Timber roof structures of the “Arsenale” of Venice

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ABSTRACT: The characteristics of the buildings that form the “Arsenale” obviously respond to the specific function of the site, i.e. the strategic production of commercial and war ships as it developed from the early 13th to the early 20th century. In particular, between the second half of 14th and the second half of 16th century, the span of the timber roofs continuously increased, according to the increasing dimensions of the ships. As the roofs became part of the “industrial machine” required by a sophisticated and specialized production process, also the applied live loads increased. The characteristics of the roofs correspondingly became more and more complex. The impression is that very “clever tricks”, subsequently lost when the construction became a “science” instead of a “skill” – permitted to counteract the weaker points of the historic timber truss structures – relatively high deformability, lack of redundancy that made them vulnerable to easy to occur joint deterioration – that could have jeopardized the efficiency of such a strategically vital “industrial” site of the Venice Republic.

1 INTRODUCTION

The “Arsenale” of Venice is composed of several series of sheds (“tese” or “tesoni”) regularly disposed around the shipbuilding (dry and wet) docks. The sheds and docks are also surrounded by more complex buildings dedicated to the production of very specialized components, e.g., in the southern part, the long building where the ropes were produced (called “corderie” or “rope factory”), or, in the eastern part, the armoury (“armerie”) (Fig. 1).

What came out after centuries of successive enlargements and developments is very similar to a modern industrial site, where the buildings have to permit, by appropriate changes and adaptations, the implementation of the most advanced available technologies into the production process.

A very interesting subsystem of the building complex under consideration is formed by the roofs, very simple timber trusses at the beginning (first half of the 14th century), large span, huge and complex spatial timber structures during the 16th century, engineered mixed steel-timber (“Polanceau”) and steel trusses in the second half of the 19th century.

The attention is focused in this paper on the products of the more mature period of the “timber technology”, from the second half of 14th to the first half of 16th century, when the skill in using timber permitted the attainment of impressive results in both building and ship construction.

Under the pressure of the developments of the ship building industry, the triangular king-post trusses, suitable for relatively small spans (that allowed the inclined strut to be formed by a unique piece of wood) and relatively small live loads (winds and snow), became larger “frame-like” and spatial trusses,
required to span larger sheds and to sustain higher live loads, not only caused by the local environmental conditions, but also by the production process (suspended loads).

Single timber pieces were no more sufficient to form the longer inclined struts, and much more sophisticated assemblages had to be employed: the number of joints in both the struts and the tie beams increased, thus introducing greater deformability and lateral stability problems. The necessity of introducing longitudinal bracings (i.e., ensuring spatial behaviour) and the adoption of construction systems capable to reduce the deformability became more and more evident.

The solution, typically used in the Arsenale of Venice and apparently aimed to reduce deformability, thus increasing stability (connected in this structures to the possible overturning more than to local material failure), is very interesting. The king and queen posts were, in fact, deliberately “forced” to be in contact with the tie beams in the typical larger Arsenale roofs. This was in contrast with the “construction rule”, which requires the posts not to be in contact with the tie beam, in order to avoid bending that combined with tension could cause the failure of the tie beam. However, the tie beam is very cleverly pre-inflected, thus avoiding the unfavourable consequences of the deformations of the truss under live loads, but also causing a kind of “pre-stressing” into the whole structure that reduces the displacements in the joints and, in general, the deformation under live loads.

This “modern” interpretation of a construction trick, which was suggested by the experience and became part of the skill of the Arsenale builders, could be probably only one example of the “conceptual” achievements of the ancient ship builders that were one of the pillars of the celebrated Venetian Republic power.

2 HISTORICAL DEVELOPMENT OF THE “ARSENALE”

The idea of having a unique large site, controlled by the state, where the entire strategically important production of large ships could be concentrated, is connected with the organisation efforts imposed to the Republic of Venice by the engagement of Doge Enrico Dandolo with the Earl of Champagne to transport the army of the IV Crusade, formed by 33500 soldiers, to the “Holy Earth”. In that occasion, 140 cargo ships and 72 “galee” had to be built in a very short period (1201-1202), and one of the many sites where ships and boats were produced in Venice (the “squero”, some of which still exist) in open air, located next to the church of S. Martino, started to increase in importance. In 1341, when the Terranova Arsenal was closed, the “Squero di S. Martino” became the “Arsenal of Venice”. During the first half of the 14th century it assumed the shape of a very organized industrial site, made of series of buildings rationanly disposed in order to optimise a “massive” production of ships. The first known representation of such site is a project for re-organising and enlarging the “Arsenale”, in a document dated 1391 (Fig. 2). There, two series of twenty regularly disposed shipbuilding docks facing a basin, each allowing two ships being built at the same time (for a total of 80), are shown.

The span of the covered docks, 53 Venetian feet or approximately 18.42 m, is precisely indicated in the drawing. The only example of buildings, whose roofs span 18.10 m, which covered this type of docks, is on what remains of the so called “Isolotto”, a line of buildings demolished in 19th century to create the large central basin required from the “modern” navy of the recently established Italian State. Furthermore, it is possible that some interventions were carried out on the roofs of the “Isolotto” during the sixteenth century. In order to understand the sequence of interventions on the roofs, analyses with dendrochronology are being currently carried out in the framework of larger investigation campaign (Valluzzi et al. 2002), aimed to the conservation and reuse of the Arsenal of Venice (Bondi et al. 2001).

Larger shipbuilding docks were then built starting from the first half of the 15th century to the second half of the 16th century, with roof structures spanning around 24 m. The structures built during this period for the water docks, whose construction was completed in 1478 in the southern part of the “New Arsenal” (Concina 1984, Lane 1978) and that can be seen in a detail of the perspective view of Venice shown in Figure 3, are particularly interesting. Still very interesting are the structures completed in the following century: the “Novissima di Loreto” (dated around 1550 by means of dendrochronology), the section of the Arsenal called “Gaggiandre” (1560–1573, Fig. 9, studied in detail in Bottaro & Forcellini 2001), the “House of Bucintoro”, the Galeazze (Fig. 8, Figure 2. Project for the enlargement of the “Arsenale”, 1391.
end of sixties of the sixteenth century), and the “Corderie” (Fig. 5, dated around 1579 by means of dendrochronology).

3 MAJOR CONSTRUCTION FEATURES

The first timber truss roofs built at the beginning of the 13th century were presumably of the simplest type, made of two inclined struts, king-post and horizontal tie beam. There are no direct proofs of that, but this solution can be seen in the image given of the Arsenale by Jacopo de Barbari (Fig. 3), who is well known for the precise details of his drawings. This hypothesis is also supported by the fact that these constructions represented the first step from the open to the covered shipbuilding docks; therefore the roofs were built just to protect the work site.

This condition changed significantly starting from the first half of the 15th century. Again, there are not direct proofs of the actual characteristics of the original roofs, as during the 19th century many renewals were performed in the arsenal and, in particular, on the roofs. In the drawing of de Barbari the shape of the trusses of these roofs is hidden by the slanting pitch on the front. However, it is known that the main interventions on this kind of trusses were of two kinds: the resection of the posts and the addition of longitudinal bracings. Therefore, on the basis of dendrochronological investigations and of the analysis of few untouched structures – those found in the Corderie (Figs 4 to 8) it can be said that many of the sixteenth century roofs are still surviving.

The interventions that most of the roof structures underwent were motivated by actual needs. For example, the resection of the posts was carried out to avoid anomalous bending stresses on the tie beams caused by the lowering of the ridge of the roof. This was occurring frequently due to the relative displacements of the struts on the tie beam, caused by the rotting of the wood, occurring in particular at the ends of the timbers that are more exposed to moisture. The introduction of longitudinal bracings was carried out in order to reduce the lack of redundancy in counteracting the overturning. This action was originally given to the secondary elements, the purlines. These could easily lose their efficiency due to the deterioration of the trusses, caused by settlement and wood rotting. Beside that, in the trusses that have not been subjected to nineteenth-century interventions (Figs 4 to 6), it can be easily noted that the tie beams present a camber and that they are placed close by the posts.

During the several conservation works carried out recently in the Arsenal (Menichelli 2001 & 2002, Piana 1994, Vassallo 1987), it was possible to notice from the observation of the wood and of the stipes that originally the king and queen posts and the tie beams were always in contact. This is also testified by the few untouched roof structures, such as those found in the Corderie (Fig. 5) and in the Isolotto (Fig. 6).

In these examples it is also easy to observe a camber in the tie beams, which characterizes the constructive technique. The examples found in the Corderie
and in the Isolotto are most likely representative of a structural and morphological typology largely used for the roof structures of the Arsenal, which cannot be still recognized in all the trusses only because of the effects of wood rotting and of nineteenth-century interventions.

The technique used to build these roof structures can be thus supposed by observing accurately the trusses of the Corderie, which were presumably built in the same manner as all the other trusses of the sixteenth-century covered docks. In a first phase, it is likely that the trusses were built with the posts and tie beams separated. The tie beams were subsequently raised until a contact with the posts was established, and finally tie beams and posts were joined by means of robust stirrups.

A reasonable hypothesis to understand why the sixteenth-century carpenters adopted this solution can be found if the role of the roof trusses in the docks is taken into account. The docks were multifunctional spaces where many of the ship carpentry works used to take place. In this kind of spaces the trusses were not only intended to support the roofing, but they were frequently used also to raise and support heavy loads. It is thus clear why such a truss could be more adequate than an ordinary truss. In this connection, it is evident also the similarity between the roof trusses of the arsenal of Venice with another kind of wooden structure conceived to carry relevant loads, i.e. the trusses of the wooden bridges. For example, the analogy between the bridge on the Cismone River, as it is known from Palladio’s drawings (Palladio 1570, Copani & Funis 1999) (Fig. 7), and the wooden trusses of the Galeazze and of the Gaggiandre (Figs 8 and 9), is evident (courtesy of Magistrato alle Acque di Venezia, survey ordered by Consorzio Venezia Nuova and carried out by Thetis S.p.A. in cooperation with BE.FA.NA.).

The use of the trusses to raise loads ended during the nineteenth century, when the construction and the maintenance of large ships with metallic hulls were moved out of the covered docks in building slips and dry docks. The docks were converted into warehouses or offices and even if the raising of loads was still necessary, the use of the bridge cane substituted that of the wooden trusses. This is probably the reason why, during the interventions on the roof structures, the original structural behaviour of the trusses was not taken into account and for the new roof trusses, mixed structures such as the Polanceau truss with wooden struts, iron ties and other elements of cast iron, were adopted (Fig. 10) (Menichelli 2003).
4 THE ROOFS OF THE "ISOLOTTO" AND OF THE "CORDERIE"

4.1 Remarks on the global behaviour of the trusses

The roof of the main shed in the Isolotto has a structure made of king-post trusses with the posts resting on the tie beams and joined to them by means of metal stirrups. The larch wooden trusses have a span of approximately 18 m and are placed at a distance of 2.3 m. The timbers that constitute the tie beams and the struts have 25 × 32 cm sections; king posts and knee rafters have 25 × 25 cm sections. The whole structure is braced with timbers, placed during the nineteenth-century conservation works (Fig. 6).

The roof of the Corderie is supported by Palladian style queen-post trusses with queen-posts resting and joined to the tie beams by means of metal stirrups. The larch wood trusses have a span of about 21 m and they are placed at a distance of 2.2 m. The timbers that constitute the tie beams have 28 × 32 cm sections, whereas struts, queen posts and straining beams all have 28 × 28 cm sections (Fig. 4).

Considering that, as already mentioned, an historical record of why the most interesting and original constructive solution adopted in the roofs of the Arsenal of Venice (i.e. the rigid node between tie beams and posts) was used, does not exist, modern modelling tools were applied to assess the influence of this detail on the global structural behaviour of the trusses. With this aim, the behaviour of the trusses was predicted by means of finite element models. Beam type elements were used to model the structure, in order to easily reproduce both the "truss" type of behaviour (introducing hinges at each node) and the "frame" type of behaviour. These two conditions, in fact, represent the farther limits between which the real behaviour of a wooden truss, similar to those here analyzed, take its place.

For both the truss typologies, two-dimensional linear elastic analyses were performed. The material properties assumed for larch wood are summarized in Table 1.

In the analyses, the trusses were subjected to a uniformly distributed load equal to 3.75 kN/m², that is a usual permanent load for the Arsenal roofs. This load is equal to a uniformly distributed load of 8.625 kN/m for the trusses in the "Isolotto", and of 8.25 kN/m for the trusses in the Corderie. Two loading conditions were taken into account: the symmetric one \( Q_1 + Q_2 \), and the antisymmetric \( Q_2 \). The geometry and the characteristics of the analyzed trusses can be seen in Figures 11 and 12.

The pre-stressing due to the pre-inflection of the tie beam in correspondence of the posts (points A and B of the static schemes), and due to the action of robust stirrups, is simulated by means of rigid link elements, which ensure the structural continuity. The
camber given to the tie beam is sufficient to close the gap between the posts and the tie beams (points A and B in Figs 11 and 12). The gap is estimated to be equal to 12 cm for the trusses of the Isolotto and to 15 cm for those of the Corderie.

It has to be highlighted that in the models where the tie beam and the post are not joined, the points A and B, being not connected at all, can have independent displacements. It is not thus considered the possible contribute of the stirrups, being sufficient, to the aims of the present study, to get a first qualitative idea on the differences between the behaviour of the truss with and without the "rigid node". The studies here presented are focused on the evaluation of the global truss deformability and of the tie beam behaviour. A direct comparison, which gives indication on the stiffening effect of the "rigid node", is given by the frequency analysis of the structural model with and without the "rigid node".

It is also easy to understand that in case of symmetric loading condition, the axial stiffness of the elements is particularly exploited, therefore, in the case of symmetric loads, there are no particular differences in the behaviour of the truss with and without the "rigid node".

The analyses performed applying symmetric uniformly distributed loading conditions, for both the king-post truss and the queen post-truss, confirmed that hypothesis. No substantial differences in the stress diagrams and consequently in the deformed shapes, were found for the trusses with and without the "rigid node". This happens also because the internal state of stress obtained by cambering the tie beam, respectively equal to 0.65 kN for the tie beams of the Isolotto and to 0.42 kN for the tie beams of the Corderie, is not relevant if compared to the actual stresses due to live loads. Figures 13 to 15 show this behaviour for a king-post truss of the Isolotto.

A second remark on the behaviour of both kinds of trusses concerns the effect of the pre-inflection imposed to the tie beam. It is evident that to obtain the "rigid node", the pre-inflection of the tie beam is necessary. This is aimed to safeguard the integrity of the tie beam when bending stresses, deriving from the settlement of the posts caused by short but also long term effects connected to the viscous behaviour of wood and to the rotting of wood at the nodes, occur. From the analyses performed, it was possible to estimate that the maximum deflection under live load is equal to 8 cm. This deflection is lower than the imposed camber; therefore it is not able to produce uncontrolled bending stresses.

This effect can be studied by adopting the loading scheme shown in Figure 16, where the tie beam is directly loaded with a uniformly distributed load. Figures 17 and 18 qualitatively show the difference in bending moment on the tie beam of the queen-post truss, when the tie beams and the posts are or are not connected.

A last remark on the global behaviour of the trusses concerns the tensile stresses occurring in the tie beams

![Figure 13. Stresses in the king-post truss without rigid node due to the uniformly distributed loading [kN].](image)

![Figure 14. Internal state of stress due to the cambering of the tie beam [kN].](image)

![Figure 15. Superposition of stresses due to the uniformly distributed loading and to the cambering of the tie beam [kN].](image)

The results are almost equal to those of Fig. 13.

![Figure 16. Direct load on the tie-beam.](image)

![Figure 17. Bending moment when tie beams and posts are not joined.](image)
due to the cambering. The value is of the order of magnitude of 0.7 MPa.

The main difference in the performances of the trusses due to the imposed pre-inflection, which allows joining the tie beams to the posts, can be detected in the flexural behaviour. This can be easily analyzed if anti-symmetric loading conditions are studied. These conditions are very likely to occur in the hypothesis that suspended heavy loads connected with the ship construction activity were present, as above mentioned. Dead and snow load, in fact, being symmetrically distributed, do not involve significantly the bending stiffness of the truss, thus producing effects that are almost independent from the type of connection between posts and tie beams.

The behaviour of the two trusses were thus separately studied with frequency analyses, under anti-symmetric loading conditions.

4.2 Trusses of the Isolotto

The influence of the internal constraint between the tie beam and the king post in the trusses of the Isolotto on the flexural behaviour of the truss is clearly shown by a frequency analysis carried out on the structure. Table 2 shows the first four natural frequencies of the king-post truss in the two cases. The first frequency changes from 0.570 to 2.535 Hz, when the tie beam and the post are connected. In particular, the first mode shape is related to the free vibration of the tie beam as a cord (Fig. 19), whereas when the tie beam is connected to the king post, the first mode shape involves the entire structure, as can be seen in Figure 20.

By the analysis of the model shown in Figure 11 when only the antisymmetric loading condition Q₂ is applied, a qualitative evaluation and comparison of the displacements when the tie beam is not pre-inflected (Fig. 21) and when the tie beam is cambered and connected to the king post (Fig. 22), can be carried out. A relevant difference is found in the two cases.

4.3 Trusses of the Corderie

The analyses carried out on the king-post trusses of the Isolotto were repeated also on the queen-post trusses of the Corderie. Also in this case, the main differences of the trusses with and without pre-inflected tie beams and connection between the tie beams and the posts, can be found by studying their flexural behaviour. Table 3 shows the frequencies obtained in the two cases.

Table 2. Frequencies obtained for the king-post trusses of the Isolotto with and without the rigid node connection.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency without tie beam-post connection (Hz)</th>
<th>Frequency with tie beam-post connection (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.570</td>
<td>2.535</td>
</tr>
<tr>
<td>2</td>
<td>1.446</td>
<td>3.214</td>
</tr>
<tr>
<td>3</td>
<td>2.875</td>
<td>5.725</td>
</tr>
<tr>
<td>4</td>
<td>5.930</td>
<td>7.125</td>
</tr>
</tbody>
</table>

Figure 19. First mode shape of the king-post truss with tie beam neither pre-inflected nor connected to the post.

Figure 20. First mode shape of the king-post truss with rigid node connection between tie beam and king-post.

Figure 21. Deformed shape of the king-post truss with tie beam neither pre-inflected nor connected to the post.

Figure 22. Deformed shape of the king-post truss with tie beam cambered and connected to the post.
Table 3. Frequencies obtained for the queen-post trusses of the Corderie with and without the rigid node connection.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency without tie beam-post connection Hz</th>
<th>Frequency with tie beam-post connection Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.425</td>
<td>2.216</td>
</tr>
<tr>
<td>2</td>
<td>1.187</td>
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</tr>
<tr>
<td>3</td>
<td>1.730</td>
<td>4.760</td>
</tr>
<tr>
<td>4</td>
<td>4.224</td>
<td>5.533</td>
</tr>
</tbody>
</table>

Figure 23. First mode shape of the queen-post truss with tie beam neither pre-inflected nor connected to the post.

Figure 24. First mode shape of the queen-post truss with rigid node connection between tie beam and queen posts.

Figure 25. Deformed shape of the queen-post truss with tie beam neither pre-inflected nor connected to the post.

Figure 26. Deformed shape of the queen-post truss with tie beam cambered and connected to the post.

which is apparently in contrast with the modern interpretation of the roof truss structural behaviour, was adopted for the truss of the Arsenal.

The structural scheme of the trusses, developed with the construction science and after the theories of materials and structure behaviour were developed between the end of the eighteenth and the beginning of the nineteenth centuries, is based on the fact that no connection is provided between the posts and the tie beam, in order to avoid that the possible settlements caused by the loads and by the relative displacements at the nodes due to short and long term effects, provoke bending stresses in addition to the tensile stresses.

A simple method to rigidly connect the tie beam to the posts, avoiding the negative effect above mentioned, was that largely used in the Arsenal of Venice and described in the present contribution, i.e. the pre-inflection of the tie beam. It is very interesting to note that this trick could significantly improve the global stiffness of the structure. This conclusion is supported by the results of structural analyses. The analyses show that the stiffening action is particularly effective when antisymmetric loading conditions, which significantly involve the flexural behaviour of the truss elements, are applied to the truss. These conditions can be found when not only the effect of dead, wind and snow loads, but also the effect of suspended heavy loads is taken into account. In the period of time during which this constructive technique was adopted, the ship production process actually required the presence of loads suspended at the trusses, thus confirming that the solution was adopted with clear understanding of its structural consequences.

5 CONCLUSIONS

The historical analysis shows that a strong link between the development of the Arsenal of Venice and in particular between the constructive techniques of the docks’ roofs and the ship production process exists. In this connection, a very peculiar constructive solution, consisting in the connection of the tie beams to the posts,
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