Structural analysis of the timber roofs of the “Arsenale” of Venice

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Summary

A study on the different typologies of trusses observed in the Arsenale of Venice is presented in the paper. Preliminary historical researches and surveys permitted their classification into the main categories of historical roof structures (simple truss, “Palladiana”, composite truss, etc.), whose specific variants have been added to modify the structural capacity, allowing the achievement of impressive results in both building and ship construction. The structural behaviour of original and modified roof system have been analyzed, by reproducing different loading conditions, in order to identify the maximum bearing capacity. Moreover, to evaluate the influence of the modification of the connection between the structural elements composing the trusses a FE modelling has been adopted. Comparative results and analyses among different typologies and conditions are discussed.

1. Introduction

The “Arsenale” of Venice was a naval shipyard that played a leading role in the Venetian republic for many centuries, representing now a large monumental complex of exceptional historical value. It is composed of several series of sheds (“tese” or “tesoni”) regularly disposed around the shipbuilding docks, whose many of them were dedicated to the production of very specialized components (e.g. “corderie” or “rope factory”, “armerie” for the armoury, etc.). The buildings of the Arsenale include also a large variability of roof structures, characterized by different typologies developed through the centuries to satisfy the various functions required by the evolution of the whole production system. It has been a real laboratory of truss experimentation, ranging from very simple timber trusses (first half of the 14th century), to large span, huge and complex spatial timber structures (16th century), up to engineered mixed steel-timber (“Polanceau”) and steel trusses (second half of the 19th century) [1].

The trusses of the Arsenale of Venice, from age to age, were modified many times, thus changing their configurations and mechanical behaviour. Therefore, they are particularly interesting, as current testimonies of the transformations of the structural frame that trusses have stood over times. As an example, the triangular king-post trusses, suitable for relatively small spans, became larger “frame-like” and spatial trusses, required to larger sheds and to sustain higher live loads, because of the evolution of the constructive techniques and of the adaptation of the protective covering to new production process, as the lifting of suspended loads [2].

Originally conceived with joined tie beam and posts, which created a “rigid node” by the lifting up of the beam against the post and their mutual connection with a metal stirrup, the tie beam assumed a upward curved structural scheme. This was probably due to a particular use of the trusses in the Arsenale, which play not only the role of bearing the roofing loads, but also of lifting up of high loads during the phases of construction, setting up and maintenance of the ships. This original configuration, followed by different typological modifications, is considered always kept in the Arsenale and widely adopted in the context of the large venetian constructions. It was definitively abandoned only in the second half of the 19th century, due to both the advent of new realizations (that used the Polanceau and “English” type) and their specific modification by the resection of the king post and its release from the tie beam [2].

The aim of the proposed study is to characterize the covering typologies that are in the Arsenal, their historical development and the transformation of the mechanical behaviour. A finite elements analysis simulating the different configurations and the assessment of the tie beam element according to the Eurocode 5 were carried out. The main results obtained on the mostly significant trusses, in particular for their lifting functions and the tug of ropes, are discussed in the following.
2. Historical development of the Arsenale of Venice

The Arsenale of Venice constitutes one of the wider parts of the insular city; together with other similar systems in Venice, it was the core of the naval industry since the 13th century. Since the 14th century it was the only public yard of the lagoon. The whole area can be considered one of the first factories in the world, since it represents one of the most important examples of large industry complex having a centralized management in the pre-industrial economy.

The first settling of a yard complex nearby the St. Martino Church are probably due to the commitment of Doge Enrico Dandolo to supply large ships to the Count of Champagne in the first years of the 13th century for the IV Crusade. In fact, 140 cargo ships and 72 combat “galee”, where produced in very short time, involving also the St Martino yard, which became later the Arsenale of Venice [3].

The original concept at the basis of the Arsenale, which can be found in the different enlargements through the centuries, is the construction of several series of shed (“tese” or “tesoni”), regularly disposed around the ship building docks. The word “tesa”, referred to the Arsenale, points the sheds where watercrafts were built. The big dimensions of the “tese” (56 x 19 x 9 m) is a typical element of the whole complex of the Arsenale. The reason for big sheds wideness is probably due to the difficulty of building foundations in the lagoon; as a consequence, thanks also to great ability of carpenters, the easier construction of roofs was preferred to the masonries one [1] [4]. The trusses are the “tese” covering structures, thus representing a constant constructive element able to solve the problem of very high spans (greater than 20 m). Trusses are generally on sight structures, thus their spatial articulations and clever structural weaving among tie-rods and struts, and also the simplicity of joints and nodes can be easily read. The factories of the Arsenale are considered as “spatial systems” [5], able to answer to two fundamental requirements: the maximum free span joinable by a wooden truss and the minimum transversal thickness for the load bearing walls.

In the course of time the Arsenale complex was radically transformed in order to adapt it to the different naval and military shipbuilding needs and the development of constructive techniques (Fig. 1).

Since the early decades of the 20th century the Arsenale suffered a slow decline, till its partial abandonment, as it was not able to satisfy the bigger needs of the modern naval units anymore.

More recently, the Arsenale was revitalized by introducing some cultural activities and by planning its recovery (Fig. 2).

In 1983, some works were undertaken by the “Soprintendenza B.A.P.S.A.E. di Venezia e Laguna” on the “Corderie” buildings, which marks the start of a first phase of studies and analysis on the Arsenale [6].

In that framework, the restoration of the roofs has a very high priority, since they are the first to be prone to the building degradation, besides all the other aspects concerning the general preservation of the area [4].
3. The typologies of truss in the Arsenale

The first typology which appear in the Arsenale is the truss with knee rafters (Fig. 3), composed by two struts, a king post and two knee rafters. Such a truss would represent the “canonical” truss [7], together with the queen-post truss (called “Palladiana”) (Fig. 4), having a double tie and queen posts. The Palladiana truss was widely used in the Arsenale in the 16th century, thanks to Andrea Palladio. In the changing of the functional architectures of the Arsenal of Venice, a suitable reference are the building of the “Corderie” (rope factory), whose covering can be taken as model for the “Palladiana” truss. The development of the “Palladiana” truss is the composite queen-post truss (Fig. 5), which differs from the previous one because of the addition of four knee rafters.

Another kind of roof structures present in the Arsenale are considered as “peculiar typology” (Fig. 6), a term which points trusses like the composite queen-post truss with some modifications.

Later on, in the second half of the 19th century, after the industrial revolution, many solutions of engineered mixed steel-timber appear. The parts subjected to tension (tie beam) are made of steel, while bending-compression and compression stresses are bore by timber elements. Also the cambered fink truss (called “Polonceau”) is present, first with timber elements as struts (Fig. 7), then, more and more often, completely made by metallic materials.

From that time onwards, the era of modern wholly metallic trusses starts, characterized by multiple rods and joints, where all the rods can work in both compression and tension. Among the steel structure trusses, the typology which is present in many building of the Arsenale, introduced with some restorations carried out in quite recent times (early 1900), is the cambered howe truss (called “English” truss) (Fig. 8).

4. The evolution of the mechanical behaviour

The trusses characterized by a “rigid node” configuration are now present only in two buildings. They are the trusses with knee rafters of the “Tese Sud dell’Isolotto” and the queen-post trusses of the “Corderie” (Fig. 9). A brief description of the buildings is given below, as their history characterizes also the development of their trusses.

4.1 The buildings of “Tese Sud dell’Isolotto” and “Corderie”

The building called “Tese Sud of the Isolotto” is located in the big dock (namely the “Darsena”) of the Arsenale. The name derives from its location previously to the excavation of a big portion of ground that originated the big dock itself (Fig. 10).

The “Isolotto” was the strip of earth that separated the “Darsena Nuova” from the “Darsena Novissima”. It was composed by two rows of sheds: the first row was realized in the 14th century (“Tese sud”), whether the second one was built in the middle of the 16th century (“Tese nord”); they were facing the “Darsena Nuova” and the “Darsena Novissima”, respectively [4].

The “Tese Sud” represents the only testimony existent in the 14th century of the boat-sheds (“squeri”) of the “Isolotto”. It is not know when the architecture was modified, but it is agreed that the main structure goes back to the factory of the 14th century [4].

The width of the boat-sheds was equal to 53 venetian feet (about 18.42 m), as it is represented in an enlargement project of the Venice Arsenale worked out at the end of the 14th century [4].
The building of the “Corderie” (Fig. 11), also called “La Tana”, from the name of the canal along which develops, as designed by A. Da Ponte [8]. The first building presumably goes back to the 1304-1307, as construction independent from the complex. It was aggregated to the Arsenale only in the 1325 [8]. The actual building is dated between 1579 and 1583 [9].

Between the 16\textsuperscript{th} century and the first half of the 19\textsuperscript{th} century the function of the “Corderie” was the production of ropes for the business naval shipbuilding. This is confirmed by the considerable length of the building, equal to 317 m, whereas the other dimensions are of 21 m in width and 12.10 m in height [10].

In the second half of the 19\textsuperscript{th} century the function of load lifting of the trusses ended because the business of the naval shipbuilding moved from the sheds to the uncovered slipways [2] and there was the introduction of the gantry, after the advent of cast iron. In this period several transformations were introduced to the building, among which the resection of the post, limited in the Arsenale to some trusses located in the “Corderie”.

### 4.2 Mechanical transformation of the truss with knee rafters

The “Tese Sud dell’Isolotto” is extremely interesting because of the presence of the oldest timber truss roof structured in the Arsenale.

At the beginning of its shipyard phase, the Arsenale had no covered structured to build ships and its first structures presumably go back to the first half of the 14\textsuperscript{th} century, like in the “Isolotto” case.

Trusses with knee rafters are present, composed of two struts (0,25 x 0,32 m), a tie beam (0,25 x 0,32 m), a post (0,25 x 0,25 m) and two knee rafters (0,25 x 0,25 m). They are characterized by the rigid node between the post and the tie beam (Fig. 12), seldom noticeable today in the venetian structures, because of many restorations performed in the 19\textsuperscript{th} century, which acted the resection of the post [3].

To analyze the mechanical behaviour of this kind of truss, a load due to the uplift of a typical boat (called “galea”), placed in a central position inside the building has been considered. In fact, the
dimensions of the carry-boats and of the military “galee” were considerably increasing and it is assumed that there was the necessity to lift them up in order to facilitate their construction and maintenance. The historic studies pointed out that a “galea”, being about 6 m wide and 35 m long, could have had a mean weight of around 2000 kN.

It is assumed that some ropes were used to lift up the military boats. This let to simplify the application of the weight of the “galea” as concentrated load acting on the tie beam. The load is distributed over the 15 trusses present in the “Tese Sud dell’Isolotto”, as represented in the Fig. 13.

Different steps of load were applied to the truss, and the bending-tension assessment of the tie beam under combined actions (symmetric and asymmetric loading condition) was performed, according to the Eurocode 5 [11].

Fig. 13: Scheme of a truss working for the uplift of a “galea”

The FE simulation of different levels of suspended loads was performed. The analysis revealed that the bending-tension condition is not verified for applied loads equal to 2000, 1500, 1000, 900 and 800 kN, being the maximum admissible load corresponding to a “galea” equal to 700 kN in weight. Fig. 14 shows the diagrams of the stress/displacement parameters, in function of the most severe combination of loads (asymmetric loading condition for bending moment and symmetric one for axial force and displacement). In Tab. 1 the maximum values of the bending moment and of the axial force, and the results of the bending-tension assessment according to Eurocode 5 [11] are given.

![Fig 14: Bending moment \([kN\cdot m]\)(a) and axial force \([kN]\)(b) diagrams, and vertical displacement \([m]\)(c), in case of two-point load with a total weight of 700 kN](image)

**Tab. 1: Truss with knee rafters: bending-tension results in case of two-point forces applied on the tie beam**

<table>
<thead>
<tr>
<th>Total value of the two point forces</th>
<th>Bending moment (kN*m)</th>
<th>Axial force (kN)</th>
<th>Bending-tension assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 t</td>
<td>-112.93</td>
<td>298.35</td>
<td>2.29 &gt; 1</td>
</tr>
<tr>
<td>150 t</td>
<td>-84.66</td>
<td>267.75</td>
<td>1.78 &gt; 1</td>
</tr>
<tr>
<td>100 t</td>
<td>-57.99</td>
<td>237.15</td>
<td>1.30 &gt; 1</td>
</tr>
<tr>
<td>90 t</td>
<td>-52.56</td>
<td>231.10</td>
<td>1.17 &gt; 1</td>
</tr>
<tr>
<td>80 t</td>
<td>-47.13</td>
<td>255.05</td>
<td>1.10 &gt; 1</td>
</tr>
<tr>
<td>70 t</td>
<td>-41.62</td>
<td>218.92</td>
<td>1.00 = 1</td>
</tr>
</tbody>
</table>
Since the maximum load bore by the tie beam is considerably lower than the weight of a “galea”, it can be supposed that only the first part of the construction of the hull of the boat took place inside the “Tese Sud dell’Isolotto”. An alternative hypothesis about the truss function can be also proposed.

It is assumed that the truss could be utilized for different activities than those concerning the construction of the “galee”, like the lifting of timber or of some other loads of considerable entities. Therefore, by taking into account the possible application of four-point forces (Fig. 15) at the tie-beam level, having the same global value as those previously considered, a new model was created.

Results of the maximum admissible load, equal to 300 kN for each point force on the tie-beam are shown in Fig. 16. Simulations were performed to assess the bending-tension state for loads equal to 1000, 500, 450, 400 and 350 kN, distributed on 15 trusses for each point force. In Tab. 2 the maximum values (asymmetric loading condition for bending moment and symmetric one for axial force and displacement) of the bending moment and of the axial force, and the results of the bending-tension assessment according to Eurocode 5 [11] are given. The global maximum load is thus equal to 1200 kN.

<table>
<thead>
<tr>
<th>Value of each point forces</th>
<th>Bending moment (kN•m)</th>
<th>Axial force (kN)</th>
<th>Bending-tension assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 t</td>
<td>-120,15</td>
<td>364,09</td>
<td>2,51 &gt; 1</td>
</tr>
<tr>
<td>50 t</td>
<td>-61,76</td>
<td>270,25</td>
<td>1,41 &gt; 1</td>
</tr>
<tr>
<td>45 t</td>
<td>-55,80</td>
<td>226,88</td>
<td>1,24 &gt; 1</td>
</tr>
<tr>
<td>40 t</td>
<td>-49,93</td>
<td>251,23</td>
<td>1,19 &gt; 1</td>
</tr>
<tr>
<td>35 t</td>
<td>-44,14</td>
<td>241,93</td>
<td>1,08 &gt; 1</td>
</tr>
<tr>
<td>30 t</td>
<td>-38,27</td>
<td>232,49</td>
<td>0,97 &lt; 1</td>
</tr>
</tbody>
</table>

The typology of the queen-post truss (“Palladiana”) is present in more buildings of the Arsenale, the trusses still sanding in the “Corderie” are particularly interesting, because there are still some examples of configurations with the post steadily joined to the tie beam.

4.3 Mechanical transformations of the “Palladiana” truss

Although the typology of the queen-post truss (“Palladiana”) is present in more buildings of the Arsenale, the trusses still sanding in the “Corderie” are particularly interesting, because there are still some examples of configurations with the post steadily joined to the tie beam.
The queen-post truss trusses are composed by two struts (0,28 x 0,32 m), a tie beam (0,28 x 0,32 m), a straining beam (0,28 x 0,28 m) and two posts (0,28 x 0,28 m).

Because of the specific function of the building, it is supposed that in the “Corderie” the loads that the tie beam should have carried were much lower than in the “Tese Sud of the Isolotto”.

Two rows of column subdivide the space in three spans: the two aisles present a intermediate suspended platform, while the nave has no interruptions in their height up to the ceiling (Fig 17).

It is not know the exactly position where the loads were raised, thus their distribution through four point forces applied in the two lateral portions of the tie beam, in proximity of the joints, has been chosen (Fig. 18).

The FE models allowed getting the stress/displacement parameters under the most severe combination to execute the bending-tension assessment.

Similarly to the previous case, the analysis is oriented to set the maximum admissible load applied to the tie beam.

For the queen-post truss, located in the Corderie, a process inverse in comparison to the previous case was adopted. First, the tie beam was subjected to a very low value of loads (1 kN for each of the four applied forces), than the load was increased up to the maximum value that the element can carry. As a result of subsequent increments of load, the tie beam is able to carry 30 kN for each point force (Fig. 19). In Tab. 3 the maximum values (asymmetric loading condition for bending moment and displacement and symmetric one for axial force) of the bending moment and of the axial force, and the results of the bending-tension assessment according to Eurocode 5 [11] are given.

<table>
<thead>
<tr>
<th>Value of each point forces</th>
<th>M (kN•m)</th>
<th>N (kN)</th>
<th>Bending-tension assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 kN</td>
<td>-27,89</td>
<td>193,85</td>
<td>0,66 &lt; 1</td>
</tr>
<tr>
<td>5 kN</td>
<td>-29,73</td>
<td>204,41</td>
<td>0,71 &lt; 1</td>
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<tr>
<td>10 kN</td>
<td>-32,72</td>
<td>217,61</td>
<td>0,80 &lt; 1</td>
</tr>
<tr>
<td>20 kN</td>
<td>-38,71</td>
<td>244,01</td>
<td>0,89 &lt; 1</td>
</tr>
<tr>
<td>30 kN</td>
<td>-44,70</td>
<td>270,41</td>
<td>1,00 = 1</td>
</tr>
</tbody>
</table>
5. Conclusions

The classification of the truss typology situated inside the Arsenale of Venice allowed improving the level of knowledge about the roof system present in the complex and to clarify many aspects of their transformation. Moreover, the study led to the identification of two buildings where constructive systems dated back to the restorations of the 16th century are still present.

The analysis of the truss typology with “rigid node”, clearly showed that the tie beams with the lower timber elements steadily joined and with the configuration of the upward curved tie beam can better satisfy the role of bearing structure for the operations of loads lifting, compared to the traditional trusses with classical open node.

Different hypotheses on the possible functioning of the modified trusses, according to the historical development of the Arsenale, have been adopted, and the related assessments have been performed. It results that for the truss with knee rafters present in the “Tese Sud dell’Isolotto”, the lifting of loads, even high, but different than a whole “galea” were mostly probable.

In the “Corderie” building, low initial values of load have been assumed, as there are not certain documentations about the presence of loads carried by the tie beam. In fact, the principal activities performed inside the building, developed principally at the ground. Therefore, it is very probable that the transformation of the truss configuration, from the case in which tie beam and post are not joined to the one with rigid node, is the consequence of the progress of the construction techniques.

Further analyses are in progress, aimed at completing the interpretation of the historical evolution of the very peculiar trusses of the Arsenale, by using the modern assessment approach.

6. References


