VOL. 8, SPECIAL ISSUE (2022)

Remarkable historic timber roofs. Knowledge and conservation practice.
PART 2 - Investigation, analysis, and interventions

TEMA
Technologies
Engineering
Materials
Architecture

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

e-ISSN 2421-4574
DOI: 10.30682/tema08SI2

e-ISSN 2421-4574
ISBN online 979-12-5477-086-3
DOI: 10.30682/tema08SI2

Vol. 8, Special Issue (2022)

Remarkable historic timber roofs. Knowledge and conservation practice
Part 2 - Investigation, analysis, and interventions

Year 2022 (Issues per year: 2)

Cover illustration: Auxiliary truss for the strengthening of the roof of San Giovanni Battista church (architectural design by P. Castelnovi, structural design by E. Zamperini with the collaboration of G. Sacco), Borno, Brescia, Italy, 1771-81/2020 by E. Zamperini. © Emanuele Zamperini (2020)

Scientific Society Partner:
Ar.Tec. Associazione Scientifica per la Promozione dei Rapporti tra Architettura e Tecniche per l'Edilizia
c/o DICATECH - Dipartimento di Ingegneria Civile, Ambientale, del Territorio, Edile e di Chimica - Politecnico di Bari
Via Edoardo Orabona, 4
70125 Bari - Italy
Phone: +39 080 5963564
Email: info@artecweb.org - tema@artecweb.org

Media Partner:
Edicom Edizioni
Via I Maggio 117
34074 Monfalcone (GO) - Italy
Phone: +39 0481 484488

TEMA: Technologies Engineering Materials Architecture
Vol. 8, Special Issue part 2 (2022)
e-ISSN 2421-4574

THE MEDIEVAL CARPENTRY OF THE BASILICA OF ST. ANTHONY IN PADUA

TEMA
Technologies
Engineering
Materials
Architecture

e-ISSN 2421-4574
Vol. 8, Special Issue part 2 - (2022)

Martina Diaz, Louis Vandenabeele, Stefan M. Holzer

DOI: 10.30682/tema08SIs

Abstract

Attics are often the most interesting rooms where to investigate historical construction techniques. Above the eight domes of the medieval Basilica of St. Anthony in Padua, lightweight timber structures attest to the use of rather archaic frameworks. The ongoing research on the domed roofs confirmed the preservation of their 13th-century configuration and the perpetuation of this model during later interventions until the 18th century.
Based on on-site measurements, the study of archival material, and dendro-dating, this paper aims at shedding light on the constructing techniques and dating of the timber domes of St. Anthony. Results from the dendro-sampling campaigns provide evidence of 13th-century elements still in place. Moreover, cross-references between on-site findings and archival materials enable the tracing of the dendro-provenance of replacements from the 16th century. Finally, a short comparison with the timber domes of St. Mark in Venice and St. Justine in Padua enhances the importance of the ancient timber structures of St. Anthony.

Keywords

Timber, Dome, Superstructures, Dendro-analyses, Medieval, Padua.

Martina Diaz*
ETH-Zürich D-ARCH: Eidgenossische Technische Hochschule Zurich, Institute Denkmalpflege und Bauforschung, Departement Architektur, Zurich (Switzerland)

Louis Vandenabeele
ETH-Zürich D-ARCH: Eidgenossische Technische Hochschule Zurich, Institute Denkmalpflege und Bauforschung, Departement Architektur, Zurich (Switzerland)

Stefan M. Holzer
ETH-Zürich IDB: Eidgenossische Technische Hochschule Zurich, Institute Denkmalpflege und Bauforschung, ETH Zürich D-ARCH: Eidgenossische Technische Hochschule Zurich Departement Architektur, Zurich (Switzerland)

** Corresponding author: e-mail: diaz@arch.ethz.ch*

1. THE TIMBER DOMES OF ST. ANTHONY

On the upper levels of the pilgrimage Basilica of St. Anthony in Padua, at the turn of a narrow medieval corridor, the visitor may stumble across spectacular attics above the eight domes of the church. Here, relatively light timber frames surmount the extrados of the masonry shells, supporting the delicate ribs of the curved roofs (Fig. 1).

In the last forty years, scholars have proposed several hypotheses on the building's development [1–3]. These imprecisely positioned the erection of the domes in different phases between the second half of the 13th century and around 1310, when historic sources report about a «magna et inmensa mutatio», probably referring to the eastern development of the Basilica [4]. However, there is no common agreement between these theories, which lack tangible proof. Later publications connected the planning of the domes to the original project of the church [5–7], yet without significantly narrowing down a possible dating. So far, the literature has only superficially described the timber structures without analyzing either their constructive features or on-site traces [8, 9].

The lack of scientific evidence regarding the dating of the Basilica and its timber domes motivated the launch of a building-archaeology project in 2019, supervised by Professor Stefan M. Holzer at ETH Zurich, in collaboration with the Pontifical Delegation for Padua and the Venerable Ark of St. Anthony, financed by the Swiss National Science Foundation (SNF). When the project started, fundamental questions were still unsolved about how and when the domes were built or the possibility of retrieving original elements. Ongoing analyses of the lower brick structures have already attached the construction of the western domes to the first building site [10]. In parallel, doctoral research has been seeking to document and date the eight timber structures, contributing to positioning their construction within the timeline of the entire building. From a methodological point of view, the research project includes on-site measurements, laboratory analyses, the recording of traces, and the study of historical sources [11].

The geometrical survey has been achieved through laser scanning of the entire building with 6 mm accuracy (using a Leica RTC360 scanner). From the point clouds, it has been possible to draw sections and build a 3D model, whereas traditional hand-measurements have been essential to document joints, repairs, and other traces.

The dendro-sampling activity focused first on possible original elements in the domes that were supposed to be the oldest. Moreover, a detailed study of the archival sources has provided additional information on the repair history of the domes.

This paper aims at answering the following key-questions: what are the particular features of the timber frames of St. Anthony, which parts are still original, and which elements have been replaced? To do so, the general history of the domes is first unveiled based on archival sources. The following section describes the constructive features of each dome based on detailed on-site surveys. Then, the discussion turns toward the outcomes of dendrochronological dating. Lastly, the timber domes are positioned in their Italian context, and their importance is highlighted in the panorama of Construction History.

2. A HISTORY OF THE DOMES BASED ON ARCHIVAL SOURCES

The most ancient known chronicle citing the domes is a description by Giovanni da Nono, dated back between the last quarter of the 13th and the first half of the 14th century. Although its precise dating is still controversial, the chronicle depicts an internal view of the church

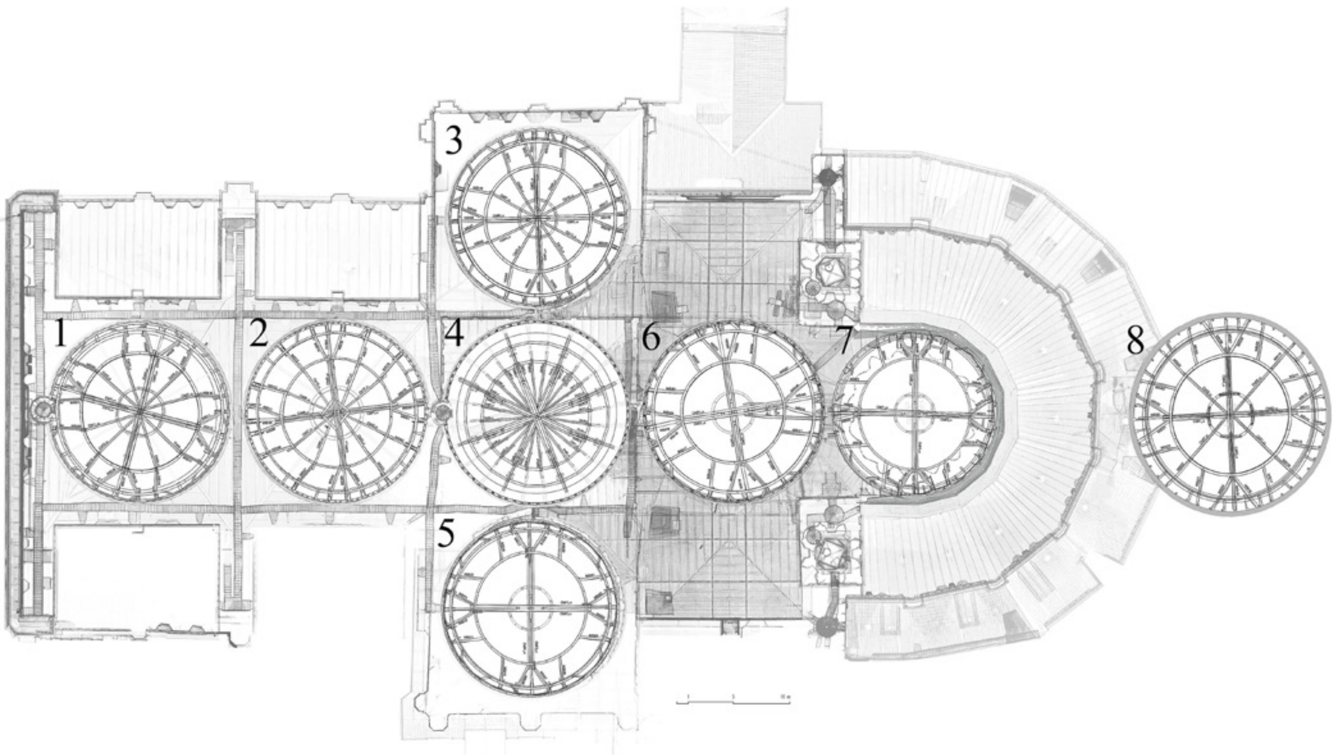

Fig. 1. *Attics plan of the St. Anthony Basilica: (1) façade dome; (2) intermediate dome; (3) St. Anthony dome; (4) angel cone; (5) St. Jacob dome; (6) presbytery dome; (7) choir dome; (8) relics dome.*

topped by seven domes, whereas only six cupolas are described from the outside. The following domes are mentioned: two on the nave, a cone on the crossing, two on the transept arms, and two on the presbytery and the choir. Moreover, another account by Bernardino Scardeone mentions the seven domes in 1330 [12]. Furthermore, two stone reliefs on tombs dated back between the 1330s and 1350s depict the domes, but these are the less reliable sources for counting due to their impreciseness. However, from these sources, one can thus determine that the Basilica had already gained its current silhouette in the first decades of the 14th century.

Due to the loss of archives related to the original worksite, the most ancient documents referring to renovation works on the domes are dated to the 15th century [13]. It is possible to trace a timeline of roofing works through deliberations and payment receipts, although the repairing activities are sketchily cited without precise descriptions. Indubitably, reparations occurred in the façade, St. Anthony, Angel, and choir domes over this century.

In the middle of the 16th century, archival documents mention a general decay state in all seven domes. Lists of building materials provided for repairs include larch beams and boards for the bearing structures and the outer cover. Skilled blacksmiths and carpenters from St. Mark in Venice and the Abbey of St. Justine in Padua took part in the works. In particular, as typical at that time in the Venetian region, carpenters had to travel towards the mountains to select the logs. Timber traders from Padua rafted the material along the Brenta River from establishments mainly located around the Asiago Plateau [14].

At the beginning of the 18th century, a new dome was built on top of the recently built Chapel of the Relics, modeled on the medieval ones. The masonry vault was completed in 1740, and the wooden frame would have been erected by 1745. At about the same time, disrepairs afflicted the façade dome, the St. Anthony dome, and the Angel cone. So far, uncertainty remains as to whether maintenance works took place. Shortly after, in 1749, a dreadful fire destroyed four of the eight domes: the Angel dome, the dome of St. Jacob, and the two above the presbytery and the choir. Historical depictions show the Basilica amputated from four wooden domes, with the exposed masonry shells that remained intact. The four burnt timber structures were quickly reconstructed. The mathematician Giovanni Poleni (1683-1761), previously involved in the structural evaluation of the St. Peter dome in Rome in 1743, contributed to the reparation plan, setting the reconstruction according to the original configuration, «secondo le idee dell'antico architetto, non restare adito a nuovi pensieri» [15]. Between 1749 and 1750, the Venetian Lamberti family provided the timber, likely rafted along the Piave River [16].

The next intense restoration phase took place more than about a century later, between 1853 and 1867, under the ruling of the Austrian government. Interventions occurred in the domes above the nave, St. Anthony and St. Jacob domes, and the dome above the presbytery. The replacements concerned the king-posts, elements of the main structure, parts of the outer skeleton, large parts of the external wooden boards and lead plates, as well as portions of the masonry drums. For some of these interventions, detailed drawings depict the pathways, platforms, and cantilevered galleries scaffolds attached around the drums installed during the worksites. Moreover, the descriptions of the workflow works include details on the elements size of the timbers and the lifting towers used on different occasions to hoist the material.

Although the scattered archival sources leave many open questions on renewals before the fire in 1749, they provide crucial information about damages, repairs, and timber supply in the 18th and 19th centuries. They also indicate that three out of the eight domes did not burn in the fire of 1749. As further discussed, the written sources reveal the perpetuation of the same construction scheme repeated over the centuries with only slight modifications.

3. CONSTRUCTION FEATURES

On the western part of the Basilica, the attics are connected through a rational network of corridors. Apart from the Choir and the Chapel of the Relics, the domes are supported by four brick arches with pendentives. Each dome is composed of an internal masonry shell, the inner diameter of which varies from 13.62 to 14.48 m in diameter from 32 to 43 cm in thickness, surmounted by a seemingly archaic timber structure covered by lead sheets. The wooden frames are installed well above the springing line of the masonry shell and are surrounded by the upper part of the drums. Together with the fact that wooden pieces are never embedded in the masonry, this observation tends to indicate that the brickwork was already in place when the timber frames were assembled.

Taking aside the cone of the Angel, the vertical bearing systems have similar characteristics. Each of them is composed of four symmetrical groups, composed of a central rafter and four secondary struts. All rafters and struts depart from short wooden supports raised from the level of the floor by stones. The four rafters, inclined by an angle of about 50°, lean up on a king-post to form two triangular frames rigidified by one or two levels of collar-beams, the ends of which are supported by the lateral struts. Four concentric rings rest successively on top of the brick parapet, at the levels of the collar-beams and close to the king-post. They support the slender ribs, forming the skeleton on which the outer cover leans. Vertical posts depart from the upper collar-beams to carry the last ring. The cover is composed of a layer of 2.5 cm-thick wooden boards and external lead plates. Similar and further features enable grouping the domes according to their configurations.

3.1. THE FAÇADE, THE INTERMEDIATE, AND ST. ANTHONY CHAPEL'S DOMES

As aforementioned, the timber structures of the Façade, Intermediate, and St. Anthony domes did not burn in 1749, so they have been considered the most ancient preserved (Fig. 2). In these frames, lower collar-beams rest on top of the masonry vault. Spokes form an additional division of the horizontal levels every 45°, except between the lower collar-beams of the St. Anthony dome. The shorter struts resting on the parapet support the lower collar-beams and spokes. In the Intermediate dome, the vertical posts that support the last ring are also set on the upper spokes. King-posts were replaced in these three domes during the 19th century, with a tapered-box profile as a reinforcement at the landing of the ribs. The three outer skeletons are composed of 99, 92, and 94 ribs, respectively, while the number halves in the reconstructed domes. The ribs are attached to the horizontal rings with iron straps and small curved cantilevers from the 19th century (Fig. 6).

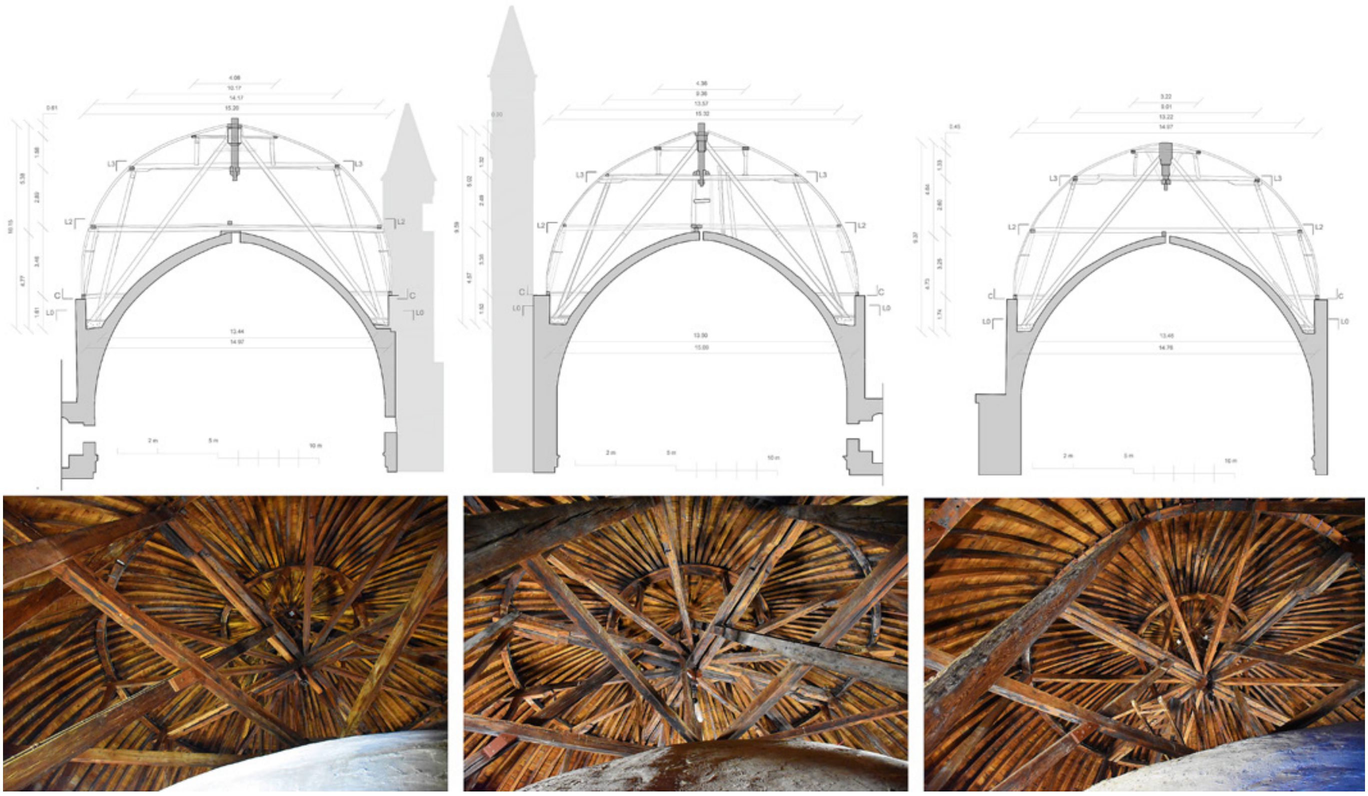

Fig. 2. *From left: the domes of the Façade, Intermediate, and St. Anthony chapel.*

3.2. THE ANGEL CONE

As reported by previous authors, the Angel cone likely evokes the Holy Sepulchre in Jerusalem [7]. Unlike the other domes, its drum is raised on a square masonry base. Most authors tend to date the completion of the masonry shell to the first Saint's translation to the crossing in 1263 [1–3]. Destroyed by fire in 1749, a description dated two years earlier confirms that its reconstruction followed the previous outline. In elevation, it is divided into five stories: the base, three intermediate levels, and an external one on top of the truncated cone (Fig. 3). The vertical bearing system counts 24 struts bearing the first horizontal grid, and as many others running in between the two following upper levels. They rest on short transversal elements, settled between the collar-beams, or directly on the spokes. Eight 13.9-meter-long struts resting on the floor reach the third horizontal level. The king-post is composed of three segments assembled by stop-splayed under-squinted scarf joints with V ends for a total length of 23 meters (Fig. 3). In the third story, a bundle of braces branches out from the king-post and stabilizes the connection with the major struts.

The two lower horizontal levels, L2 and L3, are composed of two couple of collar-beams connected to the rafters with half lap-joints, for a total length of 12 m and 9 m, respectively. In L2, these are composed beams assembled with a scarf joint. In both levels, sixteen spokes are symmetrical split into the quadrants. In the upper levels, L4 and L5, the length of the collar-beams is further reduced to 6.3 m and 3.7 m. Moreover, the number of spokes is limited to a couple in each quadrant. On the last level, vertical posts lean on transversal elements and host wind-bracings linked by lap joints. Except for the first ring on the parapet, the upper rings of the skeleton are segmented into polygonal chains. Seventy-two straight ribs spring from the first ring and lean on the upper ones.

3.3. THE ST. JACOB AND THE CHOIR DOMES

In the St. Jacob (Fig. 4) and the Choir domes (Fig. 5), there is only a high level of collar-beams, with a length of 10.5 and 9.9 m, respectively. In both cases, there are no spokes. The lateral struts, and the shorter ones around the parapet, support the third and the second rings. In the western part of the Choir dome, due to the polyg-

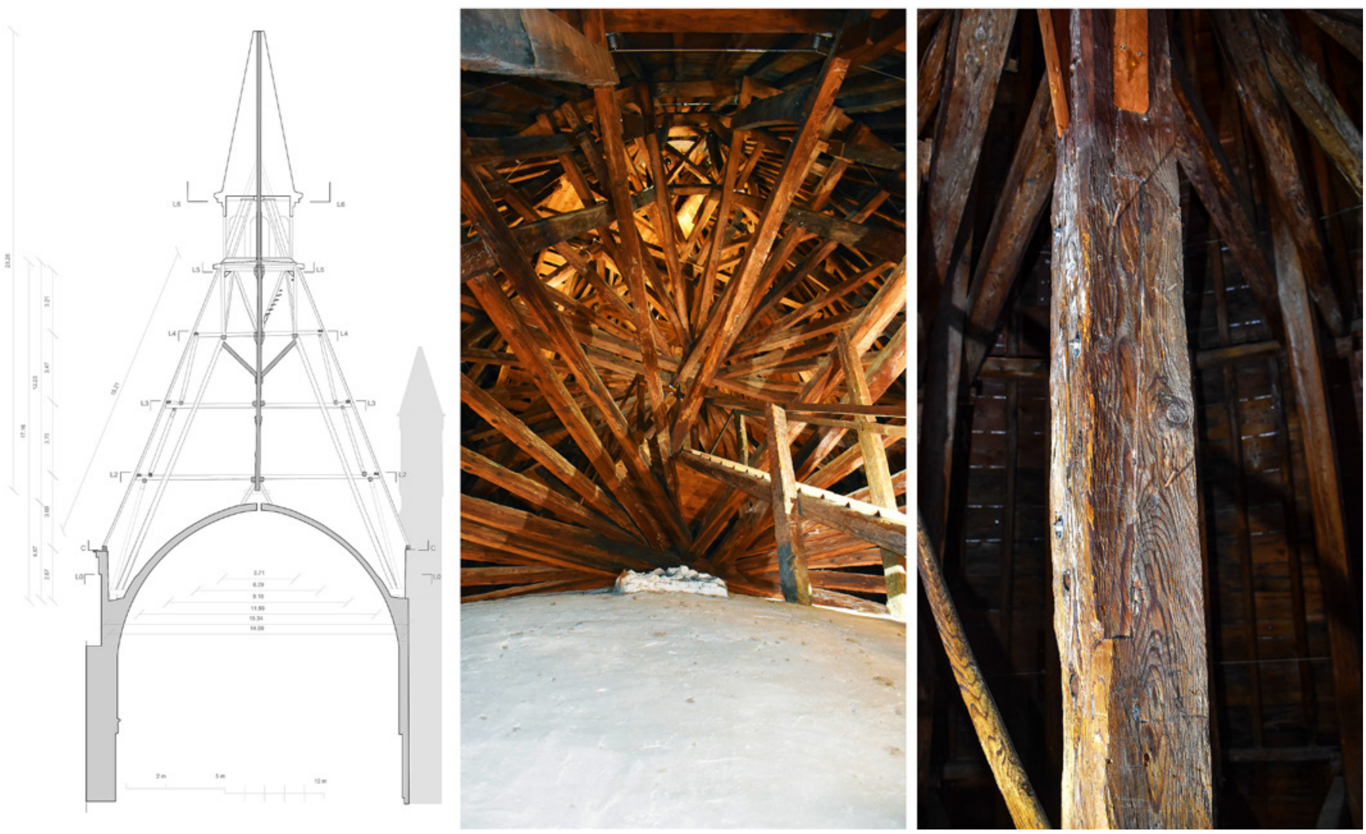

Fig. 3. *The Angel cone and a king-post's joint.*

onal contour of the masonry drum, some main struts that support the collar-beams rest on the first chain. In both frameworks, the king-post has a square profile with sharp edges and a thin cover-box at the top. Forty-eight ribs composed of two layers rise from the inner edge of the first ring. The rings are composed of three layers, the last of which consists of short segments lodged between the ribs. The ribs are tightened to the upper rings with metal straps and curved protruding boards. In general, the similarities between the two skeletons might suggest a common campaign of replacements dated the 19th century (Fig. 6). Eventually, the outer shell on the choir is characterized by a projecting profile, resting on twenty-four putlogs set along with the polygonal masonry and partly covering the gallery on top of the ambulatory.

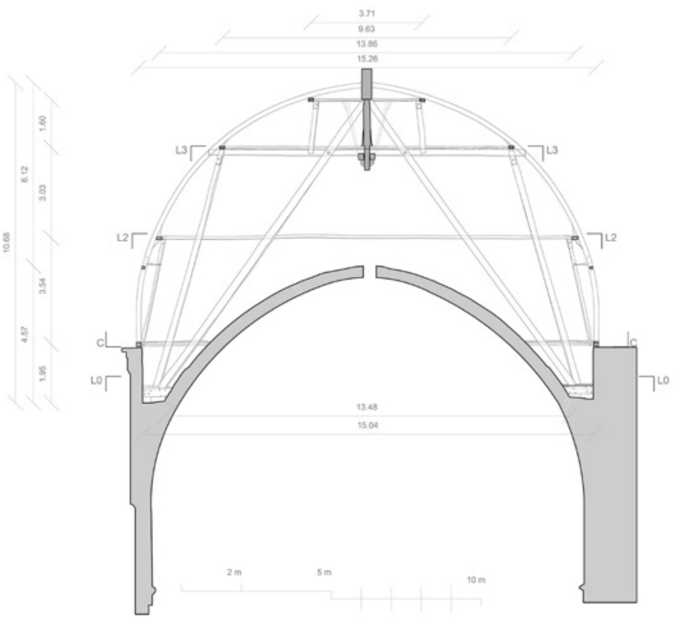

Fig. 4. *The St. Jacob dome.*

3.4. THE PRESBYTERY DOME

The Presbytery dome exhibits two twin horizontal grids, each composed of two overlapping couple of collar-beams (Fig. 5). On the lower level, these are 13.85 m long and are composed of two timbers jointed by means of a scarf joint. The king-post has a tapered profile without upper-box reinforcement and is tight between the lower level of collars. Like the above-described frames, the skeleton counts forty-eight ribs placed along the inner edge of the first ring and attached to the upper rings with the same connections as in the previous frames. Here, a modern wooden reinforcement rest between the ribs, which can also be found in the domes of St. Jacob and the Relics. In the southwestern quadrant, part of a scaffold is suspended with nails to the collar-beams. Its dating is unknown, although it can be positioned between the reconstruction after 1749 and the mid-19th century when its depiction appears in a survey of the church published in 1852 [11]. Due to the size of its elements and their cut, the scaffold would have been assembled at the same time as the reconstructed framework. Its function should relate to *manoeuvres* of liturgical apparatus inside the church through the holes visible in the masonry vault.

3.5. THE DOME ON THE RELICS CHAPEL

There is no parapet in the attic above the Relics chapel, which means that the main bearing structure and the curved ribs rest on the same floor (Fig. 5). The rafters and the major lateral struts stand on small pieces of timber. The ribs and the secondary struts are installed on the first wooden ring, which surrounds the masonry floor. An iron chain surrounds the wooden boards shaping the ring to contain the thrust forces; it likely dates back to the 18th-century construction of the new dome. It is composed of two concentric layers, each 2.5 cm thick and 7.5 cm high.

The main frame includes one level of about 10-meter long collar-beams, with four additional spokes symmetrically distributed into the quadrants. On the heads of the EW-oriented collar-beams, short transversal elements ease the connection to the second ring. The braces are anchored only on the four collar-beams. The king-post

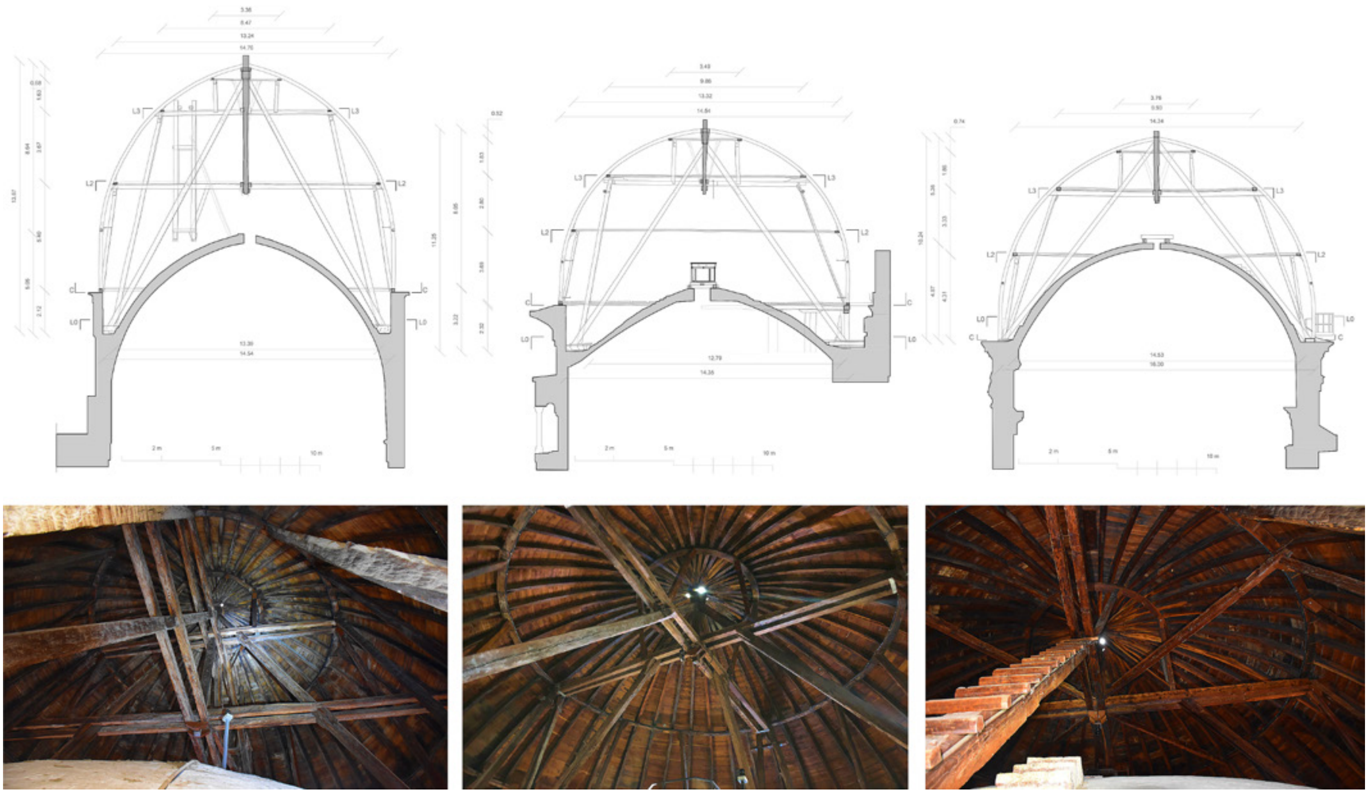

Fig. 5. *From the left: the presbytery, the choir, and the relics chapel domes.*

has an almost straight profile, like in the dome of the presbytery. Other analogies with the foregoing frames are the ensemble of forty-eight double-profile ribs, the iron straps and curved protruding connections between ribs and rings, and the modern reinforcement with wooden segments between the first and second levels of the ribs (Fig. 6). Finally, the wooden boards of the cover do not reach the floor level, they are instead supported by short wooden blocks and follow the projecting profile of the outer shell, like in the Choir dome (Fig. 7).

3.6. JOINERY TECHNIQUES

The structural integrity of the timber frameworks mainly lies in the use of lap joints fastened by iron nails and scarf joints. St.ruts and rafters are installed on short wooden elements through a simple notched joint, in some cases reinforced by an iron nail. The same type of joint is applied at the upper end of the four principal rafters leaning on the central king-post. The triangular frames formed by rafters and king-post, are stiffened by nailed connections with the horizontal collar-beams. These overlap each other through cross-lap joints. The spokes are simply attached to them with a nailed and are supported by lateral or minor struts with a nailed lap joint.

Multiple-profile elements, such as rings and ribs, are based on the layering of boards connected by different joints: tenon and mortise joints, scarf joints, or lap joints. As already anticipated for the individual frames, the connections between rings and ribs can vary at different heights. The ribs are embedded in the first ring in a 2-2.5 cm deep mortise, and modern sandwich-board reinforcements flank them. On the second and third levels, they are attached to the rings through iron straps and/or protruding elements (Fig. 6). These can consist of a curved extension of a rib's segment or small nailed cantilevers. In some cases earlier than 19th-century replacements, the ribs still lean on notches carved on the external edge of the rings. Furthermore, additional short pieces from the 18th century and later periods stiffen various connections between elements.

The simplicity of the joinery and the irregular length of the main structural elements likely facilitated their on-site adjustment and assembly. Long beams were probably cut on the spot, therefore avoiding the complex predefinition of each element forming the three-dimensional structures. However, composite elements such as rings and ribs could have been partially assembled on the ground (or on a working platform) and lifted. Firstly, circular sections of the rings were settled on the horizontal beams and top of the braces. Once rings were placed, the segments of the ribs were hoisted and lodged.

Fig. 6. *Joints between ribs and rings: choir dome (a) and façade dome (b).*

Fig. 7. *Relics dome: cover plates supported by short wooden blocks to follow the projecting profile of the outer shell.*

4. FINDINGS AND OUTCOMES

Findings from dendrochronological investigations and on-site traces help construct a chronology for the erection process of the domed attics. Xylotomy analyses confirmed all the samples and the cover boards are of larch (*Larch Decidua* Mill.). The dendrochronological activity revealed some precise dates and other *termini ante quem non* (t.a.q.n.) depending on the presence of the bark and sapwood on the elements. During four on-site campaigns, 70 samples (of 7 mm diameter) were collected. Results identified the following four time-spans [17] (Fig. 8):

1. between 1282 and 1284;
2. between 1297 and 1305;
3. between 1300 and 1317;
4. between the first and second half of the 16th century;
5. between the first and second half of the 18th century;
6. between the first and second half of the 19th century.

Between the first and second groups, there is a 10-year gap that could be explained by a preliminary stock of material or two consecutive stages of the same erection phase. These groups include rafters, struts, collar-beams, and spokes spread in the intermediate and St. Anthony domes, hereby confirming their original configuration. Elements of the third group are dated according to statistical approximations due to the absence of bark, and they are mostly located in the dome of the façade [18]. Other elements dated back to 1246 (t.a.q.n.) might belong to one of these three clusters or a previous stage. In particular, it is evident that the intermediate and the St. Anthony domes came before the façade dome. The erection process could have occurred in a sequence that started closer to the crossing and followed towards the façade, replacing probably previous roofs on the masonry shells. Eventually, the results of the fourth and fifth groups correspond to interventions reported in the archival sources, as previously discussed.

Analyses identified nine different local mean curves framed between 1023 and 1839, with morphologic similarities, each of which includes a few elements. However, their missing overlapping and chronological contemporaneity stress the timber supply from different areas.

Regarding woodworking, groups 1, 2 and 3 include sawn and axed elements. Even if sometimes hard to distinguish due to the timber age, these traces might indicate pit, cross-cut, and machine saw use. Indeed, despite possible speculations on the sawmill spread earlier, in the 13th century, the Venetian sawmill model spread in the sub-oriental alpine area. However, the length of rafters and struts, reaching up to 14 meters, would exclude a machine sawing since their standard carriage allowed a maximum of 6-meter-long logs. Nevertheless, the records align with the early medieval use of the saw in the

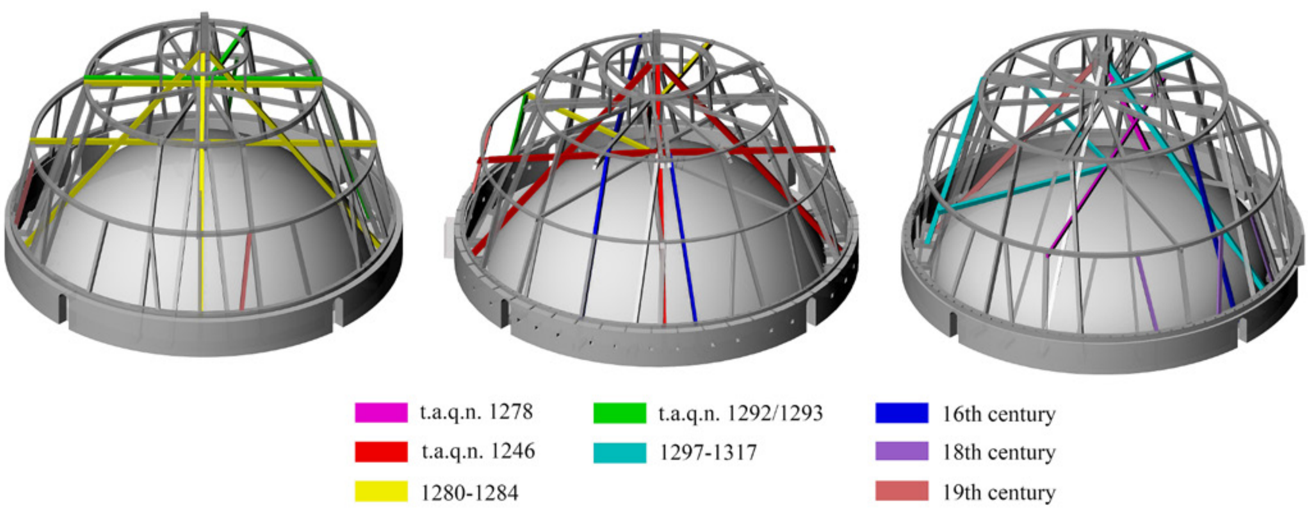

Fig. 8. *Dendrochronology results in the façade, intermediate, and St. Anthony domes.*

European context [19]. Nevertheless, the records align with the early medieval use of the saw in the European context.

From on-site observations, the absence of carpenter marks and the presence of trade signatures came out. In particular, these are evident in replaced elements in the reconstructed frames. Moreover, pegs, holes, and notches bear witness to rafting routes. The written sources, stored at the Archive of St. Anthony Basilica, contributed to deepening the knowledge about the merchants involved in the wood supply since the second half of the 16th century in Padua. The names of actors enable tracking the trade routes and the dendro-provenance. Registers of merchants indicate locations of their sawmills and the forests of their cut-license since the 15th century. The larch, cut in the sub-alpine area, was rafted along the Brenta and the Piave rivers. Furthermore, archival documents also describe some aspects of the building yards, such as sorting wood stocks by standard sizes and sawyers individually paid during building activities.

5. COMPARISONS WITH OTHER DOMES IN VENETO

The lack of preserved medieval domes in the region precludes comparison with coeval models. Nevertheless, it is worth considering carpentry and construction knowledge applied in the closest multiple-dome roofs of the Basilica of St. Mark in Venice and the Abbey of St. Justine in Padua.

Although a mosaic on the façade of St. Mark depicts the superstructures on top of the Basilica around the 1270s, their construction year is far to be known. The timber frameworks were erected as imposing outer covers on the original masonry shells. Still, the possibility of dating them precisely vanished with a fire at the beginning of the 15th century and with heavy restorations in modern times [20]. Yet, the reconstructed domes of St. Mark provide information about different construction techniques spread in Venice from the Renaissance. Like in St. Anthony, St. Mark's five superstructures are composed of a bearing system based on rafters, horizontal collar-beams, a central king-post, and circular ties. However, the frames gain in complexity and differ from each other. In the St. John dome, for instance, the vertical bearing system is repeated in two levels. The upper one leans on a polygonal tie, which is supported by tripods. Another system of tripods leans on the first horizontal level and supports the third ring. Upper struts rest on this first collar-beam level and support the last wooden ring. In the Choir dome, a unique system of struts departs from the first horizontal level to the last ring. The king-post is tightened between the upper collar-beams. A bundle of braces departs from the king-post and supports the last ring, counterbalancing the struts. The same system of braces and struts can be observed in the central Ascension dome. Here, the struts depart from a polygonal base, and the king-post extends until the lower level of collar-beams. The system of braces and struts also occurs in the Leonard dome. Finally, in the Pentecost frameworks, a double order of eight tripods and wind-crossing braces are settled in the intermediate levels. The skeletons and the outer covers recall the same described in the domes of St. Anthony. The widespread use of iron brackets and straps complies with the Renaissance and modern interventions [21] differing from the St. Anthony carpentry.

Wooden domes rose in abundance in the lagoon since the Renaissance [22]; they can be differentiated into two groups. The first relies on a king-post, with vertical rafters and struts inspired by St. Mark prototypes. Tripods or minor struts support the intermediate circular ties. Although the oldest does not exist anymore, these superstructures spread between the 13th and 16th centuries [23]. The second group consists of outer shells leaning on a simplified internal frame. In the dome of St. Mary of Miracles, elements dated back to the original 15th-century model are preserved [24]. Their configuration shows a central king-post flanked by collar-beams connected to an intermediate ring, without rafters support. Unfortunately, the rest of the frame consists of later renovations. The 15th-century timber frame of Saints John and Paul church was renewed in the middle of the 19th century. The timber superstructure of the Baroque church Saint Mary of Health does not provide much information as they were replaced in a renovation [25]. The 18th-century dome of St. Geremia church represents a model of wooden shells, without a king-post, with struts and wind-braced frames crowned by a lantern. At this point, the brief excursus about other timber domes in the Venetian lagoon excludes the exportation of the Paduan model as well as the permeation into it of other influences. Skilled carpenters were involved in Venice in the woodworking of timber traded along the Piave and Adige rivers [26].

Closer to the Basilica of St. Anthony, the Abbey of St. Justine provide another bevy of domes in the skyline further south (Fig. 9). Many architects took part in the long worksite, repeatedly reshaping the silhouette of the church. The erection of the domes started in 1587 with the internal vaulting and finished in the first decade of the 17th century. They vary in size and construction techniques. A central dome rests on the crossing, and three others crown the transept arms and the presbytery. Four additional minor domes surround the crossing at square corners. The larger domes, about 13 meters in diameter, are double wooden shells. The rafters lean on the first wooden ring and support perpendicular trusses. There is a unique horizontal level of collar-beams. The joinery includes mortise and tenon connections, scarf and nailed joints, and iron brackets typical from the late Renaissance period. In short, the joints and frames relate to a trussed roof, unveiling a more modern concept than the structures of St. Anthony. The smaller domes, about 7.5 m in diameter, are composed of a brick shell and a lighter timber superstructure, resembling St. Anthony's ones. Trademarks in the timber elements refer to 19th century replacements that could have changed the frameworks' original configurations. The differences among these seem to reflect changes of carpenters and construction practices over the centuries.

The comparison with nearby models thus enhances the peculiarity of the timber structures of St. Anthony. Their lighter configurations lay out an archaic model that was not copied in later projects. Apparently, the system was only repeated in St. Anthony after the fire of 1749. One cannot say whether they might have been inspired by the older (but lost) timber roofs of St. Mark in Venice.

6. CONCLUSIONS

The paper has described the construction techniques applied in the timber domes, which share a common bearing system yet varied types of collar beams, outer skeletons, and joints. Based on archival research and dendrochronological analyses, these differences could be explained and positioned in time. At this point of the research project, the dendro-dated components have confirmed the preservation of medieval timber elements in the domes that did not burn in the 18th century. Furthermore, there

Fig. 9. *St. Justine Abbey: longitudinal section. (Image source: photo courtesy of Pfister, 2022).*

is clear evidence that the brick shells were built before the timber structures. Consequently, the dating of the timber structures provides a precious *termine ante quem* to frame the medieval worksite of the lower masonries. The results highlight the early spread of sawn beams on the Padua market. Moreover, on-site traces and archival documents bear traces of the timber supply from the 16th century toward Padua.

Finally, the repairs implemented between the 18th century and the second half of the 19th century were carried out in a relatively conservative way. Inspired by the original joinery, with slight variations in carpentry techniques, the approach shows the continuation of medieval construction techniques over the centuries. No major innovative configurations were imported from the nearby context: neither those of the 15th-century St. Mark domes nor those of the 16th-century superstructures of St. Justine, not even those spread in the Venetian lagoon during the Renaissance. Therefore, the timber superstructures of the Basilica of St. Anthony represent a unique testimony of the 13th-century carpentry tradition in Italy.

Acknowledgments

The research team thanks the community of the Basilica of St. Anthony for their hospitality during the surveys, as well as the Pontifical Delegation and the Presidency of the Veneranda Arca for permission to investigate the monument.

Authors contribution

The resources, the investigation, and the text conception and writing were made by M. Diaz. L. Vandenabeele reviewed the manuscript and supported the onsite investigations. S. Holzer reviewed the manuscript and acquired the financial support. All photos and drawings are by M. Diaz (except those for which specific attribution has been provided).

Funding

The research project is funded by SNF.

7. REFERENCES

[1] Lorenzoni G (1981) L'edificio del Santo di Padova. Neri Pozza Editore, Vicenza

[2] Bresciani Alvarez G (1981) La basilica del Santo nei restauri e ampliamenti dal Quattrocento al tardo-Barocco, Il Quattrocento. In: Lorenzoni G (a cura di) L'edificio del Santo di Padova. Neri Pozza Editore, Vicenza, pp 83–110

[3] Salvatori M (1981) Costruzione della Basilica dall'origine al secolo XIV. In: Lorenzoni G (a cura di) L'edificio del Santo di Padova. Neri Pozza Editore, Vicenza, pp 91–81

[4] Ruzza S (2016) La Basilica di Sant'Antonio. Itinerario artistico e religioso. Centro Studi Antoniani, Padova

[5] Heinemann B (2012) Der Santo in Padua: Raum städtischer, privater und ordenspolitischer Inszenierung. Ibidem-Verlag, Stuttgart

[6] Valenzano G (2012) Il cantiere architettonico del Santo nel 1310. In: Baggio L, Bertazzo L (a cura di) Padova 1310: percorsi nei cantieri architettonici e pittorici della Basilica di Sant'Antonio Centro Studi Antoniani, pp 65–78

[7] Valenzano G (2021) L'edificio del Santo nel Medioevo: nova Jerusalem. In: Bertazzo L, Zampieri G (a cura di) La Pontificia Basilica di Sant'Antonio in Padova. Archeologia, Storia, Arte e Musica. L'Erma di Bretschneider, Roma, pp 445–504

[8] Salvatori M (1988) The Wooden Superstructures of the Domes of the St. Anthony's Basilica in Padua. In: International Association for Shell and Spatial Structures (IASS) MSÜM (ed) Domes From Antiquity to the present, Istanbul, Turkey, May 30-June 3, 1988. Mimar Sinan Üniversitesi-Istanbul, Istanbul, pp 227–232

[9] Salvatori M (1989) Strutture, vicende e restauri delle calotte lignee soprastanti le otto cupole in muratura della basilica di S. Antonio di Padova. In: Gennaro T (a cura di) Il restauro del legno. Atti del secondo Congresso Nazionale Restauro del Legno, Firenze, Italia, 8-11 novembre 1989. Nardini Editore, Firenze, pp 57–61

[10] Vandenabeele L (2021) Medieval transformations of the Basilica of St Anthony in Padua based on an analysis of the original brickwork. In: Mascarenhas-Mateus J, Pires AP (eds) History of Construction Cultures. Vol. 2. Proceedings of the 7th International Congress on Construction History (7ICCH 2021), Lisbon, Portugal, July 12-16, 2021. CRC Press, Boca Raton, pp 63–70

[11] Diaz M (2022) Le sovracupole lignee della Basilica di Sant'Antonio a Padova: analisi costruttive e datazioni. ETHZ, Zurich

[12] Scardeone B (1560) De antiquitate urbis Patavii, & claris civibus Patavinis, libri tres. Apud Nicolaum Episcopium iuniorem, p 93

[13] Luisetto G (a cura di), Archivio Sartori. Guida della Basilica del Santo, Varie, Artisti e Musici al Santo e nel Veneto. Vol. 1. Centro Studi Antoniani, Padova, pp 109–123

[14] Occhi K (2004) Mercanti e traffici nel Canale di Brenta (1571-1702). In: Perco D, Varotto M (a cura di) Uomini e paesaggi del Canale di Brenta. CIERRE, Verona, pp 55–94

[15] Negri D (1986) Giovanni Poleni (Venezia 1683-Padova 1761) e la fabbrica del Santo. Il Santo – Rivista francescana di storia dottrina arte XXVI(3):493–505

[16] Diaz M, Vandenabeele L (2022) The eighteenth-century timber trade towards the Basilica of St. Anthony in Padua through archives, shipping marks and dendrochronology. In: Campbell JWP, Baker N, Driver M, Heaton M, Ruamsanitwong N, Wall C, Yeomans D (eds) Timber and Construction. Proceedings of the Ninth Conference of the Construction History Society, Queen's College, Cambridge, April 1st-2nd, 2022. Cambridge, pp 209–219

[17] Pignatelli O (2020-2021) Indagini dendrocronologiche sulle strutture lignee delle cupole della Basilica del Santo a Padova. I-II-III-IV Lotto. Unpublished report.

[18] Corona E (1994) Anelli d'alburno in larice cisaplino. Dendrochronologia (2):91–97

[19] Agnoletti M (1993) Gestione del bosco e segagione del legname nell'alta valle Piave. In: Caniato G (a cura di) La via del fiume. Dalle Dolomiti a Venezia. CIERRE, Verona, pp 73–126

[20] Piana M (2019) Le sovracupole lignee di San Marco, dalle origini alla caduta della repubblica. In: Vio E (a cura di) La Basilica di Venezia. San Marco. Arte Storia Conservazione. Vol I. Marsilio, Venezia, pp 189–200

[21] Zamperini E (2015) Timber trusses in Italy: the progressive prevailing of open-joint over closed joint trusses. In: Friedman D (ed), Proceedings of the Fifth International Congress on Construction History, Chicago, June 3rd-7th, 2015. Lulu Press, Raleigh (NC)

[22] Ferracin M (1992) Contributo alla conoscenza delle strutture voltate a Venezia. In: Cristinelli G (a cura di) Restauro e tecniche. Saggi e ricerche sulla costruzione dell'architettura a Venezia. Arsenale editrice, Venezia, pp 82–115

[23] Piana M (2009) San Giorgio Maggiore e le cupole lignee lagunari. Annali di Architettura Rivista del Centro Internazionale di Studi di Architettura Andrea Palladio di Vicenza 21:79–90

[24] Schuller M, Lüpnitz M (2003) Rilievi e risultati delle indagini della Bauforschung. In: Piana M, Wolters W (a cura di) Santa Maria dei Miracoli a Venezia. La storia, la fabbrica, i restauri. Istituto Veneto di Scienze, Lettere ed Arti, Venezia, pp 327–384

[25] Pedrocco M (1994) Il restauro ottocentesco della cupola maggiore di S. Maria della Salute. In: Cristinelli G (a cura di) Restauro. Tecniche e progetto. Saggi e ricerche sulla costruzione dell'architettura a Venezia. Rubbettino, Soveria Mannelli, pp 122–137

[26] Šebesta G (1990) Gli edifici e l'uomo: opifici, tecniche, materie prime: dalle origini all'epoca moderna. In: Caniato G, Dal Borgo M (a cura di) Le arti edili a Venezia. Edilstampa, Roma, pp 259–307

[27] Diaz M, Vandenabeele L, Holzer S (2021) The Construction of the Medieval Domes of the Basilica of St Anthony in Padua. In: Mascarenhas-Mateus J, Pires AP (eds) History of Construction Cultures. Vol. 2. Proceedings of the 7th International Congress on Construction History (7ICCH 2021), Lisbon, Portugal, July 12-16, 2021. CRC Press, Boca Raton, pp 47–54