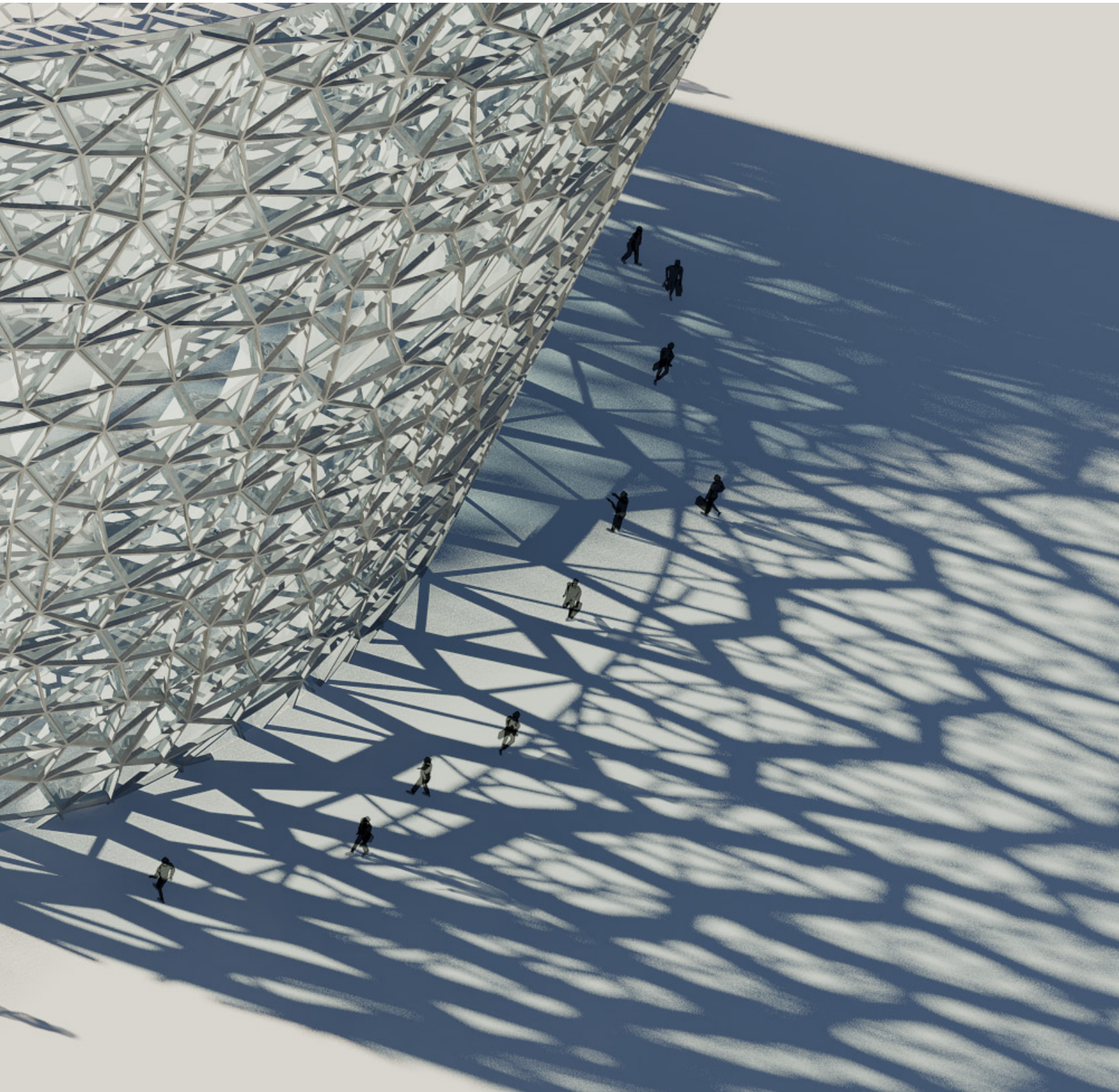


Perkins&Will

# Research Journal

2010 / VOL 02.01



## 01.

### CELL WALL:

*Resolving Geometrical Complexities in the Shanghai Nature Museum Iconic Wall*

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#### ABSTRACT

The “Cell Wall” is the iconic feature of the Shanghai Nature Museum and the main design feature from the initial competition phase. It is comprised of three layers, each with its own unique geometrical pattern and organic form, organized in an elliptical cone shape envelope of the atrium. At the core is the main layer, the structural cell layer, which emphasizes the organic cells as structural building blocks of nature. It is part of the building structure and carries the weight of the museum roof as well as supporting the 33.5 meter (109 feet) vertical span of the curtain-wall. An inner layer, which is the waterproof envelope of the building, is formed by the glass and aluminum mullion curtain-wall. The outer layer is a solar screen that emulates the cellular building block of all life forms and the traditional Chinese window screens.

The intent of this article is to document the original research done for this particular project in resolving complex organic geometries set to a full scale building. While there is a wealth of theoretical research on the subject of mesh structures, there are very few built examples where these mesh geometries fully function as structural building elements and are built to architectural scale. To that extent, a historical approach to problem-solving was of little use and an innovative, original approach was sought.

This article discusses the unique design of the “Cell Wall” system in terms of its complex geometry, design process and construction details. It explores geometric solutions for the wall, researched by trial and error, in terms of achieving the seemingly random organic patterns of the wall within the constraints of readily-available rectilinear building materials, structural realities in designing to full architectural scale and limitations of fabrication methods. It tracks its development from concept design to construction drawings through all different options and their variations to the ultimate modular solution.

**KEYWORDS:** random organic patterns, tessellated patterns, polygonal mesh structures, solar sun-screens, triangular mesh window systems, voronoi shell structures



## 1.0 INTRODUCTION

Due to advances in construction technologies and direct interface with 3D computer modeling, architectural projects have, in the past decade, achieved a complexity that was not before economically feasible. The new Shanghai Nature Museum is such an example. The project, a 44,500 square meter (479,000 square feet) new facility, was won through an international competition by Perkins and Will. As the main museum identity, a dramatic central atrium was incorporated as an organizing feature of the museum and clad in an iconic skin that resonates directly to the function of the building, an organic cell membrane symbolizing the basis of all biological life forms. It is a naturally random cell wall assembly that functions as a solar sun screen, the main building structural element and waterproof building enclosure.

The atrium enclosure, an assembly of three different distinct layers, became an exercise in geometric problem solving to address the technical requirements as well as maintaining the visual aesthetics of the winning competition design. Crucial to the project was maintaining the random organic expression of the cell based enclosure. Developing a geometric system that looked “randomly organic” while fully functioning as a building structure and envelope quickly became a main challenge for the design and technical project team.

To model the complex form and modules of the atrium, various BIM software programs were explored. The team ultimately used “Rhino” for active modeling and prototyping. 3DMax was then used for image renderings of the cell wall elements as well as graphical presentation for part of the overall building model.

It is important to realize that mesh design process and construction process balances many opposing factors: geometrical form generation, functionality, structural constraints, material selection, fabrication limitations and ultimately, economical feasibility. As architects, geometry generation alone is not the endgame, only the final built architecture is.

This article documents the process and research required to resolve a very complex geometric cell wall design while maintaining the organic nature of the iconic atrium envelope within the constraints of a real project with realistic technological requirements and fabrication constraints.

## 2.0 GENERAL MESH GEOMETRY CONCEPTS

From the onset, the approach to the geometrical solution for our nature museum was to generate a purely original design and innovative results expressing the unique nature of the project. Thus, historical research in mesh structures was not important to our process. While there has been an overwhelming amount of theoretical research done on the subject of mesh structures including numerous built examples of mesh geometries as applied to skins and decorative surfaces, actual built examples of truly structural geometric mesh systems built on an architectural scale are relatively rare.

Historically, mesh designs tend to fall into a couple of broad categories including: triangle meshes, quadrilateral meshes and Voronoi diagrams.

The current architectural trend in free form design shapes is a direct result of advances in computer-based BIM integration between designers, engineers and fabricators, which has produced a wealth of built shapes based on discrete surfaces. The most direct, structurally stable and economical means to resolve these curved planar surfaces are through the use of triangle meshes. The complexities of triangulation are, however, evident in the joint conditions where six separate arms are connecting to the same node. These triangular mesh types have been thoroughly investigated in numerous publications<sup>1</sup>. An iconic built example of this would be the Milan Expo building designed by M. Fuksas<sup>2</sup>.

An alternative way to resolve curved planar surfaces is through quadrilateral meshes, also referred to as planar quad mesh or PQ mesh for short<sup>3</sup>. Quadrilateral meshes are considered the simplest way to calculate meshes and are how computers calculate curved objects by faceting curved shapes displaying them as raster images. These quad meshes can be lighter in weight and easier to resolve in glass and steel fabrication as only four arms join at any given node. Quad meshes can also be used to resolve 3D offset surfaces, which result in conical meshes<sup>4</sup>.

A more organic looking mesh type is the Voronoi diagram<sup>5</sup>. This type of cell structure is common throughout nature and ties extensively into biomimicry concepts. The major disadvantage in architectural applications is the infinite resulting cell forms and connecting node conditions. Voronoi diagrams can easily translate into 3D mesh structures very much like a cluster of soap bubbles. The most iconic built example of the Voronoi diagram as used in architecture is the Beijing Olympic

Swimming Center, also referred to as the Water Cube, designed by PTW Architects.

Mitigating organic patterns with a more structured mathematical layout can also be achieved through regular pattern tessellation. These types of 2D decorative patterns can be found in Islamic wall tiles, in pavement pattern stamping formwork and the iconic decorative patterns developed by the artist M.C. Escher. While often simple and intuitive plays on geometry, they follow mathematical formulas<sup>5</sup>.

The atrium cell wall design for the Shanghai Nature Museum incorporates variations of the above methods to resolve the structural support as well as the curtain wall enclosure and solar-screen.

### 3.0 THE ATRIUM

The Shanghai Nature Museum uses a central atrium concept to vertically and horizontally organize the various museum spaces around it and form the nucleus and central identity of the museum. The 5-story atrium, traversing the full height of the museum, is enclosed by a curved exterior envelope system that is 33.5 meters (109 feet) high with a 164.45 meter (540 feet) linear perimeter and a surface area of 2,944 square meters (31,690 square feet). The conical-oval form of the envelope results in an angled tilt-back of the atrium envelope varying from a 9.84-degree incline to a zero-degree straight perpendicular layout at the outer edges.

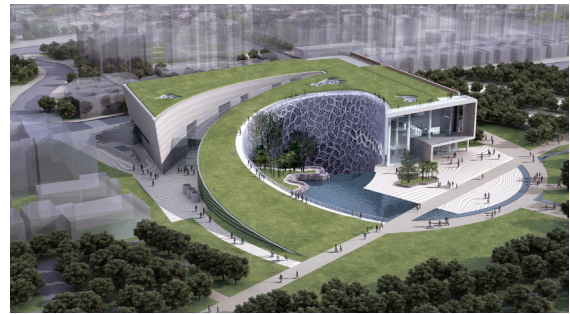
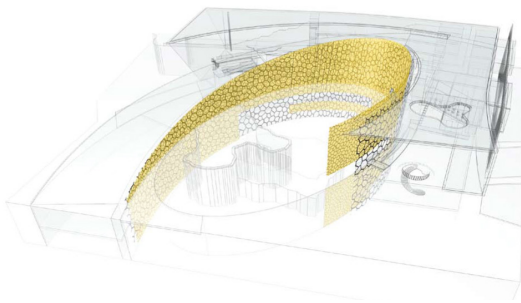


Figure 1: Shanghai Nature Museum massing.

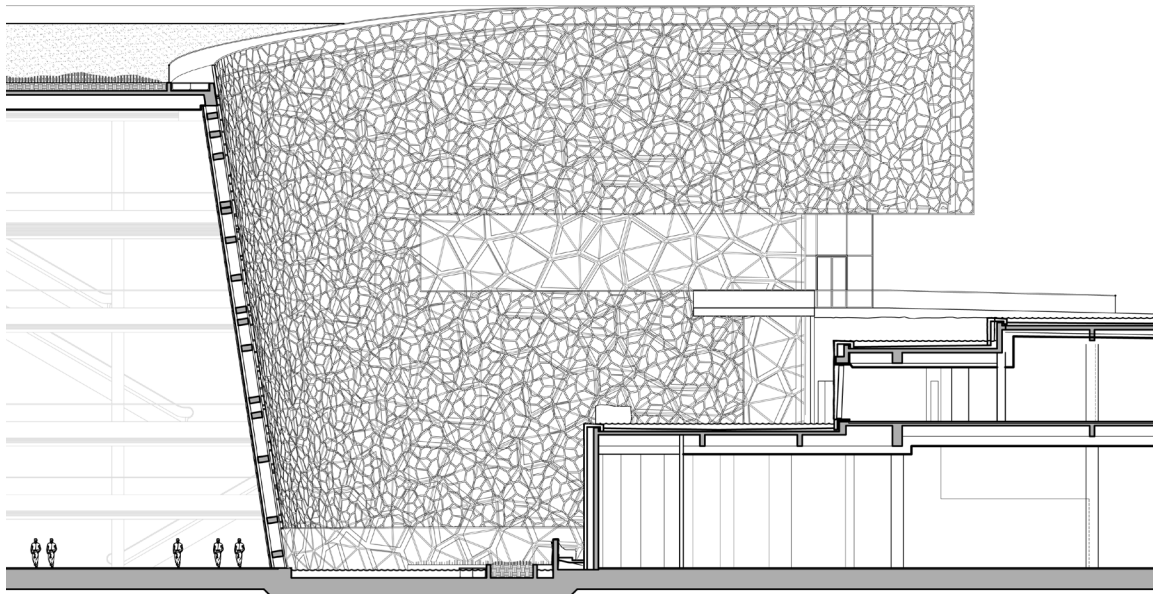


Figure 2: The atrium enclosure, section-elevation.

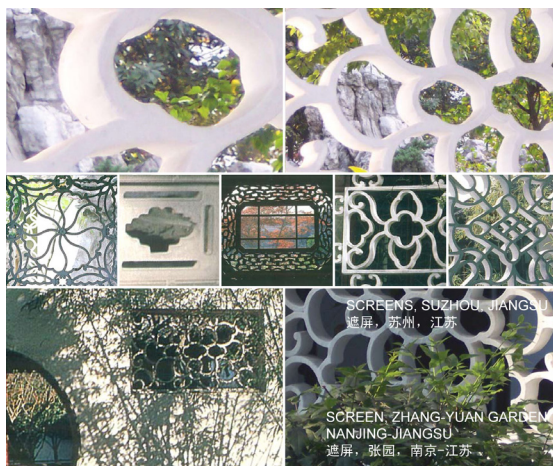
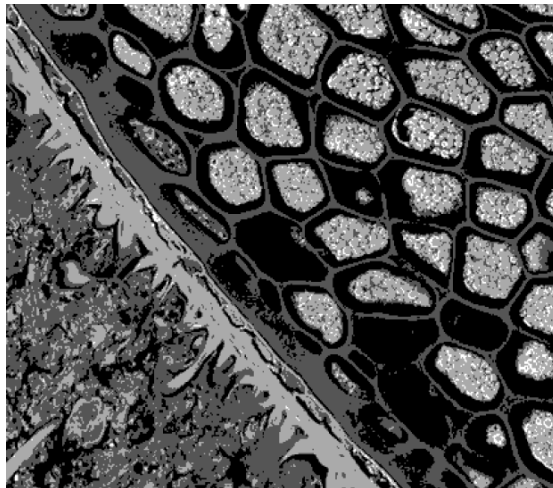
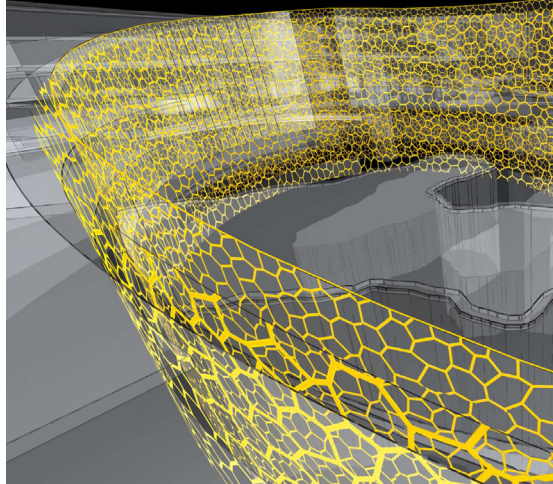


Figure 3: a) Competition atrium cell wall; b) Living organism tissue; c) Traditional Chinese screens.

As part of the winning competition, this atrium exterior envelope was expressed as an organic cell form, a direct identity to the function of the museum as well as a nod to historical Chinese window screens. The organic cells as the building blocks of all life forms being represented in the structure of the atrium wall, captured the imagination of the client and general public and became a direct cue to the major exhibits within the museum. Screens composed of abstractions of natural patterns are also abundant in traditional Chinese houses, especially garden pavilions and walls.

The atrium enclosure is composed of three separate and distinct layers: structure, curtain wall and sun screen. At center, is the atrium structure flanked by an inner glass curtain wall layer and an outer solar screen layer. Geometrically, these three layers form offset surfaces with a constant face-to-face distance from the controlling mesh. Structurally interconnected at the nodes, the resulting mesh geometry formed a 3D conical mesh rather than 2D planar net structures.

### 3.1 Structural Layer

The main feature of the atrium is the structural cell wall that spans the full 33.5 meter (109 feet) height of the atrium in an unsupported clear span. It supports the roof of the building and the full weight and lateral wind load on the envelope. The curved shape of the atrium, including the conical tilt-back condition, was fully exploited for its innate geometrical stability as a structural membrane. Preliminary structural engineering analysis confirmed the feasibility and stability of the polygonal-shaped cell membrane as a self-supporting and load-bearing structural entity.

#### Geometrical Pattern

In the beginning, various computer generated parametric design solutions were explored using hexagonal cell geometries. These resulted in solutions that generated noticeable repetitions and undesired striations in the cell pattern. Pure randomized computer generated pattern offsets produce infinite variations of cell sizes and shapes that were not practical in our application and not conducive to large scale manufacturing as required for our project. This computerized form generation approach had to be abandoned and a purely manual pattern generated solution was studied.

To achieve the desired, seemingly random and organic pattern in a conical-curved layout, a mix of hexagonal and polygonal shapes were studied. A limit of eight cell form variations was set to control the overall complexity



## Cell Wall: Resolving Geometrical Complexities

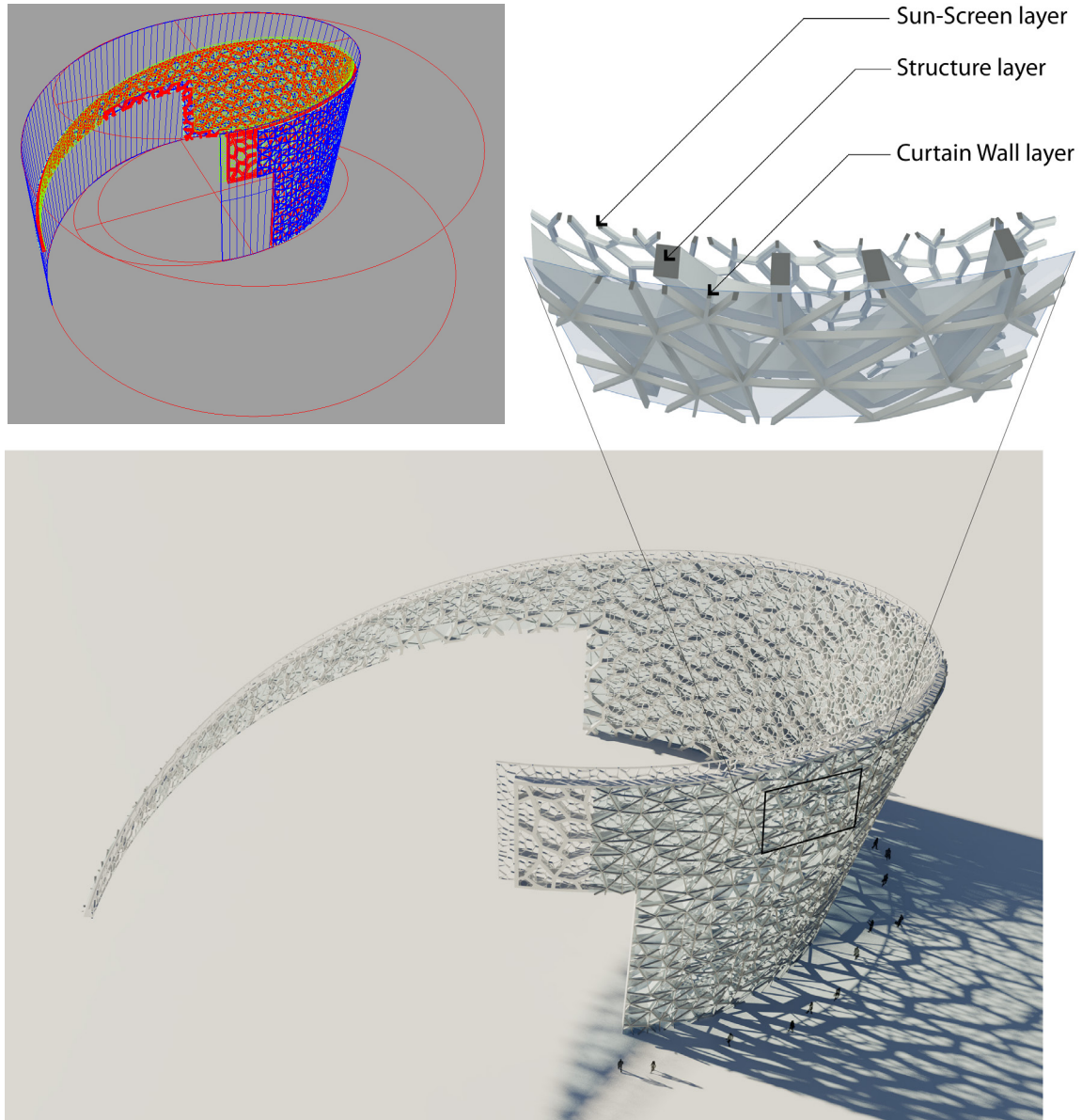


Figure 4: The atrium geometry. a) Conical ellipse overall layout; b) Cell-module layering; c) Cell-module within atrium geometry.

of the construction and allow for unitizing the steel fabrication in a shop. This number of cell variations was fully vetted with the client and their construction advisors as a maximum degree of difficulty for local constructability. The maximum size of the polygonal cells themselves was set originally as 3.6 meters by 2.5 meters (11.8 feet by 8.2 feet), based on the largest size of low-e coated insulated glass available as standard production in China.

To generate an adequate level of randomness in the resulting pattern, a repetitive geometric stencil-form approach was used. This is typical of stenciled shapes in precast-preformed paving systems, which are used to generate a visually varying and apparently non-repeating random pattern. Basically a single, complex shape that is tessellated repeatedly so that the resulting patterns merge together into a seemingly random geomet-

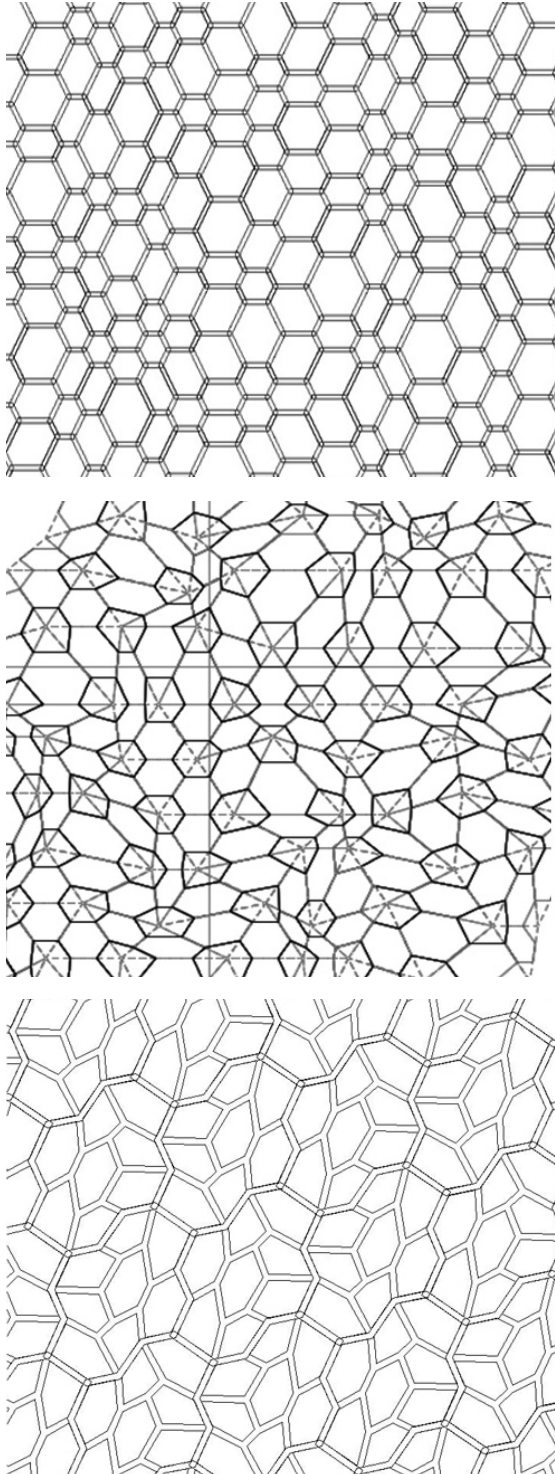


Figure 5: Cell geometry. a) Computer generated parametrics; b) Random pattern; c) Manual tessellation solution.

rical field. Such tessellation concepts were frequently exploited by M. C. Escher in his iconic art patterns as well as traditional Islamic decorative wall tiles.

Numerous cell form variations were studied, by intuitive trial and error, to arrive at a visually pleasing pattern that could be tessellated without forming a recognizable overall pattern. Since simple repetitions would always result in unintended and distracting diagonal striations, every other alternate row of the cell-module was reversed by rotating the stencil module 180 degrees. This resulted in a technically feasible limited number of construction variations, but in the random organic pattern required by the project.

#### Structural Solution

Being a full structural support element for the building and taking full axial building load, lateral wind forces, and earthquake, the structural engineers had to be fully engaged in what we were doing architecturally. While, as architects, we tend to see the cell wall as polygonal geometrical shapes and surfaces, structural engineers viewed this as a series of vectors connecting into asymmetrical nodes. Computer analysis was critical to model the entire mesh form as a structural membrane. The node connections became a critical structural constraint for the engineers, more so since the asymmetrical geometry generated asymmetrical structural forces of tension and compression within the same node. The inclusion of gusset plates and stiffeners at the nodes was reviewed and eliminated early on as aesthetically not desirable. The structural solution was to weld the intersecting steel tubes into a solid node to resolve the complicated structural forces flowing through them. The size of the cell shapes was not very consequential to the engineers, but the structural organization of the nodes was critical for transferring structural forces and as a fabrication feasibility. Limiting the structural grid to pentagon and hexagon polygonal shapes guaranteed that the intersecting nodes would be limited to three to four intersecting members. Incorporating triangular cells would have increased the number of connection to the nodes, complicating steel fabrication.

Once the main cell geometry was resolved, it was mocked up in the full curved layout of the atrium's conical geometry and analyzed visually for overall effect. While all the individual legs of the cells are straight, the curvature of the wall is achieved by the angular variations in the connecting joints. The cell structure 3D line drawing was then shared with the structural engineers in China for full analysis and engineering. A rectangu-

## Cell Wall: Resolving Geometrical Complexities

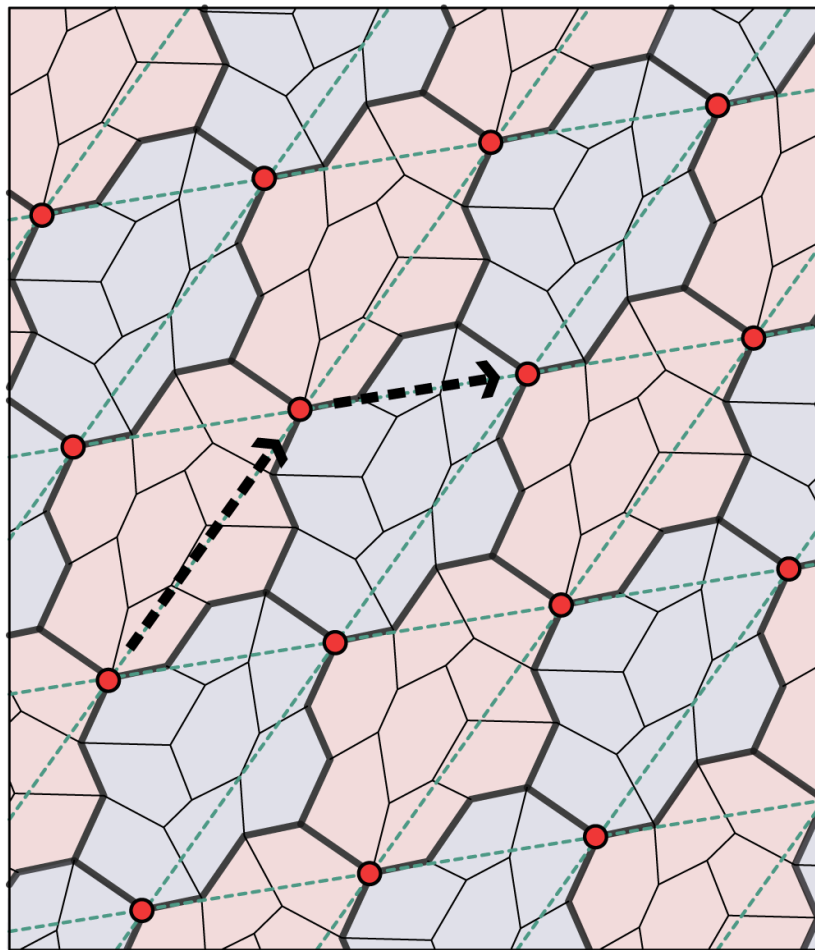
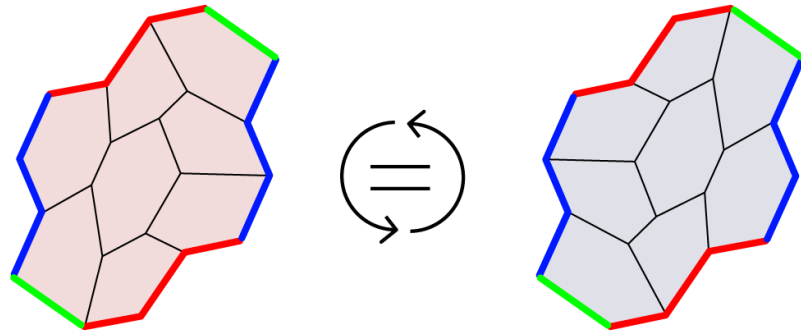


Figure 6: Geometric tessellation concept of the basic cell-module.



lar tube steel structural cross-section, 500 millimeters by 275 millimeters (19.6 inches by 10.8 inches), was chosen for buildability and structural efficiency in taking lateral wind loads over the full vertical span of the atrium. This slim visual profile also afforded less obstructed views from the atrium to the main outdoor courtyard as well as from the outside looking in.

Steel fabrication methods and on-site erection concepts were also researched for constructability. A “zipper con-

cept” was envisioned as a basic approach to steel assembly, where basic steel cell units could be pre-constructed in the factory and shipped to the job site and assembled into individual long “planks” spanning the full height of the atrium. These planks could then be tilted up in place and connecting steel members could then be used as a “zipper” to stitch the whole assembly into the final form.

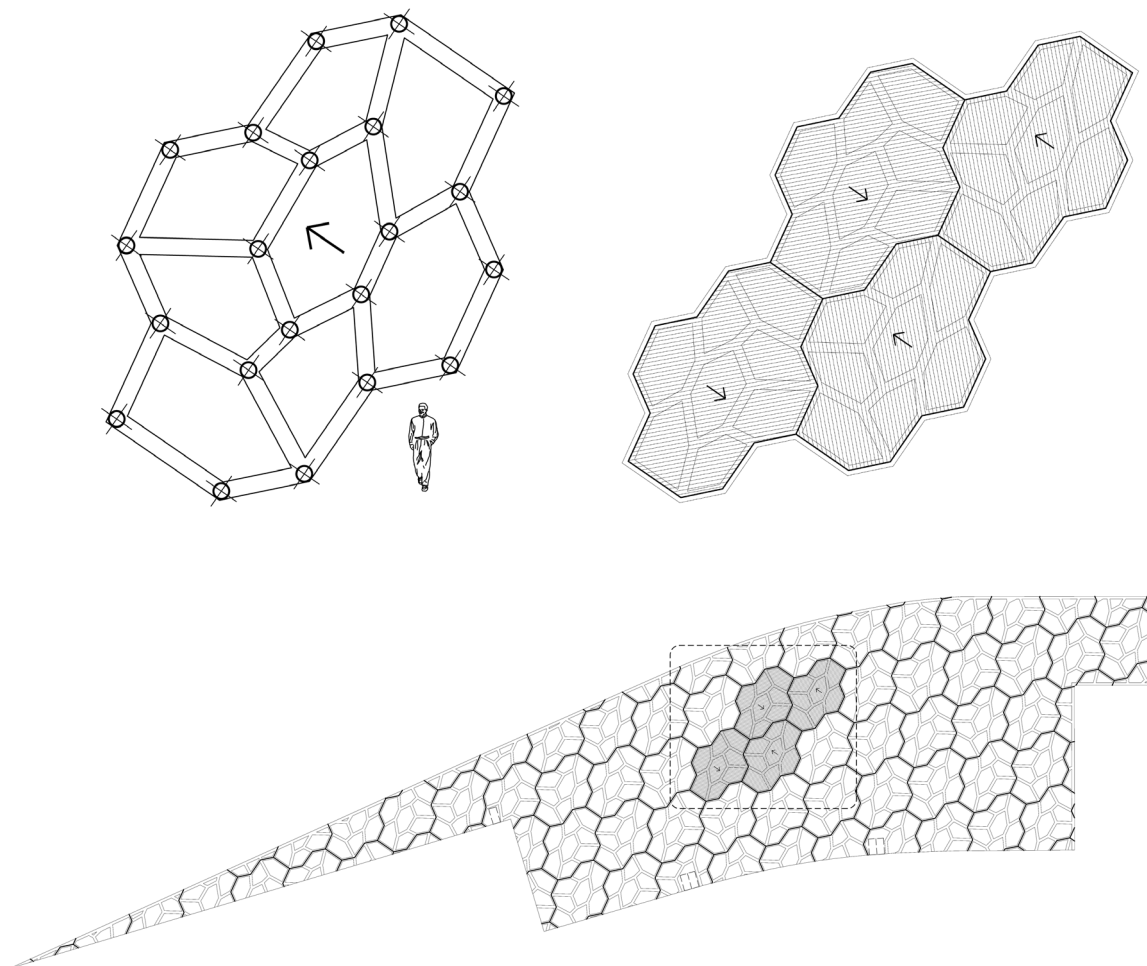


Figure 7: The structure.

a) Basic cell module; b) Basic cell grouping; c) Structural cells as laid out on the flattened skin of the atrium envelope.

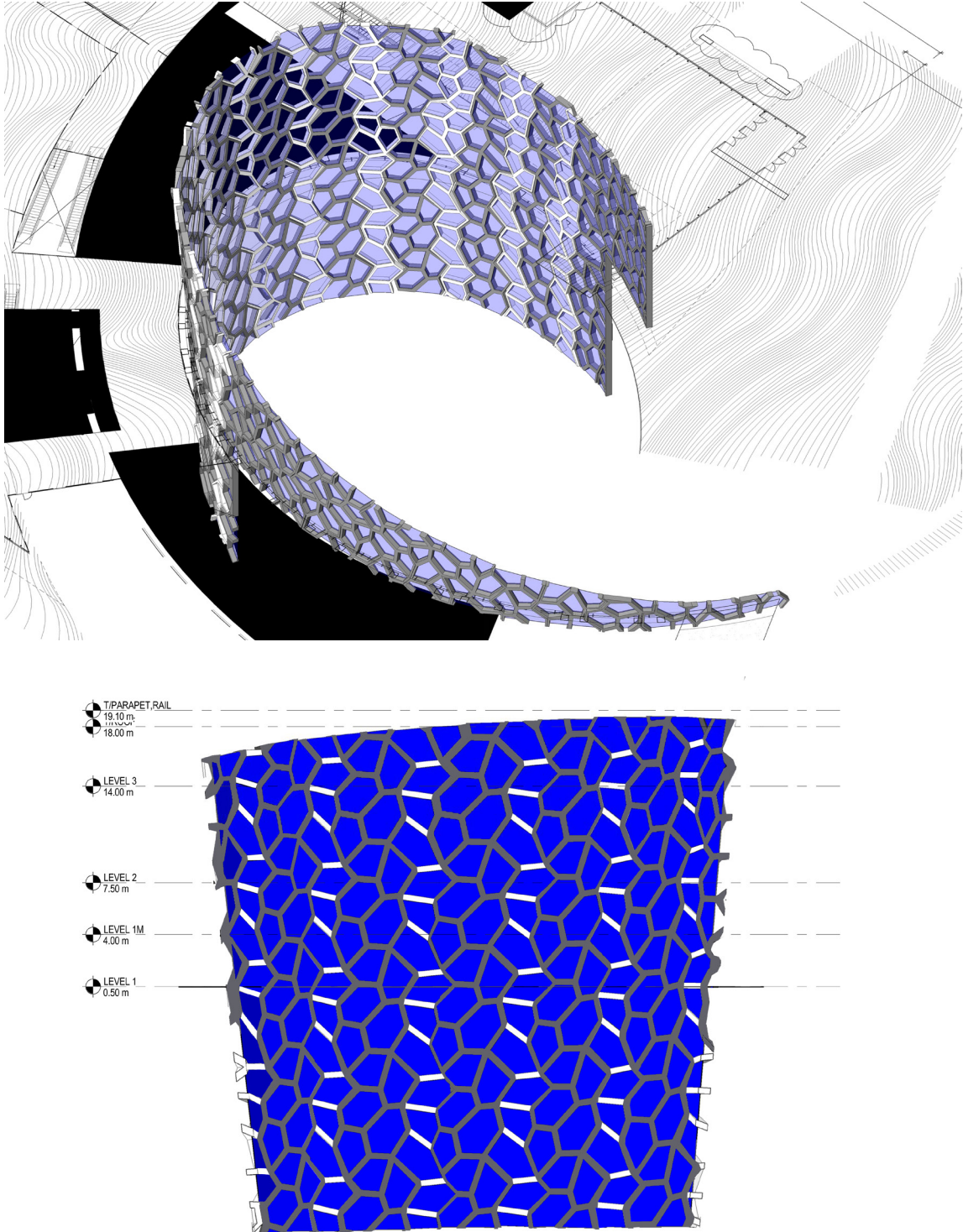


Figure 8: “The Zipper Concept”. a) “The Zipper” within atrium geometry; b) Atrium wall elevation.

### 3.2 Curtain-Wall Layer

Once the basic structural system and cell size was confirmed, the geometry and configuration of the curtain-wall layer was tackled. Three basic solutions for the curtain-wall were explored, each adding its own geometric complexity:

- A window system integrated within the cell of the structure, as a super-sized infill-window system.
- A window system, separate and independently formed, but bracketed from the back side of the structure facing the interior side of the atrium.
- An orthogonal cable-net wall with point-supported glass running independently behind the structural cell system.

Ultimately, for constructability and visual cohesiveness with the overall geometry of the cell structure, option B was chosen.

Structure, by its nature, is a vector-based geometry and in our case, the main structural cell frame has its nodes aligned along the curved conical plane of the atrium geometry. Curtain-walls are planar-faced surface geometries and reconciling the nodes of the structural cells in the same polygonal shape of the structure would have resulted in warped glass surfaces. Thus, for the window geometry to resolve itself in the curved and conical layout of the atrium within the framework of the structural nodes, the windows had to be triangulated so that they formed a seamless fold.

Triangular meshes have inherent geometrical complexities as they converge on a node. The connecting nodes had to contend with five to six intersecting members, some at rather acute angles. Despite this complexity, extensive studies showed the triangulation to work most effectively in navigating the curved geometry.

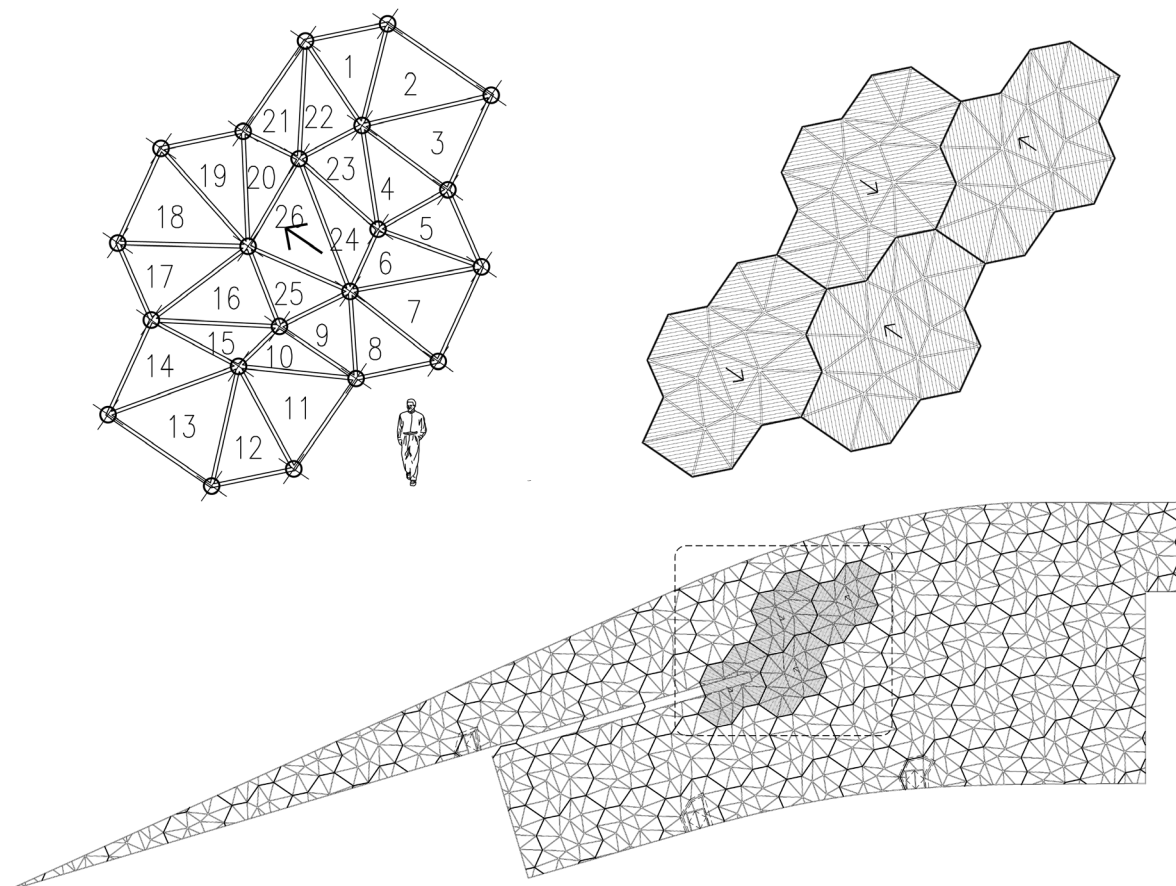


Figure 9: The curtain wall layer.

a) Basic curtain wall cell-module; b) Basic cell grouping; c) Curtain wall cells as laid out on the flattened skin of the atrium envelope.



For constructability, the curtain wall was conceived as a series of factory-unitized triangular aluminum windows bolted together at the intersecting nodes. Each structural polygon shape was divided into three or four triangular pieces for a total of twenty six unique triangular shapes. The window assemblies were then point-supported via brackets from the structural super-cells at the geometrical nodes. Due to the layout of the glass-wall within the atrium envelope sandwich, the windows would have to be installed, maintained and replaced from the interior side of the atrium.

### 3.3 Sun-Screen Layer

The geometrical solution of the exterior sun-screen was a take-off from the Voronoi module of the structural wall, and like the curtain wall, was pinned at the central nodes of the structure. A denser pattern of the tessel-

lated polygonal cell geometry had to be developed for proper sun-shading function. Since the all glass atrium wall is slightly tilting back and facing south, east and west, the density and size of the screen geometry had to be carefully studied for actual solar-shading performance while maintaining the visual aesthetic required to connect the interior and exterior spaces. The sun-screen is floated outward from the structure, breaking down the mass of the structural cells with a lacier screen polygonal grid, a miniaturized variation of the structural cells.

The screen itself was conceived as a series of simple rectangular aluminum tubes and can be easily factory fabricated into the custom cell shapes required. Larger cell groupings could then be transported to the project site and erected in place.

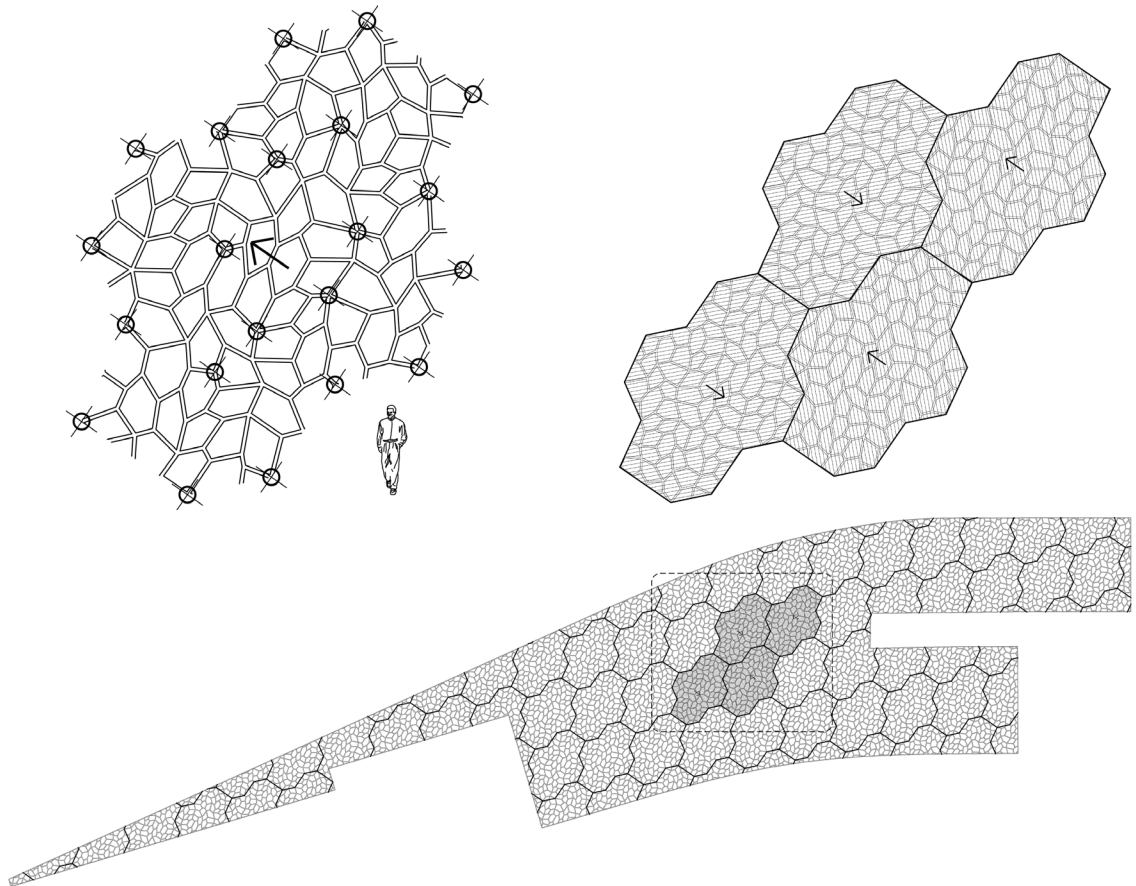


Figure 10: The sun-screen layer.

a) Basic cell-module; b) Basic cell grouping; c) Sun-screen cells as laid out on the flattened skin of the atrium envelope.

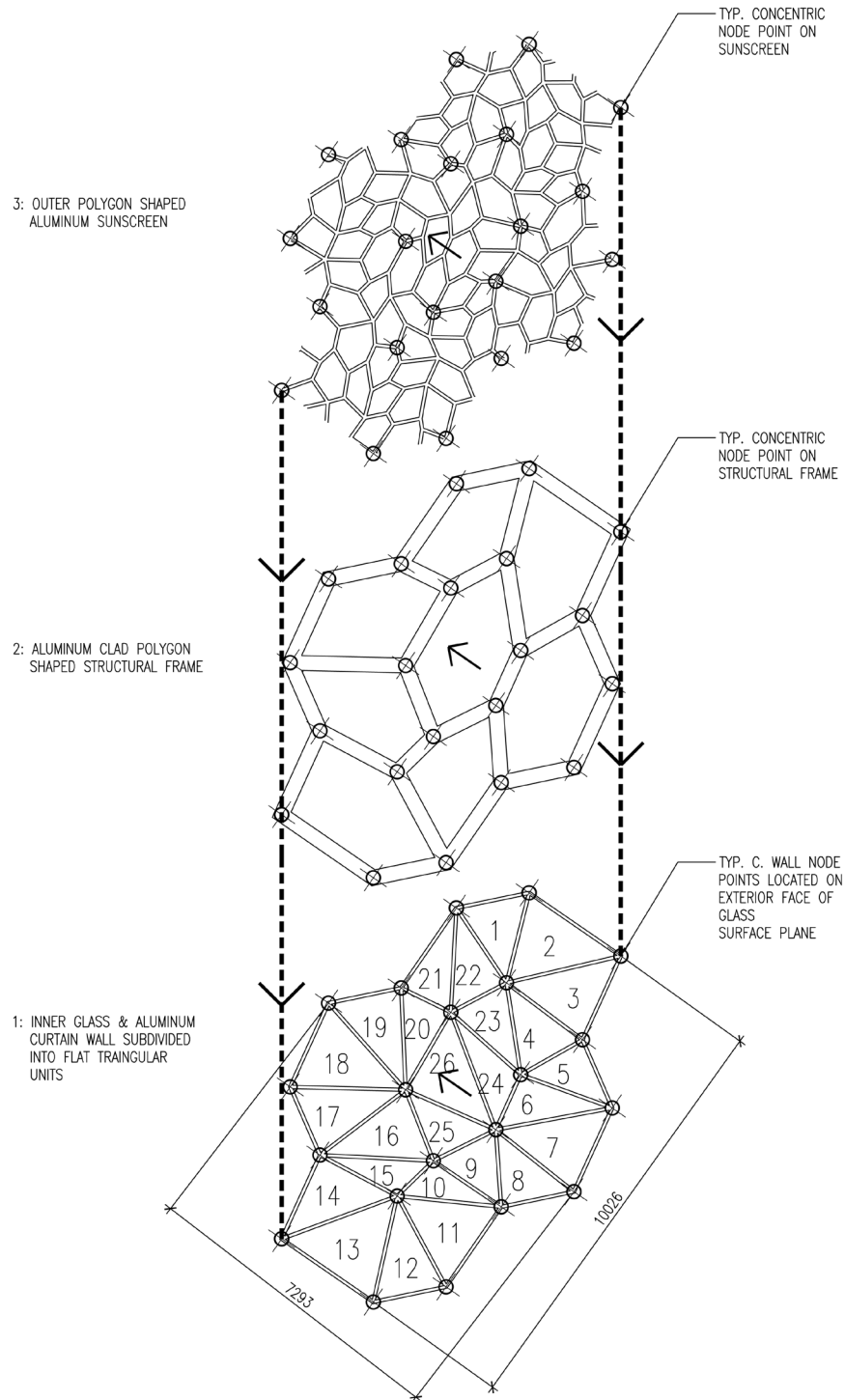


Figure 11: a) The 3 atrium layer's cell-module overlap.

## Cell Wall: Resolving Geometrical Complexities

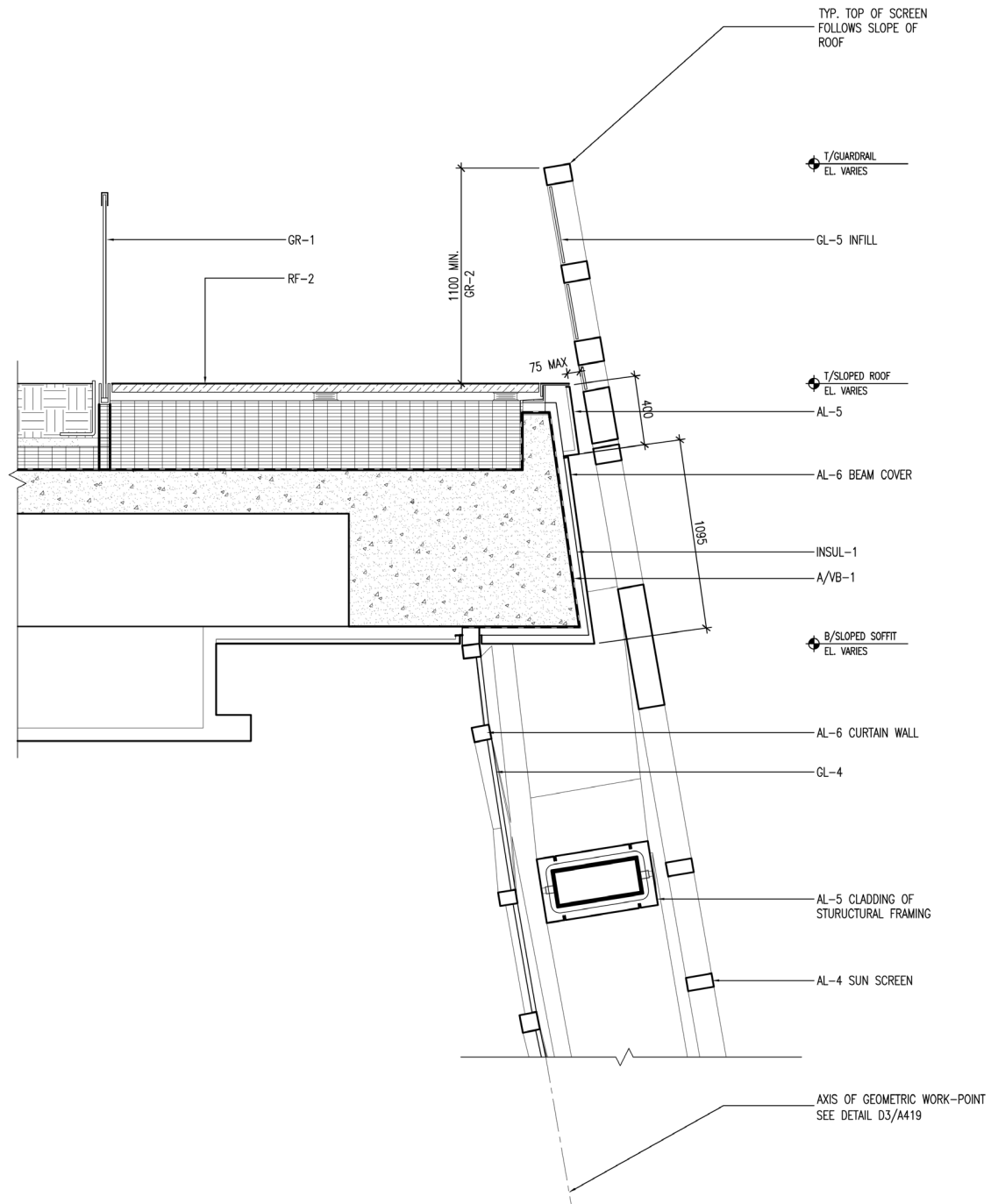


Figure 11: b) Atrium sandwich section.





Figure 12: The interior view of the atrium.



Figure 13: The exterior view of the atrium wall and museum entry.

## 4.0 CONCLUSIONS

Complex geometrical envelope systems require the active involvement of technical and design teams to tackle possible solutions simultaneously, thus constantly adding balance to the process. Inevitably, numerous dead-end solutions would be pursued and vetted quickly so as not to distract from the project schedule and project deliverables. Technical buildability and the design aesthetics needed to be constantly evaluated so as not to stray into unrealistic expectations. This dictated that the right blend of talents be fully engaged from the beginning of the project.

Designing cell structures to full building scale and with active real-world structural and economic constraints proved a lot more challenging than initially anticipated. While these systems can be relatively easily generated as patterns and decorations in a virtual computer world, executing them to the scales of real architecture produces innumerable constraints and dead-end solutions. Feasibility considerations had to be constantly applied to keep the design process real. Structural realities of overall span and incurred axial and lateral static forces produce unanticipated stresses when dealing with asymmetrical cell geometries.

Solving complex architectural conditions and geometries was simplified when simple achievable elements were considered. Since the Shanghai Nature Museum is a real project with a real design/construction schedule and budget, innovative applications of existing technology had to be incorporated. Incorporating readily available rectilinear construction elements and combining them in complex layouts was crucial in delivering a buildable design within economic realities.

Actively using 3D computer BIM models was crucial to the project in order to understand the visual design implications as well as to quickly ascertain where the actual technical complexities were. Quick 3D studies also exposed weaknesses in proposed solutions in a timely manner. Being able to share the computer model with the local Chinese engineers also guaranteed that we were all looking at the same geometry and structural data. The 3D models also became the basic visual tool to explain the atrium enclosure to the clients in China as well as to the client's engineers and construction experts.

## Acknowledgments

Exterior envelope team: Ralph Johnson, Bryan Schabel, Marius Ronnett, Ian Bush, Abul Abdullah, Hemant Thombre, Michael Tumminello, Leila Kanar and Kyle Knudson. Special acknowledgement to Todd Snapp, for his initial studies of computer-generated algorithms as a possible solution to the cell geometry.

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