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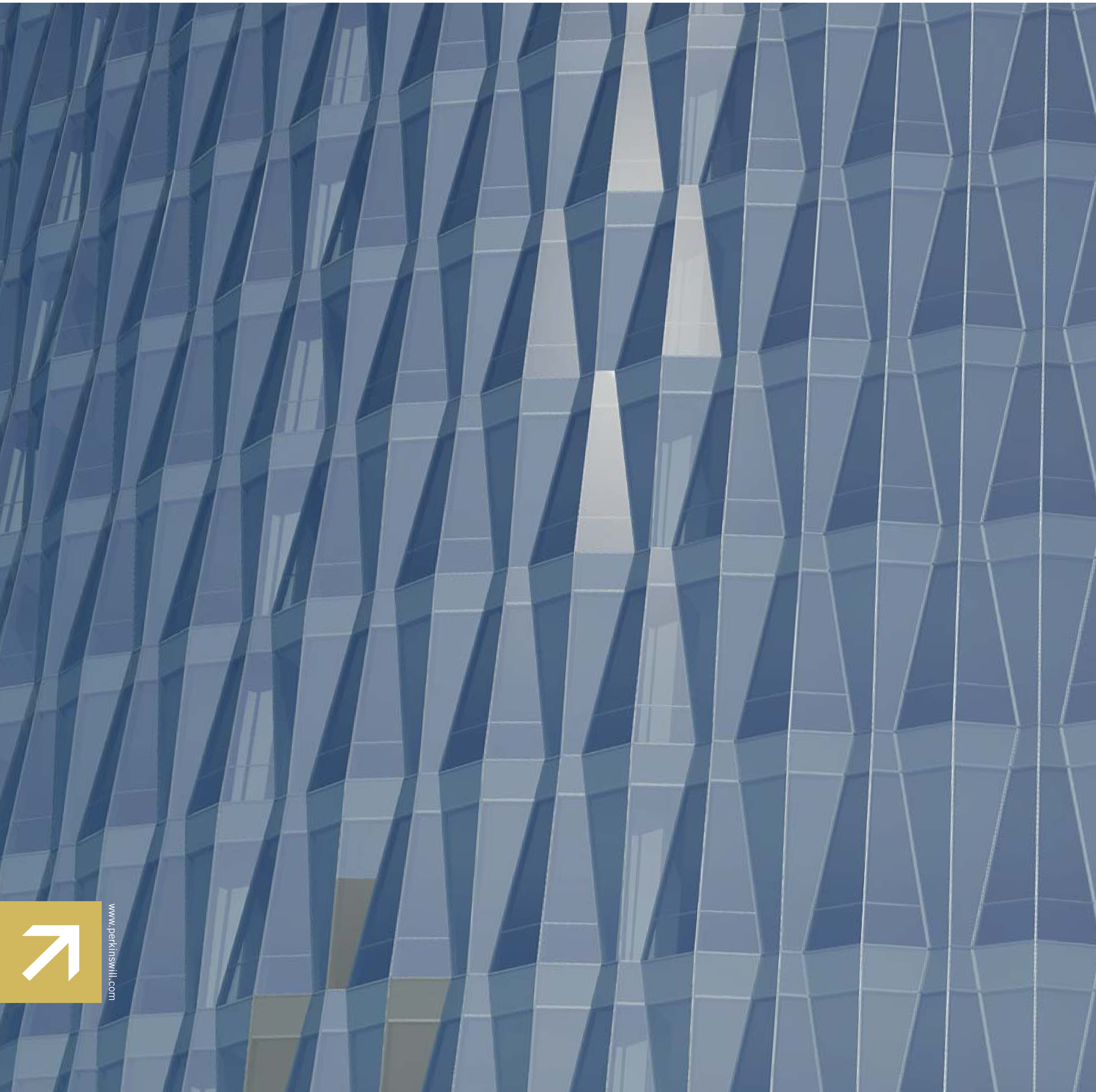

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02.
EXPLORATION OF COMPLEX CURTAIN WALL SOLUTIONS:
Shanghai Fisherman's Wharf Iconic Tower

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ABSTRACT
This article explores the various curtain wall façade system solutions as developed for the Shanghai Fisherman's Wharf project's iconic skyscraper. The high-rise tower comprises a curvilinear nautical shape, nicknamed "The Fish" and is the main iconic identity of the large-scale mixed-use project. Cladding this morphic building shape involved an intense exploration of 2D and 3D curtain wall façade systems in order to emphasize the overall nautical theme of the project and add visual complexity and unique identity to the project. Exploration relied on investigation of numerous options, aimed to achieve the desired visual impact and evaluated by our technical team and external industry experts.

Curtain wall explorations comprised from relatively simple flat rectilinear 2D solutions to complex 3D projected faceted patterns to form unitized modules arrayed over the curved façade of the high-rise tower. This article explores the visual design, technical complexity, cost implications and constructability issues over the different stages of the project. It covers the curtain wall design process from concept design through construction documents, as it became impacted by City Code constraints and client-driven building program changes.

KEYWORDS: curtain wall systems; 3D facades; faceted geometries; curvilinear facades; unitized curtain wall modules

1.0 INTRODUCTION
Curtain wall systems have evolved dramatically in the past years to more complex and customized solutions, driven in equal parts by design aspirations as well as technical aptitude. Complex building geometries together with market forces and the aesthetic desire for distinguished iconic architecture, merged with the growing technical ability of the construction industry to generate very unique solutions[1]. At the same time, Building Codes, City Ordinances and environmental constraints have become more stringent to address the growing energy use considerations in the performance of building facades, environmental awareness as well as the building's impact within its urban environment, such as light-reflectivity issues.

1.1 The Shanghai Fisherman's Wharf Project
The Shanghai Fisherman's Wharf project is a major new urban development aiming to revitalize a disused industrial portion of the HuangPu riverfront, once a heavily industrialized shipping, commercial and warehouse district. This is part of city wide efforts by the Shanghai municipality to reactivate the river shore, upgrading the flood-zone retaining-walls and providing interconnected public access shoreline developments by linking green-zones and park to the dilapidated industrial riverfront. As part of the winning master-plan competition awarded to us, a high-rise tower was envisioned as part of this development, to anchor the site visually on the riverfront, provide identity to the development and serve as a visual beacon on the skyline of Shanghai.

Figure 1: Perkins+Will winning master plan design.

This winning master plan led to a second stage design also awarded to us, for the first phase of the development. This consisted of a 48,680 square meters (524,000 square feet) site with a mixed-use program of retail, underground-parking, public amenities, public park, shoreline marina, hotel and office spaces. A curvilinear, abstract nautical design theme was set for the entire mixed-use complex anchored by a gracefully shaped skyscraper, 35-stories high and 160-meters (525 feet) tall. The program of the high-rise was set as a high-end office space for the lower half while the upper portion was set as a luxury boutique hotel.

The tower, a streamlined nautical shape, endearingly nicknamed "the Fish" quickly became the architectural challenge for our team. While from the initial competition stage of the design, it was approved and locked into its overall streamlined sculptural shape, finding a suitable curtain wall façade solution was a major challenge. It was important for the project that the tower have a unique skin to add marketing identity and to visually distinguish it from the regular rectilinear façade walls on the skyline. Maintaining the nautical emphasis of the overall shape and adding visual complexity led to multiple explorations of applicable 2D facades all the way to complex 3D faceted pattern systems.

Technical impacts on the curtain wall solutions included wind and earthquake lateral loads, constructability of façade units, patterns limited to unitized façade modules, assembly and installation restrictions, interstory drift as impacted by lateral building movement, integration of venting mechanical floors and mechanical louvers.

An added complexity to the façade was brought on by the client-driven program change of the tower occupancy very late in the design process and after construction started. The major shift in program involving the change of the top half of the building to luxury residential apartments forced dramatic changes to the permit-approved building documents and approved façade. Residential code restrictions and requirements for dedicated balconies, utility balconies, exterior utility pipe requirements and dedicated individual mechanical rooms and venting prompted major changes to the façade design.

On our Shanghai Fisherman's Wharf project, we pursued dozens of options, vetting them for aesthetic implications and technical challenges. The team relied on 3D Studio Max, Rhinoceros (building shape) and AutoCAD as well as physical scale models to study detailed curtain wall systems and their resultant visual impact on the overall skyscraper design.

1.2 Code Constraints

Shanghai's City Code impacts on the curtain wall solutions included city zoning restrictions, environmental building shadow implications over the neighboring residential zone, local ordinance reflectivity restrictions and envelope energy restrictions as relating to the façade glass and insulated wall ratios[2,3].

Local energy codes required incorporating efficient low-e (low emissivity) insulated glass with a stringent solar shading coefficient due to the hot southern climate of Shanghai. At the same time, new zoning restrictions limited the outbound reflectivity ratio of the glass to under 15 percent due to urban light-pollution concerns, thus limiting our range of low-e glass we could use. Fire Code required the façade to have a 800mm (31.5 inches) solid-wall separation between floors, which we could either accommodate by aluminum panel cladding or an insulated shadow-box spandrel. Shanghai Code restrictions of 70 percent vision glass to a 30 percent insulated solid wall ratio, interpreted as glass shadow-box spandrels in our case, had to be implemented. In the permit phase, additional zoning constraints of limiting the percentage of façade reflection (determined by surface ratio of glass area) towards the northern residential district forced inclusions of opaque aluminum panels onto the façade module. New code restrictions also required natural ventilation options to the office floors as well as ability to naturally flush out the entire floor-plates in case of air contamination.

1.3 Tower Geometry and Program

The streamline shape of the tower consists of a simple two dimensional extruded curve, trimmed in a gently curved dynamic oblong form. The shape is oriented north-south, with the flat side oriented south and the long sides facing east and west making use of the views up and down the HuangPu river and the dramatic new city skyline of the PuDong district. To the north is an older existing residential district tightly packed with low-rise and mid-rise apartment blocks. Zoning Code restricted the amount of shade that the tower could cast over the neighborhood, so as not to deprive the residential units of minimum sunlight requirements. The shape and height of the tower had to be adjusted numerous times as part of the zoning permit process as zoning impact and sun-shadow studies were developed, thus reducing the overall tower to its present 160m (525 feet) height. The south facing façade was densely screened for solar shading.

The tower was initially programmed to have 14 floors of office space, with a 4.3 meter (14.1 feet) floor-to-floor span. The upper portion of the building was to have 16 floors of luxury hotel, with a 3.6 meter (11.8 feet) floor-to-floor span. Auxiliary floors included hotel conference and meeting room floors, mechanical, hotel sky-lobby and a sky-bar restaurant level at the top. A large 16-story atrium organized the hotel rooms on the southern face, highlighting views to the south towards the river. In a later phase, with the concrete foundation already poured and extensive negotiations on building permits completed, the client revised the program to luxury residential apartments at the upper half and moved the hotel to the lower half. At publication of this article, permit documents for the new program and new façade are still being reviewed with the City Permit department, and pending re-approval.

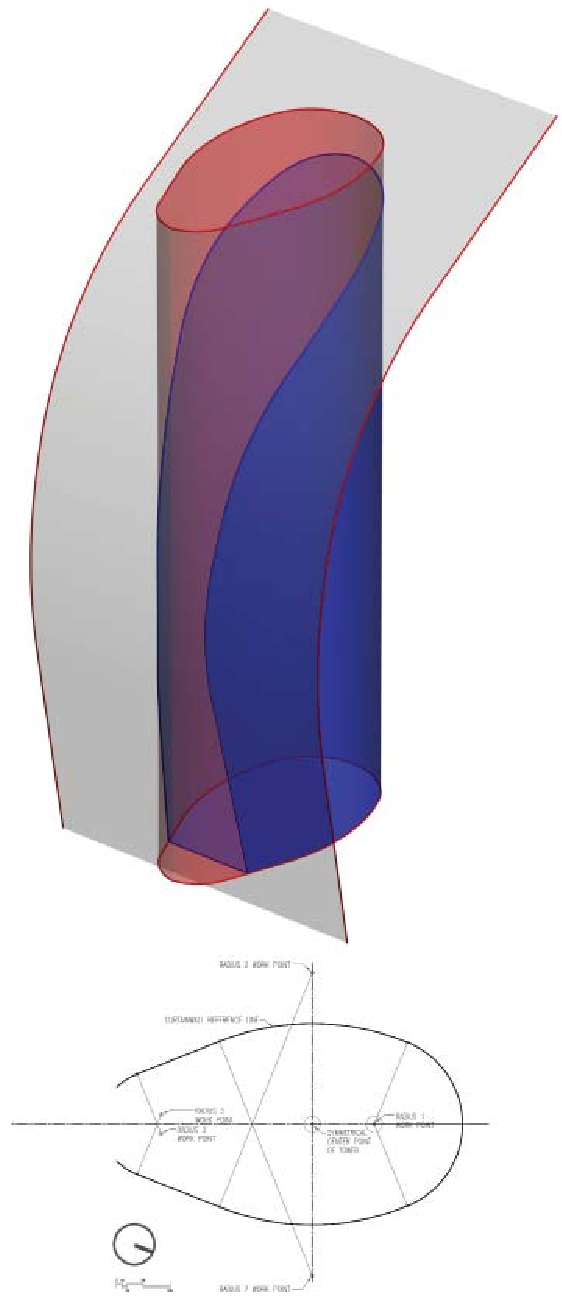


Figure 2: Tower geometry.

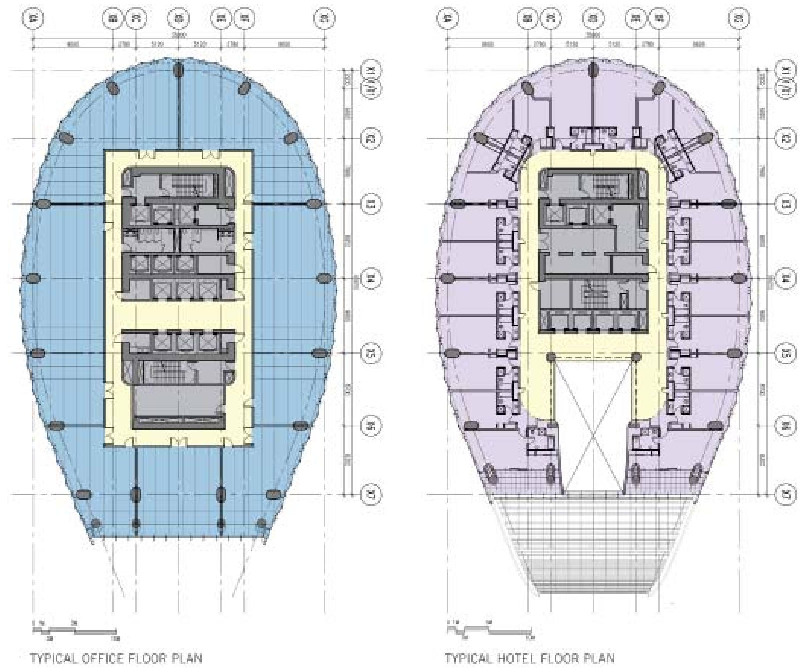


Figure 3: Tower floor-plans: a) Office b) Hotel.

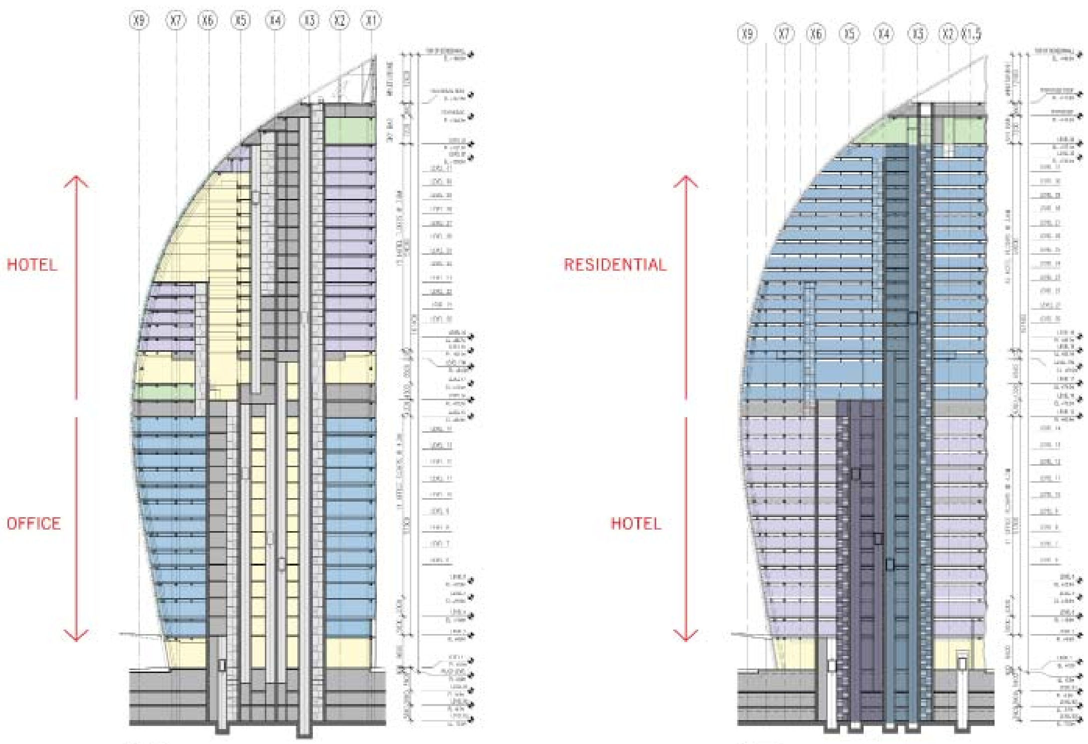


Figure 4: Building Section diagrams a) Original program; b) Revised program.

2.0 CURTAIN WALL SYSTEMS: FLAT 2D AND PROJECTED 3D SCENARIOS

From the competition phase, the tower was defined as glassy and modern with a strong unique pattern to add visual identity. A decision to stay with unitized curtain wall solutions was important to control construction quality and maintain a high-end appearance on the tower facades[4]. Double-façade systems were avoided from the onset as too expensive for the project scope as well as code restrictions on the amount of vision-glass allowed.

For manufacturing efficiency and to limit the variations in the unitized curtain wall modules, all solutions were limited to uniformly sized flat pieces of glass and straight aluminum mullions. The module was composed of 1500mm (5 foot) wide units that were equally spaced arrayed along the curved perimeter of the façade. The curvature of the façade was resolved by slightly splaying the unitized mullions at the vertical interlocking joints.

Our explorations of curtain wall façade possibilities can be broken down into two major groups, flat 2D and projected 3D modules. While flat 2D curtain wall modules are simple technical solutions, finding a visually complex pattern suitable for the building shape was a design challenge. However, projected 3D facades add a technical complexity when applied to a high-rise building, where performance issues become critical[5]. In addition, due to the folding curvilinear shape of the tower, the projected 3D forms of the curtain-wall would have to resolve themselves back to flat 2D profiles at the cantilevered building edges in progressive graduated steps.

Six different façade options are presented in this paper as broad examples of the numerous curtain wall options studied as iconic skins for the skyscraper. Three versions of flat 2D and three versions of projected 3D facades are shown. At the time of publication of this article, two separate options are pursued by the client and negotiated with the City Permitting department including one 2D façade and one 3D façade option.

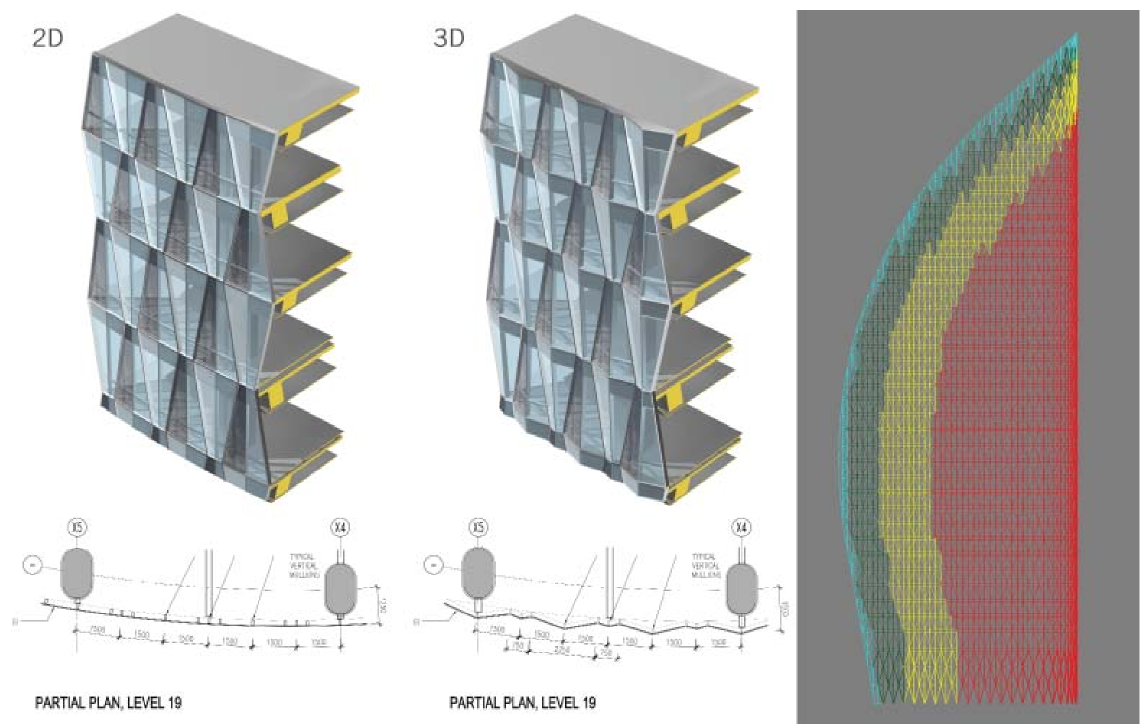


Figure 5: a) Flat 2D curtain wall; b) Projected 3D curtain wall; c) Gradated projection of 3D facade.

2.1 2D Curtain Wall: Rectangular Option

The most straight forward application of a flat 2D curtain wall module is in a typical rectangular arrangement of glass and aluminum profiles. Our "Rectangular Option" explored a very flat skin effect, stretched over the curvilinear form of the tower. Solid aluminum panels were used to create a visually random looking pattern on the façade, to add aesthetic interest and to resolve City Code requirements. This scheme was intended to work equally well in an office program as well as a hotel program. It also translated well into residential program requirements. A major drawback was the lack of grand panoramic views from inside the building due to the very fragmented mix of opaque and vision panels.

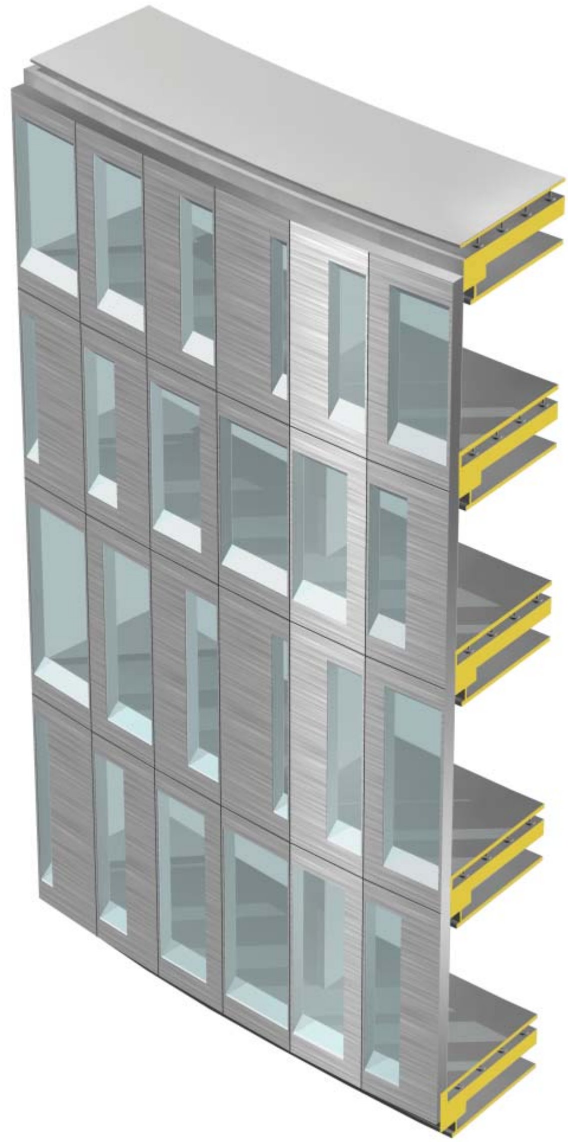


Figure 6: Flat 2D façade; Rectangular curtain wall option.

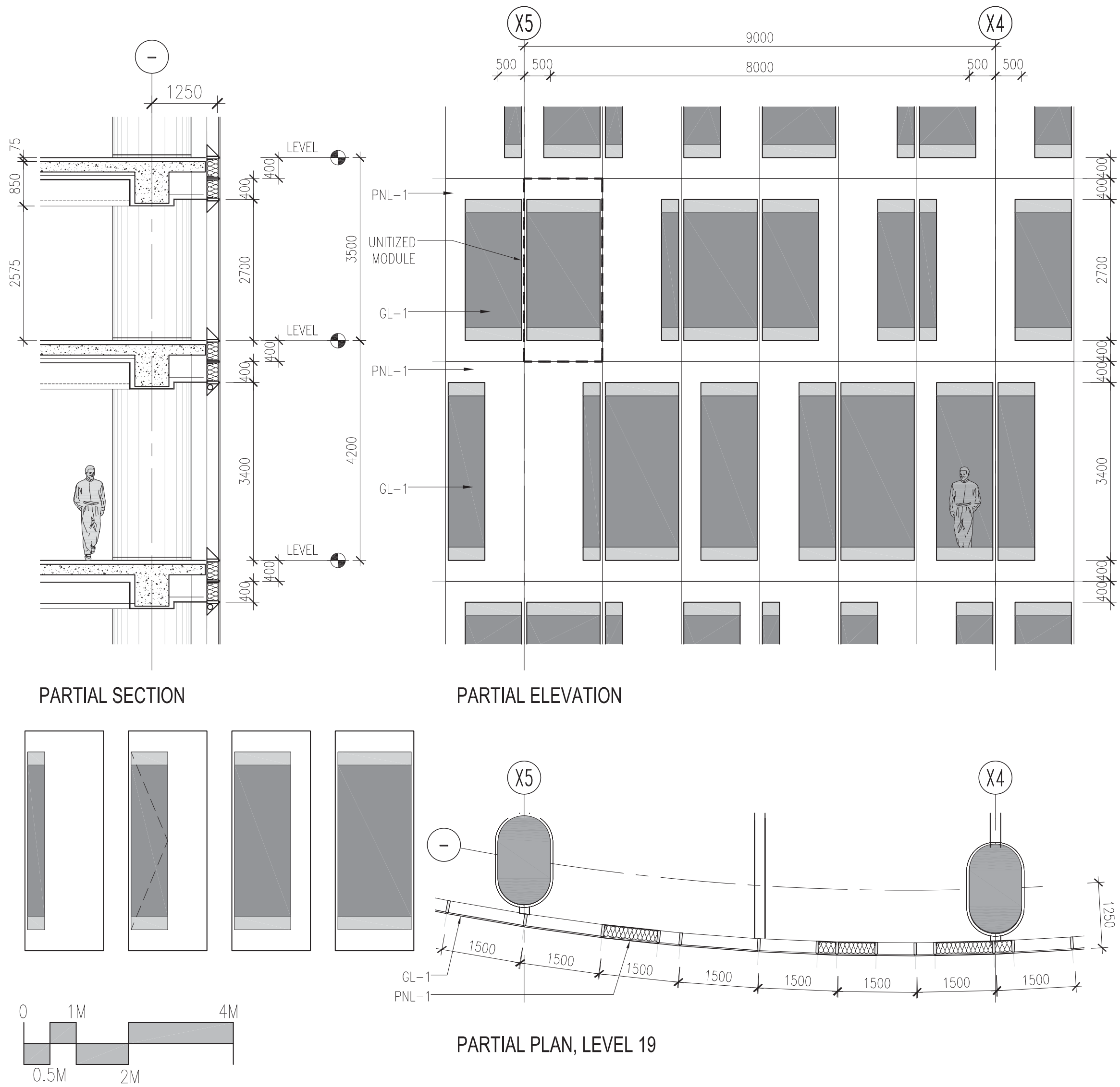


Figure 7: Flat 2D façade; Rectangular curtain wall option.

2.2 2D Curtain Wall: Oval Option

One way to express the individual units that make up the hotel and residential programs of the tower was through emphasizing the repeating nine meter (29.5 feet) structural bay module. In this option, we chose an oval pill-shaped, punched-window pattern within the aluminum panel skin to express the modularity of the program and maintain an abstract nautical expression for the tower. Incorporating recessed balconies and mechanical louvers were also easy to achieve in this scheme due to the powerful visual pattern. The city code requirements for the façade performance were also easily resolved in this scheme.

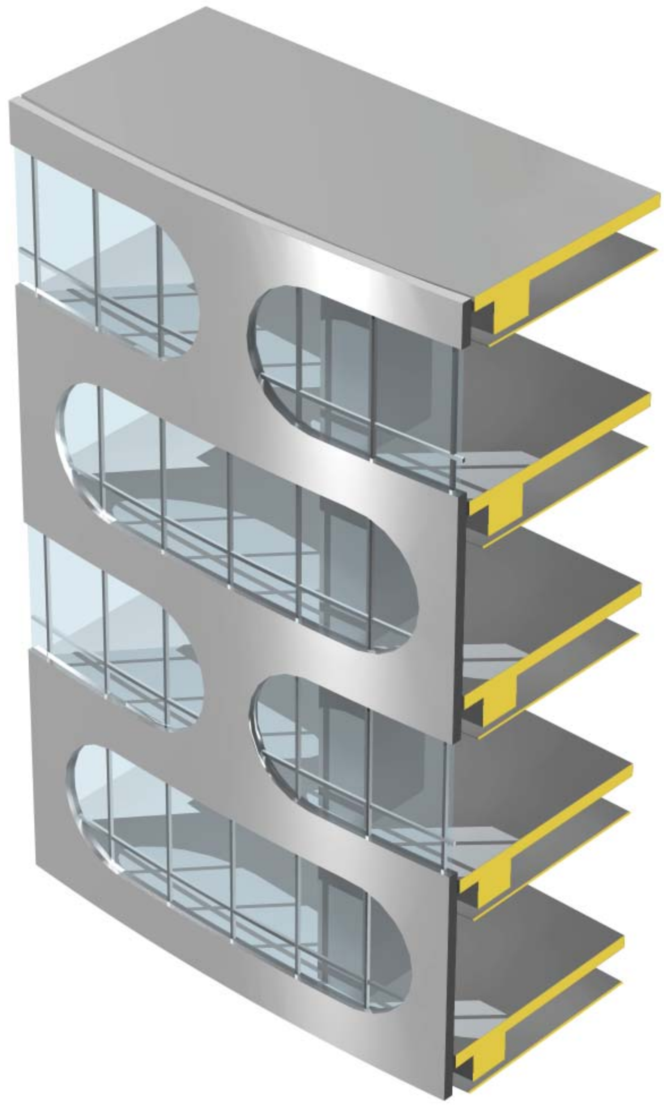


Figure 8: Flat 2D façade; Oval curtain wall option.

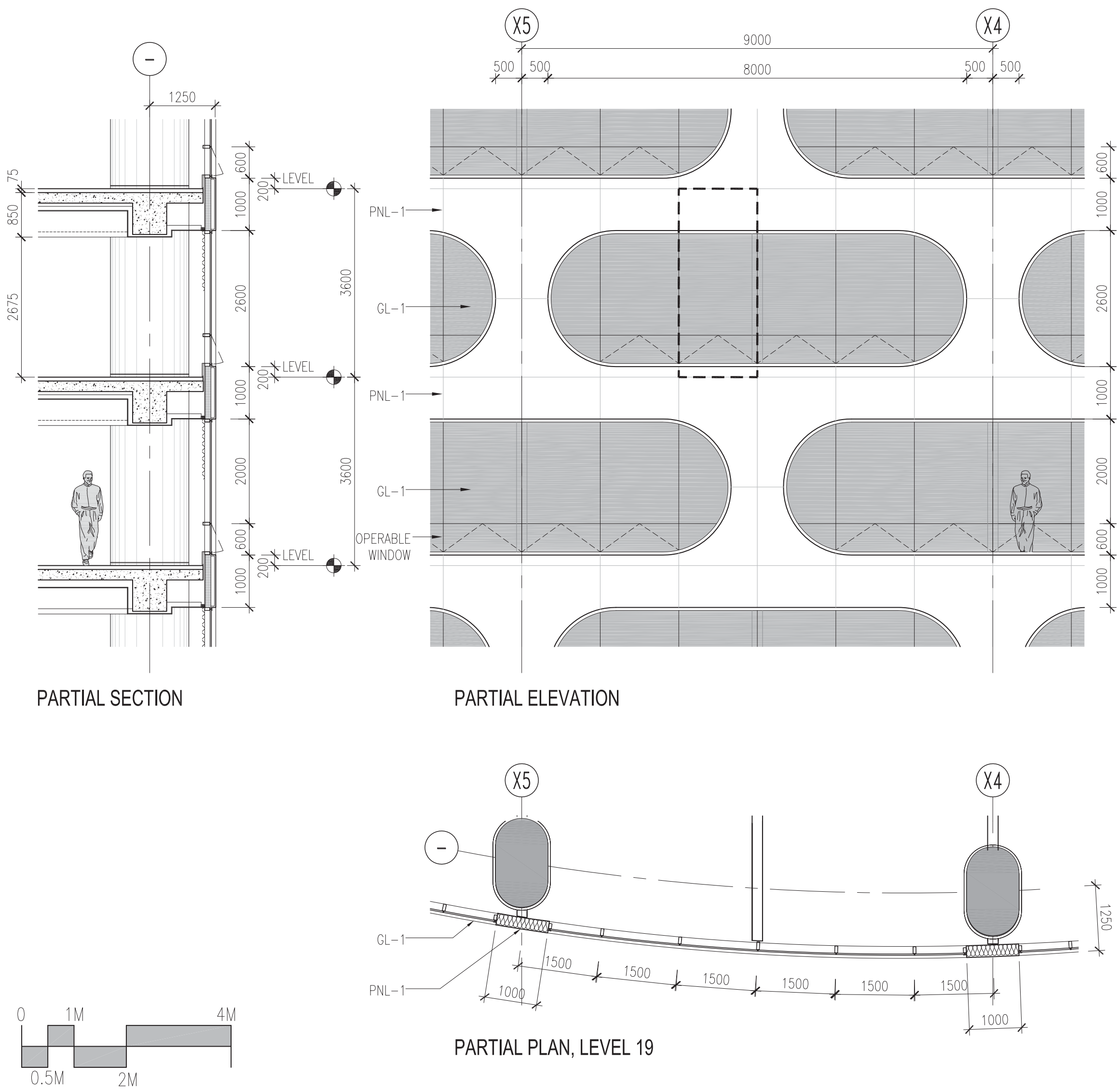


Figure 9: Flat 2D façade; Oval curtain wall option.

2.3 2D Curtain Wall: Linear Ribbon

Incorporating strong linear patterns through the use of ribbon windows within the aluminum panel skin worked very well with the curvilinear shape of the tower to accentuate its form. It added a dynamic and abstract nautical expression with minimal technical complexity. Window sizes of the stripes were varied to comply with Shanghai zoning code by reducing building glass reflectivity to the northside residential neighborhood as well as to add variety to the façade. This option also allowed easy inclusion of recessed balconies and mechanical louvers without taking away from the overall streamline shape of the tower. While this facade could be built in a simple stick-system, to maintain quality, our team and external curtain wall experts agreed that this should be looked at as a unitized curtain wall system. For technical simplicity, lower cost basis, building-program flexibility and visual aesthetics this curtain wall option was a favorite with the Client and is one of two schemes to make it to city permitting and contractor bidding phase.

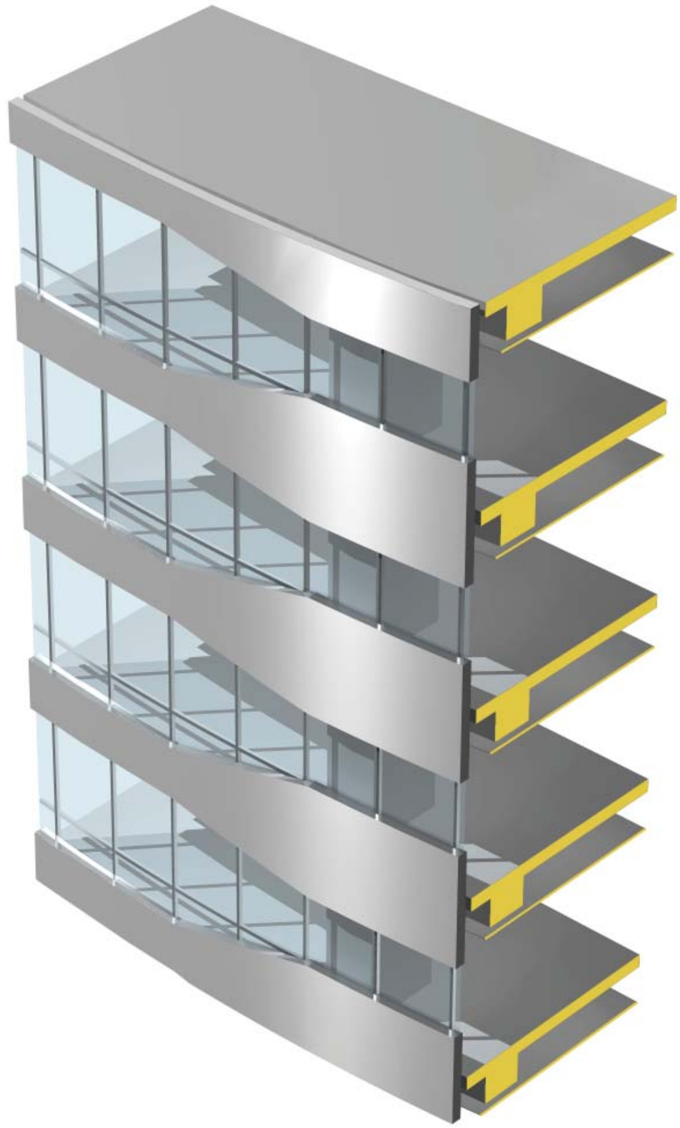


Figure 10: Flat 2D façade; Linear ribbon window option.

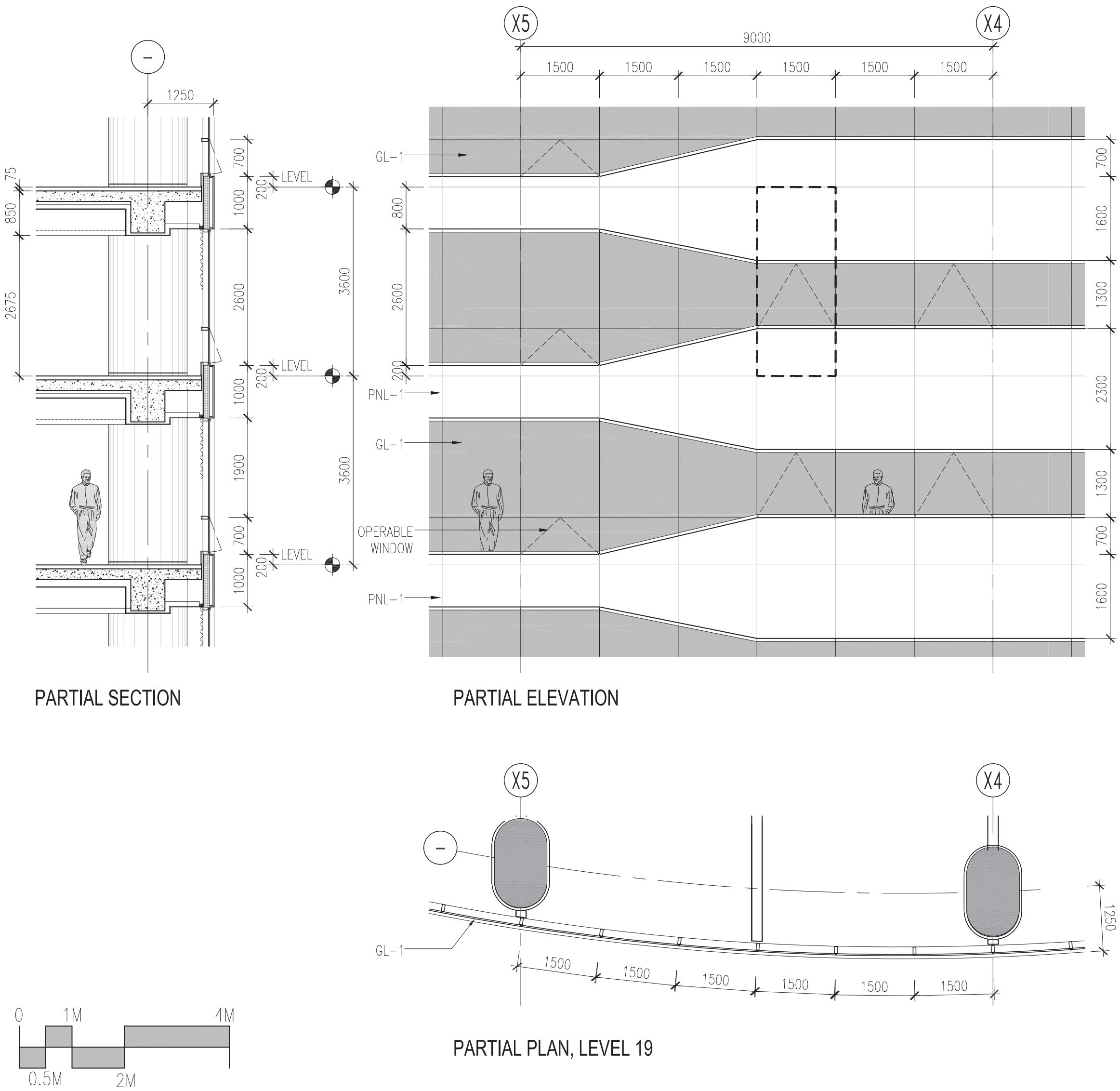


Figure 11: Flat 2D façade; Linear ribbon window option.

2.4 3D Curtain Wall: Shingles Option

Numerous 3D projected curtain wall options were explored to add visual complexity to the façade. A simple rectilinear glass and aluminum curtain wall system was used to explore 3D options by tilting and slightly overlapping the units. Operable louvers were incorporated in the concealed nested overlap to provide code-required natural ventilation. However, getting this glassy scheme to comply with Shanghai code requirements for opaque walls and limitations on glass area would have required substantial changes. Additions of solid panels and shadow-box spandrels would easily compromise the skin appearance.

Figure 12: Projected 3D curtain wall; Shingles option.

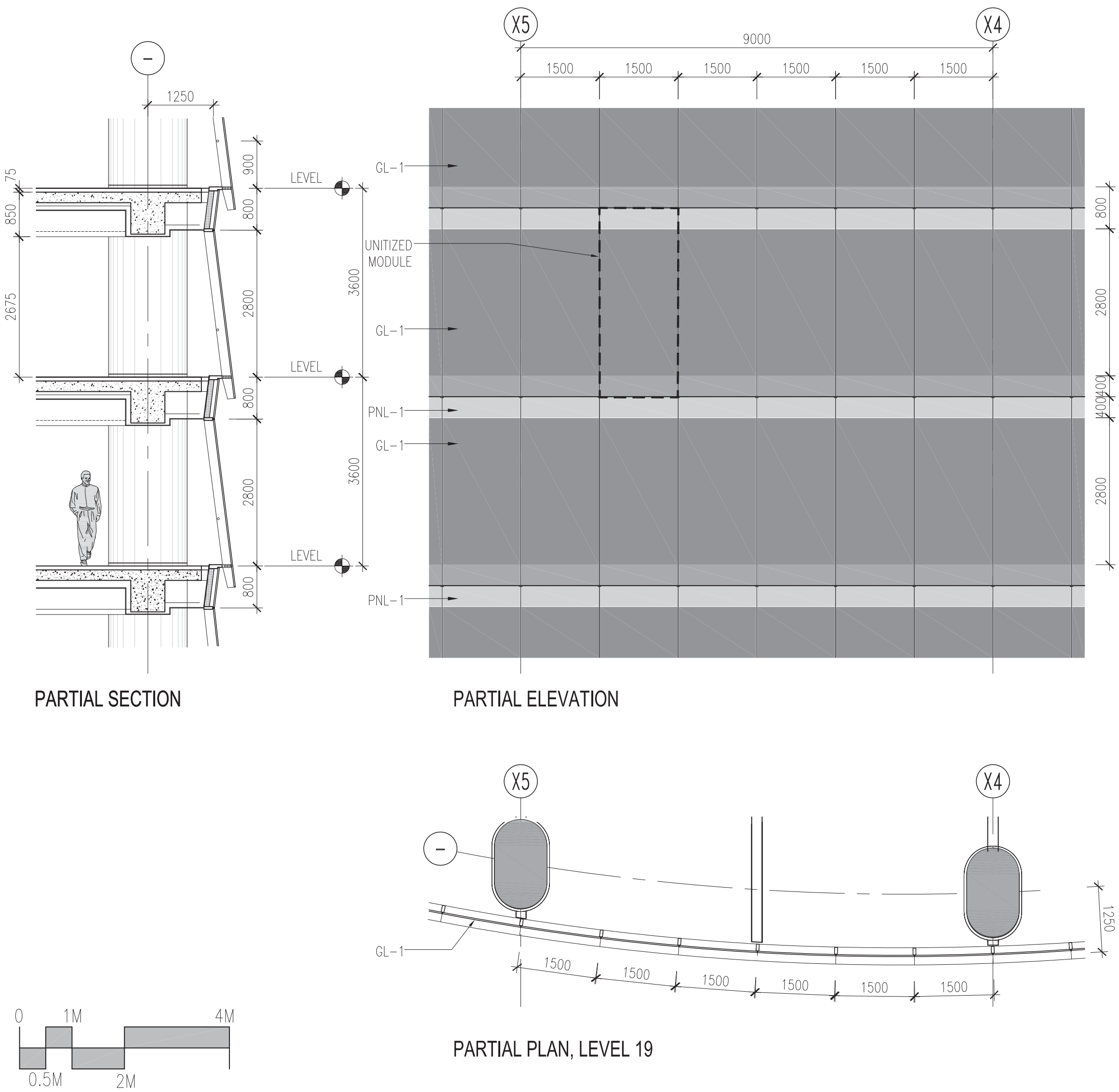


Figure 13: Projected 3D curtain wall; Shingles option.

2.5 3D Curtain Wall: Fish Scales Option

A much more complex curtain wall was to triangularize the façade and stagger the 3D projections so as to achieve a fish scale pattern. Solid panels and translucent fritted glass were intermixed with clear vision panels to further accentuate the shimmering pattern and comply with code restrictions. To resolve this façade required unitized curtain wall module solutions. Obvious technical difficulties in trying to resolve this option included the fabrication of the sharp triangular shapes of glass and structural mullions connecting at very acute angles. Structural curtain wall complications were also emphasized by the resulting staggered saw-tooth profile at the slab-edge, thus incurring lateral inter-story drift stresses. In high wind and earthquake conditions, as the building sways sideways, the floor-plates would drift slightly from vertical taking the curtain wall with it[6,7,8]. The saw-tooth plan-profile at the slab-edge would make the curtain wall resist such linear side movement (lateral drift), thus causing the curtain wall to fail. Special mullion detail connection at the sill would be required to allow for this lateral-drift movement.

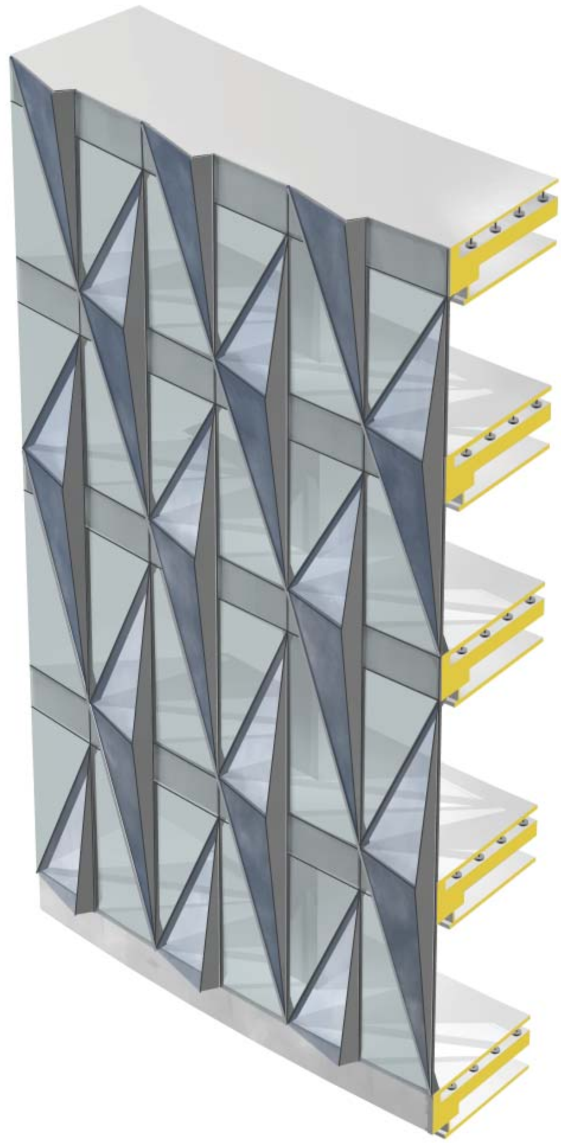


Figure 14: Projected 3D curtain wall: Fish scales option.

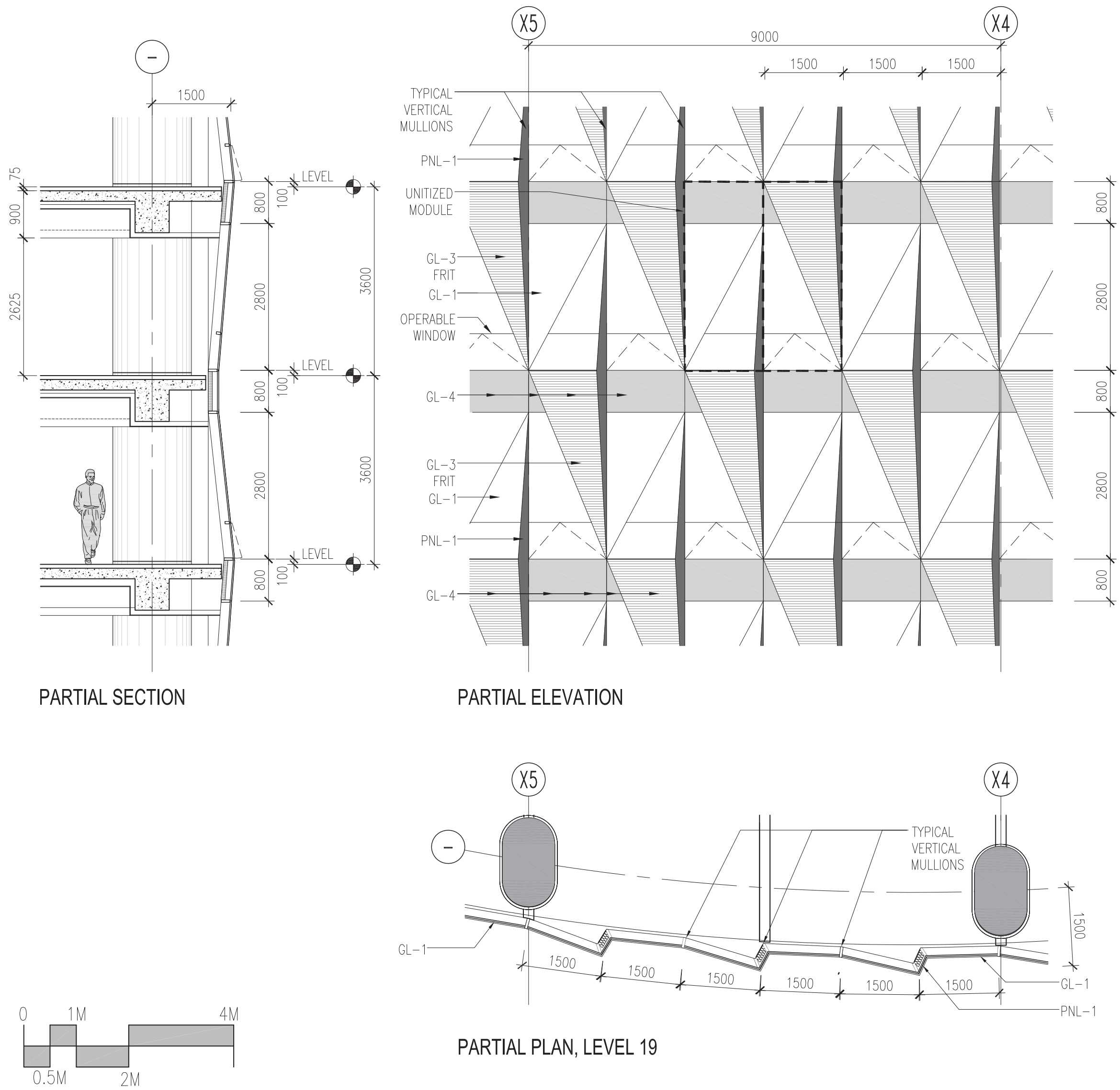
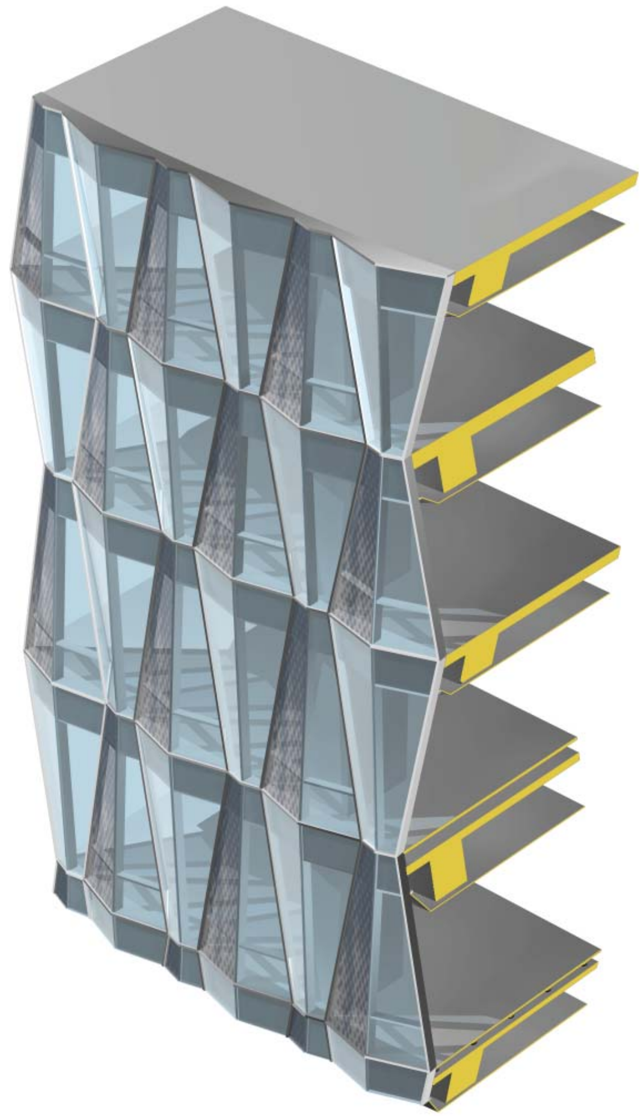


Figure 15: Projected 3D curtain wall: Fish scales option.



2.6 3D Curtain Wall: Faceted Diamond

A natural evolution of the “Fish Scale” façade option was to simplify the geometry and eliminate the sharp corners in the glass modules. To keep the flat faceted glass pieces from needing to warp, the sides of the triangular plan profiles had to be parallel. Three glass types were envisioned to accentuate the triangularized shimmer façade, one with translucent ceramic frit pattern and one with a low-e coating having a high outer reflectivity ratio to the typical tower low-e glass. In the city permitting stage of approval, the fritted glass pane had to be replaced by a solid insulated aluminum panel to pass local zoning requirements restricting outer façade reflectivity. While the saw-tooth plan layout of the sill-mullion would incur lateral inter-story drift stresses, the curtain wall engineers felt confident that they could resolve this in customizing profile details of the sill mullions.

Figure 16: Projected 3D curtain wall: Faceted diamond option.

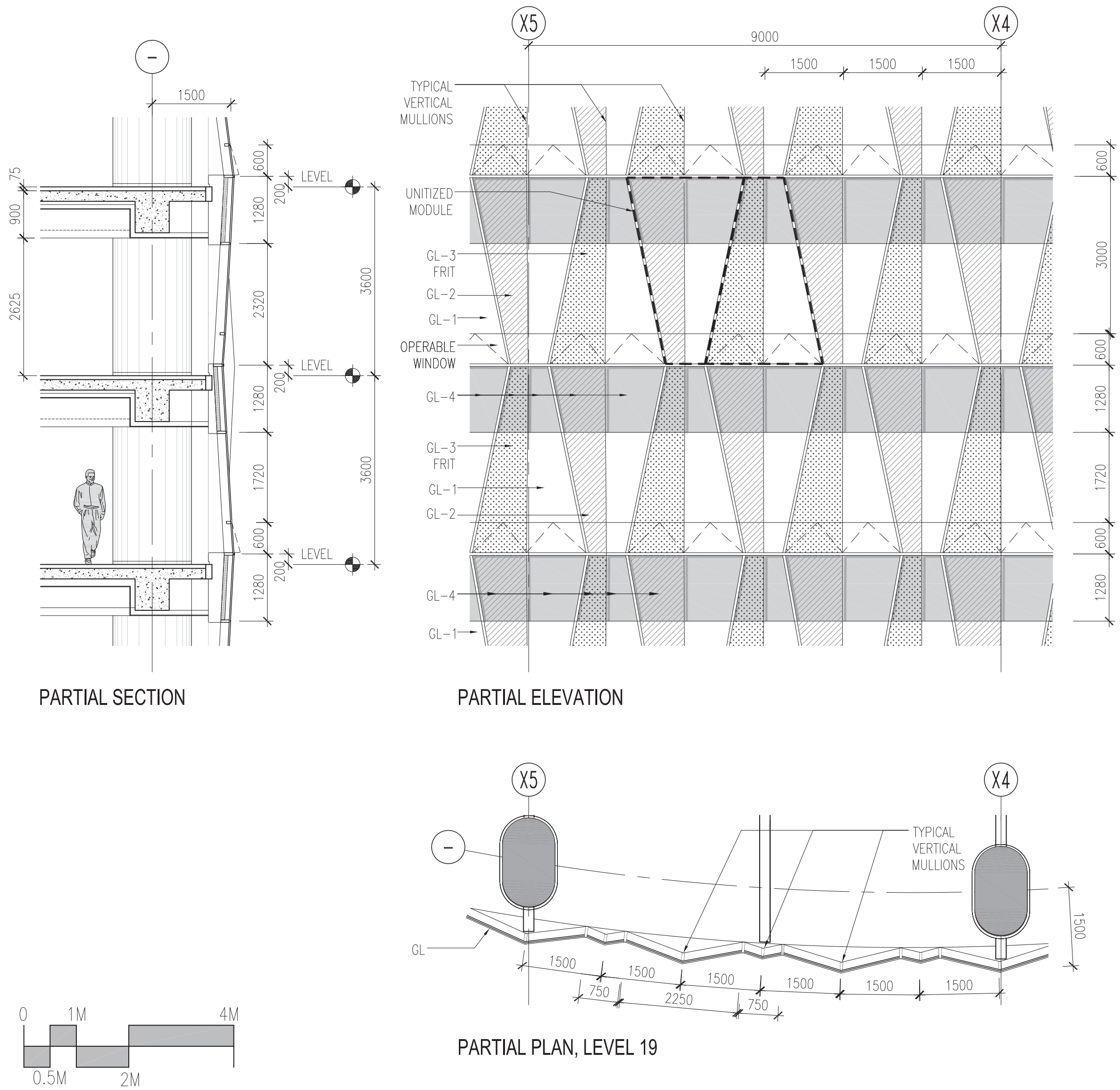


Figure 17: Projected 3D curtain wall: Faceted diamond option.

This scheme was the preferred curtain wall option by our client, infusing a visual complexity and uniqueness to the façade that would distinguish the tower on the Shanghai skyline while technically feasible in the local Chinese curtain wall construction market. Sustained dialogue with local curtain wall fabricators made this option realistically buildable for the client and their construction consultants. The cost implications of this curtain wall option, while not shared with our architectural team, was within acceptable range for the client.

However, changing the building program from office/hotel to a hotel/residential mix made this particular curtain wall option difficult to resolve and expensive to justify. A flattened 2D version of this scheme, which was previously explored but abandoned, quickly became much more financially desirable. As a residential façade, inclusions of recessed balconies and mechanical louvers were fairly easy to incorporate due to the faceted nature of the façade.

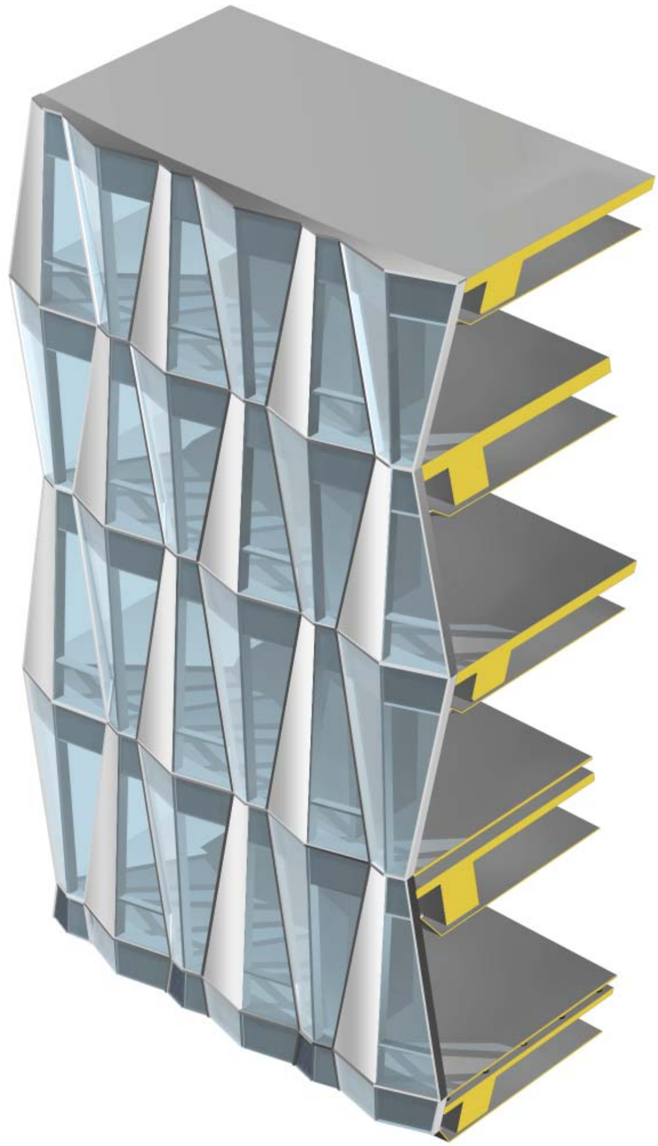


Figure 18: Inclusion of aluminum panels in building facade.

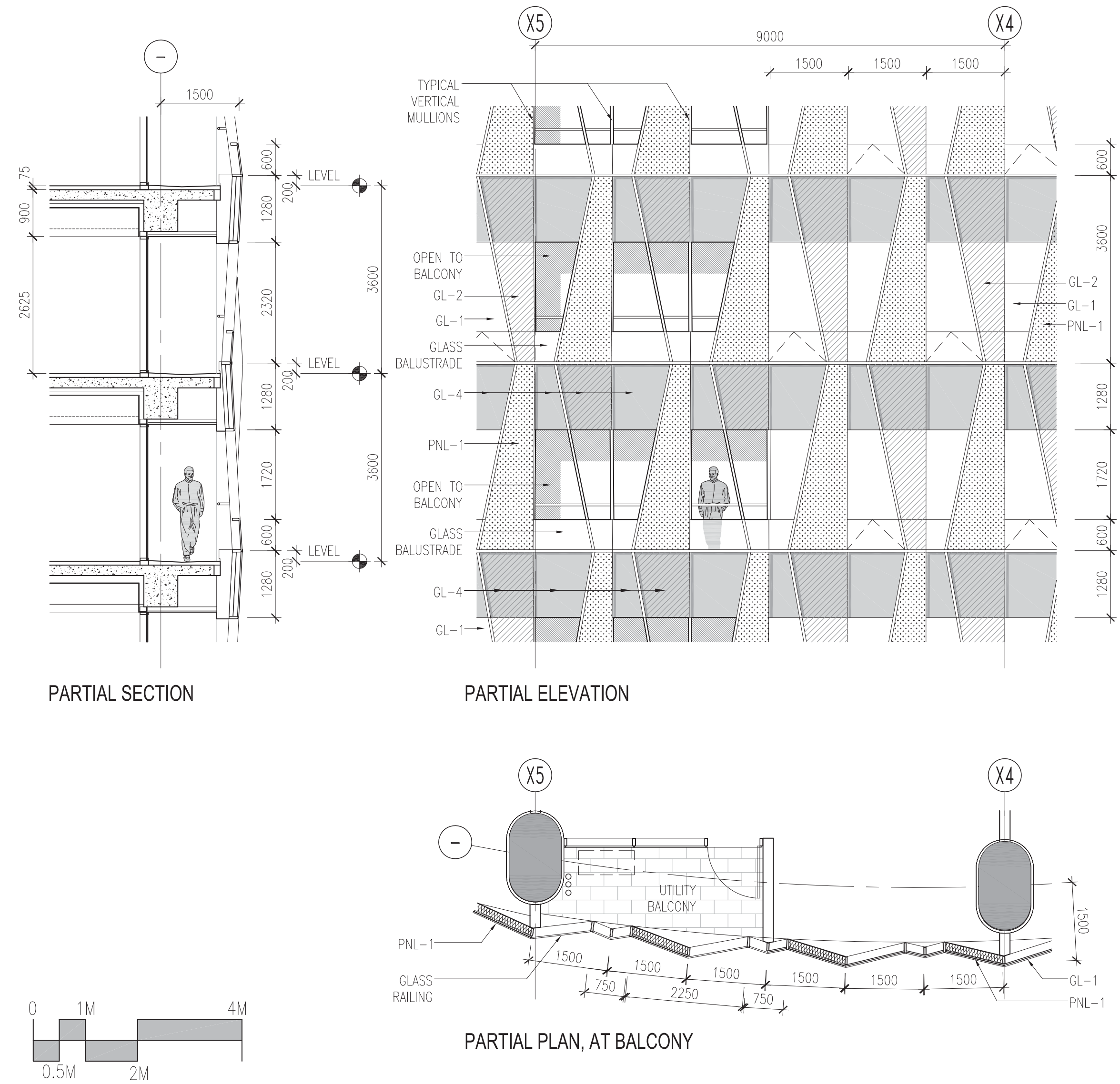


Figure 19: Inclusion of recessed balconies into facade.

2.6.1 Flattened 2D Diamond Pattern

As a fall-back to the client's preferred 3D projected faceted diamond curtain wall, we also had to develop a flattened 2D version of it. Overall, the visual impact could be similar, though without the 3D angled layout of the glass planes, the shimmering effect of the façade would not be achievable. Still, the much simplified technical resolution and detailing of this scheme was an attractive backup solution to the 3D façade option. This option became even more desirable once the tower program was revised to include residential apartments. Façade materials stayed the same as in the 3D version, relying on the faceted geometry of glass and aluminum panel layout to form the desired pattern. The unitized curtain wall module gets simplified to a regular rectangular unit. Without the projected 3D geometry, the sill and head "tongue and groove" nesting of the unitized modules was vastly simplified both structurally as well as in performance requirements. Inclusions of recessed balconies and mechanical louvers in this scheme would be the same as in the 3D option.

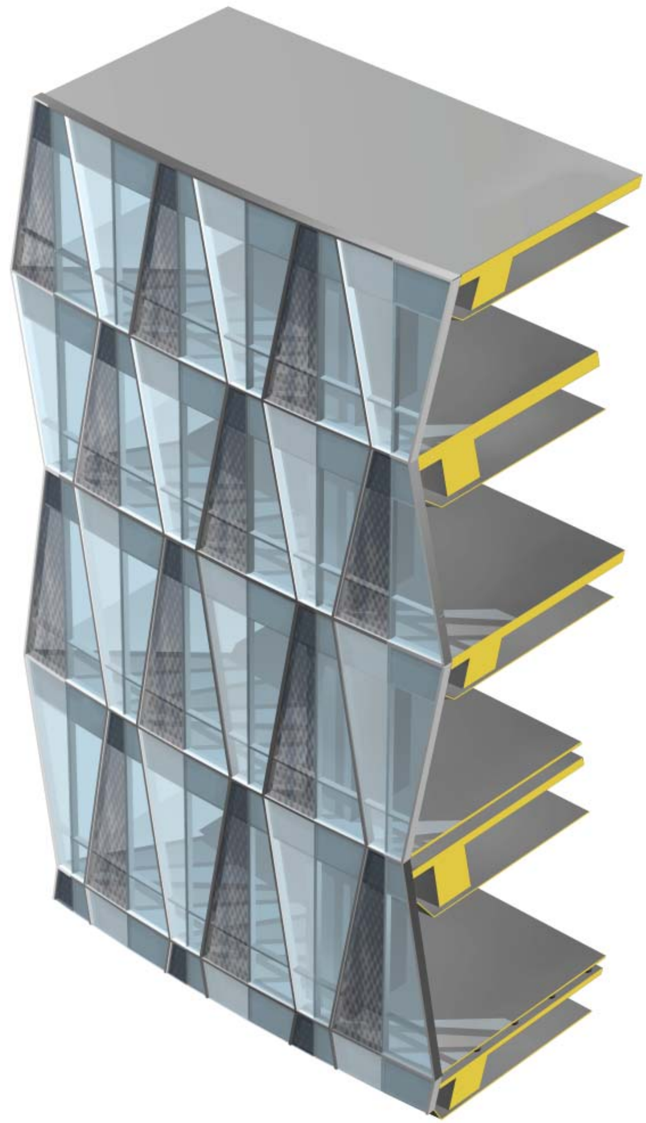


Figure 20: Flattened 2D curtain wall version of the faceted diamond option.

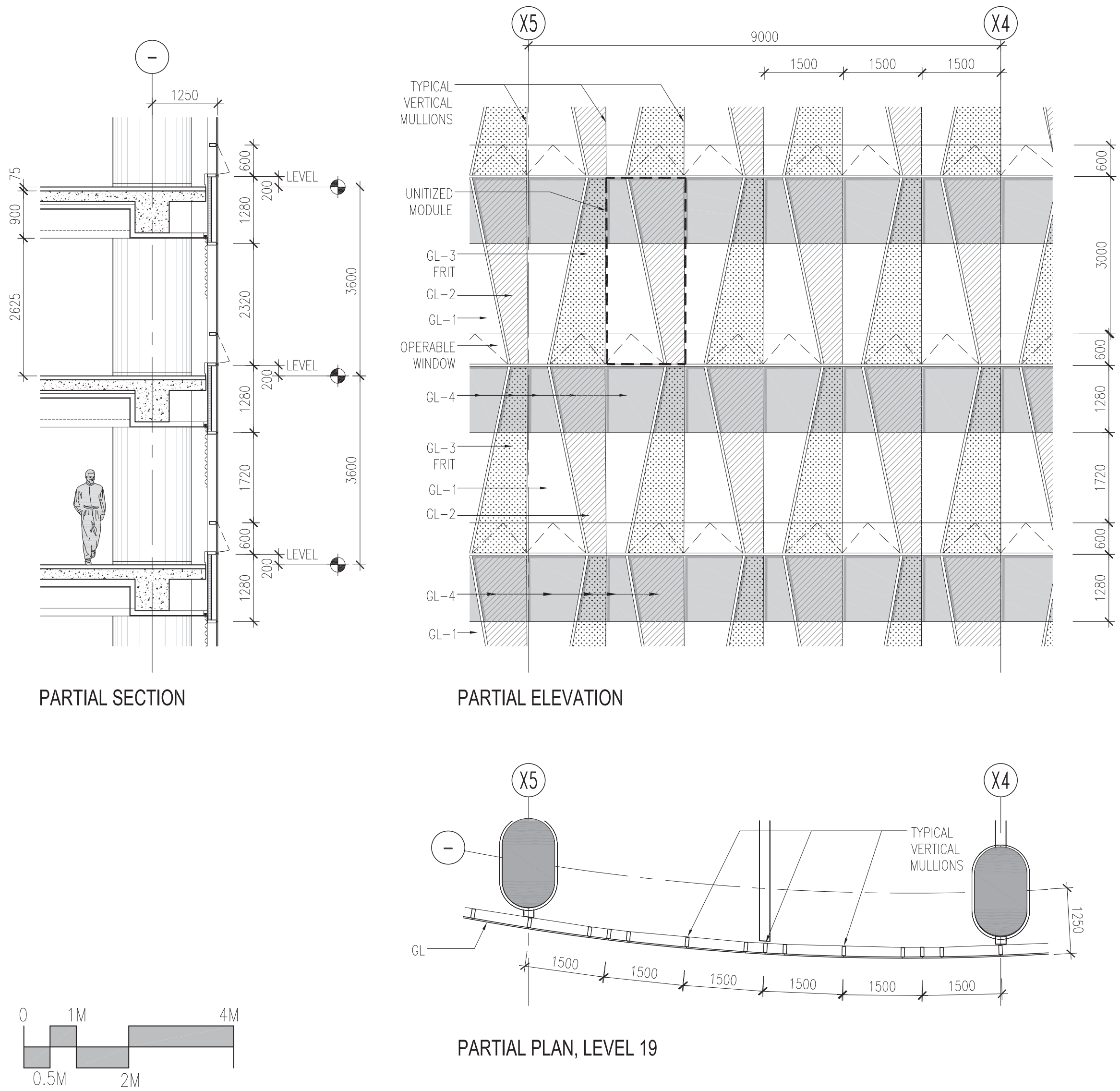


Figure 21: Flattened 2D curtain wall version of the faceted diamond option.

Figure 22: Developed first-phase design; Mixed-use site.

3.0 CONCLUSION

Creating unique curtain wall facades on a high-rise building requires constant dialogue between design aesthetics and technical solutions with heavy reliance on feedback from the curtain wall fabricators and engineers. In addition, solid and timely feedback on code interpretations is crucial, especially when designing in foreign countries and in sensitive urban environments such as the Shanghai Fisherman's Wharf site. Explorations of 3D projected facades need to be grounded in solid technical solutions particularly when dealing with the stringent envelope performance and structural requirements in tall buildings.

There are reasons why high-rise curtain walls tend to be built the way they are, thus any innovations need to look at the resulting technical and fabrication implications. Intricacies in the envelope system module, that seem easy to overcome on low-rise buildings, quickly become major issues on a skyscraper and even more so when the tower is already a complex 3D shape. Fabrication methods and ease of standardizing the façade module can have a serious impact on construction time and costs.

On our particular project, the most difficult and time consuming portion was in making alterations that would address particular code, zoning and ordinance restrictions. Permit approvals was a very drawn out process with constant options and sub-options needing quick architectural studies. Navigating complex codes written to address environmental impacts of previous generations of buildings needed constant negotiations to understand how they would impact our particular unique project. Major obstacles in our case were overcoming solar sun-shadow studies, glass reflectivity issues and resulting building reflectivity onto the residential neighborhood.

ACKNOWLEDGMENTS

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