Restoration of the historical steel vault of the Goldoni Theatre in Livorno

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ABSTRACT: The Goldoni Theatre in Livorno (1843–1847) was designed by architect Giuseppe Cappellini to offer natural lighting via a wide steel and glass vault. A significant part of the original “Best Best” English laminated steel structure, one of the oldest in Europe, has been conserved up to today. The original central part is made up of 16 vertical frames, in a sort of “umbrella structure”, each of which consists of 4 thin rectangular cross section rods converging on central complex joints. During recent restoration it has been preserved (although with significant errors), while the ’900 additions have been rebuilt to restore Cappellini’s original structural design. The glass roof has also been rebuilt according to modern performance, with a new upper reinforcing steel structure to provide hanging support for aluminium-glaze panels. The ceiling is equipped with a mechanical “velarium”, replicating the historic manual one, to darken the hall during daytime shows.

1 HISTORICAL NOTES ON THE GOLDONI THEATRE AND ITS ROOFING

The architecture of Livorno’s Goldoni Theatre is typical of mid-19th century Italian theatres. It was built by private initiative from 1843 to 1847 after the design of architect Giuseppe Cappellini (1812–1876) from Livorno. The horseshoe arrangement of the orchestra seating surrounded by four tiers of boxes and an upper gallery followed the planimetry of the San Carlo theatre in Naples and the Scala in Milan. As can be seen in the preliminary building project from October 1, 1842 (Caporali et al. 1842), the Corporali and Varoli families, who commissioned the theatre, wanted it to be able to hold daytime performances using only natural light, a particularity that gave rise to not few difficulties. To this aim in his first project draft of February 1843 (Cappellini 1843), Cappellini planned the construction of large windows at the level of the gallery and an octagonal skylight (called “lantem”) to be sustained by a pair of large wooden trusses on the ceiling. Though he originally planned the opening to be about eight meters in diameter (Fig. 1), he committed himself to making the skylight as large as possible, and therefore declared himself willing to change its arrangement as necessary. In effect, already by April 1843, a handwritten note regarding the theatre’s layout attests to his desire “to form three lanterns to reinforcing the roof and make it more solid and follow the course of the ellipse”.

When construction of the walls of the main hall, begun on March 13, 1843, were probably concluded at the end of 1844, Cappellini realised that the illumination to the hall from the planned octagonal ceiling lanterns would be disappointing. Although it is unsure whether he had already planned the supports for the wooden trusses, similar to those supporting the stage roof, he certainly did completely rethink the bearing structure of the roofing, applying the then new material steel, despite the fact that it was not yet available in Italy. In fact, although a nearby foundry, “La Magna” in Follonica, had been established in 1834 and was managed by the engineer Alexander Manetti, it produced only cast iron, while the Pinion Foundry in Florence had been opened in only 1842. However, because Cappellini had established relationships with English builders (as testified to by his prior project, the Casini Ardenza in 1838–1839), he was able to procure the materials from English entrepreneurs in Livorno.

At the time, the port city had long hosted a thriving English community including many literary luminaries (such as the poets, Lord Byron and Tobias Smollett). Due to the great development of the railroads, even the Tuscan grand duchy had turned to illustrious foreigner iron engineers, such as Robert Stephenson, from England, Henry Dufour, from Switzerland and the French Seguin brothers, who were engaged to build viaducts and other public works. Of the local engineers, Carlo Reishammer was amongst the most sought after, together with his son-in-law Alessandro Manetti, who had studied at the prestigious engineering institute “Ecole de Ponts et de Chaussées” in Paris. Incomprehensibly, Manetti demonstrated little esteem for Giuseppe Cappellini and refused his
application for membership in the Tuscan "Hydraulic, Road and Civil Engineering Corps", as documented by his letter of November 30, 1850 (Manetti 1850).

Historical documents (Messeri 1845) reveal that on January 12, 1845, the smith, Stefano Messeri, signed an estimate for the work required to construct a metal structure for the roofing of the entire stage hall. Then, on February 13, 1845 (Anonymous 1845) Cappellini received an estimate for rods made of "Best" English steel. For his part, on March 26, 1845 the carpenter Giuseppe Terreni completed (Cappellini 1847a) a scale model of the new structure of the skylight and then oversaw construction of the border roofing over the gallery, which he erected with a series of wooden trestles. Two documents, undated but signed by Cappellini (Cappellini 1845) and most likely from early 1845, list some prices for the labour costs for executing the connections of the iron rods, which were to be done through the technique of "boiling" (a process of heating metal mesh until it is white hot), as well as an inventory of the rods that he intended to use for the roofing: the inventory calls for using a total of 112 large cross-sectional bars (56 of cross section 5.83 x 3.89 cm and 56 of cross section 3.89 x 3.89 cm) and 84 smaller cross-sectional ones (3.89 x 2.91 cm), apart from 120 extremely small sized rods (60: 2.91 x 1.94 cm and 60: 1.21 x 0.97). The roof eventually raised by Cappellini was made up of 16 frames (still present on the Theatre today), arranged in a semicircle. Each frame was originally fitted with 4 large rods. A further 6 pairs of similar frames, arranged on parallel planes were subsequently demolished and, as none of the original plans have survived, it must be deduced that the missing frames were also made up of 4 pairs of metal rods, each of which was fitted with a pair of wood diagonal braces, essential for the static operation, in analogy with the diagonal ones still present in the two border frames of the semicircle.

Most of the iron structure of the roofing was erected by 1845, as testified to by the records of Giovanni Cecchi (Cappellini 1847b), the smith who had the task of emplacing the tin plates of the opaque parts of the roof, and who in November 1845 supplied the materials for fixing the glass panes of the skylight and then in December covered the roof summit with lead plates. There are moreover indications in correspondence on the work (Cappellini 1847c) of further weldings executed by Messeri on the skylight, even as late as January 1847. On August 16, 1846 an earthquake struck the city and caused some cracking in the building: there are documents of the architect’s instructions on the repairs that were to be done, though it appears that none of the glass structures were broken. Finally, Gaetano Terrieri was responsible for painting the large iron support structure of the skylight in July 1847, which he finished only a few days before the theatre's inauguration on July 17, 1847. The roof prompted a great deal of admiration even while it was still under construction. Further evidence of this comes from an April 24, 1846 note (Mugnai & Mugnai 1846)
from the stonemason, Benedetto Malfanti to the theatre's sponsors (involved in a legal dispute over delays in the work's completion), which states that not all the glass had been set yet and that the process would probably not be concluded until the following month.

The inauguration commanded a great deal of attention in the local press (Cuneo 1847), which stressed the novelty of the theatre's glass roof, which was screened as needed via a large cable- and pulley-operated velarium on a supporting iron framework. The glass and steel roofing structure was one of the largest ever built on a theatre, with a total weight of 140,000 pounds, of which 43,000 pounds were accounted for by the 1400 glass panes, 87,000 pounds by the steel support structure and the remaining 10,000 pounds by wood and the lead and copper sheeting.

The subsequent history of the Theatre and its roofing saw periods of alternating fortunes. Its owners went bankrupt and the theatre was closed for brief time. An 1851 survey by the architect Gaetano Gherardi, Cappellini's teacher, reports the presence of some water infiltrations on the roof, in the proximity of the stage arch. When the theatre was reopened, it was finally used for its intended purpose for many years. No precise accounts have survived regarding the period when the glass panes were removed and the theatre cast into darkness, though it probably coincides with the removal of the six pairs of parallel iron frames, replaced by three reticular Polanceau type trusses with IPN profile purlins, the last of which was connected to the two frames on the diameter of the original semi-radial framework. The replacement was executed from below, so that the T-bars that originally sustained the glass could be left in place. The glass panes were about 5 mm thick, as determined by some residual glass left over after the modification. Likewise, the extremities of the twelve upper cross-rods were left inserted in the wooden beams of the border trestles, poorly cut off at the edge of the trestles themselves: however these run the entire length of the trestles and into the masonry wall, where they are deeply anchored, a feature that contributes to the static stability of the wooden trestles. The velarium was also removed, though the original iron frame on which it was operated was maintained. A rigid panel ceiling was set in its place and sustained by the original velarium framework (Fig. 2). In 1949 a fire broke out in the left side (looking at the theatre) of the border wooden ceiling: the date was annotated on the wall next to the IPN purlin support and may refer to the removing the velarium and inserting the Polanceau trusses, though this has not been corroborated. In the 1970s the roofing cover was replaced with corrugated panels.

2 STATIC CONDITIONS BEFORE RESTORATIONS

In 1995 the structure of roofing was affected by some static problems, especially regarding the three reticular Polanceau trusses, while the semi-radial framework were substantially intact (Sassu 1998a): there were in
fact evident deformations for incipient peak loads on the upper crosspieces, rectified by a series of wooden props; the designer who added these was probably only concerned about controlling the plane of the trusses. The semi-radial framework, instead, did not exhibit any significant instability problems, though its shafts were far more slender. In effect, the frame's static scheme conceived by Cappellini is such that it does not produce significant compressions on the upper or lower crosspieces, which actually are subject to bending and shear according to a scheme of parallel bending beams.

The analytical modelling (Sassu 1998a), together with preliminary evaluations (Favilli et al. 1997), confirm the static conditions of the roofing. The historical semi-radial framework have two, rather complex connections, each of which unites sixteen shafts, decisive for the structure’s proper static functioning (Fig. 3).

In the roof’s centre, the extremity of each horizontal shaft of the semi-radial framework presents an eye and screw simply supported on an iron bar bent to form a semicircle (Fig. 4). Thus, the shaft cannot be loaded with normal stresses, other than by contact friction, and at the same time, it is possible to compensate for assembly errors consequent to imperfect measurements. Numerous bars of smaller dimensions, also bent into semicircles and arranged on various levels, contribute to stabilising the upper crosspieces, which are the only level of profiles expressly under combined compressive and bending stress together with the uprights (with reduced free bending span), compressed by the load transferred to the lower crosspiece.

In conclusion, the wooden perimeter trestles appeared to be in good condition. Moreover, the upper crosspieces were very well connected to the masonry by the extension of the roofing rods, and the main structures of the historical semi-radial framework were also in a good state of maintenance, lacking any significant phenomena of disequilibrium or instability, though it was necessary to insure the anchorage of the two joints of convergence for the beams and lower crosspieces. Instead, the three Polanceau trusses, elements extraneous to Cappellini’s original design, were in a precarious static state and had to be eliminated and replaced with a framework that imitated the original.
3 THE ROOF RESTORATION PROJECT

The basic idea for restoring the roof, dating back to 1999, was to preserve and reinstate Cappellini’s original design, while also supplementing it with further structural elements to bear the greater loads produced by the new glass roofing, in line with current comfort and safety standards (Milanesi & Sassu 1999). In order to minimize the dimensions of the new metal structures to be added to the existing ones and at the same time conform to functional and regulatory requisites, the proposed roofing contained the following structural elements (from exterior to interior):

a) A new reinforcement grid beam framework on the extrados, with metal box profiles;
b) New thermal-groove aluminium profile fixtures, suspended from the extrados grid framework;
c) The glass plane, with new double-layer, glass-chamber panes, arranged as in the original geometry;
d) Historical frameworks and Cappellini clones;
e) The velarium plane.

The entire structure was to be supplemented by two maintenance walkways, an upper and lower one, both with its own bearing function to assist the roofing structures. The new reinforcement grid framework called for main box profiles, aligned with each of the original frames along the direction of the roof’s slope, and secondary box connection profiles, aligned with the existing ones and in any event following the curve of the interior edge of the trestles. Dimensioning was conducted with the aim of minimizing the grid framework’s dimensions and approximate the historical structure as closely as possible. To this aim, special supports were designed for both the border wooden trestles as well as the metal structures. The new aluminium fixture was expressly designed with an “upper fin” profile so that it could be suspended from the grid framework. The presence of the thermal groove and a lower canal for condensed water runoff were essential functional requisites for spectator comfort. The glass plane was expressly designed to achieve the best possible mechanical resistance, lighting (including polarization of reflected rays) and thermal and acoustic properties, as well as ease of maintenance.

The original frameworks (steel and wood) underwent an extensive programme of maintenance and reinforcement, while the missing frames were reconstructed with metal box profiles: 100 × 50 × 5 mm for the upper crosspieces and 50 × 50 × 5 mm for the remainder. The original metal frame in the area of the semi-radial framework was preserved, not only in terms of materials, but also in terms of static performance, as it had enabled the structure to hold up for over 150 years. Instead, the area taken up by the Polanceau trusses had to be completely restructured by removing the three trusses never envisioned by Cappellini, and restoring the six pairs of frames similar to the originals (thus dubbed “Cappellini clones”), in a geometric arrangement similar to those on the diameter of the semi-radial framework, but whose cross sections were redimensioned to provide the necessary resistance.

The velarium plane is sustained by a series of 60 × 6 mm T-bars aligned with the original frames and a transverse box profiles as wind-branches. The cloth roller blinds, some rectangular and others triangular in shape, are controlled by mechanisms at the trestle borders and return cables at the centre of the velarium, which are anchored to the lower walkway. Special supports for the extrados grid framework were designed and added to the underlying structures following four alignments: a) at the top of the Cappellini clones and semi-radial framework; b) on the joints connecting the uprights, diagonal transverses and Cappellini clones; c) inside edge of the wooden border trestles; d) external edge of the masonry, fitted with an earthquake-resistant r.c. belt-course. In particular, support (a) was designed to be adjustable and connected to an extensometer cell to measure the degree of force effectively transmitted to the top of the original semi-radial framework. The supports carry out the function of reducing the grid framework’s deformability and eliminating the horizontal thrust exerted by the framework itself to the top of the masonry.

The interior walkway was constructed to act as a connecting element between the Cappellini clones and the historical semi-radial framework; it was to be anchored to the nearby masonry stage arch in order to stabilize the lower part of the historical structures. It would also serve the purpose of stabilising the equilibrium of the forces acting on the semi-radial framework, a function previously carried out by the nearest Polanceau truss and, to a lesser degree, by an original vertical bar shaped to form an arch. The external walkway instead included special load-bearing parapets with two reticular Neville trusses. It would serve to redistribute the loads acting on the upper portions of the extrados grid framework toward the Cappellini clones, so as to minimise the horizontal thrusts on the masonry summits and unload the historical semi-radial framework of most of the overall forces transmitted from the grid framework to the summit.

4 MODIFICATIONS TO THE WORK IN PROGRESS

In order to avoid any possible contestation when the work was already under way, the city administration decided to hold a contract-tender for the restoration, despite the readiness of the project described in the foregoing, they also decided to undertake the complex enterprise of directing the entire job of restoring the
Figure 5. Transverse section of the 1999 restoration project.

Figure 6. Longitudinal section of the 1999 restoration project.

roof with their own personnel, thus effectively eliminating the involvement of the project planners. With the work already in progress, a number of significant modifications to the plan were made, among which the following structural changes:

a) down-classing the original load-bearing structure of the semi-radial framework into structures to be borne;

b) removal of the inter-tie joists on the trestle borders of the extrados structure and the top of the semi-radial framework;

c) strengthening of the main extrados grid framework profiles with consequent raising of the border support;

d) down-classing the extrados walkway parapets from bearing to borne elements;

e) elimination of the reinforcement on the top masonry of the façade.

The structure of the Theatre, restored with the foregoing modifications to the original plan, has recently been completed and tested. Meanwhile, the Theatre's inauguration last January, presided over by the President of the Italian Republic, was received with great praise for the glass roofing and its velarium. Actually, viewed from the exterior from a point inaccessible to the public, the structure reveals evident errors in construction, which hopefully will affect its aesthetics alone.
Figure 7. Detail of central part after restoration (see the hanging connectors of the originary part to the modern steel structure).

Figure 8. Interior view of the restored steel vault.
Unfortunately, the summit r.c. belt-course was casted incorrectly and runs along a constant, rather than varying height: in fact, due to Theatre's “horse-shoe” layout, the constant slope of the roof calls for the supports to vary in height as a function of their different distances from the top. In order to correct for the error, they had to cast support elements with different lengths, thereby giving the visual impression that the glass runs along on a deformed plane.

The abovementioned modifications to the plan had no significant consequence in terms of economy of the tender. On the other hand, they represent significant alterations to the structural design and have substantially worsened both the planned conformity to the historical static operation of the original roof (which carried out its role admirably for over 150 years), and the intrinsic structural response of the roof and masonry borders. The following considerations will serve to outline the salient points.

a) SUSpending the historical semi-radial framework: although this saved on the costs of extensometer control of the load at the summit, it also disrupted the static operation of the entire roof, completing thwarting the aims of the structural restoration. In fact, experimental tests showed that the steel constituting the semi-radial framework was entirely intact, while global lateral stability would have been insured by the new lower walkway, whose planned anchoring was never carried out.

b) Removal of the intermediate and upper supports on the semi-radial framework: although this resulted in unloading the wooden trestles of the pre-existing load (though the upper crosspieces are suitably reinforced and anchored to the walls by the rows of upper rods originally present in all trestles) and has also enabled unloading of the original metal frames, it has at the same time increased the stresses and above all the deformations of the extrados grid framework, resulting in certain horizontal thrust on the masonry summit;

c) Increasing the free span of the grid framework: required that it be strengthen and stiffened considerably, with a consequent anti-aesthetic raising of its plane with respect to the plane of the glass;

d) Conversion of the parapets from Neville reticular trusses into ordinary railing with uprights and handrails has eliminated the beneficial redistribution of the loads among the Cappellini clones and the historical semi-radial framework;

e) Elimination of the r.c. plate reinforcement on the masonry façade has eliminated the needed strengthening against seismic actions, which was
necessary because of the increase in the roofing loads. Moreover, the reinforcement would have supplemented the masonry’s resistance to the bending moments from the roof anchorages.

5 CONCLUSIONS

From a static structural perspective, the glass and steel roof designed and erected by the architect Giuseppe Cappellini represents a feat of considerable historical value. Although the recent restoration has restored the original glass roofing structure conceived by Cappellini, through the use of modern, surely effective fixtures, glass panes and velarium mechanism, it has instead failed to respect the nineteenth-century designer’s original static conception. The structural design developed by Cappellini and those who collaborated with him in 1845–1846 has been distorted by the restoration works, moreover with the effect of attaining minor results from static safety and the building’s exterior aesthetics, respect to the 1999 project. In particular, the down-classing of the original structure of the semi-radial framework is to be considered not only a culturally improper operation, but structurally injudicious. It can only be hoped that in the not too distant future, the occasion will present itself to be able to restore the static configuration of the semi-radial framework designed by Cappellini by introducing suitable static improvements such as those presented in the foregoing (execution of an intermediate support, formation of a load-bearing upper parapet, connection of the lower walkway to the semi-radial framework) and removal (as far as technically possible) of the clumsy construction error visible on the external border.

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