Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

The Overlook – A shell structure with multi-element interfaces

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Abstract

In the last years, shell structures have received increased attention in research. However, in practice, there are still drawbacks that hinder the further spread of these structures. The present project features a reinforced concrete shell structure that serves as a landmark feature for the project but also interfaces with a range of other building systems and conventional construction practices. Specifically, this paper presents the architectural, structural, and computational methodology employed in the ongoing construction of the Overlook, a prominent vantage point situated at the heart of King Salman Park.

The Overlook is defined into three principal components. The conventional "Back of House" area adopts conventional construction techniques, primarily using cast-in-situ reinforced concrete. The Overlook's focal point lies in an intricate double curved shell geometry. Computational design techniques are employed for the generation of the form and micro texture, using surface subdivision. The shape is informed by structural analysis. A novel construction approach using lost formwork is proposed to fabricate the complex shape with high precision yet monolithic characteristics. The final phase of construction includes the installation of a water feature, utilities, a green roof, and a pathway network.

In summary, the project showcases the use of a shell structure at the intersection of traditional construction methods and programmatic constraints with state-of-the-art technologies employed for design and fabrication.

Keywords: Concrete shells, Computational design, structural design, vaults

1. Introduction

The present paper outlines the multidisciplinary design of the Overlook, a building within King Salman Park. The park is currently under construction in the center of Riyadh, Saudi Arabia. Within the park, the task was to create a network of service structures, one of which is the Overlook.

A shell structure, characterized by the striking appearance and elegant curves fitting into the landscape context was seen as suitable for the project. This structure offered several advantages, particularly offering deep shaded areas, suitable in the Riyadh climate with strong sun exposure and high peak temperatures. Moreover, shell structures exhibit durability with low maintenance requirements as well as offer efficient load distribution and the possibility to reduce material usage.

However, historically, shell structures declined in prominence throughout the 20th century due to various reasons. Crucial drawbacks were the complexities inherent in their construction processes with simpler and rectilinear shapes being favorable (Tang [1]). A range of challenges were also posed for the Overlook project. The complex design and construction of shells necessitate advanced engineering expertise and specialized construction techniques. Integrating shell structures with other design systems can be difficult, and their curved shape limits interior flexibility, posing conflicts when accommodating specific functional requirements. Moreover, while shell structures may offer material efficiency, their initial construction cost can be higher than conventional building systems due to factors like specialized materials, complex formwork, and skilled labor.

Recent advancements in computational design and digital fabrication techniques have sparked renewed interest in these architectural forms within academic research. Despite the challenges, a unique opportunity was seen in this project to contribute to this shift. This project endeavors to explore the evolving significance of shell structures, particularly in the context of contemporary architectural practice.

2. Objectives

Central to the paper's focus is the challenge of integrating a shell structure into a real-world architectural context, necessitating the interaction with a diverse set of building and landscape elements. The project is framed within a set of constraints, which highlight the importance of working within practical limitations.

Firstly, there was the necessity of embedding the architecture within the landscape, meaning that the top of the building had to be covered by an intensive green roof. Besides visual integration, the green roof's objective was to reduce the cooling load in the Saudi Arabian climate (Jamei et al [2]) and, in combination with a central water feature, increase the thermal comfort of visitors. Further, the structure had to be integrated with various functions, such as retail spaces and wet areas. Therefore, the paper emphasizes the need for a structurally feasible system that simultaneously upholds a strong design intent focused on seamless integration with the functions and natural environment.

These requirements, alongside a stringent timeline, established the project's constraints.

3. Methods

The paper presents a design scenario, where methodologies are applied and tested within the context of a building design. The project leveraged readily available design and calculation tools and adhered to existing standards to ensure its realization within the set timeframe.

The project utilizes a combination of digital tools, including McNeels Rhinoceros 7 and Grasshopper, Autodesk Revit, and CSI SAP 2000 & ETABS. These tools played a crucial role in design exploration and calculation, enabling efficient communication and execution of ideas. The design of the project was enabled by an iterative workflow between architects and structural designers. This collaborative approach allowed for the integration of design concepts and structural considerations throughout the development process.

4. Geometry

4.1. Building parts

There are several types of shell structures designed for King Salman Park. The other two typologies, hypostyle land bridges, and arcades (figure 1), were placed in less prominent locations and will be constructed in higher amounts. Therefore, their design is based on the repetition of geometric elements. In contrast, the Overlook is positioned centrally within the park and assumes a distinct significance, manifesting as a freeform structure without featuring element repetition. A further description of land bridges and arcades is excluded from the present paper.

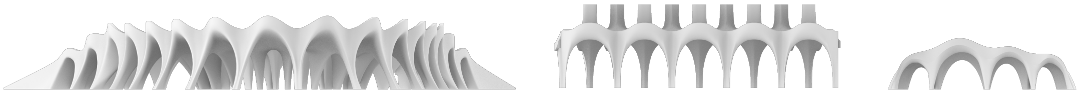

Figure 1: Elevations of all three shell structure typologies in the park, namely Overlook (left), Hypostyle land bridge (middle), and Arcades (right).

Being comprised of several main parts, the Overlook building features a shell geometry enveloping the central circular water feature. This architectural element stands out as the most prominent feature. Approximate dimensions of the structure are given in Figure 2.

Additionally, the building encompasses a back-of-house area dedicated to essential service facilities, including retail spaces, food and beverage outlets, as well as toilets and ablution spaces. To support these functions, the back-of-house includes technical rooms containing all fluid, ventilation, air-conditioning, water, and electricity supply equipment (figure 3). For the back-of-house area, conventional construction methods are used.

Both the shell structure and the back-of-house facilities are integrated and covered with the surrounding terrain, harmonizing the building with its natural environment. A layer of soil of varying depth enables the growth of large shrubs and trees.

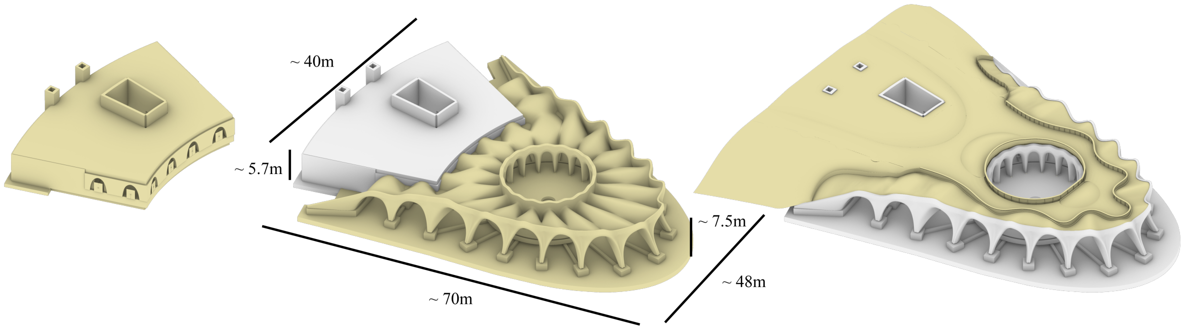

Figure 2: Back of house area (left), shell including foundations (middle), terrain (right)

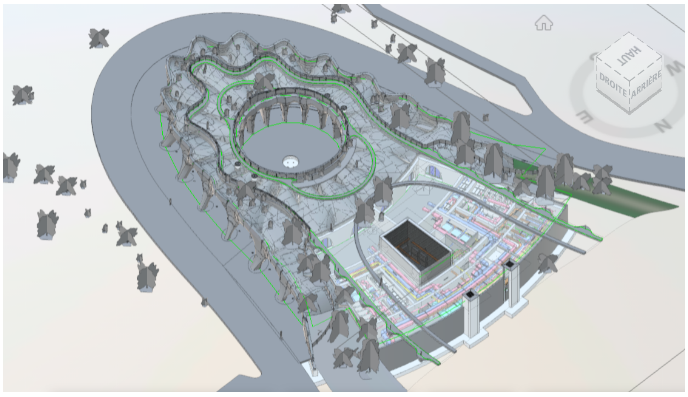

Figure 3: Revit MEP model of the back-of-house area.

4.2. Base Geometry

Positioned at the park's highest elevation, the Overlook will offer panoramic views of the surrounding landscape. At this prominent location, the structure's design derives its orientation from the terraced landscape below.

The geometry is based on a radial array of cross vaults encircling a central opening containing the water feature. There is a central axis of symmetry along which the structure can be mirrored. Each vault exhibits variations in dimension, including height, width, and length (figure 4), contributing to the dynamic appeal of the structure. The maximum height of the shell structure is 7.9m at the front column and is gradually lowered towards the back-of-house. The radial array is continued by two vaults at the ends surrounding the service spaces.

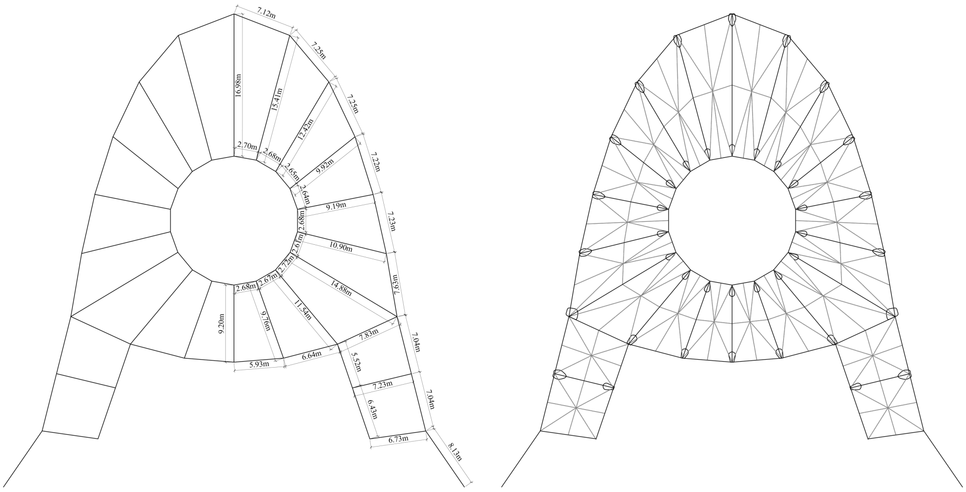

Figure 4: Main vault grids and dimensions.

To mitigate challenges associated with low headroom corner regions, the vaults are supported by columns. On the outside perimeter, these columns are inclined, following the shape of the vaulted arch.

Vertical upstands at the edge serve a dual purpose, providing deep shade while containing the soil above.

The geometry was modeled using surface subdivision (SubD) tools in McNeels Rhinoceros 7 and Grasshopper. This type of geometric modeling facilitated smooth transitions between vaults and allowed for the systematic generation and manipulation of the complex shape.

The base of the geometry (figure 5) are arc curves which were created spanning between the corners of the base grid. Based on the arcs, individual double-curved vaults with matching edges were created. The vaults were dimensioned within the height constraints given by the green roof. At the edges of the vaults, upstands were added, and the columns closed. Then, the single-layer surface was offset to create the thickness as shown in section 4.3.

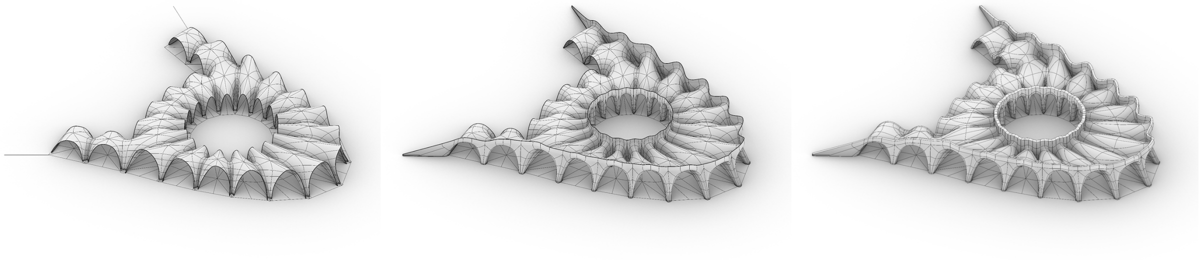

Figure 5: Single Surface base vaults (left), completed columns and upstands (middle), geometry with thickness (right).

4.3. Structural design

The structure of the Overlook has a shape that gives the structure a "self-stabilizing" behavior, elements in shells with double convex curvature (double curvature vaults). In addition, the shape of the supports, posts, or buttresses can be cast in place or molded, to offer the best possible resistance to the forces to which they are subjected.

The structure is made up of several vaults which exert thrusts on the external posts in an inclined shape. The shape of the columns accentuates the horizontal forces generated by the thrusts of the vaults at the level of the foundations. These forces are taken up by a network of sills that connect the column bases. This concept ensures monolithic operation and redundant behavior of the structure. Some areas have concave shapes on the loading side, requiring thicker shells than common areas.

Beneath the shell, a raft slab, drop-under columns, and stiffener beams reinforce structural stability, augmenting the integrity of the design. The concrete structure required a high level of reinforcement, in particular, due to three factors. Firstly, the layer of soil required for the shrubs and trees. Secondly, due to high thermal loads. Thirdly, due to the inclined concrete columns. At the junctions between vaults and columns, internal forces are high, mainly in tension.

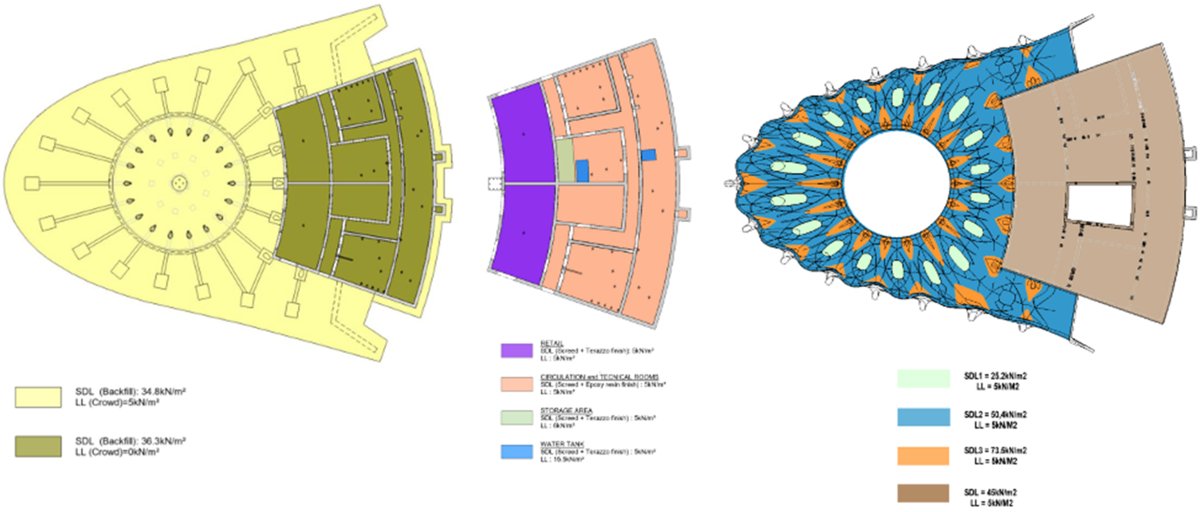

Figure 6: Loading plan for raft level (left), level 00 (middle), and level 01 (right).

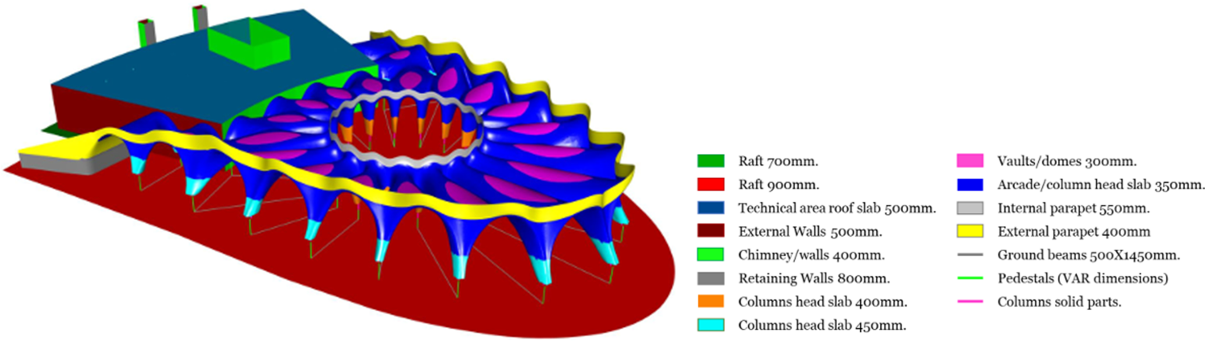

Figure 7: Finite elements model calculation (structural geometry for different elements from SAP 2000 model).

At the front section of the building with the longest spans, the design of edge columns 2,3 and 4 (figure 8) required the use of a composite steel-concrete section. The steel sections in the composite columns are mainly used to resist the expected high shear forces at the bottom level of columns.

The columns were designed in the following stages:

- For all critical straining actions, reinforced concrete and composite columns were checked in all limit states (ultimate and service) to check the stresses and crack width limits as well as the sections factor of safety.
- Conservatively, composite columns were checked again for ultimate limit state without considering the beneficially of the existing steel section to ensure the safety of concrete section and reinforcement bars alone.
- The steel section dimensions in the composite columns were checked according to article 14 – Chapter I in AISC-360-16 considering that only steel section will be used to resist the total shear forces.
- The required shear studs to transfer forces to steel sections will be calculated to ensure full connection between steel and concrete based on maximum stresses in steel section.

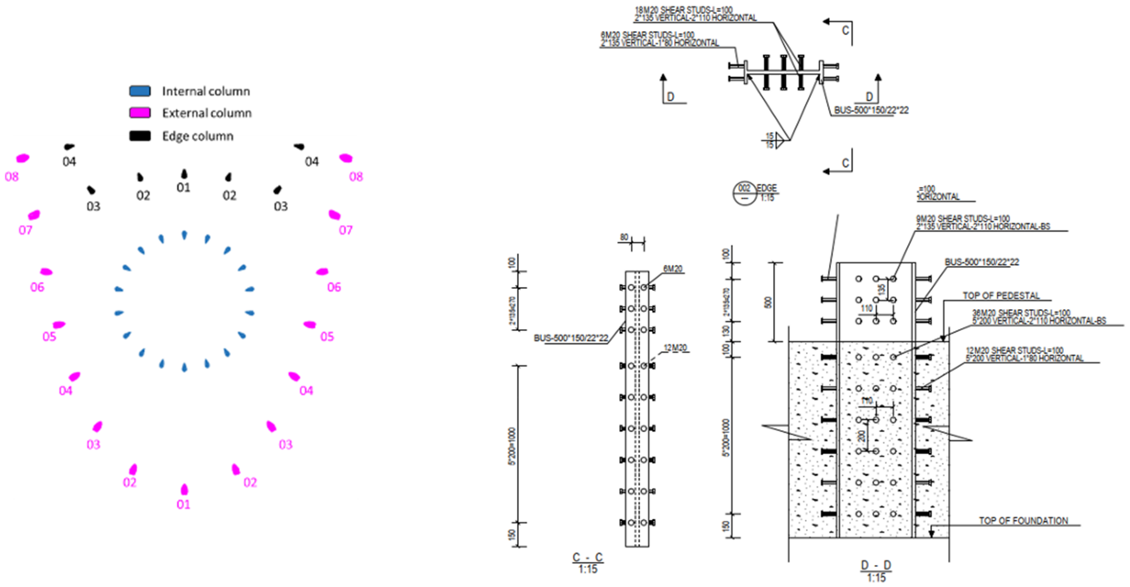

Figure 8: Column layout (left), column reinforcement intent – section of edge column 2

4.4. Iterative design

The design was developed in an iterative process between architecture and engineering (figure 9). The building was modeled in Rhinoceros 7 / Grasshopper due to the geometric possibilities. Based on the Rhinoceros model, the structural design was developed using SAP 2000 software for the verification of structural elements. If possible, the design was adjusted based on engineering input. For example, the column cross-section was enlarged during the design stage as some of them needed more material to resist shear forces. Autodesk Revit and BIM360 were used as a collaborative platform to coordinate the design, as well as produce the design documentation drawings.

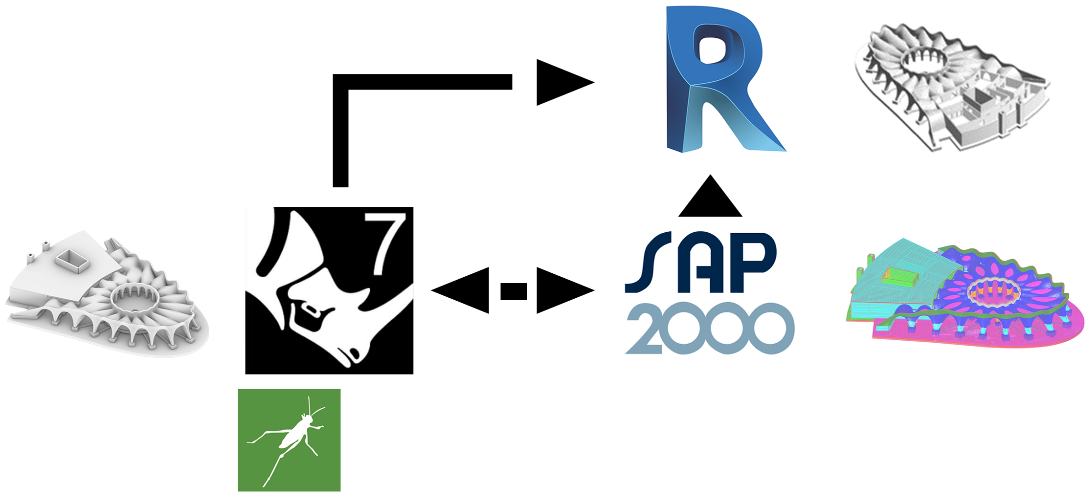

Figure 9: Design tools used by architects and engineers.

4.5. Construction methodology intent

Design stage

During the detailed design stage of the project, a study was conducted to explore innovative construction approaches, specifically focusing on the utilization of 3D printing techniques. Of particular interest was the incorporation of a fully 3d printed shell structure and how the existing calculation model for the reinforced concrete structure could be adapted to incorporate this technique.

Explorations into advanced manufacturing technologies for the formwork have been made to achieve distinctive textural effects. 3D printing (figure 10) allows for the manufacturing of intricate formwork positives, enabling the realization of complex geometry with accuracy and material efficiency.

Figure 10: 3d printed formwork negative (left), visualization of texture with pigmented concrete (right)

It was determined that designing a completely 3D-printed structure would necessitate several months of dedicated research and development to identify a suitable material capable of meeting the required strength standards, along with various tests on prototypes at different scales. Due to time constraints imposed by the client, the engineers proceeded with the design using traditional reinforced concrete methods. However, during the tender phase, it was agreed to allow the future builder the option to explore a hybrid construction approach that combined innovative 3D printing techniques with conventional reinforced concrete methods.

While the project remains a work in progress, ongoing efforts are dedicated to refining and confirming the outlined construction methodology.

Construction stage

At the time of writing of this paper, the Overlook is under construction with the completion of the foundations on its way (figure 11).

Figure 11: Construction progress at the Overlook site.

The current intent for the construction of the shell is to leverage digital tools while ensuring compatibility with established industry practices. The approach developed with the contractor envisages ultra high-performance concrete (UHPC) lost formwork (figure 12). The term describes a formwork that is used for casting concrete in situ, yet remaining in place once the curing is completed. A main advantage of the technique is that the monolithic characteristics of continuous steel-reinforced cast concrete are maintained. Further, the technique is seen as advantageous since a precise surface finish can be ensured by pre-casting the panels in controlled conditions. The UHPC is fabricated at a thickness of around 20mm, with local thickenings of 200x200mm and maximum thickness of 60mm at a 1x1m spacing. Z ties inserted at these thickenings connect between formwork and in-situ concrete steel reinforcement bars.

Figure 12: Mold used for formwork production (left), UHPC lost formwork (middle), trial mockup showing in-situ steel reinforcement awaiting placement of lost formwork and casting.

There are two additional main requirements as opposed to a removable formwork. Firstly, the formwork must satisfy high-quality standards in terms of finish, color, and precision as it will remain visible as the surface layer. Secondly, the formwork needs to be anchored with the in-situ cast concrete. Here, special attention is placed on the anchoring to account for different thermal expansion behavior of formwork and structure. Due to its ready availability, UHPC is intended to be used for the formwork, yet showing promise to be replaced by a fully 3d printed concrete formwork in a future project. This may be a way to achieve a zero-waste casting technique for complex freeform geometry, such as investigated by Gaudillière et.al [3]. However, the project's strict time frame did not allow for a lengthy research phase that was required to ensure the feasibility of the mentioned approach in the context of conventional construction processes.

4.6. Texture design

Drawing inspiration from natural phenomena such as the intricate patterns found in desert sands, the texture of the building emerges as a synthesis of both natural inspiration and the design and modeling processes.

Central to creating the texture is the further utilization of subdivision surface modeling. The process consisted of two steps. First, the global geometry as described in section 4.2. was subdivided to achieve a higher resolution control mesh. Secondly, all directionals were extracted. Every other directional was selected and offset perpendicular from the base geometry by up to 50mm toward the outside. Only at the edges, the offset was gradually decreased to zero (figure 13).

The result of this process is the creation of continuous undulating ripples that follow the contours of the structure's surface (figure 13). The texture was further used to inform the formwork joint pattern which integrates with the geometry.

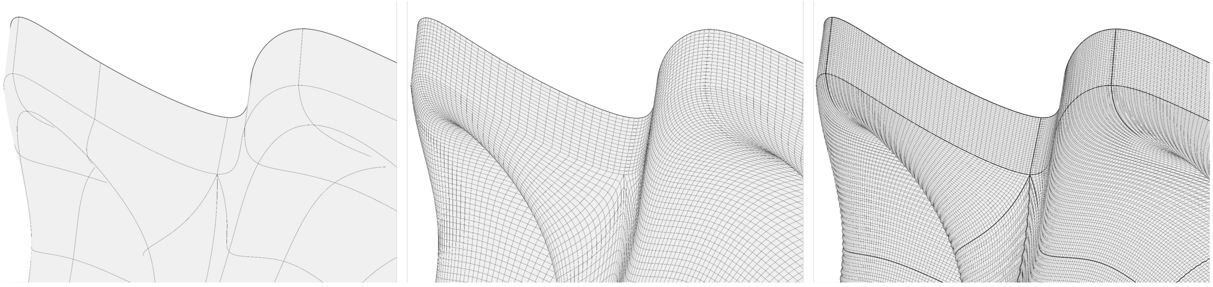

Figure 13: Base SubD (left), subdivided SubD (middle), rippled SubD with joints (right).

5. Discussion

The authors identified both areas of success and opportunities for improvement while facing difficulties in connecting conceptual ideas and structural principles in a functional building.

Central to the discussion is the overarching question of whether the structure aligns with the contextual requirements and design objectives of the project. Spatial utilization across multiple levels of the building was prioritized, therefore the flattened curvature of the building's roof allows for enhanced functionality and versatility in space utilization. The green roof buildup meant uneven loading of the shell surface. Notably, the shell structure diverges from ideal funicular designs as it works not only in compression but also in tension due to these constraints.

Consequently, the structure contains conventional steel reinforcement and does not make use of maximal material efficiency as it could exhibit as a funicular shell. Straight, vertical columns rather than inclined ones, and above all columns with uniform cross-sections, might have made it possible to reduce the amount of reinforcement and concrete required. This would however have conflicted with the intent to relate their shape to the surrounding terraced landscape.
Further, to optimize material efficiency, regular dimensioned and repetitive vaults or a form-found geometry may have been used. Form-finding tools were explored in the design process. They were used to provide the designer with an understanding of efficient shapes. While this initially held promise, the eventual exclusion of a purely form-found shape was influenced by geometric constraints and practical limitations encountered during the trial stages.

Given the described challenges, the final shape reflects a balance between the outlined constraints and structural efficiency. It can be concluded that the project shows that a shell structure had to work in complex interfaces with other landscape and building elements and does so with the drawback of reduced material efficiency. The authors see the construction methodology intent as a step towards using a fully 3d printed concrete formwork, which holds the promise to allow for zero-waste fabrication of the formwork, as opposed to UHPC. A combination of a funicular shape and 3d printed concrete such as the Striatus bridge [4] demonstrated with an in-situ cast reinforced core may allow for the material efficient creation of large shell structures.

As construction progresses, it will be confirmed if the realization of the building aligns with the envisioned design intent (figure 14). Ongoing assessment of the process will provide further insights into the efficiency and feasibility of the intended formwork fabrication and casting process.

Figure 14: Visualisations showing the anticipated outcome as seen from the exterior and interior.

Acknowledgements

The project is part of King Salman Park which is funded by the King Salman Park Foundation. The Overlook was developed in an interdisciplinary cooperation of Gerber Architekten international projects and setec tpi.

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