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The Al Hamra Firdous Tower

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Aybars Asci

Biography

Aybars Asci, AIA, LEED®, leads an award winning design group at SOM, embodying a design philosophy that combines conceptual clarity with analytical processes such as the use of algorithmic tools and building performance modeling. He specializes in the development of iconic super tall towers. The projects he led have been widely published in international architectural magazines as well as publications like Economist and Fast Company. Science Discovery Channel recently featured an episode on Al Hamra Firdous Tower, the tallest structure in Kuwait. Mr. Asci has given various lectures in academic institutions, including Architectural Association, MIT and Tsinghua University.

During his tenure at SOM, Mr. Asci has worked in designing complex institutional and commercial projects around the world, including, the United States Census Bureau Headquarters, the New York Stock Exchange, 400 Fifth Avenue Residential Tower in New York, Al Rajhi Bank Headquarters in Riyadh, Al Hamra Firdous Tower in Kuwait, Al Sharq Tower in Dubai, Qatar Petroleum Headquarters in Doha, Wood Wharf Towers in London and Anida Residential Tower in Mexico City. Mr. Asci was a design director of SOM's London office during 2007-2008. He is currently located in the firm's New York office. He holds a Master's Degree from Columbia University.

Mark Sarkisian

Biography

Mark P. Sarkisian, PE, SE, LEED® AP is the Director of Seismic and Structural Engineering in the San Francisco office of Skidmore, Owings & Merrill LLP. His career has focused on developing innovative structural engineering solutions for over 100 major building projects around the world, including the 421 meter-tall Jin Mao Tower in Shanghai, China; the US Embassy in Beijing, China; the 412 meter-tall Al Hamra Fidrous Tower, Kuwait City, Kuwait; and the Cathedral of Christ the Light, Oakland, California. Mark holds four

U.S. Patents for high-performance seismic structural mechanisms designed to protect buildings in areas of high seismicity and has additional patents pending for seismic and environmentally responsible structural systems. He has recently written a book entitled “Designing Tall Buildings – Structure as Architecture” and has taught Integrated Studio Design classes that include students from University of California, Berkeley, California College of the Arts, Stanford University and California Polytechnic State University focused on the collaborative design opportunities. He received his BS Degree in Civil Engineering from University of Connecticut where he is a Fellow of the Academy of Distinguished Engineers as well as his MS Degree in Structural Engineering from Lehigh University.

Abstract

Al Hamra Firdous Tower, rising 412 meters and scheduled for completion in fall 2011, will be the tallest structure in Kuwait. A new landmark, this super tall expresses a remarkable visual dynamism, with concrete shear walls spiraling around a central void. A parametric design process was used for this iconic structure from conception to construction, were the genesis of its sculpted form, its environmental response to a harsh desert climate, and integration of architecture and structure from the overall form of the tower to its individual components were explored.

The hyperbolic paraboloid shear walls of the tower were designed and coordinated using Building Information Modeling, and early discussions with formwork contractors influenced the curvature of the form, enabling it to be built at the same pace as the planar core walls. Clad with trencadis, a type of mosaic, the custom stone cladding system allows a seamless definition of the complex curvature of the surface. An innovative lamella concrete structure of the lobby was developed from the desire of creating a larger entry space sloping outwardly from the tower above. A complex three-dimensional finite element analysis of the structure along with parametric modeling of form was developed to create the design and ultimately the formwork system of the structure.

The curving form required innovative in curtain wall and facade maintenance systems. Rather than approximating the curvature with facets, thirty percent of the glass on the tower is bent to smoothly define the geometry of the tower. Extensive glass research with multiple mock ups was required to find an optimal solution to meet both the visual qualities and the stringent performance requirements for the harsh desert climate. Custom solutions were developed for the façade maintenance systems occupying the complex three dimensional roof geometry of the tower.

Figure 1. Al Hamra Firdous Tower Rendering

Keywords: parametric, hyperbolic parabolid, pile foundation, lamella structure, torsional

Overview

Located on a space-constrained site at a prominent intersection in the center of Kuwait City with a total gross area of 186,000 sm of commercial office uses along with a 34,000 sm podium of retail/entertainment uses as well as an associated parking structure, the Al Hamra Firdous Tower sets itself apart from other super high-rise buildings with its unique sculpted form. An example of architectural expression through structural form on a grand scale, the structural system and exterior form developed together in a process of symbiotic evolution. The building geometry is generated by a spiraling slice subtracted from a simple prismatic volume. The two resultant surfaces are hyperbolic paraboloid reinforced-concrete walls, which extend the full height of the tower and participate in the lateral and gravity force resisting systems.

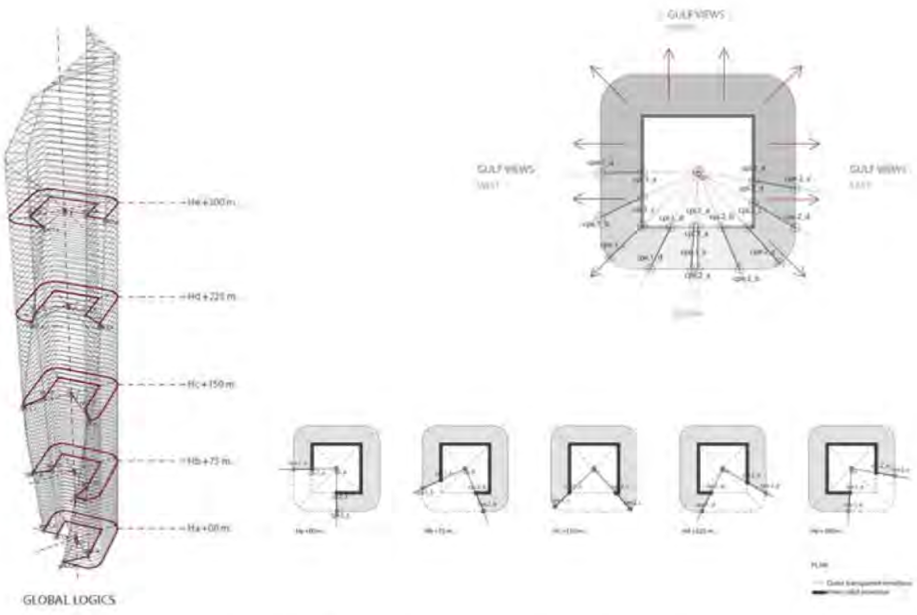


Figure 2. Defining Geometry and Views

The design of tower required consideration of challenging engineering issues complicated by both the height and form of the structure. The spiraling hyperbolic paraboloid – or ‘flared walls’ – required for gravity load support of the cantilevered wing of the building apply a torsional gravity load to the building core that necessitates consideration of both the long-term vertical and torsional deformations of the building structure.

Building a super tall tower was not the initial plan of the owners, a joint venture of a local developer and a general contractor. They had started the construction of a 50 storey tower with a 4 storey podium designed by a local architect, when Kuwait authorities changed the zoning to allow for a much taller structure on the site with the roof height limit increased from 200 m to 400 m.

Figure 3. Aerial Photo of Site

Form

During the planning process, the lease span was tested along the entire 60 meter square perimeter of the site and resulted in a 25% reduction of the floor plate to be taken meet the area requirements. The desire to maximize the views towards the water suggested that a removal of the floor plate should correspond to the southern edge of the square, facing the city. In parallel with this study, the design team analyzed solar and wind conditions to test the performance of different cut-out options. The solar analysis results favored a southwest corner cut, meanwhile the wind studies illustrated that an uneven cut was beneficial to disrupting organized vortex shedding resulting in confusion of applied wind loads. The resultant form that removes one quarter of the floor plate starting from the southwest corner at the base transitions to the removal of one quarter of the floor plate at the southeast corner at the top.

Figure 4. Form of Tower

The spiraling geometry was developed by subtracting a quadrant of a typical filleted square floor plan and incrementally rotating the subtracted portion at each higher level. The surface generated by the cut slab edges is articulated as a stone-clad continuous ribbon which connects the hyperbolic paraboloid shear walls extending from the southwest and southeast corners of the central core (termed the 'flared' walls) and the roof of the tower.

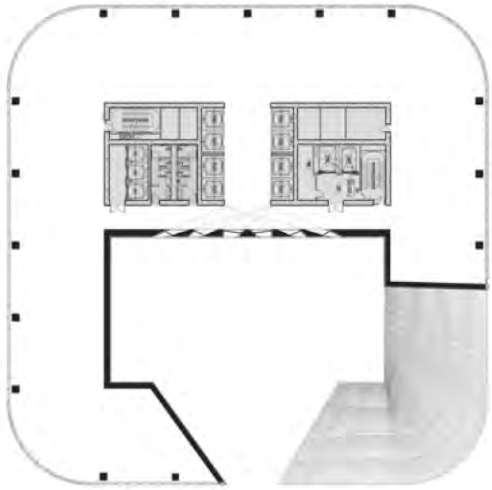


Figure 7. High-rise Floor Plan

Figure 6. Mid-rise Floor Plan

Figure 5. Low-rise Floor Plan

Figure 8. Shear Wall at South Facade

Figure 9. Framed City Views

Figure 10. Light Transmitted Through South Façade

Site

Geology
The Al Hamra site is typical for Kuwait City and consists essentially of silty sand with density varying from medium dense to very dense with cementation increasing with depth. Heavily cemented sandstone and siltstone is encountered approximately 75 m below grade. The local hydrogeology consists of a phreatic water level at 2 m below grade requiring temporary site dewatering during excavation and basement construction. The water level is predominated by rainfall that percolates into the ground with very little runoff to the sea. Evaporation leads to high concentrations of soluble salts, resulting in an aggressive chemical environment for below-grade concrete construction.

Seismicity
Kuwait City is known to be located in a region of low seismicity. However, given the low incidence of seismic activity in the area and the short history of significant urban developments, there is little published information about the level of seismicity. Seismic parameters established in TI809-04, Seismic Design for Buildings, published by the US Army Corps of Engineers, was used along with the seismic provisions of ASCE 7-02 (referenced from IBC 2003) for design.

Wind
The synoptic wind patterns in the gulf region are the result of the large scale movement of air channeled along the north-westerly/south-easterly axis of the Persian Gulf. Very localized and short term wind phenomena are known to exist in the Gulf region due to thunderstorms producing strong downbursts close to the ground. The project Wind Engineer BMT Fluid Mechanics Ltd (BMT) established a basic mean hourly wind speed of 23 m/s at 10 meter height in open terrain. This value represented the 50-year return period synoptic wind event consistent with the methodology of ASCE 7-02. After extensive study of the non-synoptic thunderstorm wind events it was determined that although these events could generate greater wind speeds than the synoptic events between ground level and an elevation of approximately 150 m, the thunderstorm events resulted in significantly lower wind speeds higher than 150 m above grade. While the thunderstorm wind profile could prove to be the critical wind event for the structural system of a tower lower than 200m in height, the gross effect of the synoptic wind profile over the full height of the Al Hamra Tower, controlled the design in all aspects other than localized cladding pressures on the lower stories.

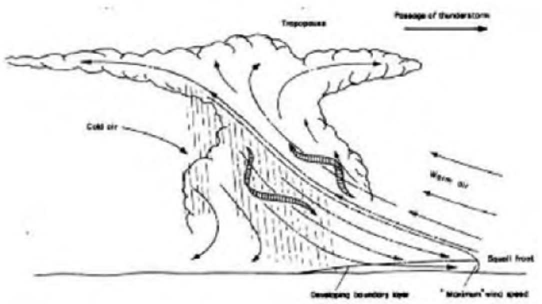


Figure 11a - Structure of a Thunderstorm Cell (from E SDU Item 87034)

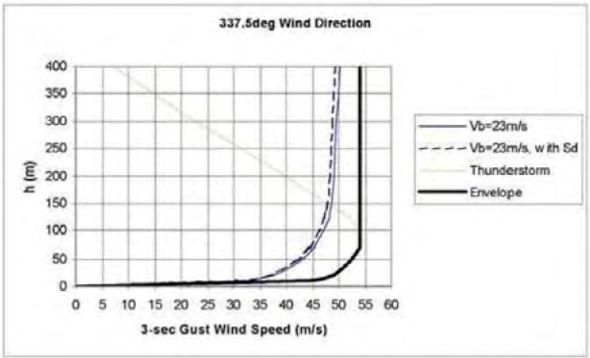


Figure 11b - Comparison of Synoptic Wind and Thunderstorm Gust Profile

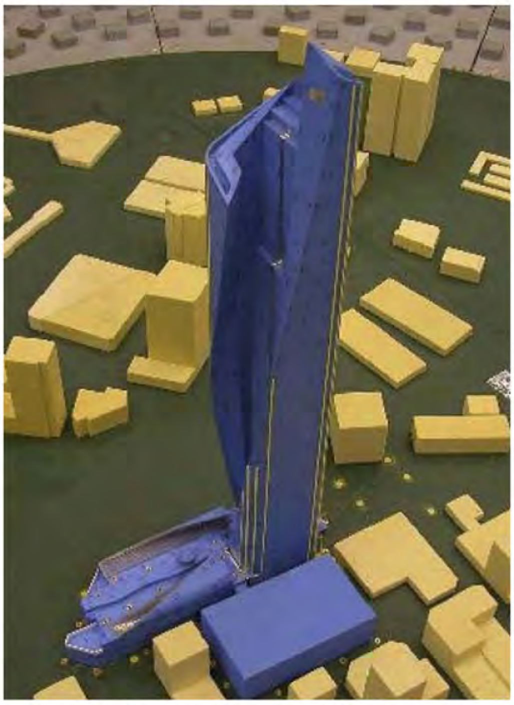


Figure 11c - Wind Tunnel Study Model

Figure 11. Wind Engineering Studies

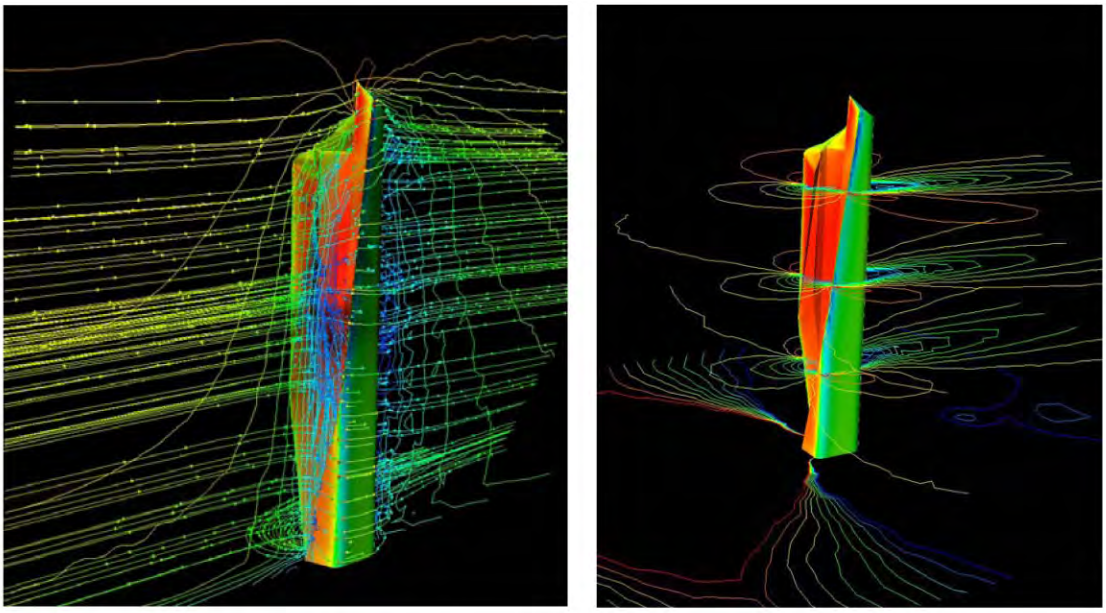


Figure 12. Air Flow Studies Considering the Tower Form

Foundations

Pile Phasing

Based on these initial calculations and the local knowledge of the geotechnical engineer, CGC Consultants, it was determined that a raft foundation supported on cast-in-place bored piles would be needed. Local construction techniques dictated the maximum pile diameter (1200 mm) and soil conditions dictated the closest allowable spacing (3600 mm center-to-center), allowing for calculation of the expected pile load demands and for the commencement of a pile load test program.

Considering fast-track construction, 289 piles were released and constructed in 7 phases working inwards towards the piles beneath the southwest flared wall. The duration of piling works allowed the design of the superstructure to mature and the final mat foundation construction drawings to be completed as work progressed on site.

Foundation Analysis and Design

Because of the complexity of the project, the San Francisco office of URS Corporation (URS) was retained to perform a peer review of the recommendations of the project geotechnical engineer (CGC Consultants) in a process including a full three-dimensional non-linear analysis of the soil strata under and around the foundations of the tower. Both analysis approaches were separately used to generate effective soil spring stiffnesses, accounting for the combined effect of mat and pile in each of the zones under the mat.

The final design of the raft foundation was for a 4.0m thick raft approximately 70 m by 60 m in plan dimension with an additional 1.6m thick triangular section of raft approximately 24 m by 12m in a region to the north, beyond the footprint of the tower. The tower raft is supported by 289 piles each 1200 mm in diameter and varying in length from 20.0m to 27.0m measured from the bottom of raft. The design concrete compressive strength of the raft was 50 MPa (cube compressive strength), and varied in the piles from 55 MPa to 80 MPa (56-day cube compressive strength).

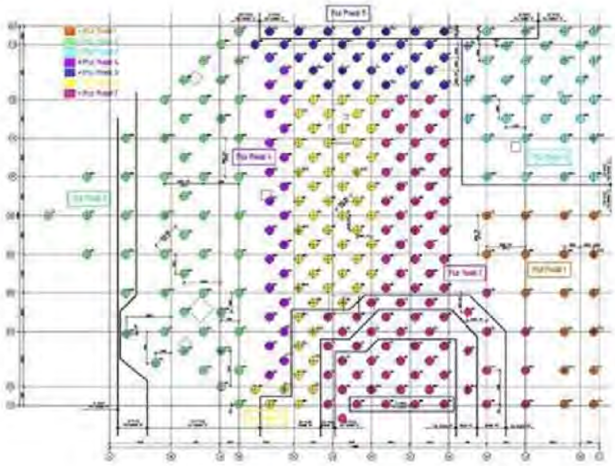
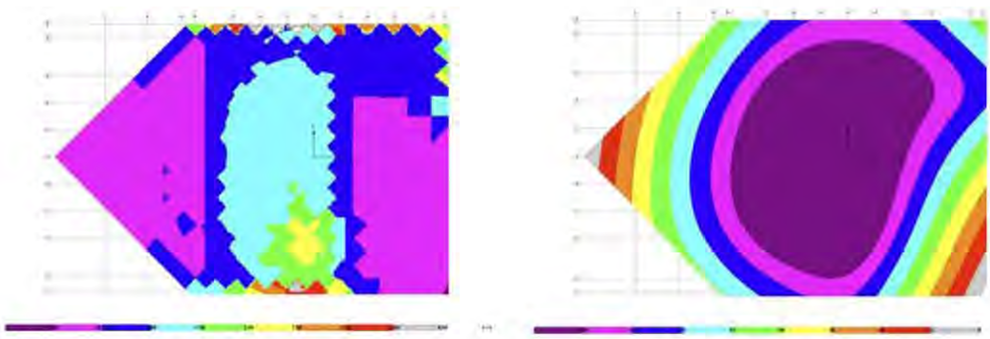


Figure 13. Pile Construction Phasing



14a. Beaming Pressures on Raft

Figure 14b. Deflected Shape of Raft

Figure 14. The Effects of Tower Load on Raft Foundation

Concrete and Reinforcement Durability for Foundations

To provide an appropriate level of durability to the sub-grade concrete construction, the effect of the corrosive environment on both the concrete and concrete reinforcement was considered. Moderate heat of hydration and moderate sulfate resistant cement (Type II) was specified for the subgrade construction. This cement was determined to be the most appropriate compromise between the corrosion resistance requirements and the need to control the curing temperature of the 4.0m thick mat in the hot desert environment in Kuwait. The subgrade construction was further protected by a complete waterproof membrane on the external surfaces of the raft and the foundation walls. The piles, the bottom layers in the raft, and the outer curtains in the foundation walls were all designed to be reinforced using corrosion-resistant reinforcement manufactured by MMFX technologies corp. Clear cover requirements of ACI-318M were also increased to 100mm to further protect the pile reinforcement. As a Contractor substitution the corrosion resistant reinforcement was ultimately eliminated from the project, replaced by an engineered cathodic protection system.

Raft Construction

The raft foundation was poured in 15 separate pours, over the total period of four months because of limit batch plant capabilities. This segmented approach to the raft pour was beneficial in limiting the peak concrete curing temperature with insulation preventing damaging temperature differentials building up near the concrete surface. Concrete curing temperatures were further minimized with the use of a high volume fly-ash cement replacement concrete mix.

Superstructure

Lateral Force Resisting System

The lateral system for resisting the controlling wind and gravity load combinations consists of a cast-in-place reinforced concrete shear wall core supplemented by a perimeter moment resisting frame. The shear wall core was designed with thicker walls on the perimeter of the core, optimizing the placement of material to maximize the resistance of the core to the gravity load induced torsion. The flared walls which connect back to the core also participate in the lateral force resisting system. As the shear wall core was resisting the majority of the wind induced forces, it was determined that the most efficient approach to the seismic design of the tower would be to designate only the reinforced concrete shear walls to be the seismic force resisting system. This allowed a full seismic design of the tower to be performed without needing to increase the use of materials anywhere in the structure. The reinforced concrete shear walls in the Al Hamra Tower vary from 1200 mm to 300 mm in thickness, and from 80 MPa to 50 MPa in compressive strength (cube compressive strength). The moment resisting frame beams are typically 800 mm wide by 600 mm deep and are poured with the floor framing using 40 MPa concrete (cube compressive strength).

Figure 15. Tower Under Construction

Shear walls on the south façade were engineered to incorporated complex, unsymmetrical cuts that placed to control heat gain and light into interior spaces. Custom reinforcing solutions were incorporated around each opening with specific geometry defined. A series of small openings are experienced by occupants as they circulate around the floor and look directly outward from the elevator lobby to allow for views of the city and the desert beyond. When walking along the interior of the south wall one experiences solidity with only light entering into the space through “cracks” in the wall.

Gravity Force Resisting System

By using a 160 mm slab spanning between beams at 6.0 m on center, only slightly more material was used than a solution with a thin slab spanning 3.0 m on center, but a greater proportion of the materials used contributed to the diaphragm shear capacity of the slabs. 700 mm deep reinforced concrete gravity beams span 10.6 m between core and perimeter frame. The perimeter columns vary from 1200 mm square to 700 mm square. Composite columns are used from mat foundation level to level 29, with embedded W360 steel column sections of varying weights, allowing 1100 mm square columns to be used in all typical office floors from level 40 down to level 5. 1200 mm square columns are required below level 5 due to the increased story heights within mechanical floors and double height podium levels. Reinforced concrete in the perimeter frame columns varies from 80 MPa to 50 MPa (cube compressive strength), and beam and slab floor framing is all constructed using 40 MPa concrete (cube compressive strength).

Lobby Lamella Structure

Lobby Column Bracing

At the north side of the building is the main lobby of the office tower. The lobby is a 24 meter-high space that extends from the building core to the perimeter frame. To increase the area of the lobby the north columns of the tower, which are vertical from level 12 to the tower roof, slope away from the building core following a circular arch. The result of this movement is that the main tower columns passing through the lobby are 24 m-tall and curved, developing large bending moments in the columns.

Stability Analysis

A complete three-dimensional finite element analysis model of the lobby lamella structure was built to study the effectiveness of the bracing scheme that had been developed and to guide the architectural design of these elements. A series of non-linear buckling analyses were performed on the lamella scheme, each model adding the next layer of bracing elements. The models analyzed included “A” elements alone, “A” and “B” elements, all elements except “D” elements and finally all the lobby elements. The buckling mode of the first model was weak axis buckling of the “A” elements. The addition of the “B” elements reduced the weak axis buckling length of the “A” so that strong axis buckling controlled and reduced the proportion of the applied load that was carried by the “A” elements, due to the “B” elements sharing the load. The product of these two factors was that the buckling load increased by a factor of two. The addition of the “C” and “E” elements reduced the strong axis buckling length of the “A” elements, nominally increasing the buckling load further. However, up to this point the buckling load of the “A” elements was still slightly lower than their load demand. The addition of the “D” elements had the single biggest impact on the buckling load of the system. By tying together the “A”, “B”, “C” and “E” elements, buckling failure of any of these elements is effectively prevented and the critical buckling mode became the buckling of the “A” elements at the first conventional story above the lobby. This study confirmed the concept of the lamella bracing scheme and demonstrated the structural importance of all the elements in the lamella.


Figure 16. Rendering of Lobby Entrance

Lobby Construction

To prevent the duration of construction of the lobby lamella from having a negative impact on the overall construction schedule, the observations of the incrementally beneficial effect of adding bracing elements was incorporated into the design schedule. While the “A” and “B” element must be in place prior to the construction of the floor slab above, construction of the typical floors above is allowed to proceed as work continues on the lobby lamella. A limit on the number of floors that may be poured prior to installation of the “C” and “E” elements as well as another limit prior to installation of all the “D” elements. Shop drawings for all the work were generated from three-dimensional models of the lamella structure using Gehry Technologies’ digital software , with fiberglass formwork moulds being fabricated directly from these models.

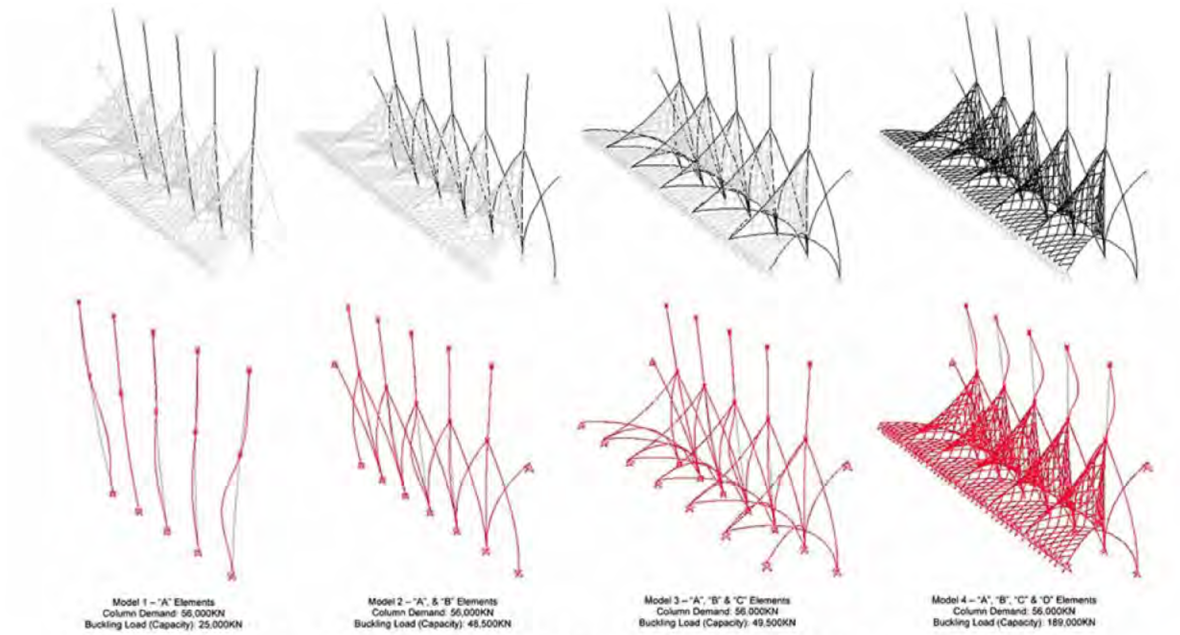


Figure 17. Buckling Analysis of Lamella Structure

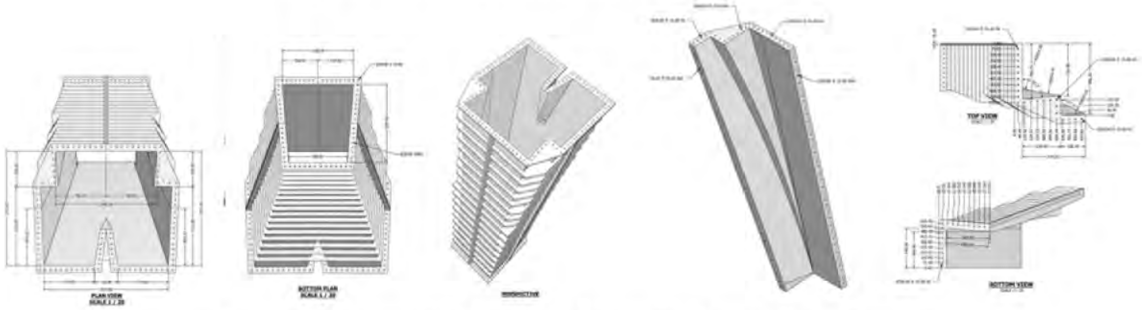


Figure 18. Parametric Modeling of Lamella Formwork System

Exterior Wall Systems

The conceptual development of the building enclosure reflects the conceptual framework of the tower. The outer boundary of the tower is conceived as a *'tectonic'* glass and metal curtain wall – that offers panoramic views of the Gulf from the office floors, whereas the sculpted inner surfaces of the tower are clad with limestone panels, reflecting the *'stereotomic mass'*– that shield the tower from intense solar exposure.

The unitized curtain wall is formed by typical panels of 1500mm by 4200mm in size. The performance objective in glass selection is to optimize the visible light transmittance to allow for maximum transparency, meanwhile minimizing solar loads. The daylight studies are also performed to avoid glare problems in the office spaces. The aesthetic objective is to visually create a tower as light in color as possible. In order to achieve a silver/white appearance for the building a series of mock ups tested fritting, inter-layers, coatings and a combination of all these. An important challenge in glass selection was that the 30% of all the glass used on the project is bent glass, which meant that insulated glass unit make-up had to be bendable.

Figure 19. Lamella Structure Under Construction

The south wall and the sculptural flare walls are all clad with jura limestone. The south wall has a staggered pattern of punched windows. The deep set windows allow for framed views of Kuwait City and the desert beyond. The enclosure is designed to create an open joined wall, following a pressure equalized rain-screen principle. The sculpted flare walls are rationalized as a series of hyperbolic paraboloids to enable ease of construction for the self climbing jump form system. The initial cladding option for these walls were to use 1400mm by 600mm stone slabs on a metal frame attached to the concrete substrate. In order to create an efficient panelization system, an advanced computational script is used. The resultant panelization allowed for 94% of stone slabs to be identical in size. Subsequently, the team has revised this wall type to a trencadis tile system that adheres directly to the concrete substrate. This artisanal approach uses jura lime stone in small randomized tiles. The resultant wall perfectly follows the doubly curved surfaces of the concrete, and much lighter than the initial panelized wall system.

Figure 20. Tower Construction Including Exterior Wall System

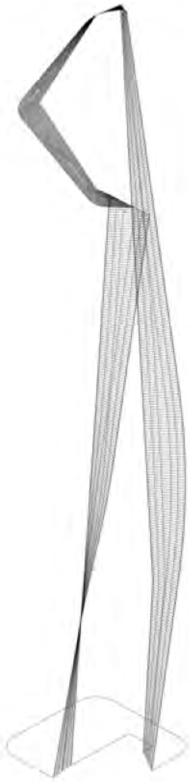


Figure 21. Parametric Modeling of Cladding

Figure 22. Sample of Trencadis Tile System

Figure 23. Trencadis Tile System Under Construction at South Façade

Conclusion

The concept for the tower was holistic, one that combined an iconic form with practical, regularly occupied spaces with a structure where all primary elements are functional while corresponding directly to the architectural solution. The regular reinforced concrete frame responds directly to organized and regular office spaces while the punched reinforced concrete shear wall on the south façade is used to control heat gain and light on interior spaces while efficiently resisting gravity and lateral loads.