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MAAT - Museum of Art, Architecture and Technology, Lisbon

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Abstract
The design of the building for the MAAT challenged the architecture and structural engineering teams to provide integrated and creative solutions to materialise the concept of a distinctive building blended with the landscape, while also providing flexible and fluid exhibition areas. This paper describes the approach to its structural design, namely the evolution of the solutions since conceptual design and the focus on proactively adapting them to allow the architects to freely implement the intended curved complex shapes without letting the structure take the spotlight.

1 Introduction

The new Museum of Art, Architecture and Technology (MAAT) is an outward-looking museum located on the banks of the Tagus river in Lisbon designed by British architect Amanda Levete and opened to the public in October 2016.

With a complex architecture based on curvilinear shapes, besides office and technical areas, there are three large and fluid exhibition spaces, which can work combined or totally independent: the Oval Gallery, the Main gallery and the Project Room. The main exhibition room, the Oval Gallery, consists of a double-height space that opens up from the main entrance through a ramped gallery along the winding curve that descends inside the building from the entrance hall to the ground floor.

Conceptually, the public pedestrian path along the riverfront is transformed, as it rises to the building roof from both extremities, into a large space that can serve as a multipurpose space with a 360º panoramic view that is merged with the surrounding landscape of the Electricity Museum and the riverside promenade.

The south-side cantilever and curved façade that distinguish this iconic building were clearly the highest challenge posed to the design team. This paper describes the various systems that were proposed for this part of the building and their evolution throughout the project as a result of a fruitful interaction between structural engineers and architects.

2 The initial concept

The initial architecture concept that established the base for starting the project is presented in Fig. 1. The building should allow visitors to walk over, under and through the building and is characterized by its curved shapes, especially the south façade that rises from the ground and advances in the direction of the river with an impressive cantilever. The exposition spaces should be open and flexible allowing the Museum to be filled with light, and thus, enhancing the visitors experience. To assure the intended fluidity with the pedestrian pathway along the river, the same granite cube pavement was extended to the roof. In contrast, the façade was proposed to have a bronze metal finishing.

Fig. 1 Initial Architecture study for the building.

The structural solution for the large south cantilever that was proposed by the structural engineers who advised the architects for the initial schemes is presented in Fig. 2. The cantilever is supported by several alignments of triangular structures that transfer the forces to the ground by a set of compression and tension struts crossing the Oval Gallery and the Main Gallery.

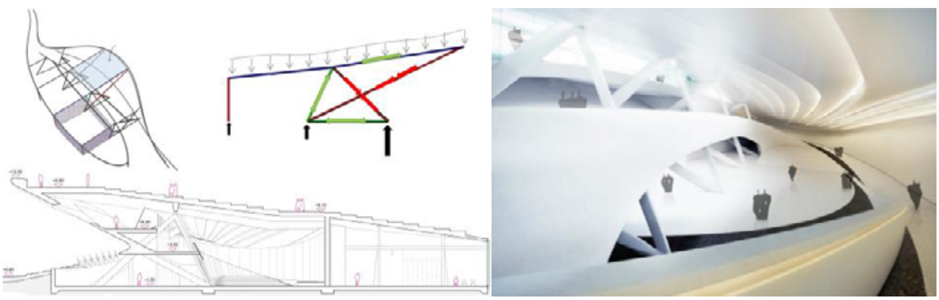

Fig. 2 Initial idealized structural scheme for the south cantilever and Oval Gallery.

This solution allowed materializing the intended architecture concept for the exterior of the building, but imposed important restrictions the Oval Gallery.

3 Initial solution for the structure of the south cantilever and Oval Gallery

Even though the initial structural solution for the support of the south cantilever is effective in assuring the intended geometry for the building, the presence of the triangular shaped supports inside the Oval Gallery and the Main Gallery strongly affects the flexibility and fluidity of the exhibition areas. Also, from a structural standpoint two important issues arise:

- The high unbraced length of the compression struts implies using wide sections to provide an adequate buckling resistance.
- Some foundations are submitted to high tension forces; thus, a complex foundation solution shall be required.

At the initial stages of conceptual design an alternative structural solution was sought for this part of the building. The main pursued objectives were the following:

- The exterior shape of the building should be kept as it is the main feature that distinguishes it.
- The number of supports inside the exhibition areas should be minimized or ideally, fully eliminated.
- The structure for the roof should be adapted to its curved geometry to avoid a heavy filling with non-structural materials.

An alternative structural solution complying with these criteria was proposed. One single steel truss oriented along the longitudinal direction of the building positioned at the interior façade of the building, i.e., at the restaurant balcony (see Fig. 3 – left) is considered in replacement of the triangular shaped supports. It is divided in two spans of 40,6m and 25,1m with the intermediate column positioned at the separation between the restaurant and the main entrance. The structure in the perpendicular direction is composed by steel trusses evenly spaced at every 5,0m and positioned on the roof level following its shape. Their maximum spans are 24,6m between the back wall of the Oval Gallery and the main truss, and 17,1m as cantilever from main truss to the extremity of the roof at the south façade. Purlins at 2,5m centres span over the 5,0m between the steel trusses and serve as support for a composite slab on trapezoidal plate.

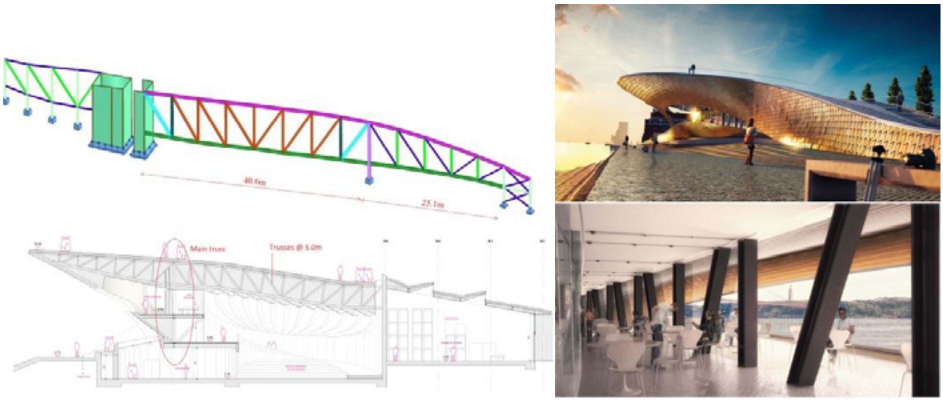

Fig. 3 Alternative steel truss solution proposed for the south cantilever and Oval Gallery.

Besides simplifying the structural concept for the building, the proposed solution is also able to eliminate all the visible supports inside the exhibition areas, while keeping the overall shape of the building. In contrast, the main steel truss could not be placed at the glazed separation between the inner space of the restaurant and its balcony, where it would be better integrated and less visible from the exterior. This would provide an important imbalance between the cantilever and inner span, making it difficult to control deformations at the junction with the façade. Even though the presence of the main truss in the restaurant balcony does not impair its intended use, it has an important visual impact from the exterior (Fig. 3 – right).

4 Final solution for the structure of the south cantilever and Oval Gallery

Before going forward with Detail Design, one additional attempt was made to fully hide the structure. Given the curved shape of the south façade and cantilever, the structural design team proposed a bold solution, where the main truss is replaced by an inclined arch. The arch could be fully hidden inside the curved shaped façade, while also allowing to use the wall separating the restaurant and the Oval Gallery as an additional interior support, which was not possible before due to the imbalance between the spans. The main steel truss could be removed and the spans of the perpendicular roof trusses reduced due to the introduction of the new interior support and the more favourable position of the support provided by the arch. The initial sketches with the proposed updates to the structural concept are presented in Fig. 4. The arch would span not more than 85m with a chord height of about 13,5m, resulting in a span to chord height between 6 and 7, which is considered adequate for a well-balanced structural performance.

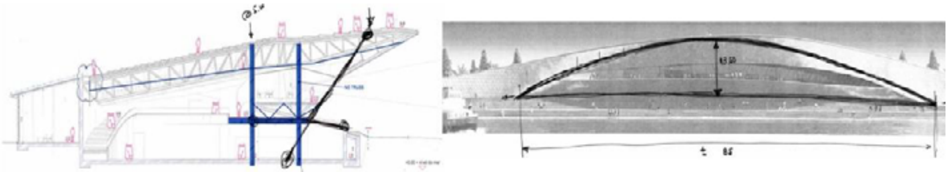

Fig. 4 Arch solution for the south cantilever and Oval Gallery.

As this proposal was considered to fit the intended architecture concept and to provide a significant improvement to the project, the study for the definition of the arch structure was continued. The following conditions to establish its geometry were considered:

- The arch shall be fully hidden inside the curved suspended south façade ceiling.
- Ideally, the arch shall be positioned within one single plane, even though inclined, to better control its structural behaviour. Also, its contour lines shall be perpendicular to the vertical planes defined by the secondary trusses.
- The shape of the arch shall follow the anti-funicular of the applied loads.
- The span of the arch shall be limited to the minimum required to avoid it to be visible.
- Due allowance shall be given to the requirement to provide the arch with adequate flexure resistance in its plane to sustain the live loads in an unbalanced configuration and to provide adequate buckling resistance.

The first step for the definition of the arch geometry was to identify the plane slope and its position along the direction of the secondary trusses, so that the arch can be fitted inside the suspended façade ceiling, while providing well balanced spans for the secondary trusses and an adequate chord height for the arch. The plane was set at an angle of 32,4° to the vertical and positioned as close as possible to the surface of the suspended façade ceiling without intersecting it. For the definition of the arch geometry within the inclined plane the starting points on the west and east side were fixed at levels +6,60 and +5,60 respectively (around the first-floor level), together with a free span of 73m. The highest point positioned roughly at midspan was set at +14,55 (right below the roof level).

The configuration of the arch is not circular or parabolic, but rather follows the configuration of the antifunicular of the applied loads. Thus, the arch is composed of straight segments with variations of slope occurring at the intersections with the secondary trusses. For the determination of the final geometry of the arch, the forces applied to the arch by each roof truss due to the permanent and the uniformly distributed live loads were first determined. By imposing the fixed coordinates and applying a graphic statics procedure [1], all the points at the intersections with the secondary trusses were determined so that the final configuration of the arc is the antifunicular of the applied loads (Fig. 5). The estimated arch axial load obtained from the global finite element model was 35,1MN, which is close to the estimate obtained through the graphic statics method.

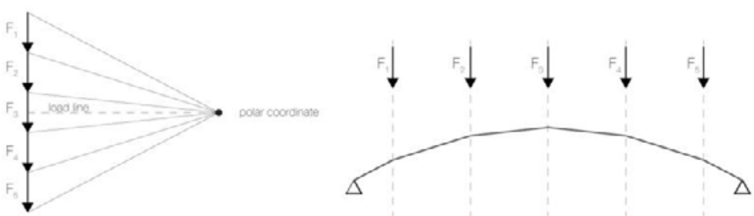

Fig. 5 Graphic statics procedure for the determination of the antifunicular of the applied loads [1].

Due to space limitations, steel was favoured as the material for the arch. A hot finished (EN10210-1 [2]) circular hollow section with 711mm diameter and 60mm thickness (CHS711x60) in S355NH steel has been used. The option for a hot finished and tubular section is related to its higher resistance to buckling. It can be observed in Fig.6 – left that the arch fits well inside the geometry defined by the architecture team for the suspended façade. With the purpose to reduce the buckling length of the arch and to increase resistance to unbalanced loads, a truss was materialised in its plane by introducing diagonals, an upper chord at the level of the roof slab and a lower chord at the lower level of the suspended façade ceiling (Fig.6 - right).

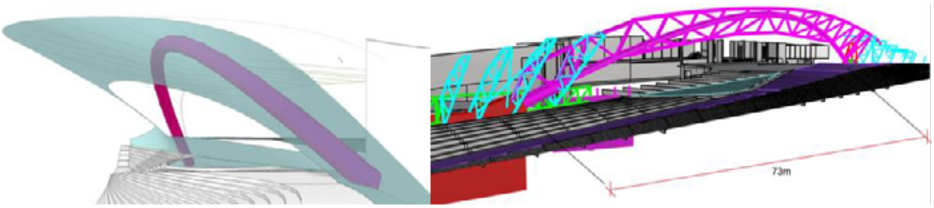

Fig. 6 Final solution – arch inside the suspended façade volume (left) and complete trussed arch (right).

The arch supports are composed by 1,20m thickness RC walls which are fully disconnected from the surrounding structure and are oriented in plan according to the horizontal projection of the starter segments of the arch. Both walls are interconnected at the foundation level by a prestressed concrete beam with 2,10x2,10 cross-section that ties the outward-oriented horizontal forces introduced by the arch to the structure.

"Pratt" type steel trusses at 5,0m centres lean over the arch, having a maximum interior span of 14m between the RC separation wall and the arch, and a 12m maximum cantilever span south of the arch. Even though these trusses are on the same alignments of the Oval Gallery trusses, it was decided not to provide bending moment continuity over the RC wall so that the trusses remain isostatic, ensuring a more precise control over the vertical loads transferred to the arch. The structural configuration of the building roof and stability concept for the south cantilever are represented in the 3D model view from Fig. 7.

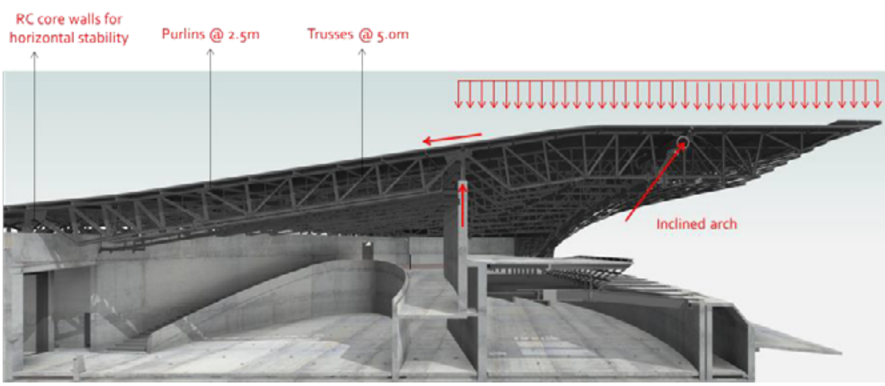

Fig. 7 3D section from Revit model with structural concept for the roof.

As illustrated in Fig. 7, due to the insertion of the arch in an inclined plane, its stability relies on a horizontal force developing at each node which must be absorbed by the roof structure. This is achieved by directing these forces to the RC core walls at the back of the building through membrane forces in the roof composite structure (trusses and slab on trapezoidal plate). The connection of the roof structure to the RC walls is established by steel columns complemented by diagonal bracings (Fig. 8). This solution resulted from the decision not to extend the RC walls to the variable inclination roof slab, thus reducing the interaction between steel structure and reinforced concrete works.

Fig. 7 Roof bracings.

Given the arch is laterally stabilized by the trusses that are supported by it, a temporary shoring in specific locations along its length was required until the completion of the roof. These locations were carefully studied during detail design, where the maximum reactions at each point were determined and dedicated foundation piles were included. The extremity of the south cantilever was surveyed during the removal of the shoring and 14 days after the end of the operation. The maximum deformation after the complete removal of the shoring was 18mm (lower than estimated), having stabilized at 23mm 14 days after with a portion of the roof revetments already in place.

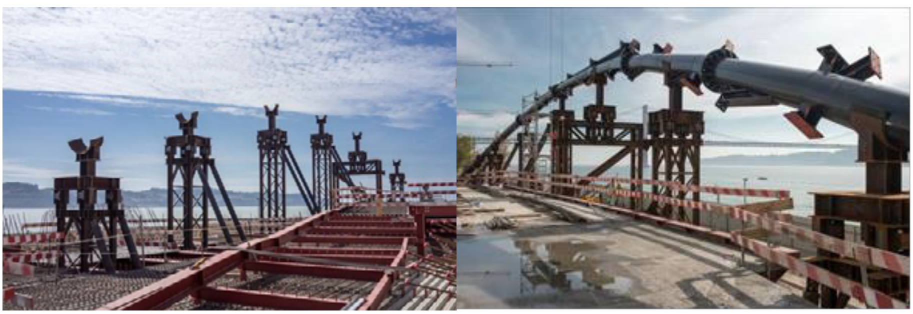

Fig. 8 Temporary shoring and assembly of the arch.

IPE220 purlins at 2,5 centres span perpendicularly to the trusses and provide support to a 13cm thick composite slab on a trapezoidal plate. The purlins are inclined along their longitudinal axis and their cross-section is rotated to the vertical (Fig. 9 – right) so that the composite slab can follow the intended shape for the roof and, thus, minimizes the required filling over the slab. However, the upper chord of the trusses is not rotated to the vertical, because it would be impractical to assemble. Instead, it still follows the roof shape longitudinally, but the axis of its upper flange is lowered 2,5cm relative to the purlin level to avoid the slab thickness to be locally reduced above the trusses (Fig. 9 – left).

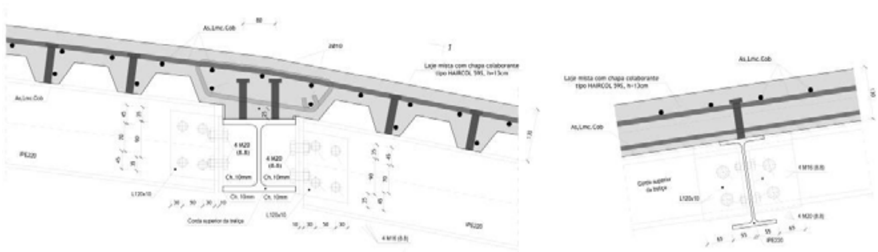

Fig. 9 Roof purlins details – lateral elevation (left) and front cross-section view (right).

5 The south façade

With the development of the project, the architecture team abandoned the initial idea of a metal finishing for the south façade for a solution inspired on the rich Portuguese tradition of handicrafts and ceramics. It consists of about 15000 pieces of three-dimensional ceramic mosaics producing a complex surface that offers different perspectives of light, water and shades. Its complex geometry required a highly adaptive steel structure to assure that each piece is positioned at the correction location and with the correct rotation. Three levels of structure were required:

- "Vertical" steel trusses at 5,0m centres which, depending on their location, are supported on the building concrete structure (east and west of the arch zone – Fig. 10 - right) or are suspended from the roof trusses (arch zone – Fig. 10 - left). To provide enough clearance, these elements are placed at a minimum of 30cm to the interior of the surface that defines the façade.
- SHS 100x5 purlins at 1,0m spacing connecting the vertical alignments and rotated according to the façade configuration (Fig. 10).
- Closely spaced aluminium profiles placed in vertical planes and supported by the purlins (Fig. 10 – left). Two aluminium profiles are provided per each alignment of ceramic pieces (one at the edge and one at the centre), which are fixed to the steel structure by specially designed adjustable clamps.

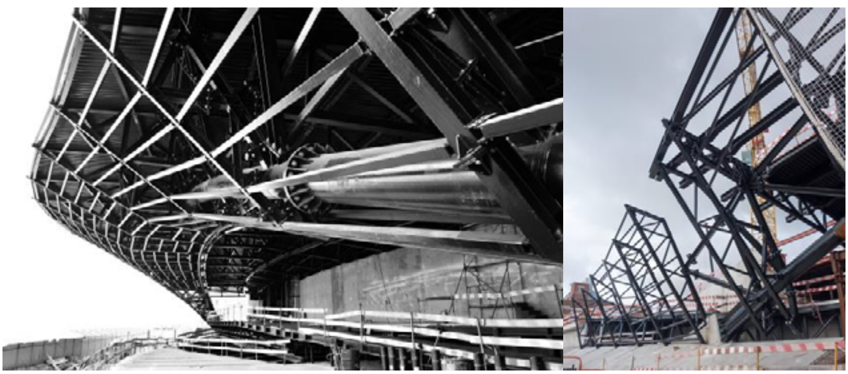

Fig. 10 South façade structure – "vertical" trusses and purlins suspended on the roof trusses (left) and supported on the concrete structure (right).

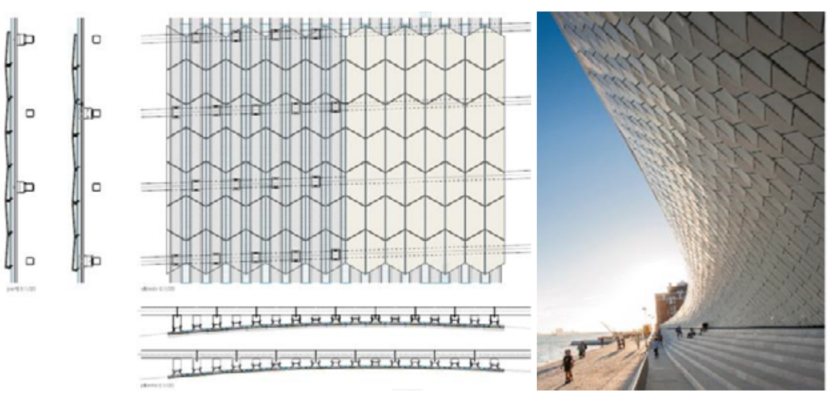

Fig. 11 South façade ceramic mosaics and adjustable aluminium profiles – details (left) and photo after construction (right)

6 Final remarks

The purpose was to build an iconic building in one of the most remarkable locations in Lisbon. The intended architectural concept was to integrate the building in the landscape, by gently extending the riverfront walkway into the building's roof, allowing the public to freely walk over, under and through the building. In parallel, the curved shape of the building posed a significant challenge as it is complex not typical for buildings in Portugal.

The strict cooperation between the architecture and structural engineering teams and a correct understanding of each discipline's needs since conceptual design phase and through the whole project was deemed fruitful. Even though the initial structural scheme considered by the architects was adequate to materialise the exterior shape intended for the building, the structural supports in the Oval Gallery and Main Gallery affected the flexibility and fluidity of the exhibition areas. To address this issue, an initial solution was proposed to include a steel truss along the main direction of the building that could replace those supports, liberating the exhibition areas from any visible structural elements. Even though this solution was able the keep the building's shape and brought significant improvements to its functionality, the proposed truss positioned at the restaurant's balcony had an important visual impact from the exterior, partially offsetting the fluidity of the curved façade. Finally, the truss was replaced by a large span arch fitted inside the façade false ceiling, thus optimizing the spans of the roof structure and most of all, being able to completely hide all structural elements inside and outside the building. This solution brought enormous advantages to the overall quality of the building, where at the end the structure is considered to effectively fulfil its main purpose of providing stability to the building without affecting the freedom of architecture to freely express its creativity.

Since it opened to public, MAAT is considered a landmark building featuring in various advertising campaigns, being awarded several architecture prizes and with the 2017 ECCS Award for Outstanding Steel Structures.

Fig. 12 Photo of the finished building.

References

[1] Liem, Y. 2011. "Graphic statics in funicular design: Calculating force equilibrium through complementary energy." Graduation thesis, TU Delft.

[2] CEN. 2008. "NP EN 10210-1: Hot finished structural hollow sections of non-alloy and fine grain steels - Part 1: Technical delivery conditions.", Brussels