

The structure of the Grand Théâtre de Rabat: from digital design to local fabrication

AKT II Ltd.

100 St. John Street, EC1M 4EH, London, UK

Nicolas STERLING

Associate Director

Eur Ing, CEng, MICE, Arch. DPLG

nicolas.sterling@akt-uk.com

Jeroen JANSSEN

Associate

MSc. MArch.

jeroen.janssen@akt-uk.com

Peter HIND

Director

Eur Ing, BSc(Eng), CEng, FICE, FStructE

peter.hind@akt-uk.com

Abstract

This paper describes the structural design from concept to delivery of the Grand Théâtre de Rabat in Morocco. The project includes a 1,800-seat theatre, a large open-air amphitheatre, secondary experimental performance and rehearsal spaces and a panoramic restaurant, as part of a national programme of cultural development located on the Bouregreg River between the ancient twin cities of Rabat and Salé. The complex nature of the programme and the form demanded an advanced digital design process for the structural design. The most prominent example of the 3D process is the structural envelope wrapping around the entire building. The concrete skin is stiffened by a regular grid of ribs, rationalised, but following the complexity of the shape and spanning in an efficient way that provides a continuous system together with the concrete roof deck to support the façade cladding. A highly automated and parametric workflow was set up creating the geometry of the concrete ribs and shell, closely derived from the architectural design. The concrete ribbed shell and roof envelope went through an iterative process of rationalisation, informed by constructability constraints. The fabrication and delivery of the Grand Théâtre de Rabat is a technical and cultural challenge, with a digital-driven design process in London bridging a local traditional and analogue construction process.

Keywords: Theatre design, Zaha Hadid Architects, delivery overseas, complex geometry, form rationalisation, concrete and steel structure setting out, exposed concrete, ribbed structure, complex and long-span steelwork, earthquake design, liquefaction, acoustic constraints



Figure 1: Artist's impression of the architectural design of the theatre complex and its surrounding landscape.
[Zaha Hadid Architects Ltd]

The essence of design of the Grand Théâtre de Rabat

The Grand Théâtre de Rabat is part of a national programme of cultural development initiated by King Mohammed VI, located on the Bouregreg River between the ancient twin cities of Rabat and Salé. At the heart of the Bouregreg Valley, following on from the Hassan Tower and the Mausoleum Mohammed V, the Grand Théâtre de Rabat is symbolic of the Moroccan capital's cultural revival. The building was designed by the architect Zaha Hadid. Equipped with high-quality infrastructure, this futuristic building will host a wide range of cultural and artistic events. The project includes a 1,800-seat theatre, an open air amphitheatre with capacity for 7,000 people, secondary experimental performance and rehearsal spaces and an extraordinary restaurant for 350 people.

The Grand Théâtre de Rabat obtains its energy from the Bouregreg River and integrates with the environment of the valley. The dynamic of the river is represented on site; the project generates the landscape of the park that engulfs the theatre as well as the outdoor amphitheatre. This fluidity provides an intuitive visual and physical guide for visitors. The building envelope, sculpted from the upper part of the amphitheatre, mediates between the principal functional spaces and its terrace ensures a magnificent view over the valley. The fluid sculptural form creates a seamless spatial experience that flows into the main foyer, moulding the grand staircases. In contrast, the main auditorium has a crystalline geometry inspired by traditional Moroccan muqarnas.

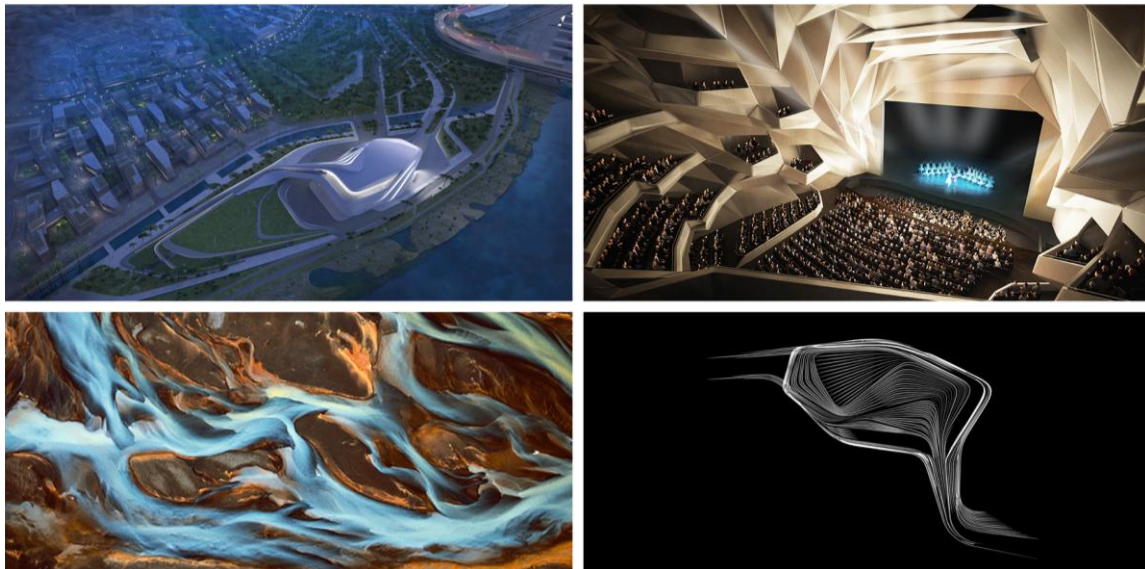


Figure 2: Artist's impressions of the architectural design of the theatre complex and its surrounding landscape.
[Zaha Hadid Architects Ltd]

The principal structural concept of the Grand Théâtre de Rabat

The structure for the Grand Théâtre de Rabat has been designed by AKT II, consulting structural and civil engineers in London. Close collaboration was required with Zaha Hadid Architects and Max Fordham, MEP service engineers who also have their offices in London.

The site is located on the South bank of the Bouregreg River in an area where the upper 12 metres of the ground strata are susceptible to liquefaction during a seismic event. The level underside of the basement structure is close to the water table. The foundations consist of deep large-diameter piles which are designed to provide lateral load resistance through bending should the ground liquefy.

In order to minimise the transmission of vibrations through the structure, the acoustic solution is based on a "box in a box" concept in which the internal space is structurally isolated from the external structure by an air gap created through the construction of independent double walls and also a thick raft at basement and lower basement level (Figure 3).

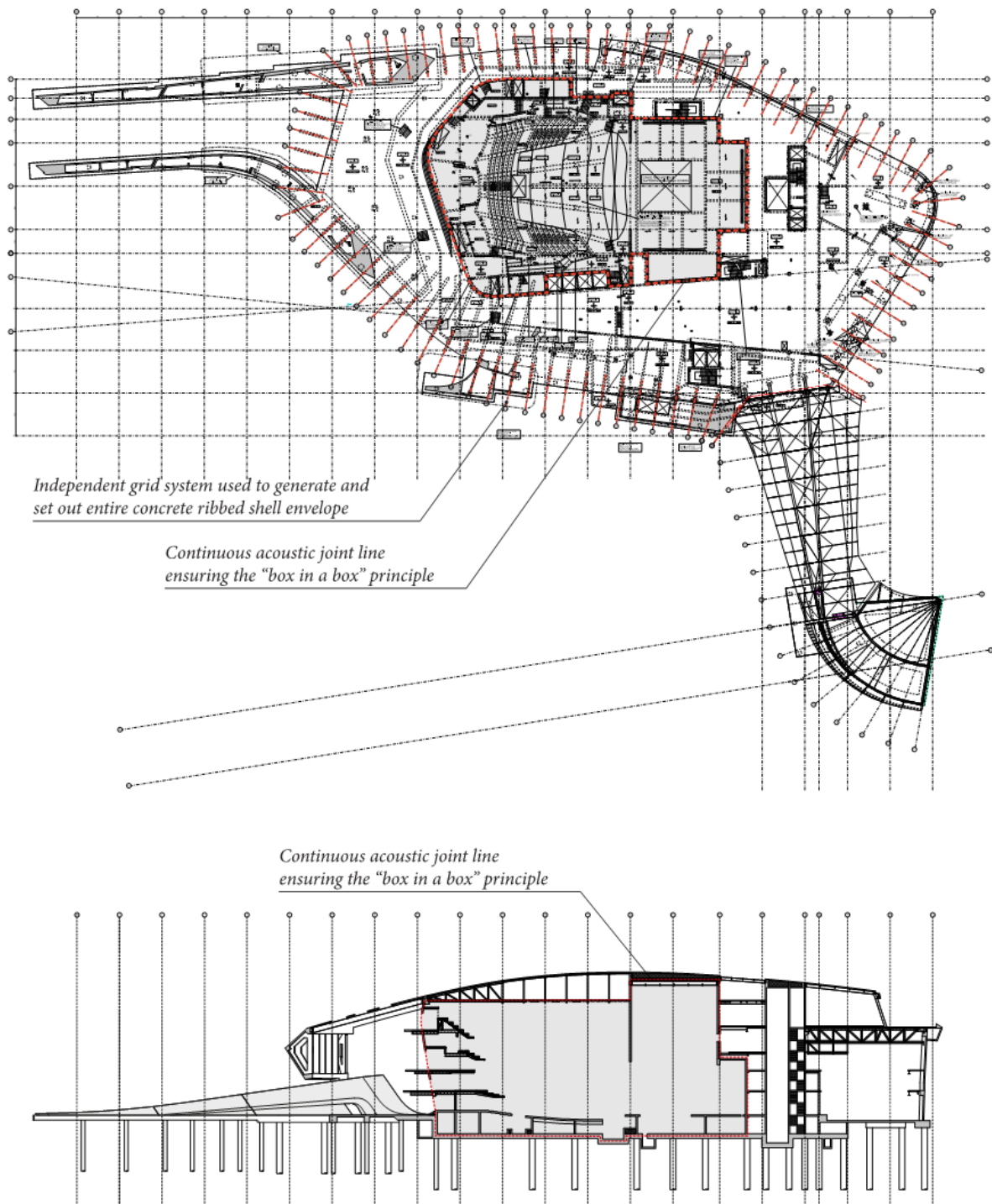


Figure 3: Plan and section highlighting the main structural elements for the building design. [AKT II]

The main foyer of the building is surrounded by balconies which sweep around the front and sides of the auditorium, providing the main circulation and connection to the restaurant at the rear. The fly tower, which lies between the auditorium and the backstage, is approximately 30m in height and houses the main theatre equipment, including the pulley system rooms for the scenery. The main cores and auditorium walls rise up in the middle of the building to support a large span steel roof over the central part of the building. The tail of the building is an architectural feature which extends the building via a walkway to the outdoor amphitheatre at the rear (Figure 4).

Other noteworthy features of the building are a number of large, free-span, staircases in the foyer area, the largest spanning in excess of 20m. The structural elements were required to fit within the proposed surfaces of the cladding. This presented significant challenges to the structural design team, particularly in keeping the dynamic response within acceptable limits. Comprehensive structural setting-out drawings in 2D were generated for these staircases directly as an extract from the central 3D coordination model via a custom developed digital workflow. Additionally, the 3D model was passed to the fabricator to facilitate the preparation of the fabrication drawings and construction.

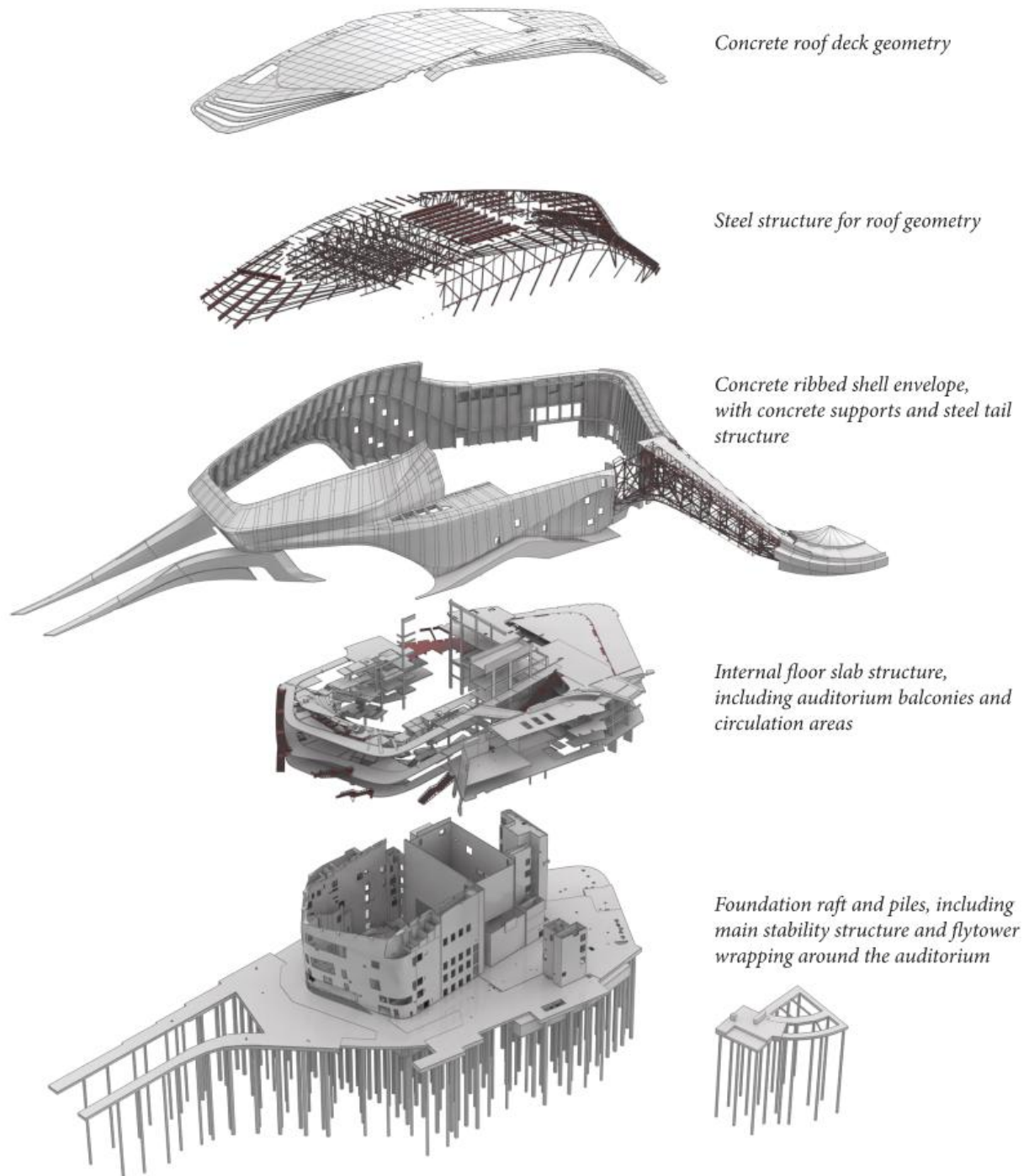


Figure 4: Exploded view highlighting the main structural elements for the building design. [AKT II]

Structural concrete skin

The structural principle of the envelope is a concrete skin stiffened by a regular grid of ribs (Figure 5). Together with longitudinal arches and beams, the ribs connect the supports and offer rigidity in the minor axis of the walls or vaults. The outer shell structure is a continuous system together with the concrete roof deck. Finally, the longitudinal ring beams close the system and deal with local eccentricities. The ribbed structure of the external shell follows the complexity of the architectural shape of the building and enables the creation of large spans with an efficient structure. A level of rationalisation has been introduced in order to find more direct load paths and to simplify the on-site fabrication within a local Moroccan context. The structural concrete shell will be clad with almost 5,000 white-coloured glass-reinforced concrete (GRC) panels held by 20,000 individual brackets.

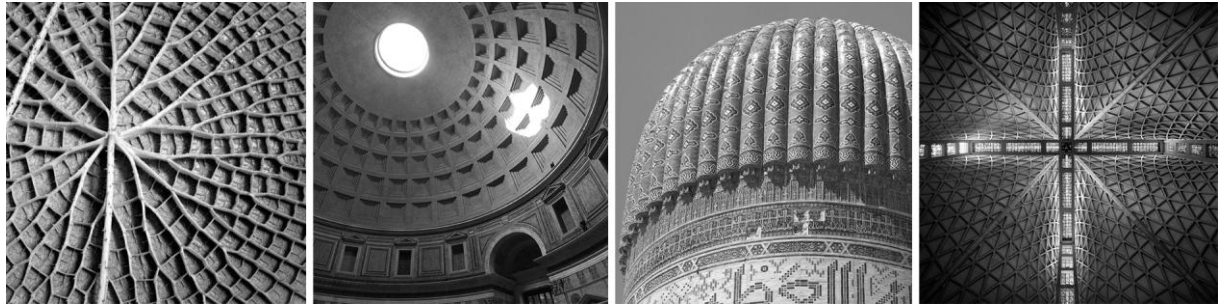


Figure 5: Inspiration from nature, historical examples, Islamic domes and modern architectural landmarks such as the work of Pier Luigi Nervi for the structural envelope of the Grand Théâtre de Rabat.

The digital generation of the structural envelope

The complex nature of the project demanded a highly digital design process. Many digital models have been produced between the multiple parties in the design team, all serving different purposes and generated in multiple software packages. The structural engineering team used finite element analysis models that have different requirements to the 3D CAD and BIM models used for drawing production and project delivery, while communication with architects and other consultants needed a third set of models. In order to accurately analyse and predict the structural behaviour of the design, it was essential to create a geometrically accurate model, directly derived from the architect's digital models. This central geometrical model became pivotal, forming an intelligent central node within the process which responded to updates from the design team, transferring information to the analysis software and automatically generating the 2D fabrication information for the complex areas of the project.

The most prominent example of this process is the structural concrete envelope wrapping around the entire building. A highly automated and parametric workflow was set up to extract the necessary information from the architect's models, creating the geometry of the concrete elements, applying the required rationalisation for fabrication, and subsequently transferring the information into an automated method for drawing production.

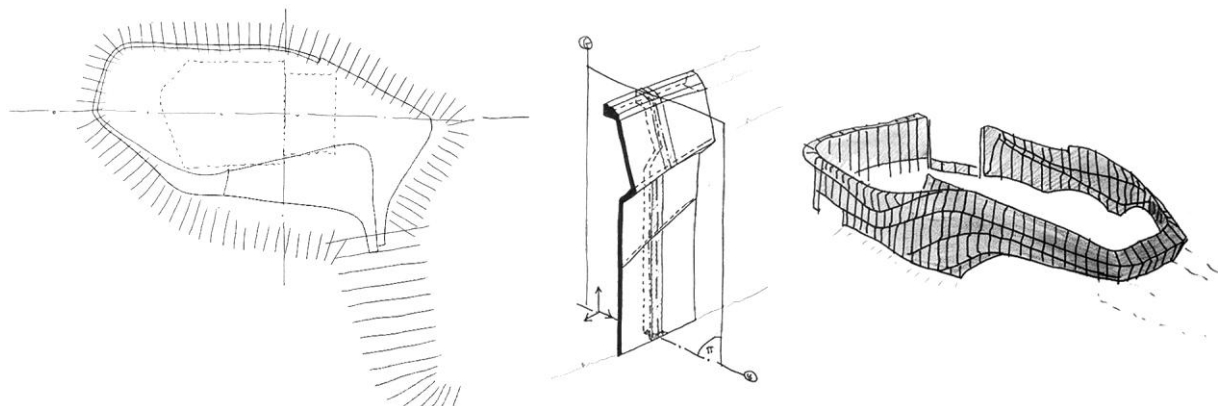


Figure 6: Concept of a radial perimeter grid and concept of vertical planes and 3D skeleton. [AKT II]

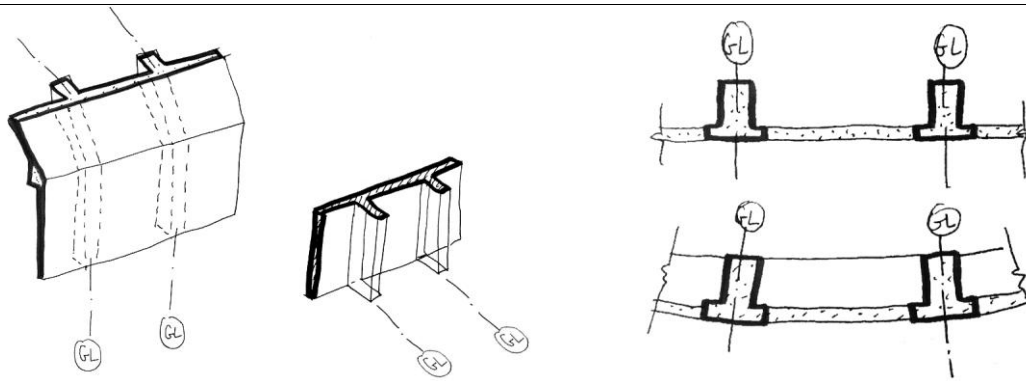


Figure 7: Principle of out of plane restraint – ribbed concrete wall and shell. [AKT II]

The structural design team made the important decision early in the process to propose an independent structural grid, closely following the external shape of the building with grid lines perpendicular to the façade. These grid lines were positioned in a few key points along the envelope to ensure critical ribs to touch the supports, with the rest of the grid lines distributed with an equal distance between them.

These grid lines were the base for a set of vertical planes on which the main structural ribs reside. Forcing the ribs to be vertical proved to be a beneficial feature for easy fabrication and allowed the rib geometry to be described by means of 2D sections and elevations (Figure 6). The vertical ribs were then connected and tied together through a set of longitudinal beams closely following the pronounced creases of the architectural form. Subsequently, the voids were filled in with concrete panels, completing the structural concrete shell (Figure 7).

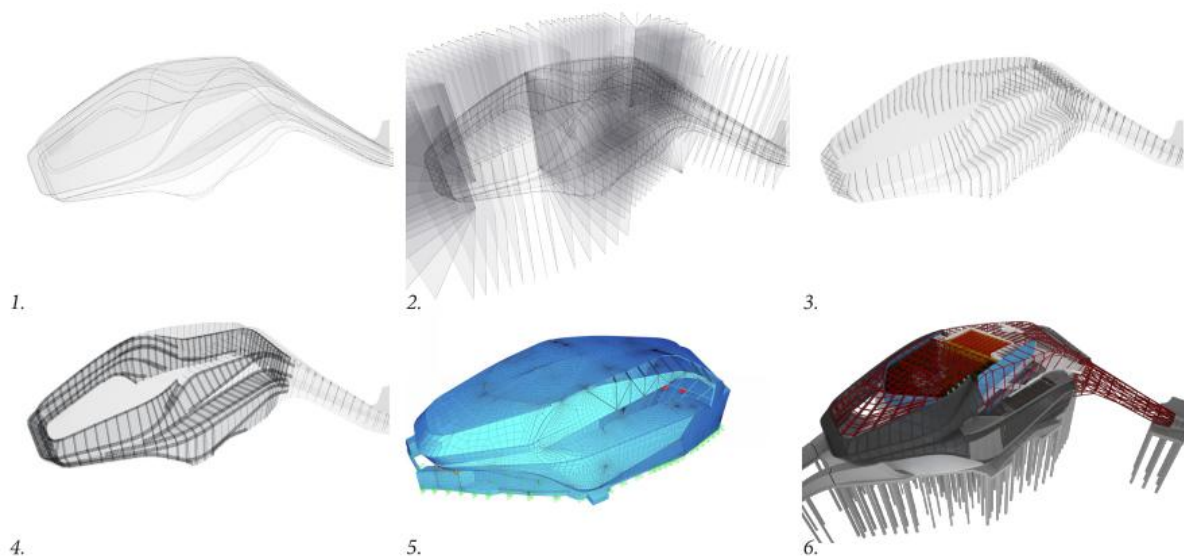


Figure 8: Parametric set up generating the central intelligent digital design model used by the structural engineer to design the building. [AKT II]

1. Geometry of the creases in the architectural model are extracted as inputs.
2. According to the façade grid lines, vertical planes are generated and intersections with the envelope geometry generated.
3. Vertical rib geometry is generated by offsetting the section lines with the correct thicknesses.
4. Together with a system of longitudinal beams and arches, the ribbed shell is formed.
5. This model is then automatically exported to the global finite element structural analysis models.
6. The model also serves as a geometric model used for setting out and coordination.

The concrete ribbed shell and concrete roof envelope went through an iterative process of rationalisation informed by constructability constraints. It was designed so that a defined tolerance was accommodated within the bracket system supporting the GRC cladding panels, while the structural concrete shell was a more rationalised system in order to simplify the production and fabrication of formwork. This rationalisation ensured planarity of concrete panels between the grid lines where possible, and, where this was not possible, for the panels to be singly curved (Figure 9).

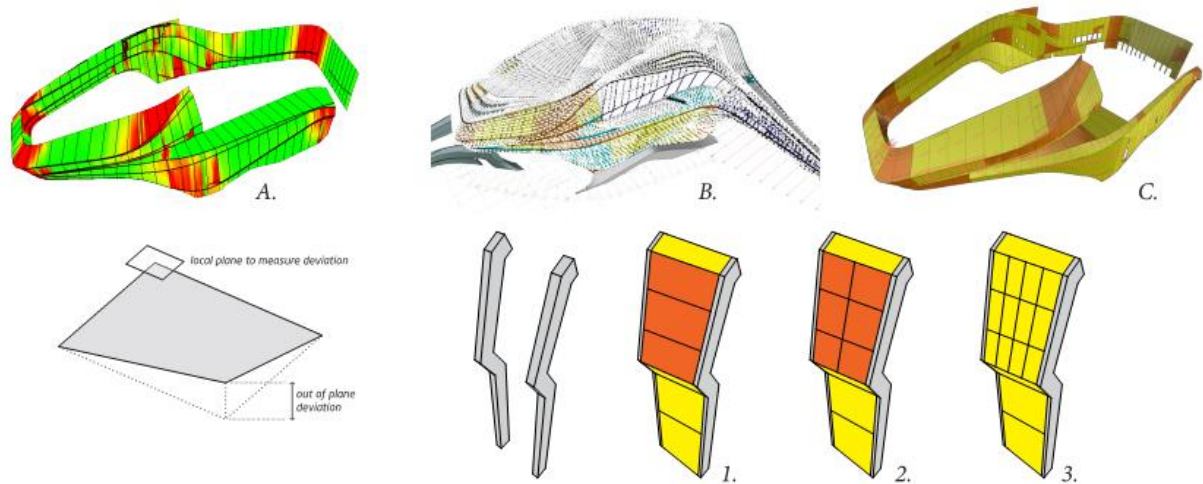


Figure 9: Parametric study for rationalisation strategy for the concrete shell. [AKT II]

Due to the doubly curved nature of a ‘true’ offset of the surface (A), and the 20,000 fixings for the cladding panels (B), the concrete had to be rationalised to enable the fabrication (C). This was done through the following steps:

1. Between each rib panels are generated and tested for planarity.
2. If the test fails, the panel is subdivided and tested again.
3. If the panel is planar it can be generated with flat formwork, otherwise the panel is highlighted orange and a bespoke solution is required.

In the final stage of the process, the concrete shell had to be set out purely by means of 2D construction drawings. This set of 2D drawings described the complexity of the entire structure and was used by the contractor on site to set out and build the formwork for the structural elements. As there was no repetition in the concrete shell elements, it was essential to set up a fully automated process to transfer the information from the 3D geometric models (Figure 10) - which were verified in size and shape by the structural analysis - into the 2D delivery software and onto the drawing sheets. This process involved the automated extraction of XYZ-coordinates for every corner of the concrete geometry and providing a tag for each of these corners. These tags were then positioned on the drawing via built-in software methods, while the coordinates were extracted in a spreadsheet format. Furthermore, embedded information regarding the planarity or curvature of the concrete panels was reported onto the drawing sheets.

While the main structural shell will be clad with GRC panels, the concrete supports and side arch were designed as architecturally exposed concrete and set out to the required architectural shape, contrasting with the structure it supports above. All curved surfaces were described as ruled surfaces, with the geometry automatically extracted from the digital models and set out by coordinates to enable the contractor to build the formwork shutters.

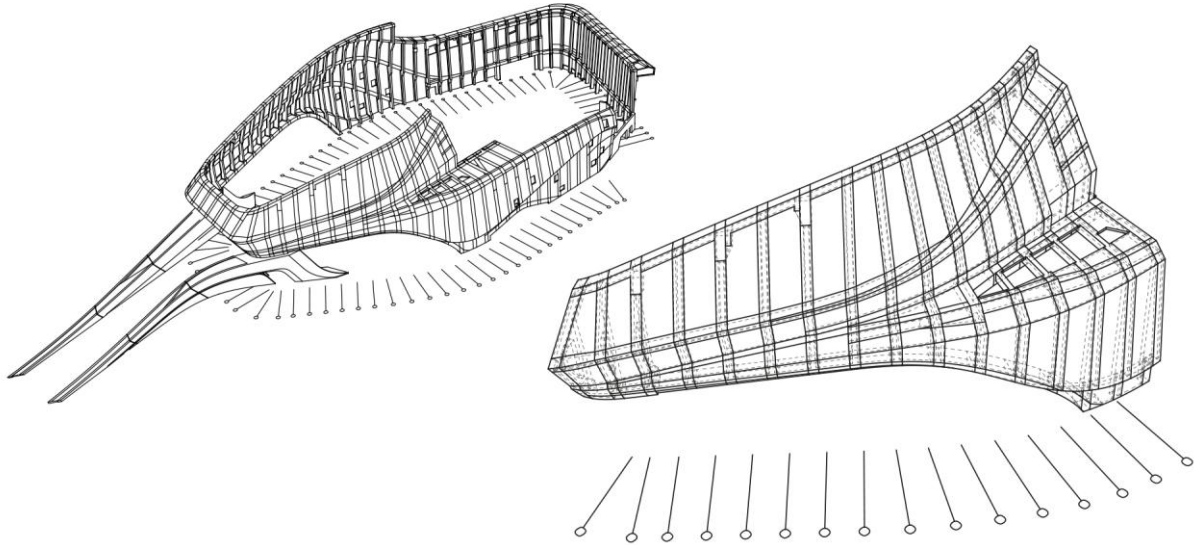


Figure 10: Isometric view of concrete shell and front buttress supports together with a close-up view. [AKT II]

The fabrication process and construction delivery of the Grand Theatre

The fabrication and delivery of the Grand Théâtre de Rabat proved to be quite a challenge, as the digital-driven design process in London needed to be bridged to a local traditional and analogue construction process. Whilst the local contractor is the largest in Morocco, they had very limited experience of constructing buildings with this level of geometrical complexity. The construction process is heavily dependent on 2D drawings from which every structural element is built on site. It is important to transfer all the information embedded in the design stage to the construction drawings, while maintaining the intelligence of the design intent, as well as describing the geometry in a precise and clear way so that the local labour force can easily construct the project from this drawing set. Every piece of formwork is a piece of bespoke timber craftsmanship constructed and read from the setting out drawings. In a similar fashion, the reinforcement bars are cut and bent directly from the information held in the 2D reinforcement schedules (Figure 11 and 12).

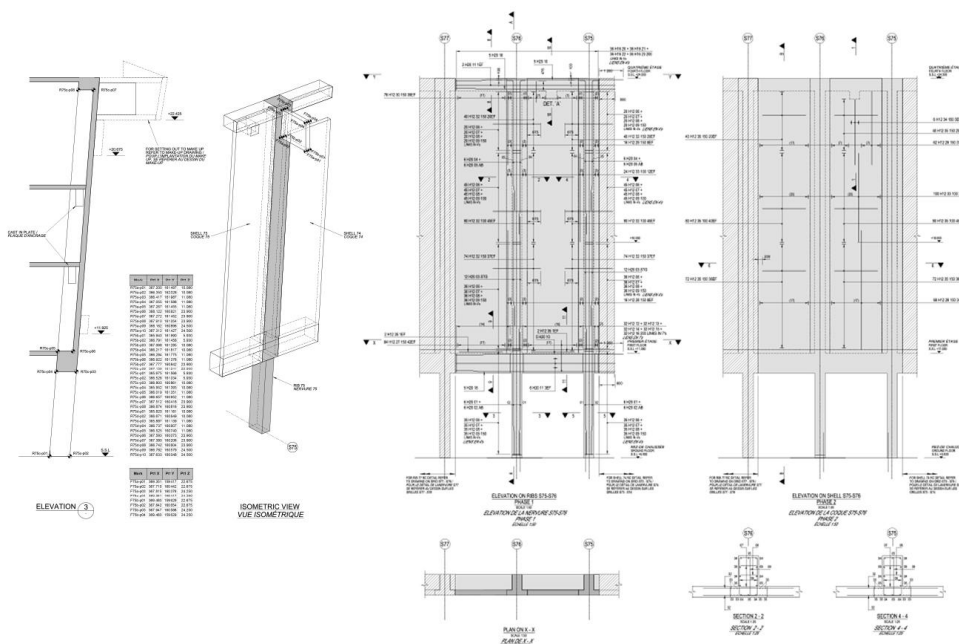


Figure 11: Typical setting out and RC-detail drawing for concrete shell, showing a tag for every corner with XYZ-coordinates reported in table format. [AKT II]

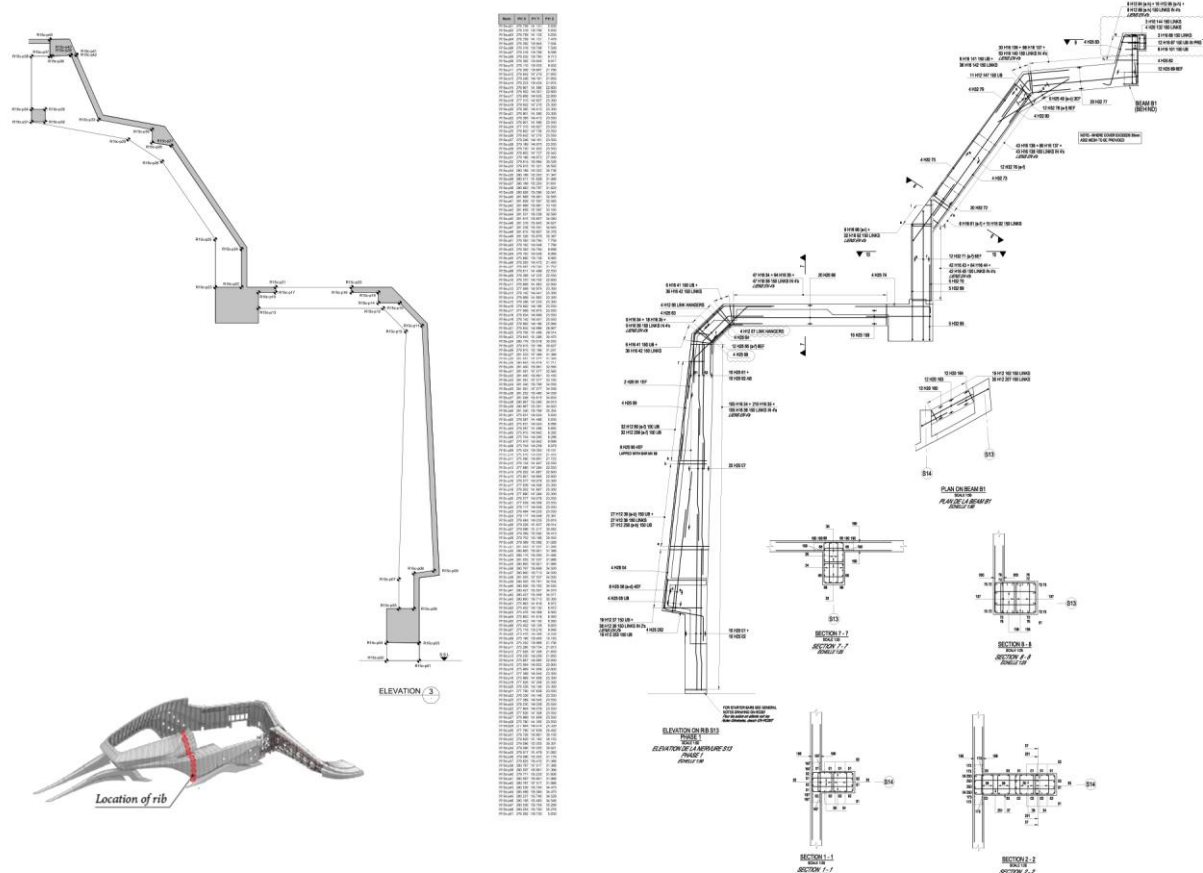


Figure 12: Typical setting out and RC-detail drawing for a concrete rib, showing a tag for every corner with XYZ-coordinates reported in table format. [AKT II]

A large part of the preparation of construction information consisted of managing the transfer of data from the 3D design models to the 2D drawing sets. Digital and automated workflows were set up to deal with this process in an efficient way, allowing the 3D design to still be developed and updated up to the latest drawing issue. This enabled a consistent system of data transfer amongst all the different building elements, despite them having a large variety of geometrical shape and complexity.

As mentioned earlier, the concrete envelope shell was automatically transferred to the drawing sheets, with every corner tagged and the XYZ-coordinates reported in a spreadsheet. In total, this resulted in 83 rib drawings, one for every rib on a grid line, together with 82 shell drawings for the panels and longitudinal beams in between. The reinforcement detail drawings followed a similar set up reporting one or two ribs at a time, with the information described in 2D details. The automatically generated drawings were then printed locally and used on site to construct all the structural elements.

References

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Figure 13: Overview of on-site progress of construction works. [AKT II]

1. External view of back of house construction.
2. Construction of shell in the back of house.
3. Internal view of ribbed shell structure.
4. Partial south elevation.
5. View of the main auditorium stage with proscenium and VIP loges under construction.