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Structure and Transparency - Engineering the Shanghai Expo Cultural Park Greenhouses

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Abstract

Three glazed volumes weave around an existing industrial hall interconnected by a central circulation spine. The structures for the Expo Cultural Park Greenhouse Garden are a part of a larger urban masterplan to reconfigure the site of the previous World Expo 2010 in Shanghai. Designed by Delugan Meissl Associated Architects (DMAA), engineered by Bollinger+Grohmann, with an energy concept from Transolar, this project represents an interdisciplinary collaboration among all consultants where the architectural intent, structural engineering, and climatic design truly intertwine.

This paper sets out to highlight the design process from concept through to the realization of these lightweight steel structures. From the very initial stages of conceptualization, steps were taken to consider the rationalization of the façade/structural columns for fabrication and ease of assembly. Circle packing systems, coupled with optimization procedures, were developed for the roof design in order to strike a balance between achieving maximum sunlight entering the structures while maintaining their load-bearing capacities. A synergy between workflows was vital to achieve a sense of weightlessness in the overall structure: by maximizing the slenderness and performance of the façade columns and minimizing the structural heights in the roof as much as possible to achieve maximum transparency.

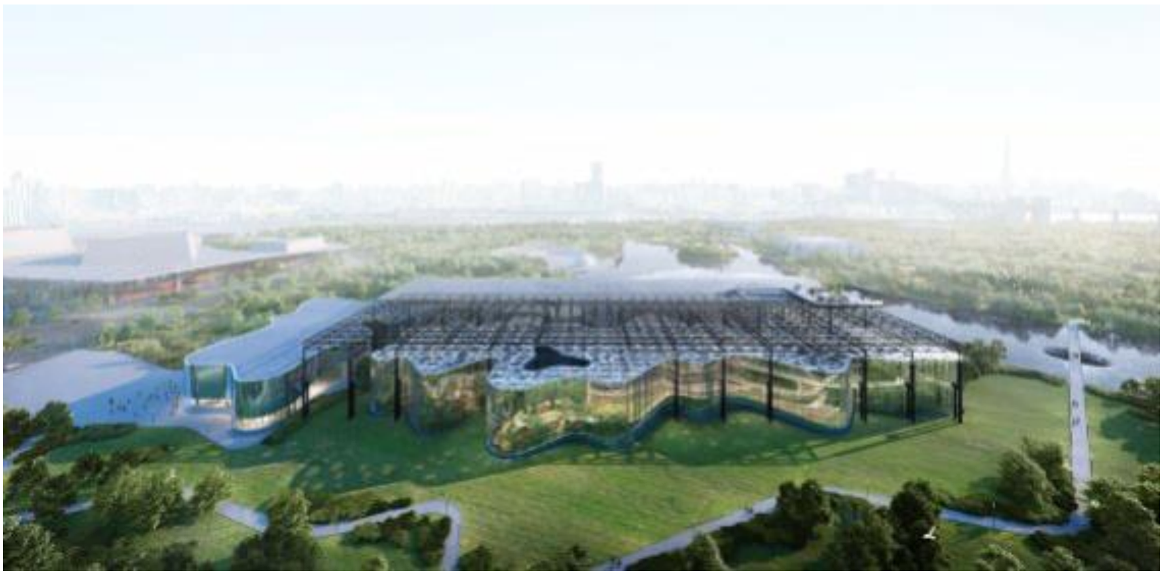

Figure 1: Rendering of the Expo Park ©DMAA & Toni Nachev

Keywords: steel structures, slender structures, organic architecture, tension rod systems, optimisation, rationalisation, sustainability, cultural buildings

1. Introduction

The Expo Cultural Park Greenhouse Garden represents a holistic integration of architectural vision with advanced engineering workflows to redefine the landscape of Shanghai's urban renewal initiatives. Sitting on the site of the previous World Expo 2010 in the heart of Shanghai, Delugan Meissl Associated Architects (DMAA) have designed a series of greenhouses as central to this urban revitalisation. Central to this development is the orchestration of three main glazed volumes woven around a pre-existing industrial hall, a challenge adeptly met by the collaborative efforts of an interdisciplinary team. The structural design, engineered by Bollinger+Grohmann, is characterized by its lightweight steel and aluminium framework, not only supporting the architectural concept but also enhances it, achieving a delicate balance between aesthetic appeal and structural integrity.

This paper aims to dissect the structural design and engineering facets of the main pavilions of the cultural park during the design development phases, offering insight into the conceptual underpinnings and the pragmatic solutions that facilitated the project's materialization. It will delve into the technical details of the structural optimization processes, particularly focusing on the facade and roof systems, and examine the strategies employed for integrating the new constructions with the existing steel structure of the industrial hall. Furthermore, the paper will contextualize the role of sustainable design principles within the structural framework, illustrating how energy efficiency and environmental considerations were woven into the fabric of the project's design and execution. Through a technical lens, the narrative will explore the project's contribution to the field of structural engineering, underlining the innovative approaches and methodologies that define the Expo Cultural Park Greenhouse Garden as a landmark in urban architectural development.

2. Project Context and Objectives

Nestled in the heart of Shanghai along the Bund, the site encompasses 47 000 m² [1] of the almost two km² [2] urban park. Having evolved from natural wetlands to farmland and then a base for heavy industry it is set to become one of the major cultural landmarks of Shanghai. Adjacent to the greenhouse is the currently under construction Opera House, Equestrian Centre, Shaungzi Mountains and several other existing structures from the World Expo as well as park landscapes. DMAA won the competition for the design of the Cultural Park in 2017, with the interplay and balance between the existing industrial hall and the new lightweight structures core to its design concept. The Cultural Park has a gross volume of 340 000 m³ [1]. Construction started in 2018 and the building is expected to finish in mid-2024.

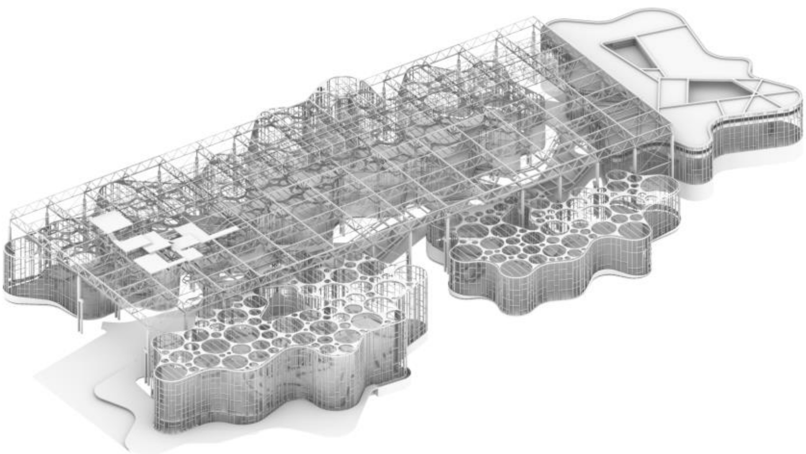

Figure 2: Overview of the Architectural Scheme ©Bollinger+Grohmann

The site is divided into four main pavilions, one housing the main entrance hall and the three remaining housing individual greenhouses with specific themes. These geometries of the new pavilions grow organically in between and around the column grid of the existing hall forming a natural and vivid silhouette that respects existing framework by never touching it. The greenhouse pavilions are designed as lightweight steel framework with circular windows in the roof to maximise the sunlight exposure essential for plant growth. An elevated pathway acts as a central spine connecting the individual structures navigating future visitors through the various greenhouse experiences. The pavilions are all connected underground with a basement that mainly houses the technical infrastructure to support the aboveground greenhouses. The team of Bollinger+Grohmann were engaged with engineering the structure and façade working in close synergy with the architects DMAA and energy consultants Transolar during the design development phases.

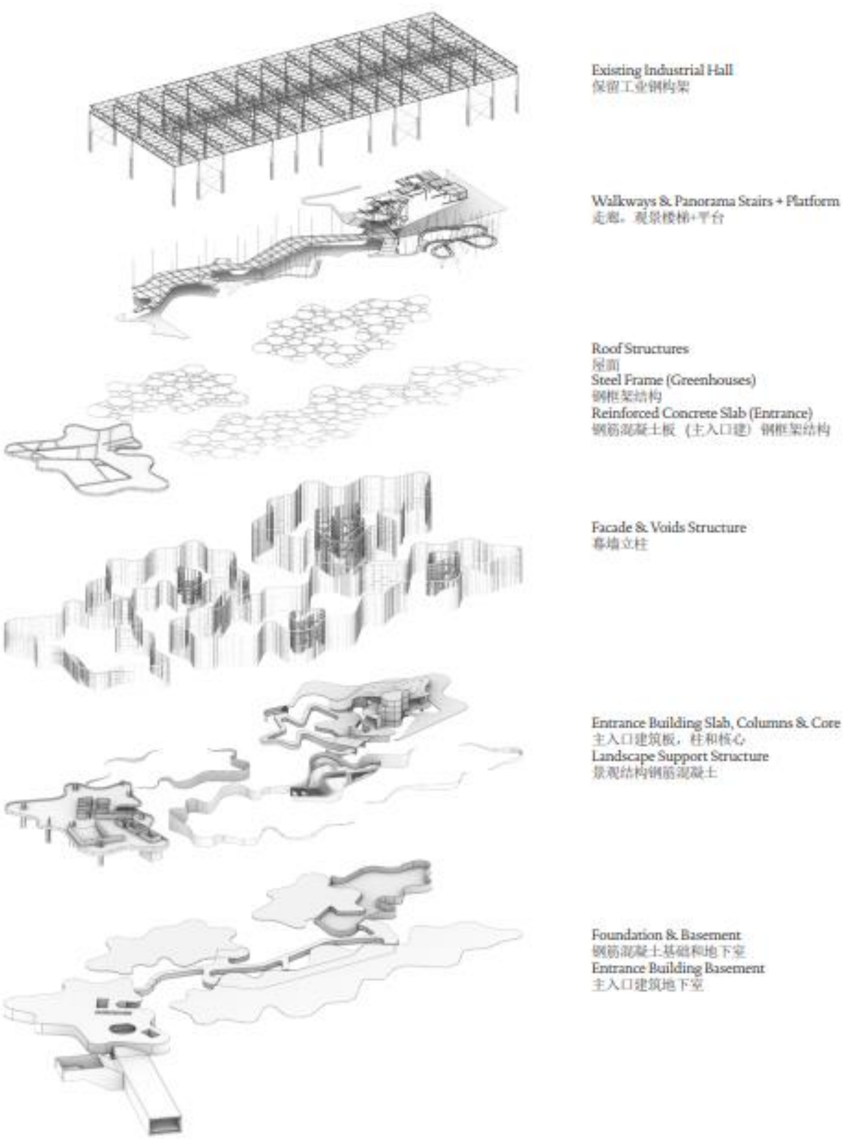

Figure 3: Axonometric Explosion of the Key Structural Components ©Bollinger+Grohmann

3. Structural Design Concept

To understand the complexity of the project and the challenges faced by the engineering team, an overview of the entire project is presented in Figure 3. The existing hall was to be relocated from its former site to the Expo Park and form the heart of the project for which the other components of the design lean itself towards. The existing steel columns, roof trusses and beams were all accessed for their structural viability. Lightweight steel and aluminium framing was implemented for the greenhouse structures where several rationalisation and optimisation processes were run to maximise efficiency, transparency, constructability as well as minimizing cost whilst respecting the design intent. The entrance building and basement structures are designed as reinforced concrete structures and other auxiliary components as steel-concrete composite construction. This paper focuses on the specific engineering of the main greenhouse pavilion structures themselves, but also touches on aspects of the additional auxiliary elements.

4. Detailed Structural Analysis and Development

4.1 Main Greenhouse Structures

There are three greenhouse structures, the smallest being the Arid Desert, then the Natural Rainforest housing flora from the tropics and lastly the Cloud Garden with a diversity in vegetation with flowers, fruit and palm trees embedded in a foggy and cloud-like environment. The greenhouses follow the same design language where organic shapes weaving around the existing industrial hall follow a simple geometric extrusion with an inclined cut at its top. The external façade structure is kept rather slender to maximise transparency and inner voids are used carefully positioned to provide lateral bracing. All three greenhouses sit on a reinforced concrete base and edge beams. These concrete structures support the steel façade framing of steel columns and transoms and a roof structural system of aluminium beams which are additionally held with either steel cables and rods or steel cables suspended from the existing industrial hall. Measures were taken to ensure maximum structural lightness in the roof maximising solar gain and thus performance of the greenhouse. The calculation results depicted in this paper are for the Tropic Rainforest Greenhouse, since it has the highest façade height of 20m and the largest free span of 30m.

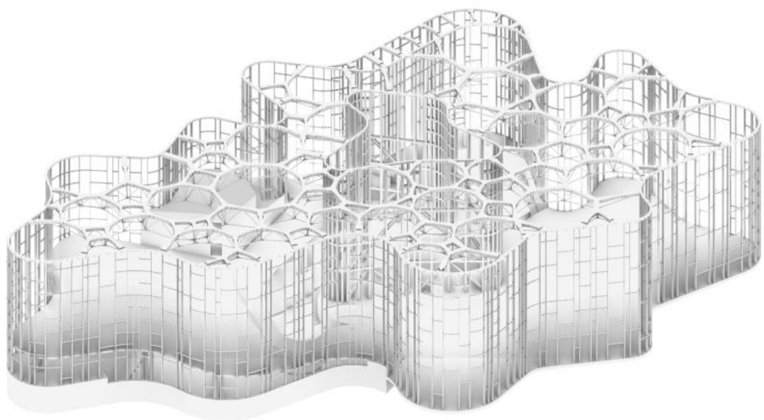

Figure 4: Overview of the Structural System Framing of the Tropic Greenhouse ©Bollinger+Grohmann

4.1.1 Facade Columns

To be able to realise the freeform greenhouse structures it was critical to develop a logic that will allow for ease of fabrication for the structure and the façade as well as maintaining the design's aesthetic integrity. Computational methods were employed to refine the architects' design curves, aligning them with all necessary design parameters. The greenhouse facades, which are affixed to both the vertical steel columns and the horizontal structural elements along the facade, exemplify a synthesis of architectural vision and environmental considerations. The undulating skin is composed of linear and curved glass panels with a constant radius and based on an 80cm grid following the perimeter of the global shape. Panels can be 80cm, 160cm and 240cm wide with a maximum height is 6m. This allows for a uniform basic division pattern for the facade columns. For the arcs only six different radii were used to optimize fabrication. The facade column dimensions are optimized according to the internal forces of the structure and the columns, together with the horizontal members of the façade structure act like a Vierendeel structure. The columns of the greenhouse facades are connected to the upper edge beam as a true pin-joint with rotational freedom out-of-plane. This detail also enables the compact design of the edge beam including the gutter.

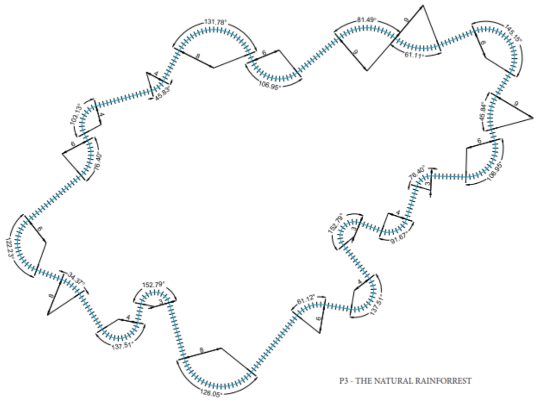

Figure 5: Rationalisation Procedure of the Façade Design Curve ©Bollinger+Grohmann

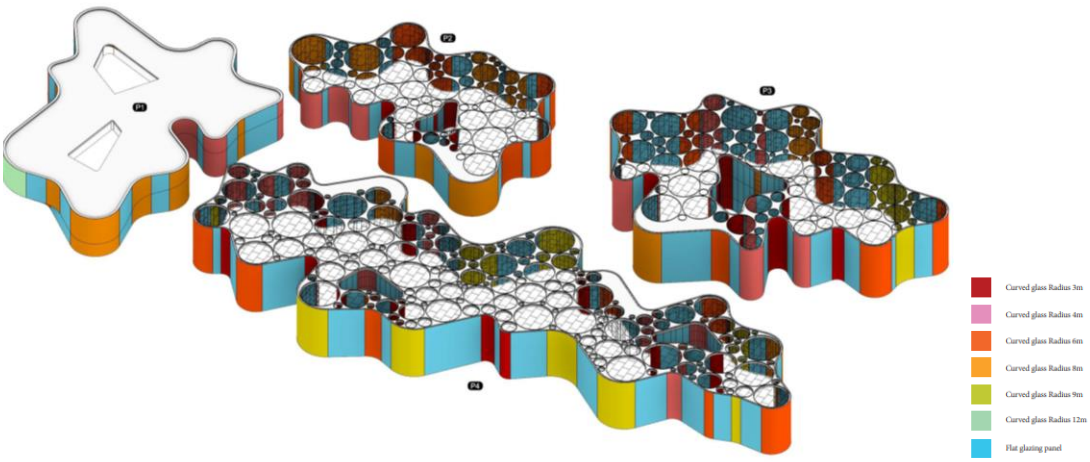

Figure 6: Optimised Façade Curvatures ©Bollinger+Grohmann

The columns of the greenhouse facades are connected to the ground depending on the requirements of horizontal deflection limits of the different greenhouses. Their ground connection also could be a true pin-joint with rotational freedom. However, if the horizontal deflections are too large the connection can be fully fixed, but therefore the buckling length needs to be set to two times the system length $L_{cr} = 2{,}0 \times L$. Columns were generally designed as pin-pin connections at the foundations and where required, with fixed connections to minimize horizontal deflections. Adjusting the position of the supports was crucial to satisfy the slenderness requirements for seismic design [4] for the critically long columns.

The system for horizontal bracing is composed of the void structure and the landscape support structure made of reinforced concrete (See Fig. 8). The structure of the outer facade of the Greenhouses is designed thinner and lighter than the void structure. The void facade structure is hidden behind mirrored glass and acts as a main horizontal bracing. The elevated landscape design of the Greenhouse is used to give additional horizontal stiffness to the façade in specific regions.

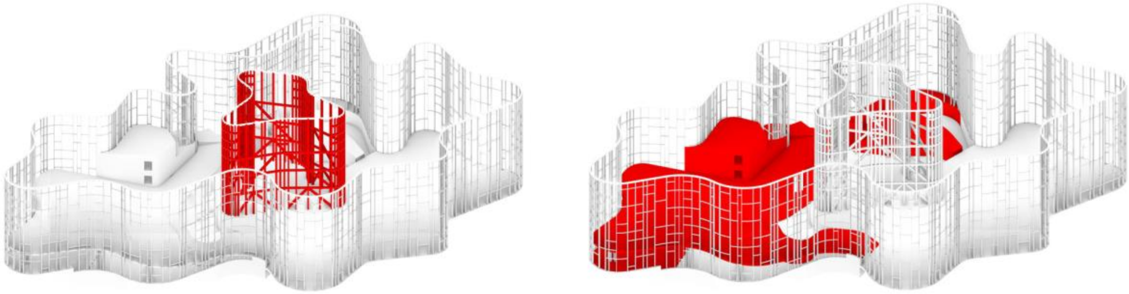

Figure 7: The void (left) and landscape (right) of the Tropic Greenhouse ©Bollinger+Grohmann

Figure 8: Initial mock-up of the structure and facade ©Yiju Ding

4.1.2 Roof Structure

Each greenhouse within the Expo Cultural Park features a roof designed as a horizontal slab, gently sloped at 3% to facilitate water drainage. These roofs are characterized by their expansive openings, framed by a network of beams reinforced by thin plates, providing additional in-plane stiffness. The sizes of the greenhouses vary significantly, with the Arid greenhouse covering a roof area of 2,800 m^2, the Tropic Greenhouse extending over 4,000 m^2, and the Cloud Greenhouse, the largest, spanning 75,600 m^2.

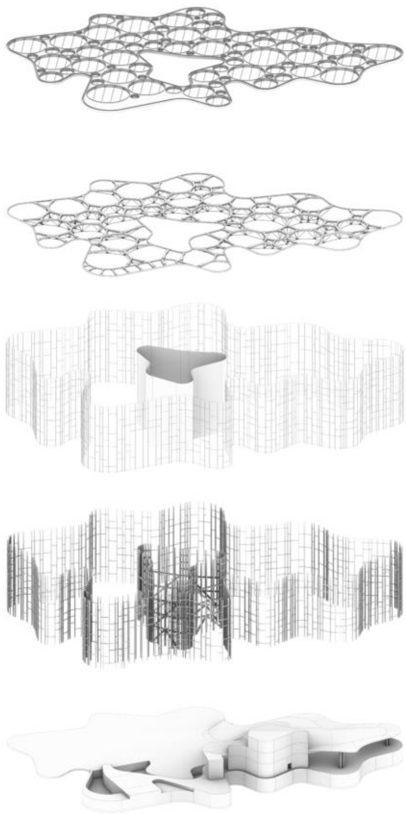

Figure 9:Exploded Axonometric of the Tropic Greenhouse showing the concrete structures; external facade and void façade columns; façade glazing; roof structure; and roof cladding and openings ©Bollinger+Grohmann

These roofs are composed by circular windows, designed to evoke the infinity sense of the sky on our universe, working seamlessly with the organic geometry not imposing any fixed directions. These windows vary in size from 3m to 12.6m in diameter, are optimized to allow for maximum roof transparency and are enclosed with fixed and openable double-glazed windows. The effective transparency of the roof is calculated larger than 70%, including the secondary beams of the circular windows with approximately 4% shading of the entire roof. Larger openings are split via parallel secondary members according to rational glass size dimensions. The secondary structure of the circular windows are single span beams with a larger structural height in the middle and do not contribute to the global primary structural behaviour.

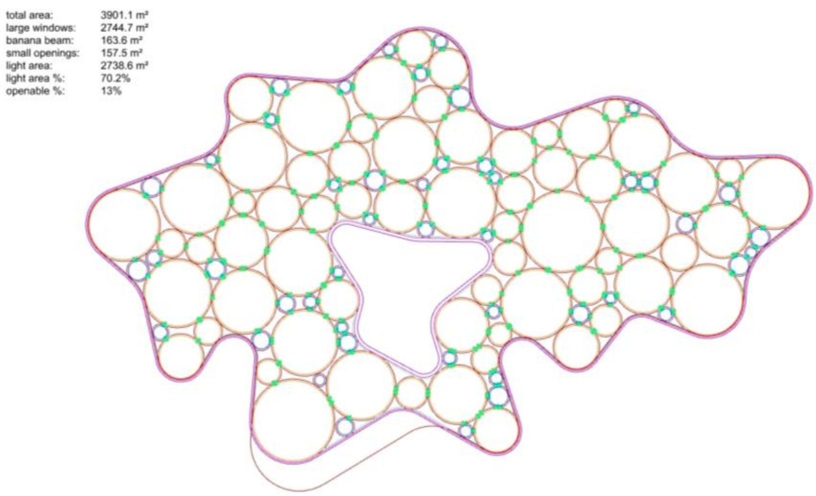

Figure 10: Circle Packing Algorithms to Position the Roof Openings ©Bollinger+Grohmann

The positions of the circular roof openings where optimised employing a circle-packing algorithm to achieve maximum transparency across the roofscape (Figure 10). A pattern of roof beams is aligned with the openings to ensure a seamless integration into the roof geometry. It was paramount to minimize the totally structural and constructive height of the roof to maximise solar penetration. Steel was originally accessed for all primary structural elements for the roof beam grid, due to its strength and slim profile. During the later design phases, an aluminium structure was finally selected due its reduction in total weight, whilst maintaining a slim design profile. The design procedure was set up to intricately optimise the radius and positioning of the circular openings, along with the cross-sectional dimensions of the roof's beam structure, ensuring that each element contributes effectively to achieving the desired levels of natural light.

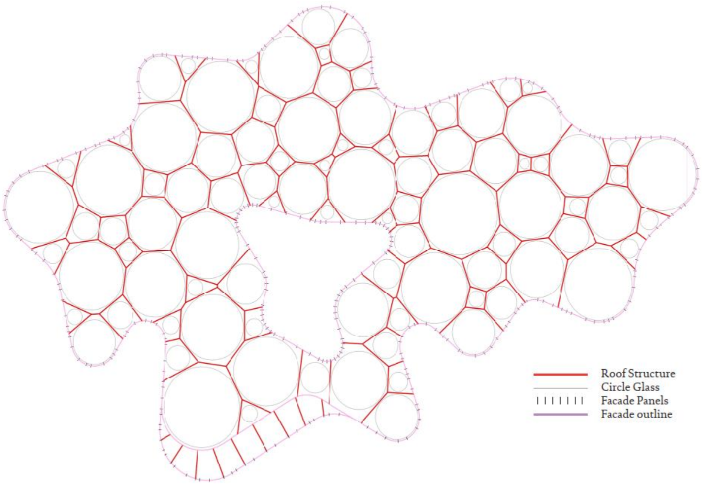

Figure 11: Pattern of the Roof Structure in Alignment with the Circular Openings ©Bollinger+Grohmann

Initially many variations for the roof pattern were investigated to study how the structural system would impact the architectural and environmental quality on the greenhouse pavilions (Figure 12). These included a simple projection of the façade grid geometry onto the roof; directly implementing the boundaries of the circular openings as structural profiles; as well as a simplification of the circular curvature into a bream grid. In the end a structural system whereby the integration of a suspended tension rod / top chord beam system was selected for the final structural proposal.

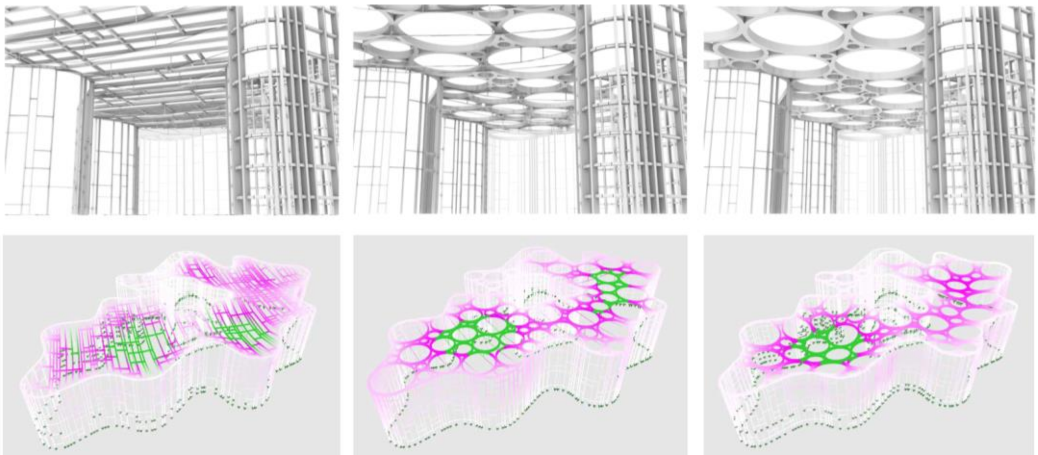

Figure 12: Studies for the Roof Structural System ©Bollinger+Grohmann

The grid of beams is supported by a series of tension rods, a design choice that enables a slender and lightweight roof construction. This suspended framework of rods is designed for simplicity and efficiency. The maximum structural height of the tension system of the Greenhouses can be significantly increased at the middle the roof span, thus reducing the structural height of the main top chord beams

(Figure 13). The tension elements are anchored to the roof slab near the facade and create structural height towards the mid of the span. This way the roof slab can be very thin. The axis geometry of the tensile beams is defined by a form-finding algorithm, using the theory of constant tension.

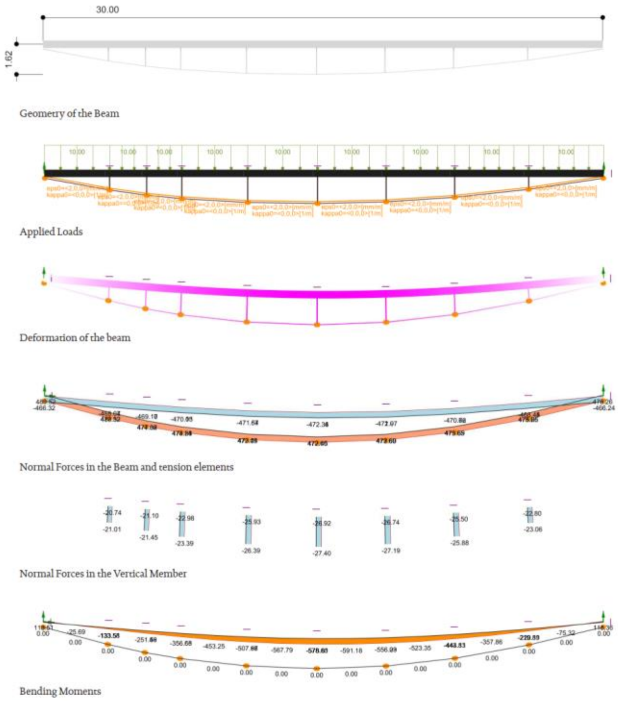

Figure 13: Simplified calculation model of a beam with suspended tension structure ©Bollinger+Grohmann

4.2 Existing Building

The existing building sits as the cornerstone of the entire project, and it was critical to ensure its presence on its newly relocated site. The columns and girders of the existing steel structure are completely re-used in the structural concept of this project. Some columns and girders of the existing hall were to be statically strengthened whenever required (Figure 14). Thin plates were welded onto the existing members after they are demounted to strengthen them. Should the strengthening of the trusses not be economically feasible (due to the additional hanging loads), they were replaced with new trusses that are optically similar. For all girders that do not carry any additional hanging loads, they would not need to be reinforced, as the load is assumed to be reduced by the incline of the roof. Through examination of the existing structure and a renewal of the corrosion protection of all existing elements was in any case required.

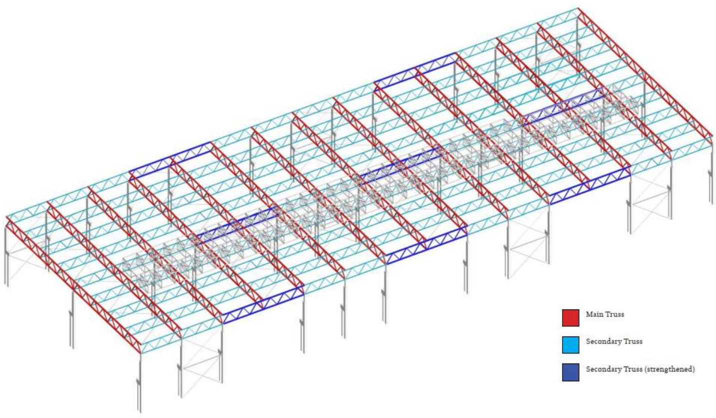

Figure 14: Existing Hall structure showing the main and secondary trusses ©Bollinger+Grohmann

4.3 Auxiliary Structures

The entrance structure comprises a three-level building, accommodating a restaurant, office spaces, and the main entrance. Within the building, clusters of circular reinforced concrete columns are carefully placed to support the upper floor slabs and the roof, allowing very expansive open areas on the ground level. Horizontal stability was ensured by the reinforced concrete cores and various walls on the first floor. Large reinforced concrete beams are integrated into the reinforced concrete slab as upstand and down stand beams to support the top floor and roof. While the entrance building's facade adopted a design approach akin to that of the greenhouses, it did not serve a structural role in the building's framework.

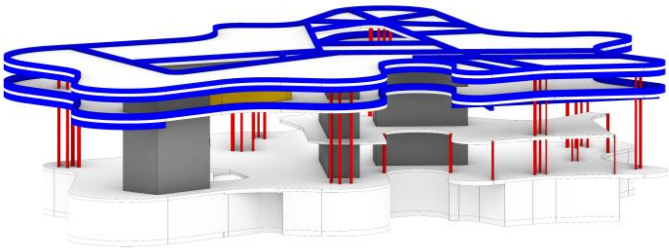

Figure 15: Overview of the Entrance Building and its Structural Components ©Bollinger+Grohmann

There are two main walkways on two levels which connect the entrance building to the three greenhouse buildings. The lower walkway is a reinforced concrete slab which is supported on the ground with columns and walls. The upper walkway is composed of a lightweight steel grid with trapezoidal sheets and a thin concrete topping. The walkway is partially suspended from the adapted industrial hall structure at higher areas and is supported by similar column clusters like the entrance building in lower areas. The walkways are supported horizontally by the greenhouse entrance structures and columns, which are fixed at the bottom. The underside of the upper walkway is covered with a thin metal sheeting. The walkway structure is designed for crowds ensuring vibrations above 5Hz to provide safety and comfort.

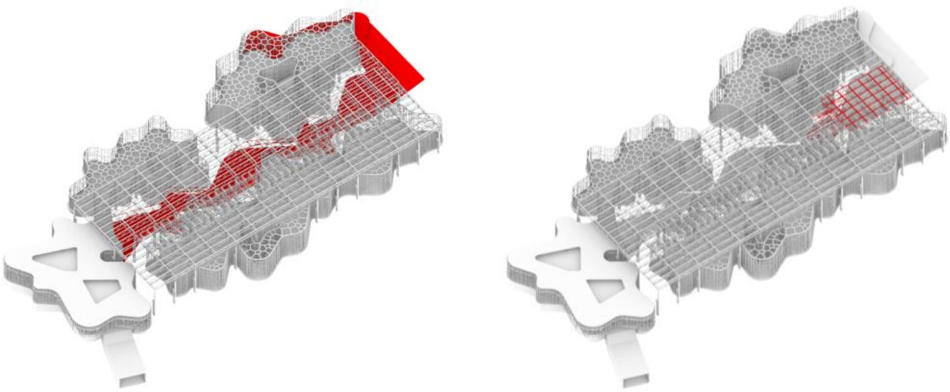

Figure 16: The walkways that connect the entrance building and three greenhouses ©Bollinger+Grohmann

4.4 Foundation

The basement passageway connects the individual greenhouses and entrance building the subterrain level (Figure 17). A central corridor contains mainly the ventilation ducts and technical equipment and is used for maintenance and support. It is not accessible for visitors. The structure of the basement is a reinforced concrete structure. The foundation of the greenhouse structure is designed as a simple reinforced concrete strip-foundation following the geometry of the façade. Columns supporting the walkway are placed on single point foundations. The foundation of the existing structure is designed as a foundation slab located at each column in combination with three to four micro piles according to necessity and ground conditions. Additionally, the foundation concept of the columns of the existing hall were carefully considered especially because of the high level of ground water which forms an artificial lake around the entire complex. The foundation and basement walls of the entrance structure further connect to an additional underground passage linking to the proposed metro extension.

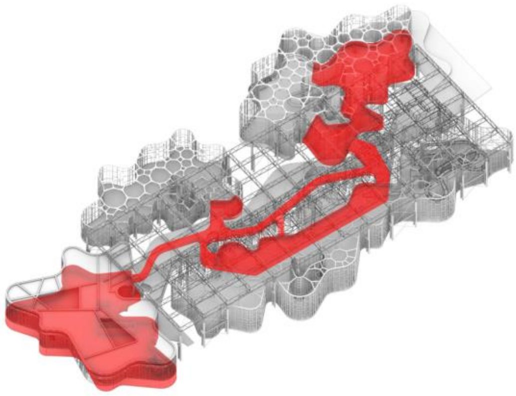

Figure 17: Overview of the Basement Connecting all Overground Structures ©Bollinger+Grohmann

4.5. Energy and Environmental Integration

The structural design of the Greenhouse structures intricately intertwines with its sustainability and energy efficiency goals, creating an ecosystem that supports both plant growth and visitor comfort with minimal environmental impact. The intention to decouple the structural systems of the new greenhouse pavilions from the existing industrial steel workshop's structure, not only aid in having distinct and clear structural load takedowns, but strategically improve the energy efficiency, whereby thermal losses can be prevented. The use of transparent facades and circular roof openings is pivotal, aiming for a 70% openness to ensure ample natural daylight and maintain a visual connection with the sky, thus reducing the reliance on artificial lighting. Deployable roller blinds and solar protection devices are integrated into the façade and roof openings to improve the overall G-value at peak summer hours.

A strategic use of water for cooling and irrigation is carefully integrated into the entire planning process. The entire roof is zoned according to the rainwater flow capacity. Two main gutter types are designed in the project. Primary gutter is situated all along the periphery of the building and is integrated in the roof edge detail. A secondary gutter is designed all along the primary roof structure following the Voronoi pattern. The secondary gutters have relatively smaller section and integrate in the opaque roof claddings.

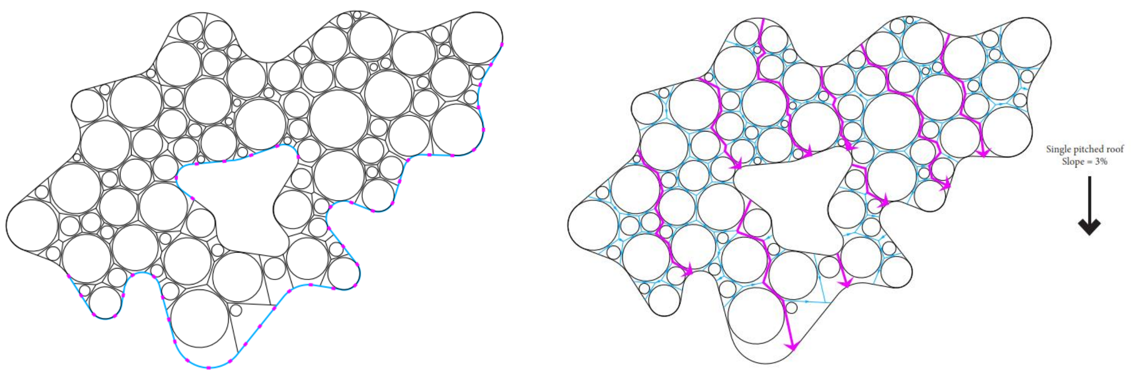

Figure 18: Rainwater Drainage ©Bollinger+Grohmann

Further enhancing the greenhouses' environmental performance are innovations such as the dry-mist system in the Tropical Rainforest and Cloud Garden greenhouses, which not only supports plant life but also improves visitor comfort through evaporative cooling. Larger natural ventilation openings embedded in the outer facade allow for 100% passive ventilation [3] which integrate seamlessly into the façade grid layout, reducing the need for mechanical cooling systems. These thoughtful design considerations reflect a holistic approach to sustainability, seamlessly integrating structural design with innovative environmental solutions to reduce energy consumption and enhance the greenhouse environment for both flora and visitors.

5. Challenges and Solutions

The project faced two primary challenges throughout its duration: the design of an exceptionally lightweight roof that adhered to all design requirements, and the simplification of the project's complexity to streamline construction, installation, and communication among project partners. The need for specific light transmission and natural ventilation ratios, as stipulated by energy consultants and facade planners, significantly influenced the roof's design flexibility. In response, through collaborative discussions with the project team, a solution was devised incorporating an integrated top chord beam with a suspended rod system. This design met the architectural, energy efficiency, and structural prerequisites while maintaining aesthetic integrity.

To further address the project's complexity, considerable efforts were made to simplify the suspended rod system. Designed for ease of installation, the system features the capability for pre-tensioning using turnbuckles, eliminating the necessity for cables, and facilitating a more efficient assembly. The decision to remove diagonal rods during the development phase was a strategic move to reduce system complexity. Various configurations of the rod system were explored to ascertain their feasibility and effectiveness. In areas where the greenhouses seamlessly merged with the existing industrial hall, the roof structures were adeptly hung using tension rods from the hall's framework, thereby obviating the need for an independent tension beam system. This thoughtful approach to design and engineering not only solved key challenges but also ensured the project's success in meeting its multifaceted goals.

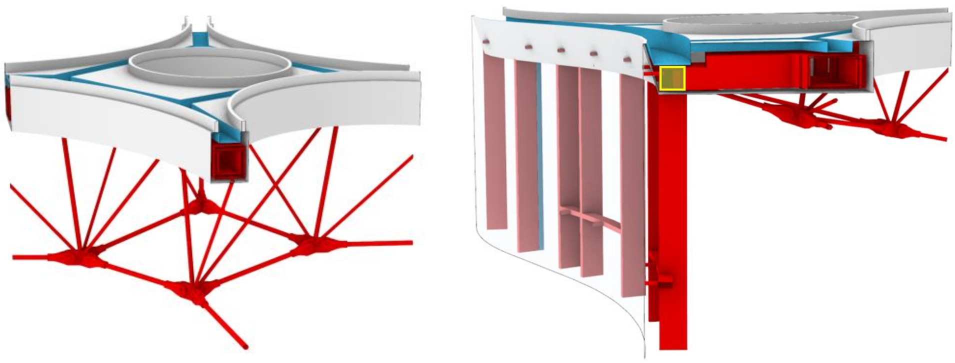

Figure 19: Suspended rod system (left); Roof & Façade Junction depicting the Rainwater Gutters (right) ©Bollinger+Grohmann

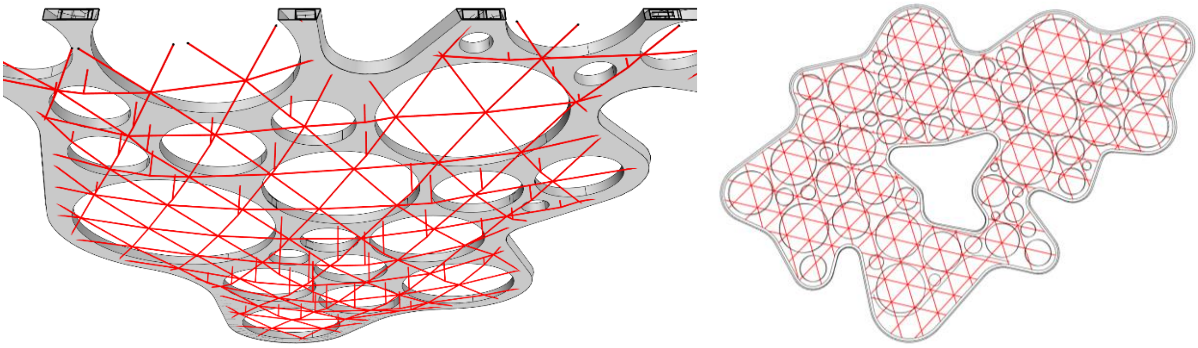

Figure 20: Tri-directional Cable System ©Bollinger+Grohmann

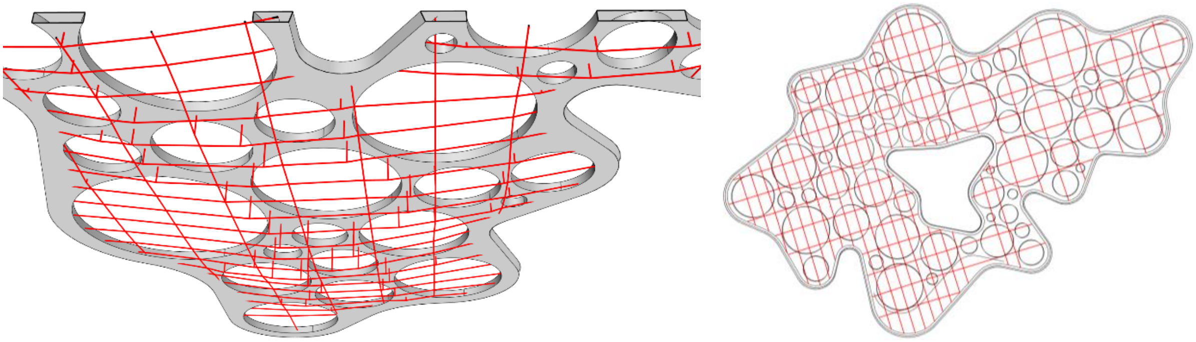

Figure 21: Bi-directional Cable System ©Bollinger+Grohmann

The architecture of a conventional roof is composed of multiple layers, each contributing to the final construction package. In this project, every component of the roof's construction was meticulously optimized to reduce any unnecessary increase in height beyond the structural beam layer. This optimization was particularly crucial given the roof's expansive free spans, and reducing the overall structural profile posed a significant challenge. To address this, detailed architectural models were developed to analyse the roof's geometry, including the composition and thickness of the architectural layers, the inclination of the roof for water runoff, and the strategic placement of drainage systems. These analyses enabled a further reduction in the height of the edge beams, areas already subject to intense stress concentrations, enhancing the roof's overall efficiency and aesthetic sleekness.

6. Conclusion

As the Expo Cultural Park Greenhouse project advances towards its projected completion in 2024, it exemplifies the integration of advanced architectural concepts with precise engineering methodologies, particularly in the realm of urban regeneration in Shanghai. Situated on the site of the previous World Expo 2010, this endeavour is poised to transform the urban fabric by fusing the industrial legacy of the existing structure with the contemporary, eco-conscious design of the new greenhouses. Detailed coordination and technical execution by the consulting teams, involving the application of lightweight steel structures and strategic daylighting and ventilation strategies, highlight a deep-rooted dedication to principles of sustainability and energy efficiency.

The fruition of this project is expected to not only augment Shanghai's green infrastructure but also establish a paradigm for urban renewal initiatives. The concerted effort among architects DMAA, structural engineers Bollinger+Grohmann, and other project partners has facilitated the resolution of intricate design and engineering quandaries, positioning the Cultural Park as a model of sustainability, functionality, and aesthetic beauty.

Figure 22: Construction Photo ©Yiju Ding

Acknowledgements

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Executive planning: SIADR Co.Ltd

Energy Design: Transsolar Energietechnik GmbH

Landscape Design: Yiju Ding

General Contractor: Tongzheng Construction Technology Group

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