Basilica of San Domenico and its truss type.*

and, of course, higher deformations. In the Basilica of San Domenico, the use of monolithic timber elements to build-up the tie-beams implies higher stiffness and fewer deformation effects.

Out of plane displacements are different for each truss and depend on various factors, such as the joint's type between trusses' elements, the connections between truss and purlins, and their arrangement along the rafters and the roof shape itself. It is difficult to find a principle that relates both roofing behaviors, as these are linked to each building's specific characteristics. It should be noted that in both cases, the trusses are not equipped with bracing elements that allow for mutual connections outside the vertical plane, to guarantee a more uniform roofing behavior and increase the rigidity of the roof pitch.

For the Basilica of San Domenico's trusses, the trusses' ridges seem to undergo a translation towards the choir wall, almost as following the ridge beam. In San Salvatore's Church, the peculiarity of the joint on top of the queen post, in which all timber elements are discontinuous (as shown above in Figure 6), allows rotations on two axes. The lower trapezoid part formed by tie-beam, sub-rafter, queen posts, and straining beam can rotate around the tie-beam axis. The upper triangular part formed by top-rafters, king post, struts, and straining beam can rotate independently around the straining beam axis. The only elements contrasting such movements are the newly introduced metal brackets connecting timber elements and stiffening the joints, which in many cases are not effective.

Summing up, the loading conditions in both cases are almost the same; weights carried, ground subsidence, horizontal thrusts due to wind or earthquake and snow, but the behavior of the trusses, and in general of the roofing, depends on the particular solutions and construction schemes adopted in each building. The high awareness of the builders, therefore, emerges. They seemed to know how to adapt the choice of a specific static configuration to the peculiar characteristics of the entire building. Both Mazenta, who designed the Church of San Salvatore's roof, and Dotti, the architect who raised the Basilica of San Domenico's pitched roof, evidently did not limit themselves to the mere application of a known scheme. The analyses carried out on both wooden roofs clearly show that the truss configurations were best suited to the peculiar static conditions of each building.

7. FUTURE DEVELOPMENTS

The protocol developed using parametric modeling for the interpretation of displacements and deformation of wooden trusses has proved to be efficient and effective. The results obtained in the various case studies are consistent and comparable. The next development foresees the generalization of the algorithm created for 3D models rendering, which is different case by case since it is linked to the shape and geometric characteristics of each type of truss. The ultimate goal of the research is to bring together the different experiences in order to obtain an algorithm as general as possible as well as adaptable to a more significant number of trusses' types, thus laying the foundations for a fully automated process, where it is only necessary to input the cross-sections of each timber elements and obtain the 3D models as output. This generalized algorithm must also have to cluster specialized operations that have to be applied to each truss, trying to be easy to understand even for those who never dealt with parametric modeling and Grasshopper software.

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