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Building for the Elysée and Mudac museums, Lausanne

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Abstract

The design of the new building housing the Elysée and the Mudac museums in Lausanne started back in 2015 after the design team led by architect Manuel Aires Mateus was selected through the architecture competition in connection with the second phase of the "pôle muséal". The bold architecture concept implied strict cooperation between the architecture and structural design teams seeking to find the best solutions to implement the laureate idea, while bearing in mind the constraints encountered during the design process. Besides providing a general description of the different parts of the building, due to its higher complexity, this paper focuses on the aspects related to the design of the central volume, by presenting the different solutions that were studied at concept design phase, the criteria involved in the selection of the solution for detail design and its adaptations during construction.

1 Introduction

The building integrating the new arts district project (Plateforme 10) in Lausanne that will house the Elysée Museum and the Museum of Design and Contemporary Applied Arts (mudac) is at the final stages of construction.

Above ground, the building comprises a central and an annex volume, the latter being built around the former. Two underground levels are aligned with the central volume. In strict cooperation with the architecture team, fair-faced concrete is used throughout the project: grey concrete for the annex building and white concrete for the central building.

The most remarkable feature of the building is the central cube-shaped volume that emerges from the ground level. The MUDAC, dedicated to design where natural light is welcomed, will be housed by the upper volume of the cube at the first floor. The ELYSÉE, dedicated to photography where light shall be strictly controlled and artificial, is located at the basement. The ground floor is destined for services common to the two museums, like the library, cafeteria and ticket office. The annex building around the central volume will house the offices, workshop areas, deliveries and an auditorium. Additionally, this building extends further beyond the area around the central volume to include the complementary programme, the art info area and a restaurant.

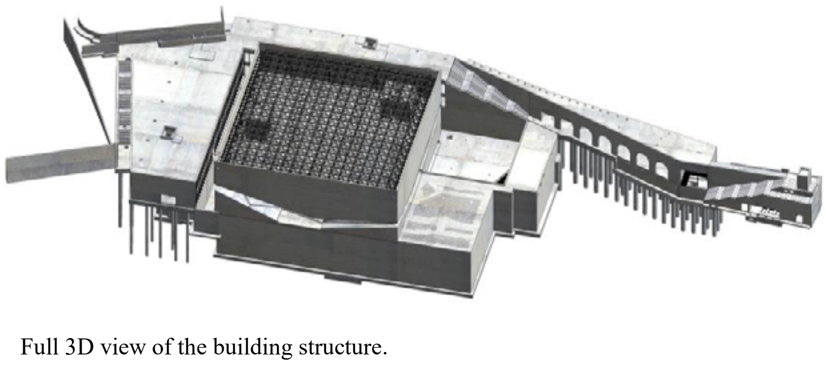

Fig. 1 Full 3D view of the building structure.

This paper describes the structural solutions adopted for the central volume of the building and how they relate to architectural considerations, while also describing alternative solutions that were equated at conceptual design phase.

2 The idea for the building

The architecture concept for the building was well defined right from the start of the project at architecture competition phase back in 2015. The supporting and service facilities should be located in a detached body, which merges with the existing topography that is prolonged into its roof and is vertically cut by its façade. This allows the main central volume, where the two museums will be housed, to stand out at the centre of the site, fully detached from the peripheral building. It resembles a cube cut in two parts that touch only at three interior points, where the ground and ceiling topographies meet, symbolizing the two museums that coexist in one single building. The separation between the two parts of the cube also aims at the extension of the public space from the railway station through the recently built MCBA Museum ("Musée Cantonal des Beaux-Arts") into a very transparent interior, where all public activities shall be concentrated. The four upper volume façades present a trapezoidal shape and are materially continuous with the lower ceiling, which is composed of several faceted panels with different slopes.

The east extension of the peripheral building for the complementary program also merges with the existing environment by replicating the existing stone arcades using a different, but also visually strong, material: concrete. In fact, material uniformity was pursued by the architects by favouring the use of apparent concrete throughout the project for all public spaces.

Fig. 2 Renders of the central volume from Aires Mateus for the architecture competition in 2015: general view of the cube (left) and interior view of the foyer (right).

3 MUDAC – Upper volume of the cube

Given the complex nature of this project and the impact the structure has on architecture and vice-versa, the strict cooperation between both disciplines started right at the competition phase, even before the project was formally initiated. Obviously, the main focus was the upper part of the cube.

The first relevant conceptual decision to be taken was the number of supports for the 43,8x43,8m cube-shaped elevated volume, which should be reduced to a minimum and placed at the interior of its square shape to achieve the intended visual separation from the lower part, while also assuring the necessary conditions for the stability and accessibility of the upper part. Three support points were proposed for the structure, positioned next to the façades, but slightly recessed in order not to expose them from the exterior, and equally spaced between each other as much as possible, so that the vertical load is similar at each one. This is also the minimum number of supports in a three-dimensional structure to avoid bending moments at the supports due to unbalanced loads. They were materialized as three rectangular shaped cores with minimum free distances between them of 23.5m 24.3m and 22.2m, which were also proven sufficient to incorporate the required staircases, elevators and ducts.

The choice of the structural solution and composition for the façades was probably the aspect that involved more reasoning from engineers and architects at conceptual design. Different solutions were discussed and tested as presented in the conceptual sketches of Fig. 3.

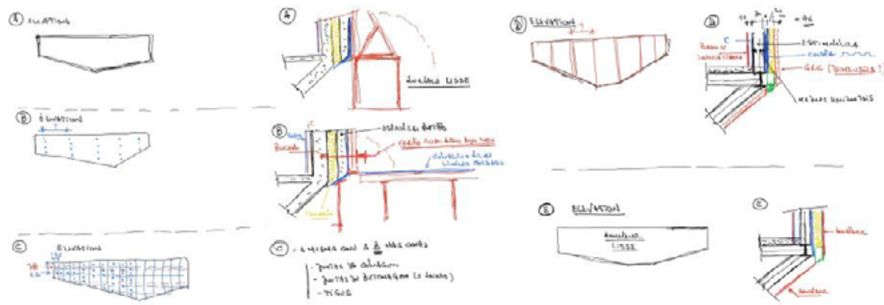

Fig. 3 Sketches of the different solutions equated at conceptual design for the façade composition.

The preferred solution for the architects has always been the use of fair faced white concrete for the central cube. Three different solutions using “in-situ” fair faced white concrete with different exterior finishing were considered: a) no visible construction/formwork joints and no plug holes due to the use of form ties for formwork stability; (b) no visible construction/formwork joints but with plug holes due to form ties used for formwork stability; (c) visible construction/formwork joints and with plug holes due to form ties used for formwork stability. Each specific requirement has a relevant impact on the construction methodologies to be used:

- The absence of construction joints leads to one single pour per façade. Given the length and height (12.7m maximum) of each wall, an adequate vibration of the concrete at the bottom of the formwork is not plausible, suggesting the use of self-compacting concrete.
- The absence of visible formwork joints with the purpose of obtaining a smooth and uniform finishing requires lining the fully assembled exterior formwork surface with a continuous coating. A solution using a linoleum coating with welded invisible joints was studied. Its application involves assembling the formwork offset from its final position to allow enough space for the lining procedure. The full assembly must be ripped to its final position through jacking, before the pouring operation.
- The absence of plug holes requires the replacement of the typical form ties that self-restrain the high wet concrete pressures by a massive formwork retention structure capable of absorbing the horizontal loads at each side of the wall.

The requirements above were presented in order of increasing complexity. While a single pour per façade is attainable with the use of self-compacting concrete and a carefully prepared concreting operation, the lining of the formwork surface with a continuous linoleum sheet requires free space around the façades for the assembly and coating of the formwork outside its final position and a jacking operation which is not common in building construction. Finally, the elimination of plug holes due to the use form ties is clearly the most demanding requirement, as a dedicated steel retaining structure needs to be specifically designed for this purpose, considering high horizontal loads and strict deformation limits to assure an adequate performance of the formwork system and the required high quality surface finish for the walls.

Two additional requirements were given special attention when considering the solutions involving fair faced concrete for the façade: obtaining a high-quality thermal envelope by avoiding thermal bridges and the strict control of cracking which is deemed important to protect the concrete against freeze-thaw cycles. To address these requirements a double wall solution was envisaged: an interior non-apparent RC wall that provides the required resistance and stiffness for the peripheral distribution of forces and an exterior apparent wall that is suspended at the top by the inner wall using sliding bearings. This allows the wall to freely deform in its plane with the purpose to minimize longitudinal tensile stresses and thus, to minimize the risk of cracking due to concrete shrinkage and temperature gradients. The thermal insulation is placed continuously between the two walls avoiding any kind of thermal bridges, while also serving as formwork for the inner face of the exterior wall.

Besides the solutions using fair faced concrete, lightweight solutions were also equated, with the façade’s structure being composed by steel trusses. Two different options for the exterior finishing were considered: (d) precast glass fibre reinforced concrete (GFRC) panels attached to the interior steel structure with thermal insulation in between; e) cement boards (AQUAPANEL) or external thermal insulation composite system (ETICS), both with painted smooth finish and with incorporated thermal insulation, attached to a secondary steel structure. While the first solution implies accepting the visual impact of the joints between the precast panels, the latter allows obtaining a fully continuous and smooth surface. The construction techniques for both solutions are much simpler than the solutions involving reinforced concrete. However, from an architectural perspective, much of the intended character for the cube is lost with these solutions: the expressiveness of the joints between GFRC panels overshadows the idea of one big cube cut in two pieces, while the very smooth surface obtained with the cement boards takes away much of the visual force and roughness that is obtained with the concrete solutions. Also structurally, the solutions with RC façade walls and suspended ceiling were proven much stiffer than the solutions with the steel structure coated externally with a non-structural finishing.

From the five initially considered solutions, two were retained for further studies, both structurally and architecturally:

- Solution "b" with fair faced concrete façades and faceted ceiling slabs having no visible construction/formwork joints, but constructed using traditional formwork systems with form ties; the structural system is based on continuous and monolithic RC elements (Fig. 4 (left)).
- Solution "e" with a continuous and smooth façade and faceted ceiling panels formed by cement boards or ETICS supported on a steel structure, mainly composed be trusses (Fig. 4 (right)).

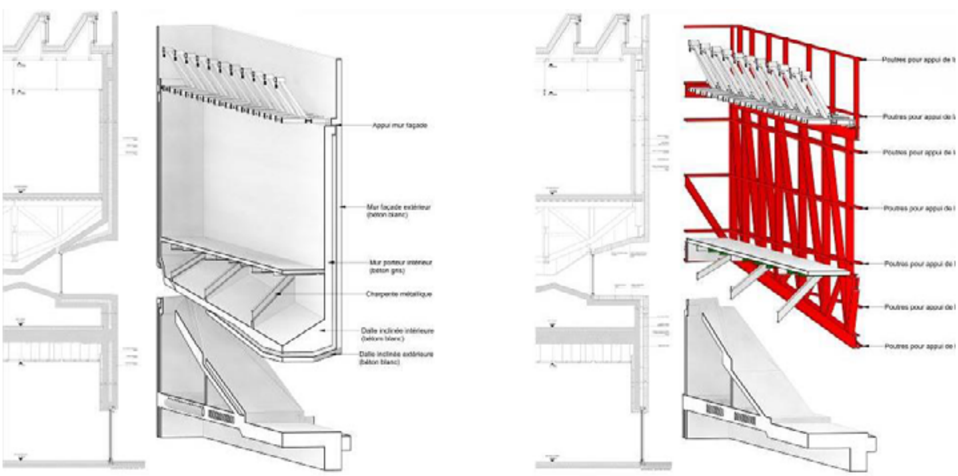

Fig. 4 Architecture section and structure 3D view with concrete solution "b" (left) and lightweight solution "e" (right).

The main advantages and disadvantages associated with the concrete and lightweight solutions are summarized in Table 1.

Table 1 Comparison between concrete and lightweight solutions.

Solution	Advantages	Disadvantages
Concrete	▪ Aesthetics ▪ Better integration with the lower volume, where some RC elements are kept ▪ Higher stiffness ▪ Better distribution of vertical and horizontal loads ▪ Fire protection	▪ Long duration shoring required ▪ Reinforcement complexity for the faceted slabs
Lightweight	▪ Simpler construction techniques ▪ No long duration shoring required	▪ Lower stiffness ▪ Higher contribution from the roof structure required for global stabilization ▪ Secondary steel structures required inside the technical false ceiling

Even though being more complex from a construction point of view, the important advantages associated with the concrete solution and its higher identification with the architectural idea for the building played a major role in the selection of this solution at the end of conceptual design phase. The main structural elements supporting the elevated part of the cube are the inner RC walls, which distribute the peripheral loads to the locations where the floor structure is more rigid, i.e. near the supports materialized by the three RC core walls, and the floor structure itself. It is composed by the lower ceiling RC faceted slabs attached to the first floor slab above by Warren type steel trusses, allowing these elements to work together as a more rigid composite structure. The steel trusses are supported at the corners of the core walls by pot bearings. The concave down shape of the faceted slabs also allows these to transfer a portion of the vertical loads to the core walls by arch effect. The RC elements in contact with the exterior (façades and ceiling slab outside the glazed façade at the foyer level) are doubled with thermal insulation in between. The exterior façade walls are suspended at the top through corbels with free sliding bearings and shear connectors that are fixed in the transverse direction throughout the full perimeter, but are blocked longitudinally only at the centre parts of the walls. Additionally the outer walls are attached to the inner walls by articulated turnbuckles that are suited to take both tension and compression loads. The purpose of this system is to allow a continuous thermal insulation envelope, to preserve concrete as the only apparent material (from outside and from the foyer) and to minimize the cracking risk of the exterior apparent concrete elements.

Besides the typical structural plans ad details required for tender, a detailed description of the intended construction sequence and techniques was also deemed fundamental. The most relevant requirement for the construction sequence is to keep the shoring of the interior peripheral walls and faceted ceiling slab until completion of the roof steel structure, because the structure is stable only from this phase on (Fig. 5 (left)). For the assembly of the façade walls formwork and it’s lining with continuous linoleum, a temporary steel structure is proposed to be assembled alongside the building and scaffolding is put in place between the temporary structure and the building, making it possible to assemble the formwork panels and to coat them with a 4mm thick linoleum film, providing a uniform surface without joints as intended by the architects (Fig. 5 (right)). This film is glued to the formwork panels and the joints are welded and smoothed so as to be imperceptible. After the reinforcement, connecting rods and thermal insulation being assembled against the interior wall, the formwork panels are ripped on rails by means of hydraulic jacking to their final position. One pouring operation per façade with self-compacting concrete is envisaged, using either a chute from the top or pumping bottom up from a valve.

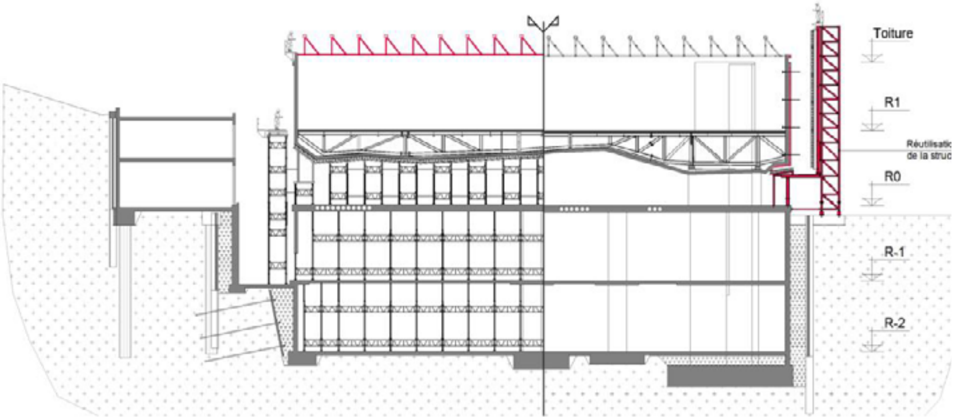

Fig. 5 Shored structure until completion of roof structure (left) and apparent façade wall construction with formwork assembly offset from final position (right).

The structure was successfully tendered, with the main competitors validating the proposed solutions and presenting preliminary drawings for the temporary steel structure with the jacking system and for the faceted slabs formwork, including the linoleum coating.

With the purpose to reduce the risk associated with the complexity of the construction techniques and to favour the construction schedule, during construction, the design team searched for simplifications of the defined methods and solutions, while always keeping in mind the requirements to maintain the initial architecture concept. The following changes to the initial solution were introduced:

- The double wall solution with insulation in-between was abandoned; only one wall at the position of the previous exterior wall was considered, which has both a structural and aesthetic function.
- All thermal bridges arising from the elimination of the double wall solution have been analysed by the building envelope specialist and corrected, as much as possible, from the inside.
- The linoleum coating was eliminated and the position of the formwork joints was carefully defined by the architects, considering 4,0x2,0m formwork panels; as a consequence, the temporary steel structure for the assembly of the formwork alongside the building is no longer required.
- A light prestress in the form of 4-strand flat ducts was added to the façade walls in order to minimize the increased risk of cracking arising from the higher restraint for deformation of the walls along its plane.
- The pot bearings for the support of the floor steel structure are eliminated to facilitate maintenance; instead, the trusses in the alignments of the supports are embedded inside the core walls.
- Removal of the shoring was anticipated by removing all the interior shores after the faceted slab, composite slab at first floor and floor steel structure were built; only the peripheral shoring was left until completion of the façades and roof steel structure.

A comparison between the initial and the as-built façade solutions is presented in Fig. 6.

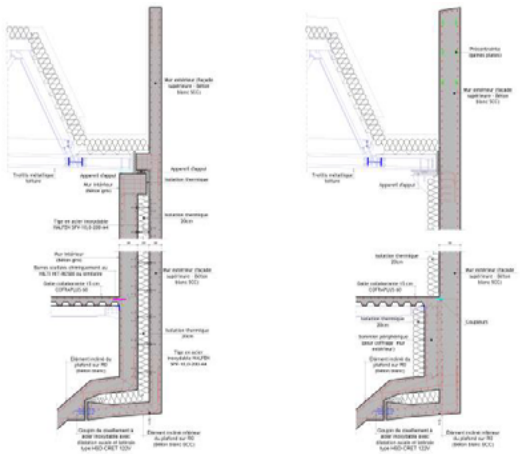

Fig. 6 Initial tendered façade solution (left) and as-built façade solution (right).

Photos of the elevated structure right after the removal of the peripheral shoring are presented in Fig. 7.

Fig. 7 Photos of construction after removing of peripheral shoring.

A surveillance campaign has been put in place to evaluate the real vertical deformations of the elevated structure and to compare them with the expected theoretical values. Even though it is known that measured deformations in reinforced concrete structure may deviate substantially from the theoretical values, this comparison was considered relevant to assess the actual behaviour of this complex structure.

Six survey points were selected: one point at each façade corner and two inner points at the suspended ceiling. Five survey instants were defined:

- Survey 0: after completion of the structure and before starting the removal of the peripheral shoring
- Survey 1: after removal of the peripheral shoring at the north-west corner
- Survey 2: after removal of the peripheral shoring at the south-west corner
- Survey 3: after complete removal of the peripheral shoring
- Survey 4: 2 months after complete removal of the peripheral shoring

The total measured deformations after the complete removal of the peripheral shoring (survey 3) and 2 months after that instant (survey 4) together with the theoretical deformations for the same loading scenarios – self-weight only and no long term effects for survey 3, and total dead loads and partial long-term effects for survey 4 – are presented in Fig. 8. Finally, the maximum theoretical serviceability deformations (quasi-permanent combination and long-term effects) are included for information.

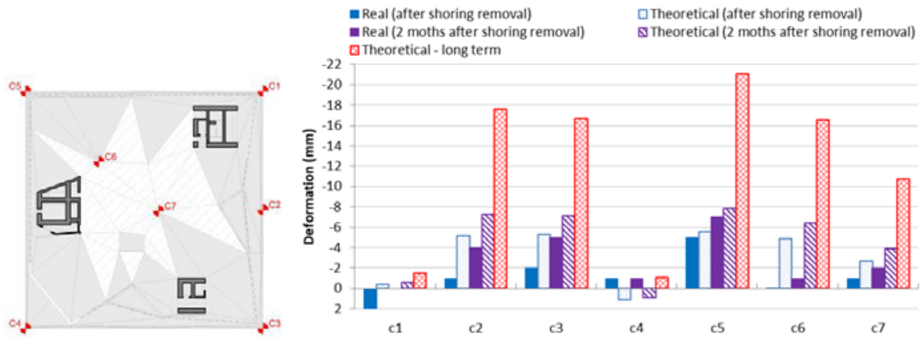

Fig. 8 Measured and theoretical vertical deformations.

It is observed that the real deformations after removing the peripheral shoring are in line with the theoretical estimated deformations for some of the survey points and are lower for others. The point with maximum deformation has a 5mm actual deformation, while the expected theoretical deformation is 5.6mm. The deformations two months after the shoring removal are still in line with the theoretical deformations, with the maximum measured deformation being 7mm and the corresponding theoretical estimate being 7.8mm.

It should be pointed out that long term deformations have been estimated using a creep factor of $\varphi(\infty,t_0)=2.0$. However, for comparison with the survey after two months of the shoring removal a lower creep factor must be considered. Besides 2 months not being enough to develop full creep, two other factors were observed during construction that are considered to have an effect on the creep factor: concrete resistance was proven higher than prescribed (C40/50 instead of C35/45) and the higher than usual age of concrete at the time of loading (around 120 days) due to the extended period the structure was shored. By applying the formulation in EN1992-1-1 [1], the creep coefficient at time of survey 4 is estimated at $\varphi(t,t_0)=0.58$.

4 Final remarks

By analysing the as-built structure, both aesthetically and structurally, it is concluded that the strict cooperation between the architectural and structural design teams throughout the different design phases and during construction allowed to effectively materialize the initial idea for the building, while still adapting the technical solutions to the encountered constraints. Visually, concrete is the only apparent material, as initially intended. It was possible to introduce the formwork joints to the façade walls without offsetting the visual impact of the big cube cut in two parts, allowing however an important simplification to the construction techniques for the execution of the façades. Besides the modifications that were introduced throughout the project and the challenge that the reduced number of supports and complex geometry posed to structural engineers, a high structural performance was always pursued. The increased risk of cracking due to abandoning the double wall solution was effectively solved with the introduction of prestress. The deformations of the structure were kept within strict limits, with the theoretical values being confirmed through on-site survey. Special consideration was also given to the reduction of maintenance operations for the structural components by replacing the support solution for the floor steel structure through pot bearings by embedment of the steel trusses in the core walls.

References

[1] CEN. 2004. *EN 1992-1-1: Eurocode 2 – Design of concrete structures – Part 1-1 General rules and rules for buildings*. Brussels.