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PART 2 - Investigation, analysis, and interventions

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Cover illustration: Auxiliary truss for the strengthening of the roof of San Giovanni Battista church, Borno, Brescia, Italy, 1771-81/2020 by E. Zamperini. © Emanuele Zamperini (2020)

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WIDE-SPAN TIMBER TRUSSES IN THE AREA OF BOLOGNA: A CASE STUDY ANALYSIS AND COMPARISON

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Abstract

This paper summarizes a larger research project that used an innovative method to study several timber roof structures in Bologna. The research was focused on developing a support tool for analyzing the geometry and the structural behavior of these structural systems, utilizing a Terrestrial Laser Scanner (TLS) and point cloud geometric information via visual programming generative algorithms. In addition, the method has been developed to collect and trace data on various types of timber trusses and function as an information system.

Specialized literature frequently oversimplifies the comprehension of these structural systems by basing its theories on structural analysis methods that originated in the nineteenth century. This approach typically needs a thorough understanding of material properties and structure deformations, which cannot be easily obtained.

Innovative methods of research, as well as typological construction investigations, can help gain a thorough understanding of these objects. Such knowledge is essential for the conscious conservation of these amazing construction systems. This paper compares five types of timber trusses from the roofs of noticeable buildings from the 17th and 18th centuries, associating their typological and construction characteristics with the geometric and deformative information from previous research. The study provides a deeper understanding of these objects in the Italian context by highlighting some critical issues.

Keywords

Historical timber trusses, Structural efficiency, Terrestrial Laser Scanning, Parametric modeling algorithms, Displacement analysis.

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1. INTRODUCTION

The difficulties in accessing and moving inside old wooden roofs and the lack of visibility of trusses, frequently hidden by masonry vaults, have reduced them to minor issues in the fields of Conservation and Restoration of Cultural Heritage. Roofing systems are often ignored until severe deterioration or damage threatens the building's safety. Few studies correctly understand the actual behavior of large-span trusses and their evolution over time. Furthermore, the specialized literature frequently oversimplifies their structural conception, basing their theories primarily on methods of investigation and calculation associated with the traditional idea of elastic structures. At the same time, the contemporary approach is overly specialized or dictated by the need to solve accidental or local problems. Interventions often overlook factors of primary importance, such as the transformations of these building systems over time and the actual behavior of joints, generally modeled as pure hinges. These factors complicate the numerical quantification of the actual behavior of these complex structures and put traditional calculation models at stake.

The configuration of the historical trusses belongs to the Art of Construction rather than the Science of Construction [1]. The trusses' strong intertwining of history, architectural technology, and material culture suggests that their conception is not easily referable to simple structural schemes unless at the cost of high approximations. Timber trusses are mostly statically indeterminate structures, and their structural safety is linked to good execution, junctions and connections implementation, material quality, and long-term preservation. Deeply understanding the current state of a truss means going back in time to see how this structure evolved throughout its service life.

Since the beginning, this multi-year research experience has proposed to overcome the principle of classification and schematization, which is typical of the 19th-century culture of Construction Science. Therefore, the "epistemological" approach has been favored over the "technicist" approach for knowledge, interpretation, and analysis of structural behavior [2]. It entails the use of an innovative and non-invasive method of investigation based on digital Terrestrial Laser Scanner (TLS) surveys, integrated with the collection of other data, such as historical and archival research, in-situ surveys, reverse engineering procedures, parametric modeling algorithms, and data science techniques.

An investigation method for deepening knowledge of these construction elements has been developed by approaching this issue differently. The analyses enabled the systematization of a procedure for highlighting some displacements that timber trusses commonly experience during their life cycle in terms of rigid body motions and deformations [3, 4]. This three-step method has been applied to various case studies and gradually updated and implemented to consider any type of timber truss. The first step is to acquire data on-site using TLS survey techniques. In the second step, the method enables a fast and reliable virtual representation of the trusses using 3D parametric modeling and Building Information Modeling (BIM) software [5, 6] due to the consistency of digital information. The third step allows different types of information to be associated with the 3D digital models. These models can be linked to archival documentation, monitoring data, and information on intervention hypotheses for the conservation and functional recovery of these examples of historical construction.

In this paper, five case studies are briefly introduced, adding references to more comprehensive studies that cannot fit this short essay. Then, the geometric characteristics of each truss type are compared to the theoretical schematizations of a popular manual from the second half of the nineteenth century [7, 8]. The goal is to link pre-nineteenth-century building practice and emerging nineteenth-century technical-scientific knowledge. Finally, the application of the method provides an interpretation of the displacements these systems have undergone over time, highlighting any recurrence or typical behavior. The objective is to prepare the ground for a more in-depth and structured understanding of the Bolognese trusses built between the seventeenth and eighteenth centuries and pave the way for the same method of investigation to be applied to other national and international case studies.

2. THE CASE STUDIES

In the mid-sixteenth century, the city of Bologna, which was at the apex of its political and cultural importance in the Pontifical State, had nothing to envy other important Italian and European cities. It was true for the splendor and uniqueness of its built heritage, as well as the dynamics of its economic and social structure's development. The constant presence of scholars granted by the University, which always drew prominent figures from all over Europe, and the close relationship with the Papacy acted as driving forces for the edification activity. The city's fabric was gradually enriched with significant buildings to meet the demands dictated by the social status of influential families and the powerful Curia. It is no coincidence that in 1575 Pope Gregory XIII, the Bolognese Ugo Boncompagni, commissioned a fresco of his hometown for his private apartments at the Vatican

Palaces, depicting all of the most important religious and theatrical buildings, in addition to the noble palaces.

The need to build roofs for these numerous large-scale halls has undoubtedly favored the development of trussed roof systems. Indeed, many advantages were provided by these roof structures, which differed significantly from North-European wooden roofing systems with steeper slopes since they enabled the construction of relatively light non-thrusting roofs while also overcoming large spans. Even though obvious variations of the base type emerged over the years, it is immediately possible to say that construction practices and production processes can be considered relatively stable during this period. However, it should be noted that, in many cases, existing trusses are in a different state than their original configuration, having been subjected to consolidation interventions or changes in the use of the spaces beneath [9].

The trussed roofs on which the method has been fully applied are listed below in descending order of complexity and span covered:

- the Teatro Comunale of Bologna (TEA) was built in the late 17th century. It was initially designed by the architect Antonio Galli Bibiena [10] and completed by the architect Lorenzo Capponi in 1763. The 5 timber trusses, with more than 25 meters span, were erected right after the construction of the great eighteenth-century hall [11]. The municipal architect Giuseppe Tubertini addressed severe deterioration issues that had arisen in the timber trusses in the early nineteenth century, despite the building's young age [12]. Other strengthening interventions on the roof structure occurred around 1980 [13] when the great hall's wooden ceiling was hung with tie rods to the reinforced trusses [14];
- the Cathedral of San Pietro (PIE) was rebuilt in the mid-12th century after being destroyed by fire [15]. Since then, the church has undergone several changes. In the early sixteenth century, architect Giovanni Ambrogio Magenta took on the construction site, which was later modified and continued by master carpenter Niccolò Donati. The construction was completed in 1748 by the architect Alfonso Torregiani who erected the façade [16]. Among the eighteen trusses of the central nave, which span more than 25 meters, sixteen of them date from the early 17th century, while the other two were built after the mid-18th century, at the same time as the new façade;
- the Basilica of San Petronio (PET) began construction in 1390 and was built intermittently over the following centuries. Due to a lack of funds, famine, and political changes, the church was built in one or more bays at a time until the mid-1600s [17], when the central nave was raised and the roof was made. Girolamo Rainaldi designed the timber trusses according to his expertise dating back to 1625, in which he proposed modifications to the original project of Francesco Terribilia. Today, the roof over the nave is made up of 35 original trusses that span just under 19 meters, built between 1646 and 1658, plus 7 trusses that were replaced in 1905;
- the Church of the Santissimo Salvatore (SAL), of late-medieval origin, was rebuilt in the fifteenth century and then, between 1600 and 1623, took on the current form of a baroque church. The design can be attributed to Giovanni Ambrogio Magenta, who was active in Bologna during that period. The project was inspired by the Basilica of Massenzio, according to Magenta's writings, and later modified by the architects Onorio Longhi and Carlo Maderno. The trusses of the central nave, with a span of about 18 meters, date from this period. In 1980, a restoration intervention involving the entire church was carried out, replacing the most degraded timber elements of the trusses and renovating the upper enclosure;
- the Basilica of San Domenico (DOM) is the patriarchal church of the Dominican order, and it was commissioned in the mid-13th century [18]. Between 1298 and 1654, the church was renovated several times. Then, the architect Carlo Francesco Dotti designed and coordinated various structural interventions around 1730, including the roof replacement, which was raised to match the new façade. The existing timber trusses, which span 17,5 meters, date from that period and are almost entirely original, particularly those above the choir. Other restoration work was done on the building in the 1900s.

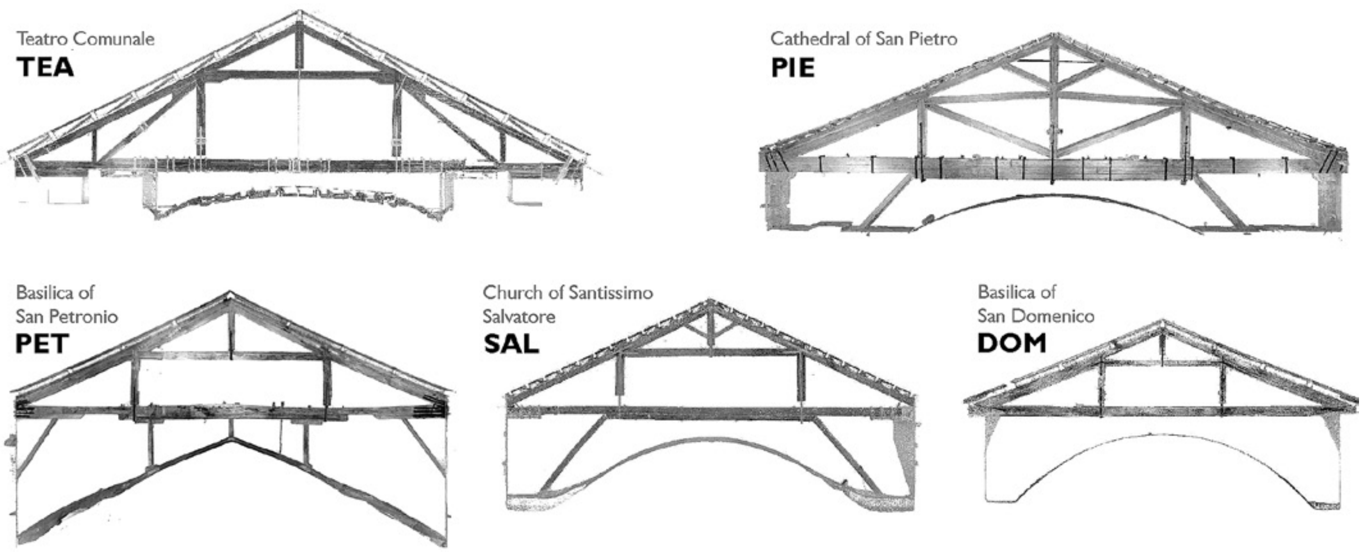

Fig. 1. *Orthophotos of the analyzed R-trusses extracted from the TLS digital survey.*

To make a transversal comparison between the case studies, it was decided to select a Reference-truss (hereafter named R-truss) for each building. The R-truss can be considered the one that best represents the series of trusses that form the entire roof of each building in terms of regularity, deformation state, and originality (Fig. 1). The use of an R-truss is acceptable because all the trusses in each building are very similar, differing only in a few elements due to construction inaccuracies or local substitutions. The 5 selected R-trusses were analyzed with the latest version of the developed method to compare the results [5].

Tab. 1 summarizes some of the major time evolutions of the analyzed trusses. PIE owns the oldest trusses, which date from the early 17th century. Following these are the PET (mid-17th century), DOM (early 18th century), and SAL trusses (early 18th century). The most recent trusses are from TEA and date from the mid-18th century. The comparison of the ages of each truss and the corresponding building reveals that the trusses were only built concurrently in the case of TEA. In all other cases, the truss framings in place today could have been made years, if not decades, after the walls beneath. After the realignment of the ridge to the new façade, built by Dotti in 1730, DOM, for example, had the entire roof rebuilt. Other interventions on PIE and PET have also been documented and can be considered somehow historicized. According to the information gathered, these roof configurations can be thus regarded as homogeneous.

On the other hand, the SAL and TEA trusses underwent significant consolidation work at the end of the twentieth century. In the first case, several eighteenth-century beams were replaced. In the second case, a metal tie rod was added to work alongside the wooden one, and metal straps were added at some joints. As a result, it is critical to recognize these changes to avoid a superficial interpretation of the numerical data obtained through the digital analysis method.

	Teatro Comunale (TEA)	Cathedral of San Pietro (PIE)	Basilica of San Petronio (PET)	Church of San Salvatore (SAL)	Basilica of San Domenico (DOM)
Construction phases					
Masonry structure	Mid-18th century	13th to late 18th century	Late 14th to mid-17th century.	Beginning of 17th century	From mid-13th to 18th century
Timber trusses	5 Mid-18th century	16 early 17th century; 2 mid-18th century	35 mid-17th century; 7 early 20th century	11 early 17th century	11 early 18th century
Deep renovations and strengthening	1818-1820; 1980-1981	-	-	1980	-

Tab. 1. *Historical background of the analyzed trussed roofs.*

3. IDENTIFICATION OF R-TRUSSES

The trusses are analyzed on two scales: a general scale related to the scheme of the R-trusses and a detailed one related to the joints. Accurate observation and an extensive photographic campaign in situ are essential to achieving this. Nonetheless, the TLS survey proved critical for extracting orthophotos and obtaining proper graphic restitution (Fig. 1).

Comparing different R-trusses allows for the assignment of specific typological characteristics to the deformation properties of the entire roof system, leading to a better understanding of each R-truss behavior and clarifying the role of each timber beam within the construction system.

Smaller span R-trusses (PET, SAL, and DOM), ranging from 17 to 19 meters, show only minor differences and can be traced back to the recurring Italian type known as Queen post truss or *palladiana*. This truss scheme has two principal rafters, two queen posts, one king post, a straining beam, and a tie beam [9]. When assembled with spliced or scarf joints in the longer members (typically tie beams), queen post trusses can cover a 20-meters span.

The two larger R-trusses (TEA and PIE) represent more complex schemes, almost unique, even though they can be traced back to the concept of compound trusses with straining beams [19]. The strutting arrangements are different. In PIE, the straining beam is divided into two inclined elements connected by a king post; in this case, the straining beam becomes a sort of discharging arch. In TEA, the straining beam is connected to the tie beam by compressed struts and two additional lateral posts. These latter are also compressed, working as props that transfer the load acting on the truss to the structures of the theatre hall.

Tab. 2 summarizes the typological and geometric properties of the analyzed R-trusses, which are discussed further in the following paragraphs.

3.1. FRAMING SCHEMES

In terms of framing, each analyzed case has unique characteristics due to the shape of the bearing structures beneath and the span covered. In general, all trusses are of the queen post truss type, with minor variations in the number and size of beams, supports, and joints. This geometric scheme consists of a lower trapezoidal shape and an upper triangular shape. These two parts seem to correspond to two successive stages of assembly: the tie beam, rafters, and straining beam are erected on-site first, followed by the completion of the triangular upper part. As partial evidence, it can be considered that principal rafters are always doubled in cross-section, except in SAL, by using a second timber element to strengthen the rafter/straining beam joint. This second overlaying rafter is usually continuous near the joint, while the first one, due to construction needs, is interrupted by the queen post.

The presence or absence of additional beams produces different alternatives due to how the roof structures are connected to the masonry elevation walls and the span length. This standard scheme is used in case studies with a shorter span (PET, SAL, DOM) (Fig. 2). While considering the tie beams, three variations can be found: the tie beam resting on the vault via masonry supports (PET), the tie beam loading the sidewalls via structural timber brackets (SAL), and the tie beam resting on masonry abutment supports (PET) (DOM). These alternatives suggest a process of refinement in construction over time and possibly reflect the availability of materials and the technical skills of the builders at that moment. For example, PET construction has suffered from significant financial difficulties, resulting in less care in the works.

The other two case studies have non-standard characteristics and do not fit into a typical typological scheme. The PIE truss has undoubtedly piqued the public's interest with the widest span of all the analyzed examples. This truss has an additional discharging arch system; the king post divides the straining beam into two parts, and the elements are slightly inclined towards the queen posts. This choice expresses the architect's intention to streamline the function of these compressed elements by resorting to a solution relatively uncommon. The TEA case is also unusual, with lower sub-struts that allow loads to be discharged on two intermediate supports that connect to the tie beam. As a result, the Bolognese case is rich with variations and a fertile field for investigation.

	Teatro Comunale (TEA)	Cathedral of San Pietro (PIE)	Basilica of San Petronio (PET)	Church of San Salvatore (SAL)	Basilica of San Domenico (DOM)
General strutting					
Classification	Queen post truss with additional posts resting on 4 external supports	Queen post truss with internal discharging arch and double struts	Queen post truss	Queen post truss with struts	Queen post truss
Beams number	13	14	9	11	7
Joints number	9	9	5	7	5
Beams assembly					
Tie beam	Assembled	Assembled	Assembled	Assembled	Continuous
Straining beam	Continuous	Continuous	Continuous	Continuous	Continuous
Principal rafters	Interrupted	Interrupted	Interrupted	Interrupted	Interrupted
Stiffening rafters	No	Yes	No	No	Yes
Joints and notches					
Ridge/rafters	Head of king post	Head of king post	Head of king post	Head of king post	Head of king post
Rafter/straining beam	Head of queen post with wood corbels	Head of queen post with struts and stiffening rafter	Head of queen post	Head of queen post	Head of queen post with stiffening rafter
Tie beam/rafter	Double step	Double step	Single step	Single step	Single step
Metalwork					
Ridge/rafters straps	No	No	No	Added in 1980	Added (undated)
Rafter/straining beam straps	Yes	No	No	Added in 1980	Added (undated)
Tie beam/rafter straps	Yes; Restored in 1980	Yes	Yes	Added in 1980	Added (undated)
Tie beam straps/ bolts	Yes; Restored in 1980	Yes	Yes	No	No
Queen post stirrups	Yes; Restored in 1980	Yes	Yes	Restored in 1980	Restored (undated)
External Supports					
Sidewalls support number	2	2	2	2	2
Other supports number	2	2	5	2	0
Total supports	4	4	7	4	2
Sidewalls support type	Masonry	Masonry	Masonry and timber brackets	Masonry and wood corbel	Masonry corbel
Other supports type	Masonry	Three-voussoirs timber arch	Wood props on the vault	Three-voussoirs timber arch	-
Roofing and vault					
Roofing type	Masonry tiles	Wood planking	Masonry tiles	Wood planking	Masonry tiles
Vault type	Hanging wooden ceiling	Barrel vault	Groin vault	Sail vault	Sail vault

Tab. 2. *Typological characteristics of the R-trusses analyzed.*

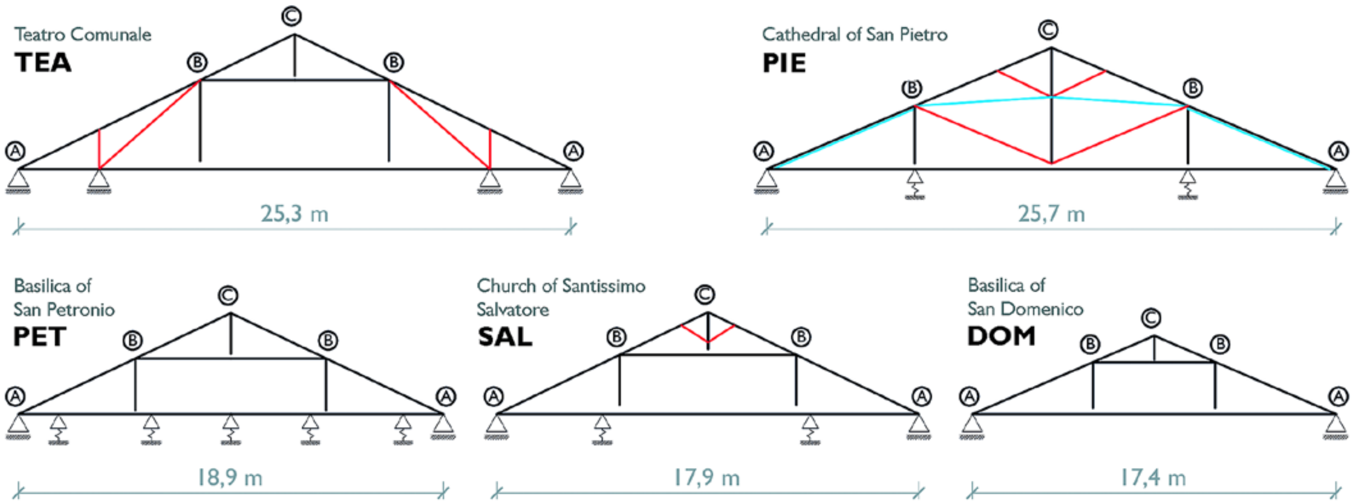

Fig. 2. *Framing schemes of the analyzed R-trusses. In black, the elements referable to the scheme of the standard queen post truss; in red, the additional struts; in cyan internal discharging arch elements. The line thicknesses do not represent the proportioned real cross-sections of the elements.*

3.2. ASSEMBLING PROCESS

Concerning the timber used to realize the truss elements, it is well known that one of the most critical points in their assembly has consistently been material availability. It was nearly impossible to find sufficiently long trunks to produce single continuous beams of eighteen meters or more, and the materials (spruce in almost all of these cases) had to be transported from long distances to Bologna. Besides, assembled beams of greater length also had thicker cross-sections. Assembled beams are made up of several timber elements connected by metal strap junctions. These joined elements become sufficiently rigid and flexural stress-resistant [19–23]. Tie beams are assembled by double-length or triple-length elements, being the longest members in a timber truss. The cross-section of the tie beams is nearly doubled at the midpoint (PIE, PET, SAL). The 26-meter-long PIE trusses have a tie beam cross-section of 30 cm x 90 cm formed by connecting three elements. In contrast, the DOM tie beam is the only example of a single-length element tie beam among the analyzed case studies.

The tie beams longer than 19 m in the examples analyzed are all assembled, except those of DOM, the most recent ones, which are made with a single timber piece. It should be noted that during an intervention in 1980, the SAL tie beams were replaced or consolidated. The solution for the assembled tie beam of the PET truss, made of three different pieces scattered but overlapping in the middle of the span, is quite fascinating: fearing the excessive bending of the assembled tie beam or directly observing a considerable displacement, the builders decided to support the elements with masonry pillars, loading the vault below and affecting the vault's thrust line. Conversely, the straining beams are all made in a single piece and have a maximum length of 11 m, as are the struts, posts, and other minor elements.

The rafters show significant construction variability because of the interference with the queen posts and the straining beam. Builders used a variety of solutions to create these junctions, which are subject to compression and flexural stresses. Except in the case of DOM, where the elements are continuous from the lateral support to the ridge, in each of the five case studies, the rafters are interrupted at the joint with the straining beam to allow the truss assembly in two stages. SAL is the simplest case, with rafters made up of only two beams separated by queen posts. In other cases, the rafters are surmounted by continuous beams, which can be considered as stiffening elements – stiffening rafters – installed at the end of construction.

3.3. JOINTS FEATURES

The analysis of joints is critical for understanding the system's behavior as well as tracing the structural evo-

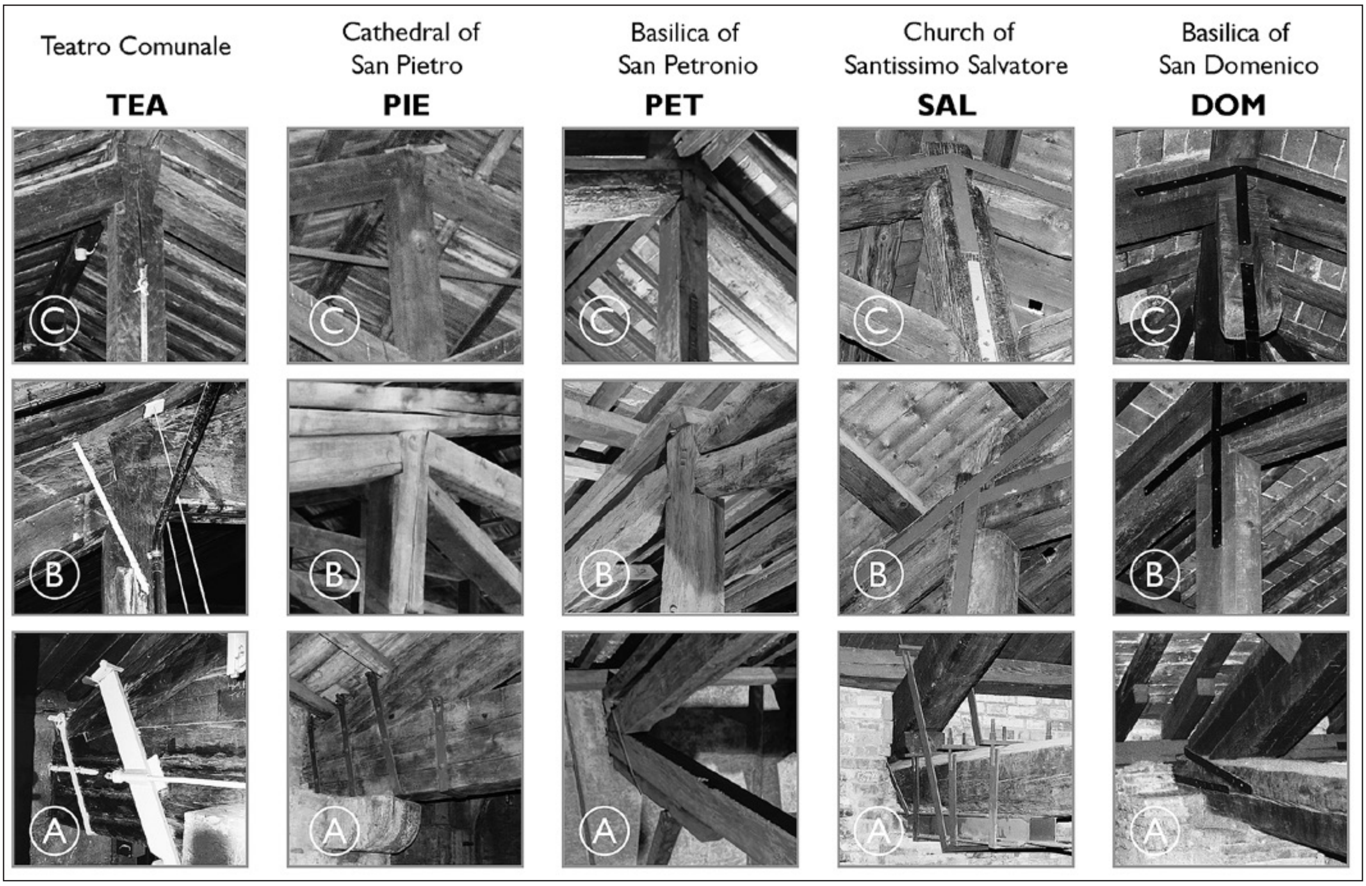

Fig. 3. *Pictures of the main structural joints of the analyzed R-trusses.*

lution of timber trusses over time (Fig. 3). Refinement and higher precision of the notches at the ends of the beams were achieved as practices and techniques continued to evolve during the period studied, particularly in DOM. In general, the complexity of junctions confirms that trusses belong to the Art of Workmanship rather than the Science of Construction. In the actual case studies, the joints, often reduced to mere internal hinges in modern structural schemes for simplicity, exhibit a difficult-to-describe behavior. It is directly understandable by evaluating the equilibrium between the elements convergent towards the joints themselves. On the other hand, the small rotations of the queen posts show a minimal transmission of the bending moment through the members.

For each of the five R-trusses, in Figure 3, the three more significant types of joints were collected: the ridge connection (C), the rafter-tie beam connection (A), and the joint between the rafter, the straining beam, and the queen post (B). This comparison is critical to understanding the different kinematics and activated deformations in each framing scheme.

All type C joints have very similar notch characteristics, and the timber elements are let into each other with minimal variation in all case studies. Consistent metal strapping is present in these joints, but in the case of TEA, SAL, and DOM, they have been clearly integrated or modified recently. On the other hand, joint B differs from case to case, and its configuration varies depending on whether the rafter is interrupted or in single-length. For example, in PIE and DOM, the presence of the stiffening rafter increases the rotational rigidity in joint B. The most straightforward B joint is found where the top rafter is interrupted, for example, in both PET and SAL; in these cases, the truss sizes are similar, and the strutting layouts are less rigid. The B joints in SAL and DOM cases have been stiffened recently with metal straps to counteract their rotation and the consequent kinematics of the whole structure. A unicum is the R-truss of TEA, in which the lower sub-rafters, more likely acting as struts, are let into the B joint of the queen posts and side blocked by short lateral posts that rest on secondary supports on the inside walls of the great hall underneath.

The notching between the principal rafter and the tie beam is fundamental to ensuring the whole system works. The outwards thrusts from the rafters need to be correctly transferred to the tie beam, thus avoiding horizontal push/pull actions on the walls below. In the case of R-trusses with single-length, principal rafters leaning onto bottom sub-rafters, the latter are the ones that are let into the notches on the tie beam. The variable shaping of the principal rafters affects the configurations in the tie beam scarfing, which can be "single step" or "double step" joints. PET presents the less complicated and refined A joint among those analyzed. More exemplary construction skill in wood carving is evident in the A joint of TEA, a symptom of a specific evolution of timber construction practices between the 17th and 18th centuries.

3.4. METALLIC CARPENTRY

Another critical piece of information for interpreting the behavior of the trusses is the analysis of the metallic carpentry (Fig. 3). Metallic straps allow a congruent deformation of the cross-section along the axis of the assembled elements, primarily the tie beams. Brackets, nails, wedges, and keys at the joints block the rotations of the beams in the truss plane, which could compromise the overall system's stability. Bracing straps can also be used at the foot of the posts to ensure that the posts and tie beams stay on the same plane.

During the service life of a truss, metal components are probably the easiest to modify and integrate. The most recent strengthening interventions, especially when the truss timbers did not need to be substituted, have frequently focused on replacing or integrating metal plates in the joints to prevent movement. The interventions performed in the 1980s on TEA and SAL trusses and the undatable interventions performed on the DOM trusses clearly demonstrate this approach. On the contrary, the PET and PIE trusses have kept their original metallic carpentry, implying that the elements were more stable from the start and maintenance was accurate.

Metalwork is present in only two analyzed cases in correspondence with the C joint, and both are later additions. As a result, it can be assumed that truss construction in the seventeenth and eighteenth centuries did not generally foresee the presence of metallic elements in this junction. Original metallic parts are only found in the trusses of TEA for joint B, but they do not connect all the converging elements and are thus partially effective. Metallic plates of more recent origin are present in DOM and SAL but not in the others. In all cases, there are metallic straps at joint A, often dating back to the original construction of the trusses or added later.

Analyzing the assembled tie beams, the TEA R-truss contains a significant amount of metalwork, most of which dates to the 1980s intervention. Numerous metal straps on the tie beam of the PIE truss also appear to be original based on their craftsmanship. On the other hand, the "keyways" or connection bolts of the PET tie beam are relatively sparse and strikingly different from those of the other case studies. Tie beam-holding stirrups are present in all cases, mostly replacing the originals.

3.5. LATERAL SUPPORTS

The A joints, which serve as the lateral supports for the tie beams, are built directly into the brickwork elevation structures that are typical of the Bologna area. The span of the tie beams is reduced by supporting brick corbels or timber brackets. Steel hammerbeams were recently installed in the SAL trusses to reinforce the heads of the tie beam. Additional intermediary supports are used to limit deflection and improve its static effectiveness. These internal supports are implemented in various ways and are slightly yielding, depending on the technical solution used.

The R-trusses in PIE and SAL use a three-voussoir timber arch solution with rafters and a crossbeam. This contrivance suggests that the builders may have been similar – the construction period is comparable –; this timber arch under the tie beam was probably the most common practice to support the beams in naves with large spans and vaulted masonry ceilings. The TEA and PET intermediate supports, on the other hand, appear as situational solutions. In the first case, the intermediate supports are provided by small walls resting on the masonry structures of the bell-shaped plan of the theatre. In the second case, the tie beams are supported by various wooden props directly resting on the vault. There are no intermediate supports in the DOM truss, which has the shortest span.

4. GEOMETRIC FEATURES AND STRUCTURAL EFFICIENCY

The investigation continues by analyzing the geometric characteristics of the R-trusses. TLS surveying techniques are commonly used with reverse engineering methods to draw interpretations of the trusses' structural efficiency. The geometric information, organized in the form of an indexed point cloud, can be processed using parametric programming software to remodel the hypothetical original undeformed condition of the R-trusses at the time of construction [5]. The five R-trusses utilized as case studies were analyzed with the most recent version to ensure homogeneity in the results.

Tab. 3 illustrates the dimensions and geometric proportions of the analyzed trusses.

4.1. STRUTTING DIMENSIONS AND PROPORTIONS

The dimensional analysis of the timber elements provides interesting information when correlated to the geometric scheme of the trusses and the scantling of the members (Fig. 4).

In the analyzed buildings, the spans (L) vary from 17 m (DOM) to 26 m (PIE). The PIE trusses, still original, are believed to be the largest in Europe at the time of their construction. Table 3 and Figure 4 show that the schemes' complexity rises in the number of members and joints as the span increases. The slope of the pitches (P) is between 22° and 26°, typical values in the Bologna area and also very close to the graphical ones proposed by Valadier (≈24°) [8].

The distance between the axis of symmetry of the trusses and the queen posts (D) is the parameter that significantly differs from case to case. This length defines the proportions of the reference queen post truss scheme adopted. In TEA, D equals about 4 m, resulting in the top rafters being about half as long as the bottom ones. In PIE, having a similar span, D equals about 6 m, thus causing the rafters to be divided into two almost equal parts. The comparison reveals that

	Teatro Comunale (TEA)	Cathedral of San Pietro (PIE)	Basilica of San Petronio (PET)	Church of San Salvatore (SAL)	Basilica of San Domenico (DOM)
Layout dimensions					
Span (L) - m	25.30	25.70	18.90	17.90	17.40
Total Height (H) - m	6.30	5.60	4.40	4.70	3.60
Straining beam Height (D) - m	4.40	5.90	4.00	4.20	2.60
Queen post Distance (E) - m	4.00	3.00	2.40	2.50	2.20
Spacing (I) - m	4.10	3.20	2.50	2.90	2.90
Slope (P) - °	26.00	22.00	25.00	26.00	23.00
Layout Efficiency					
Truss Total Area - m^2	86.10	88.20	60.40	52.10	39.30
Void Area - m^2	58.40	47.20	33.80	33.70	20.80
Wood Area - m^2	27.70	41.00	26.60	18.40	18.50
Tributary Area - m^2	115.41	88.70	52.13	57.76	54.82
Layout Efficiency (Tributary Area/Wood Area)	4.17	2.16	1.96	3.14	2.96

Legend

min. → max.

Tab. 3. *Geometric data of the analyzed R-trusses. Higher values on each row are highlighted in red.*

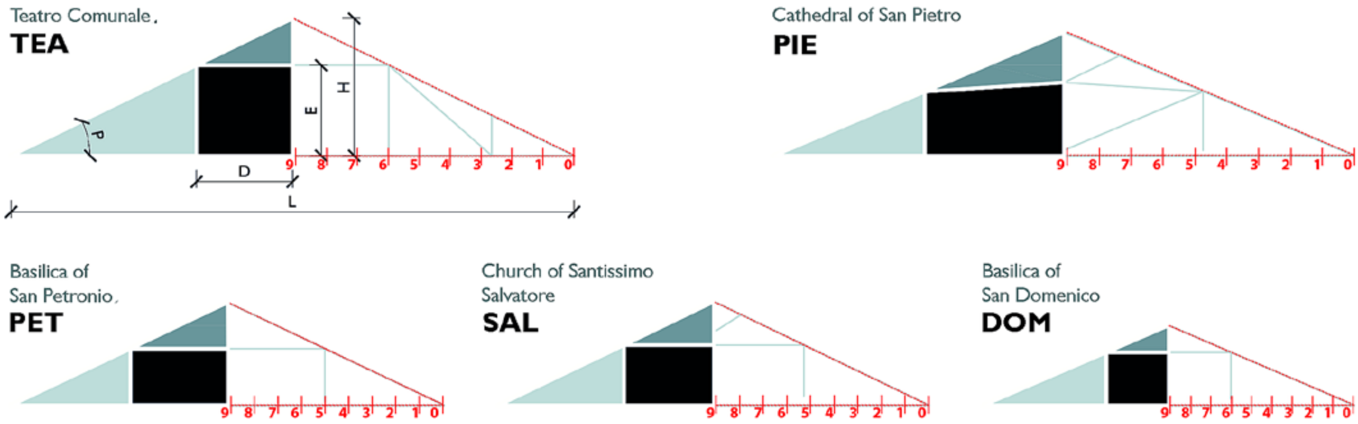

Fig. 4. *Framework proportions of R-truss layouts. The red dotted line highlights Valadier's dimensioning procedure.*

in the two most recent R-trusses (TEA and DOM), the black shape in Figure 4 tends to be a square. This fact is ideally in line with the practical suggestions given by Valadier's manual [8, fig. 2, tav. LXVI]. By dividing half the tie beam into nine parts, the queen post should stand near the five- or six-ninths from the lateral support, that is, in other words, one-third from the centerline. In the case of TEA, there is a further lateral post and an additional strut element, which prefigures nineteenth-century truss schemes and hence the need to divide the truss into three parts. In the case of DOM, the greater length of the bottom rafter, two-thirds of the total, is compensated by increasing its flexural rigidity using two assembled timbers. In the reported examples of queen post trusses by Pizzagalli and Aluisetti [19], the queen posts divide the principal rafters into almost equal parts.

4.2. LAYOUT EFFICIENCY

The total amount of wood used in relation to the span and spacing of each truss can be a parameter to quickly assess these systems' degree of structural efficiency, keeping in mind that structural redundancy is, on the contrary, an indicator of robustness and durability. Starting from the layout of each R-truss in its vertical plane (Fig. 5), it is possible to calculate the frontal wood area (in gray) by subtracting the void area (in black) from the total area of the R-truss.

Calculating the ratio between the frontal wood area and the total area of the R-truss and not considering the spacing, TEA (0.32) seems to be the most efficient and PIE (0.46) and DOM (0.47) the most robust one. The other values range from 0.35 (SAL) to 0.44 (PET). The frontal area of trestles in PIE and SAL and the masonry intermediate supports in TEA and PET is not considered.

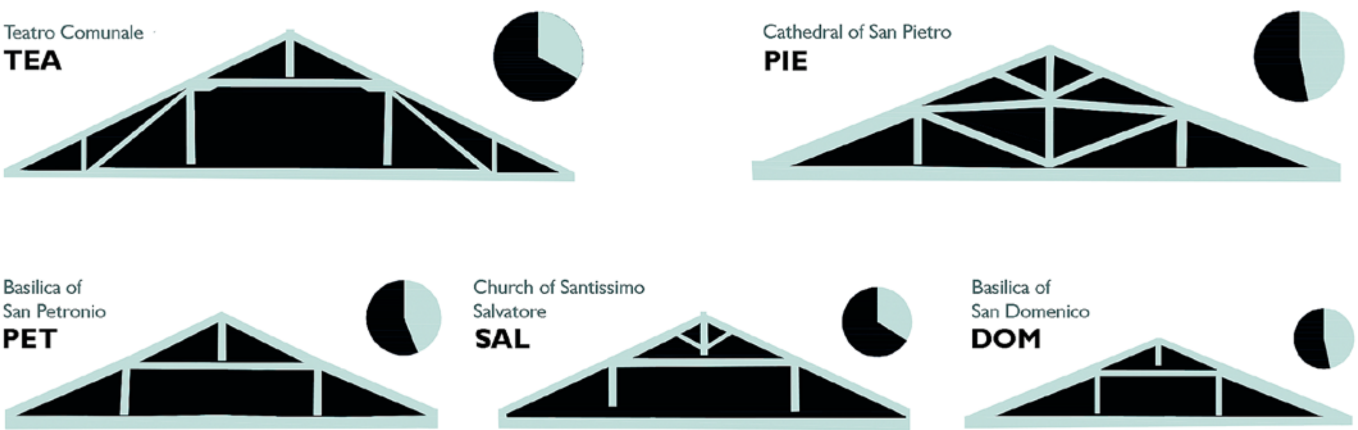

Fig. 5. *Wood and Void areas of the analyzed R-trusses.*

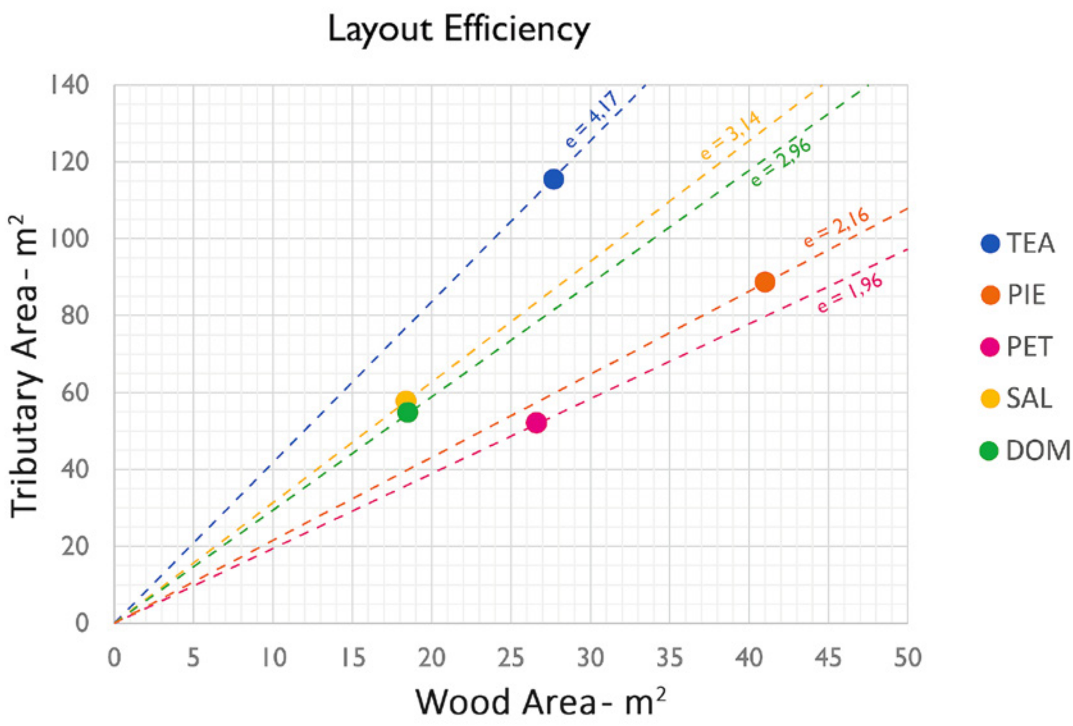

Fig. 6. *Layout efficiencies of the analyzed R-trusses.*

The layout efficiency is defined as the ratio between the tributary area and the wood area of each R-truss. The greater the value of this parameter, the lower the relative amount of material used in the whole roof and, as a result, the greater the level of structural optimization. Table 3 shows the layout efficiency values without considering the supporting gantries and the intermediate supports.

Despite the wide span, TEA has the most efficient framing system; DOM and SAL's classical queen post truss schemes are attested to intermediate values, while PIE and PET have low layout efficiency. The presence of masonry-made supports justifies TEA's efficiency. DOM has good results, regardless of the absence of wooden supports under the tie beam. Perhaps it represents the real optimal target at the end of the considered period. Its redundant static scheme against a remarkable span may justify PIE's low efficiency. PET's un-efficiency, instead, can be ascribed to the poor construction skills of the builders and its scattered construction process with poor materials, already mentioned during the presentation of case studies.

The graph in Figure 6 relates the wood area (x-axis) and the load area (y-axis). In this case, the layout efficiency is indicated by the slope of the line connecting the value plots of each R-truss with the origin. The greater the slope, the more efficient the strutting adopted.

4.3. COMPARISON WITH NINETEENTH-CENTURY MANUALS

The dimensional data of the beams refer to the main elements found in all the schemes examined: the tie beam, straining beam, and principal rafters.

Table 4 collects some dimensional data from point clouds surveyed using TLS techniques. The first three lines for each member show the total length (L), real base (Br), and real height (Hr). As expected, the measured values increase with the span covered by the R-trusses. Tie beams typically have a larger cross-section area than other members because they are assembled by multiple timbers.

A comparison was made between the values of the R-trusses and the theoretical dimensions proposed in nineteenth-century manuals. The goal was to match the results of the strutting practice of the seventeenth and eighteenth centuries and the outputs of the structural theories developed in the following century (Tab. 4).

As a reference text, the practical construction guide published in 1877 by Achille Lenti [7], a nineteenth-century scholar, was chosen. Lenti's observations on the scantling and cutting of timber elements highlighted a fixed relationship between cross-sections and the length of the truss members. These empirical formulas were deemed correct for designing the tie beams and the principal rafters of a classical truss with a king post and stiffening struts.

Lenti indicates the following practical ratios:

- Rafters: Hi/L = 0.048; Bi/L = 0.034; where (Hi) is the ideal height and (Bi) is the ideal base;
- Tie beams: Hi/L = 0.030; Bi/L = 0.020; where (Hi) is the ideal height and (Bi) is the ideal base.

Even though Lenti's formulas refer to the simple king post truss scheme, he seems to have considered in his writings the proportions suggested by Valadier in the volume *L'architettura pratica. Libro II* [8]. Analyzing Valadier's text (page 37), tables (page 16), and drawings (tav. LXVI), the proportions between cross-sections and length of the truss members are similar to those proposed by Lenti. The strutting for the queen post truss seems to be even more slender than the king post one. Furthermore, Lenti adds information about both the base and height of the cross-section, in this way helping to compare the dimensions of members and the span of R-trusses (Fig. 7). According to Lenti's proposal, the cross-sections of the tie beams, given the same lengths, are smaller than those of the rafters, which must withstand flexural and compression stresses.

	Teatro Comunale (TEA)	Cathedral of San Pietro (PIE)	Basilica of San Petronio (PET)	Church of San Salvatore (SAL)	Basilica of San Domenico (DOM)
Tie Beams					
Span (L) - cm	25,300	25,700	18,900	17,900	17,400
Real Base (Br) - cm	34	30	26	34	39
Real Height (Hr) - cm	55	62	53	37	44
Br/L	0.013	0.012	0.014	0.019	0.022
Hr/L	0.022	0.024	0.028	0.021	0.025
Straining Beams					
Span (L) - cm	8,800	11,600	7,900	8,400	5,400
Real Base (Br) - cm	30	30	26	30	24
Real Height (Hr) - cm	36	30	29	23	25
Br/L	0.034	0.026	0.033	0.036	0.044
Hr/L	0.041	0.026	0.037	0.027	0.046
Top Principal Rafter					
Span (L) - cm	4,900	6,400	4,400	4,700	2,900
Real Base (Br) - cm	31	30	26	27	21
Real Height (Hr) - cm	35	30	24	29	23
Br/L	0.063	0.047	0.059	0.057	0.072
Hr/L	0.071	0.047	0.055	0.062	0.079
Bottom Principal Rafter					
Span (L) - cm	9,200	7,800	6,100	5,900	6,500
Real Base (Br) - cm	30	30	26	28	25
Real Height (Hr) - cm	34	61	29	34	50
Br/L	0.033	0.038	0.043	0.047	0.038
Hr/L	0.037	0.078	0.048	0.058	0.077

Tab. 4. *Real dimensions of the main members of the analyzed R-trusses. Br/L and Hr/L values for each R-truss.*

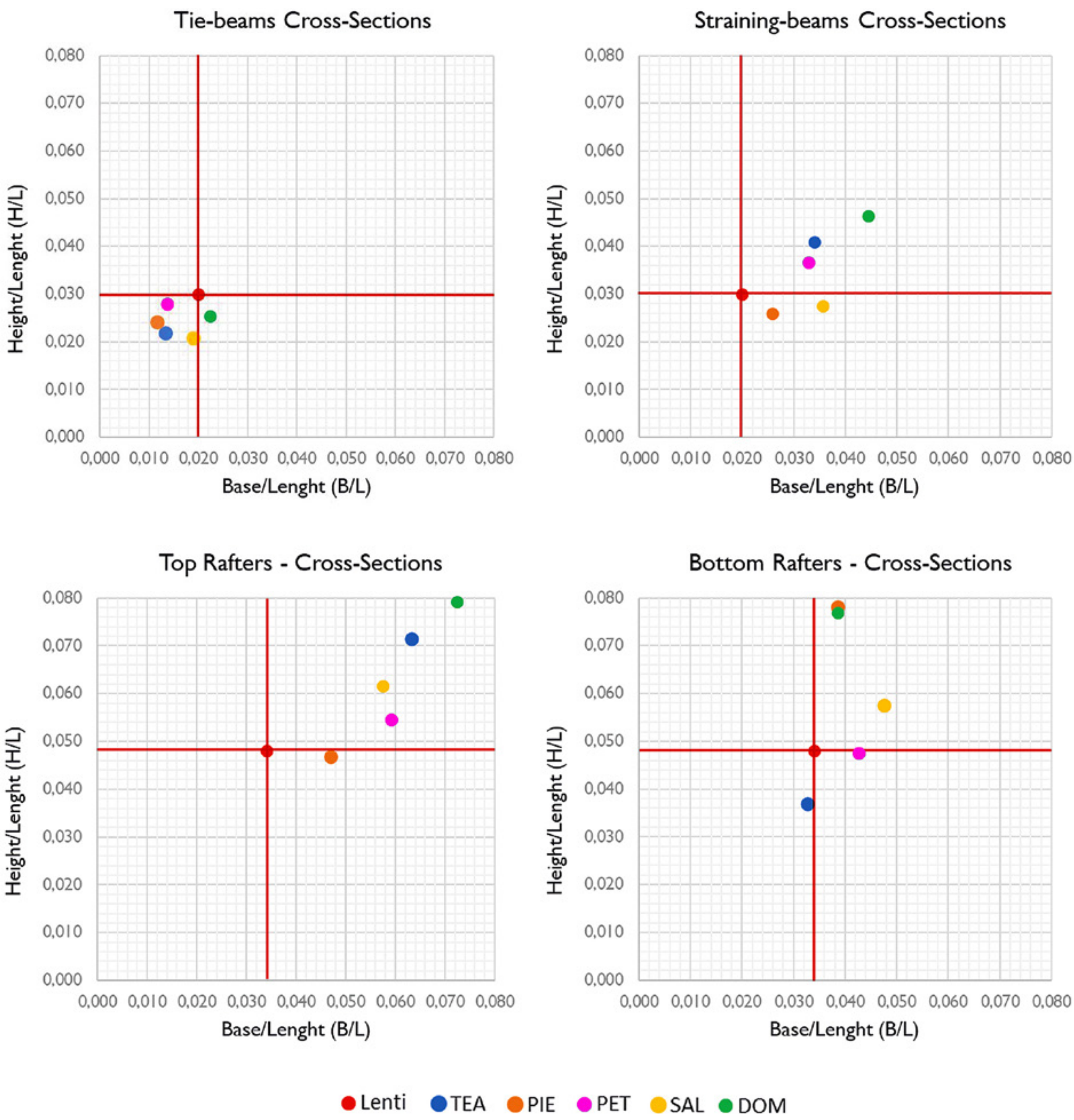

Fig. 7. *Measured cross-sections scantling with respect to Lenti's practical guide. Tie beam and rafter ratios for each R-truss.*

The graphs in Figure 7 show the Br/L and Hr/L ratios of the element sections belonging to the five trusses under study to compare them visually. The red points identify the dimensional ratios suggested by Lenti for the tie beams and rafters. In particular, the lengths and sizes of the top and bottom rafters were considered separately since all the truss layouts present interrupted rafters. The straining beams of the five R-trusses are also evaluated with the same formulas.

What emerges is that the tie beams are generally slightly undersized. Given the approximations used, this fact proves the function of the intermediate supports and the gantries in the case studies. The builders knew, even empirically, that the length of the tie beams, which were typically made in double or triple lengths, could be a weak point in the system. The straining beams are generally oversized, especially concerning the base dimension. A greater cross-section is probably due to construction opportunities, given the sizes of the other transported elements.

Since the top rafters are always shorter than the bottom ones, they are generally oversized, given the same considerations drawn for the straining beams. Even the bottom rafters are generally oversized, although closer to Lenti's proportions. TEA bottom rafter results as an anomaly in the values because they are significantly longer than in all the other case studies and are supported by detached sub-struts. This data comparison backs up what has already been said about the layout efficiency in the analyzed cases. The particular slenderness of the elements of the TEA R-truss is due to the introduction of new elements in the design, which helped meet the requirements of an economical construction [11], as well as to the presence of the intermediate props, which allowed for more freedom in strutting.

5. DISPLACEMENT ANALYSIS

TLS surveying techniques and truss modeling helped carry out a displacement analysis on a geometric basis. The analysis method is based on identifying the most likely kinematics and displacements to which the actual timber truss may be subjected under vertical loads.

Starting from the point cloud, the truss framing is transformed into a wireframe model of linear elements through an appropriate algorithm and then brought back to an ideal undeformed condition. The standpoint is always the truss's hypothetical initial undeformed condition compared to the actual state. In particular, the main displacements considered are those in the truss's vertical plane and the orthogonal direction (out of the plane). The displacements are measured in correspondence to the joints and at the center of the tie beams. In the truss plane, the basic assumptions are that the ridge joint (C) may sag, the queen posts joints (B) may lower and/or rotate towards the inside of the truss (following the rotation of the principal rafters and favoring the rotation of the queen posts), while the lateral wall supports (A) remain fixed. The downward tie beam deflection is also considered.

Figure 8 depicts the displacements and deformations in the vertical plane of the highlighted R-trusses on a magnified scale, with respect to the hypothetical perfect linearity of rafters and tie beams in the absence of any load, neither permanent nor transient (ideal undeformed situation). No dangerous situations have been encountered. The assumed kinematics and displacements are respected in all cases, with all R-trusses exhibiting approximately symmetrical behavior. It has always been possible to attribute some punctual differences or deviations to local factors, such as asymmetries, which have had a decisive influence on that non-compliant behavior. Furthermore, it can be stated that observing a difference frequently serves as an alert signal to highlight local problems.

A common outcome is that C joints have smaller displacements than B joints. The R-trusses that have undergone interventions during their life cycle (TEA and SAL) exhibit sagging values that are not as high as those left as originals. Along with minor sagging, there is evidence of a rotation inwards of the posts in TEA and DOM trusses, going in the opposite direction than the others, and this is not linked to the deformation of the straining beam but to the position of the queen posts at one-third of the rafter length.

Tab. 5 shows the sagging values (∂) of a few control points (joint C, joint B, and tie beam midpoint T), as well as the sagging/length ratio.

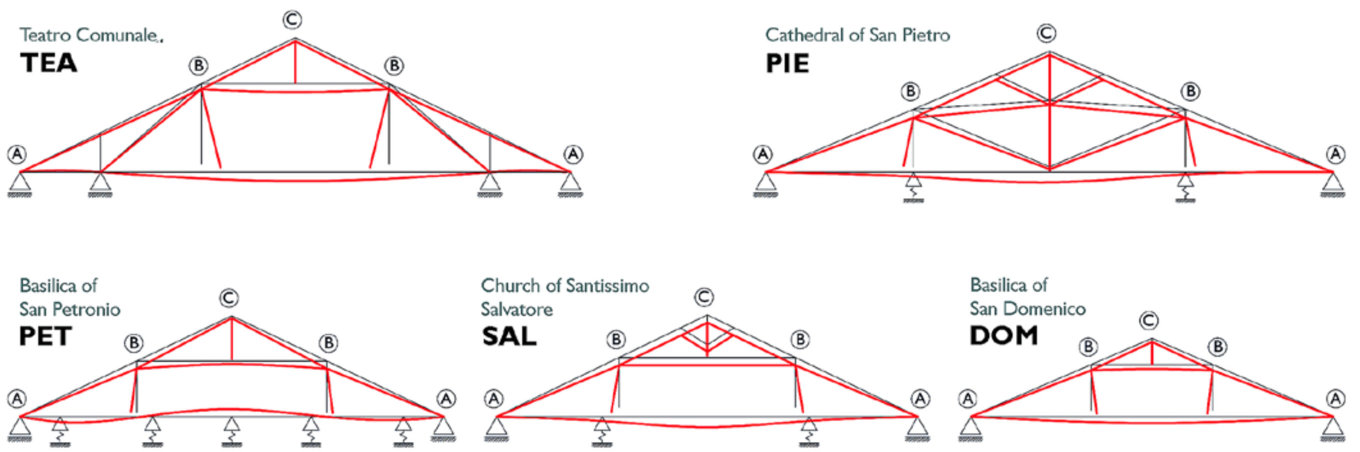

Fig. 8. *Qualitative deformation kinematics of the analyzed R-trusses.*

	Teatro Comunale (TEA)	Cathedral of San Pietro (PIE)	Basilica of San Petronio (PET)	Church of San Salvatore (SAL)	Basilica of San Domenico (DOM)
Control points displacements					
Vertical displacement joint C (∂_C) - cm	1 cm	1 cm	3 cm	2 cm	1 cm
Vertical displacement joint B (∂_B) - cm	2 cm	7 cm	6 cm	5 cm	5 cm
Span to vertical sagging ratio (∂_B/L) - %	0.07%	0.27%	0.47%	0.28%	0.29%
Queen post rotation (Ω_B) - °	0.57° (inward)	0.17° (outward)	1.48° (outward)	0.46° (outward)	0.47° (inward)
Tie Beams Deformations					
Midpoint vertical sagging (∂_T) - cm	4 cm	7 cm	-12 cm	11 cm	4 cm
Span to midpoint sagging ratio (∂_T/L) - %	0.16%	0.26%	0.61%	0.63%	0.23%

Tab. 5. *Deformations and main displacements of the analyzed R-trusses.*

In order to grasp more relevant information, some of the values in Tab. 5 have been correlated to the span of each R-truss. Figure 9 shows both the tie beam and the rafter sagging as a function of the span. The red dotted line highlights the average values, meaning that points above the line stand for higher sagging while points under the line stand for minor sagging. The rafters' behavior is somehow in line with the increase in the span. The wider the span, the higher the sagging, except for the case of the TEA R-truss, which was restored in 1981. In general, the tie beams' behavior seems to vary independently from the span.

The TEA R-truss is the one that supports the heaviest loads of all the case studies; it spans approximately 25 m and has a spacing of approximately 4 m. The TEA R-truss also has higher layout efficiency and members with high slenderness. According to the traditional approach, these factors would imply poor truss behavior in capacity/demand satisfaction in the strength and stiffness of the various members. However, its displacements are pretty small. In that regard, some determining factors must be considered. Firstly, there are more elements and external supports; in fact, the TEA R-truss is the most recent (mid-18th century), and the static layout has inevitably evolved compared to older R-trusses. Secondly, it should also be noted that the significant strengthening interventions increased its efficiency and reduced its deformations. The eighteenth-century truss of Milan's Scala Theater, which had a very similar configuration, was built in the same period and was deemed extremely slender and criticized at the time.

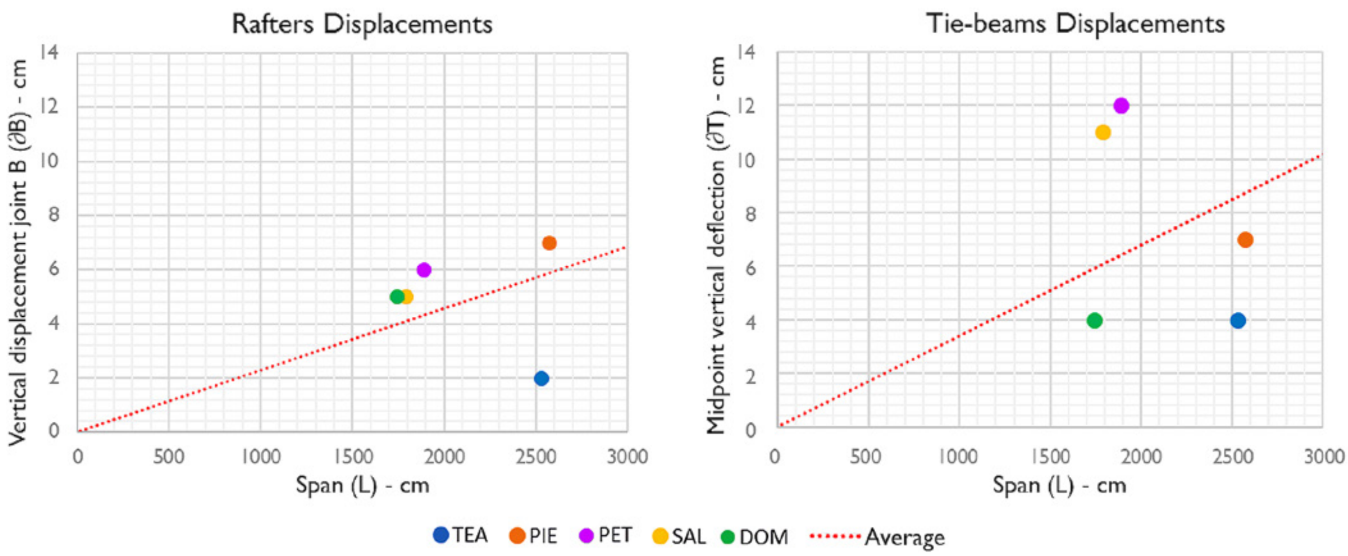

Fig. 9. *Displacements' analysis of joint B and tie beam midpoint for the R-trusses.*

The oldest and most complex PIE R-truss has demonstrated good behavior without significant interventions. Despite its large size, the displacements it has experienced are relatively lower than those of the other case studies, indicating particular robustness derived from the execution and design concept. The presence of an intermediate discharging arch, a continuous king post, and large diagonal struts demonstrate the overall rigidity of the static scheme. Even the construction methods identified in the historical documentation attest to a very high level of design care and significant financial commitment, which is supported by the accounting records [24].

The PET R-truss has a much smaller span than the TEA and PIE trusses and a smaller spacing and tributary area than the other case studies. As a result, it also has the lowest level of stress. It has an average void/solid ratio and the simplest pattern among the various R-trusses. Its origins are older than PIE and SAL, dating back to the mid-17th century. The builders' confidence appears to be smaller than in the other case studies. Using timber brackets to shorten the span and intermediate props on the vault to support the tie beam confirms that the builders relied primarily on masonry walls. Straight cuts are also used to notch and assemble the double-length tie beams without precise scarfing. This incorrect solution tends to absorb tensile stresses less effectively, resulting in excellent system deformability, mainly when dealing with horizontal loads.

The SAL and DOM R-trusses are substantially in line with expectations, presenting a standard framing typical of many other Italian wooden roofs and demonstrating a good stiffness of the principal rafters. Above all, the DOM R-truss is the only one with a single-length tie beam. As a result, its behavior is more understandable, with reduced flexures of the rafters and tie beams and a slight inward rotation of the queen posts.

The findings show that each case has construction quirks and an evolutionary process that must be thoroughly examined. In general, variations in the realization of the static scheme (presence of timber brackets or corbels, position and arrangement of the joints, intermediate supports such as masonry props on the vault or three-voussoirs timber arches, principal rafters length, and scantling) are thought to have a more significant effect than dimensional variations of the members. The use of rapid and non-destructive digital techniques provides a real opportunity to improve the understanding of timber trusses in a relatively short time.

6. CONCLUSION

The paper presents a few findings from a study of a few timber trusses in the Bologna area located in historically significant buildings between the 17th and 18th centuries. This study is based on a novel approach that employs TLS digital survey technologies and parametric modeling algorithms to obtain geometric and spatial data that would be impossible to achieve using traditional methods. Furthermore, this approach allows for the systematization and tracking of information gathered through other types of investigation (documentary, instrumental, and photographic), establishing itself as a sort of information system for analyzing and interpreting results.

When applied to the five case studies, the method identified shared and unique characteristics of the R-trusses used in each wooden roof under consideration. The archival research enabled the collection of important historical data from all case studies. The typological analysis confirmed how each case presents itself as a variation of the classical queen post truss, demonstrating that each construction reveals its individuality, which is primarily determined by the workers' knowledge and economic constraints. The geometric analysis enabled a sharp and precise assessment of the dimensional and proportional differences between the roofing systems used in the various study buildings. The comparison of the dimensions of the timbers surveyed and the theoretical ones proposed in the first engineering manuals of the nineteenth century revealed significant deviations, confirming how member sizing is more related to builders' experience than scientific theorization. Finally, displacement analysis has allowed estimating the significant deformations that these systems have experienced over time, which has aided in understanding their behavior. This final analysis, which extensively uses generative algorithms, is based on some hypotheses about truss deformation kinematics. These kinematic mechanisms were identified first from a theoretical standpoint and then from experience, and they were confirmed after the elaborations.

The cross-analysis of the data collected across the different case studies allowed for a deeper understanding of the construction culture of the timber trusses and proved to be especially significant because it refers to study samples from a relatively short period (150 years) and a well-defined context. Traditional structural modeling, which simplifies geometric specifications, cannot always account for the types of displacements experienced by the trusses over their lifetime. This paper demonstrates how seemingly similar cases have undergone more or less significant displacements due to multiple factors, such as the characteristics of the construction joints, the assembling of the members, and the scantling of the cross-sections.

The many transformations applied over time, in particular, frequently alter the original conception. The ability to structure the information embedded in the method enables a back-office analysis. Previously, this analysis could only be done roughly during the survey campaign. It becomes critical during the diagnostic phase and allows for critical considerations about the health of these structures in terms of conservation, maintenance, and enhancement.

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