



Title: **New Frontiers in the Design of Integrated Exterior Wall Systems**

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DECORATION

How do we see structures? Frames decorated with exterior walls? Some of these walls are quite fancy, using expensive materials to create a desired aesthetic often responding with color and geometry to particular site conditions or sometimes simply ignoring them.

In building construction, many have drawn analogies to the human body, citing the comparative relationship between bones (frame), circulatory system (mechanical / electrical / plumbing systems), and the skin (exterior wall). Isn't there more?

In many areas around the world, particularly Asia, structures can be considered decorated by the exterior wall system. Some good structural systems and their inherent ideas are covered to only be rediscovered with the eventual demolition, removal of the exterior enclosure or exposed through the occasional technical paper.

The idea that a structure is designed and built and merely decorated to achieve a desired aesthetic is of course not accurate although one might wonder the motivation behind many building projects. The exterior wall certainly serves many other purposes, not the least of which is to provide a weather enclosure, control exposure to sunlight, protect the occupants, and respond responsibly to energy use. From a structural engineering perspective, this exterior boundary defined by the building form provides great opportunities for sustainability, structural efficiency, and beauty.

HISTORICAL DEVELOPMENTS

The fire of 1871 devastated the City of Chicago, but created an opportunity to re-think design and construction in an urban environment, to consider the limits of available, engineered building materials, to expand on the understanding of others, and to conceive and develop vertical transportation systems that would move people and materials within taller structures.

In the late-1800s technological advancements led to the development of cast iron during the United States' industrial revolution. Although brittle, this material had high strength and could be prefabricated, enabling rapid on-site construction. The first occupied multi-story building to use this technology was the Home Insurance Building located in Chicago. Built in 1885 with 2 floors added in 1890, it was 12 stories tall with a height of 180'-0" but since has been demolished. It is considered the first skyscraper.



FIGURE 1 – HOME INSURANCE BUILDING, CHICAGO, IL



FIGURE 2 – MONADNOCK BUILDING, CHICAGO, IL

The 16-story Monadnock Building located in Chicago and constructed in 1891 used 6'-0", thick unreinforced masonry walls to reach a height of 197'-0". The structure exists today as the tallest load-bearing unreinforced masonry building. The 15-story, 202'-0"-tall Reliance Building built in 1895 used structural steel and introduced the first curtain wall system where buildings now could be conceived clad structural skeletons with building skins erected after the frame was constructed. The Reliance Building also represents the opportunities of creating enclosure and changing use over time. This building was converted from its original use as an office building to a hotel and still exists on State Street in Chicago.

Identity and egos fueled a tall building boom the late 1920s / 1930s with other urban centers outside of Chicago getting involved. The Chrysler Building in New York, the world's tallest was constructed with the Empire State Building in New York soon to follow. These structures and others were mostly constructed of regular steel frames clad with stone and metal.

World War II temporarily halted homeland construction because of the need for steel products in the war efforts. It wasn't until the late 1950s and early 1960s that interest in large scale buildings was renewed. Great architects such as Mies van der Rohe used structural steel to create a minimalistic architectural approach. His building projects included 860 & 880 North Lake Shore Drive (1951) and 900 & 910 North Lake Shore Drive (1956) as well as Crown Hall at IIT and the central post office in Chicago. Skidmore, Owings, & Merrill (SOM) developed building designs that used structural steel to create long, column-free spans allowing for flexible open office spaces while creating a corporate identity through the finished building. These projects included The Lever House – New York (1952), the Inland Steel Building – Chicago (1958), the Crown Zellerbach Building / One Bush Street – San Francisco (1959), and the expressive Alcoa Building – San Francisco (1964).

Developments in the 1960s, largely lead by Dr. Fazlur Khan, resulted in buildings where its exterior structure not only dominated its architecture but led to great advancements in management of imposed loads and structural efficiency. The Brunswick Building (1964) and Chestnut Dewitt Tower (1965) located in Chicago were major structures that incorporated this technology as well as an increased understanding of concrete's chemical and physical characteristics where consistently higher compressive strengths led to an economical option to structural steel in taller building structures. Many would argue that it wasn't until the design and construction of the John Hancock Center (1969) in Chicago that architecture and engineering were synergistically bonded with optimal structural efficiency.



FIGURE 3 – JOHN HANCOCK TOWER, CHICAGO, IL

OPPORTUNITY

Two office towers spaced 65 meters apart on one site created an unusual opportunity for an entrance pavilion for the Lenovo Raycom Phase II project. Inward facing shear wall cores allowed for the development of a minimal long-span structure using tensile members for primary support. This bridge concept allowed the walls to act at vertical piers accepting suspension cables. Exterior walls of the pavilion were created by regularly spaced vertical cables spanning from the roof structure to foundation and aligning with the glass module for the enclosure. Horizontal spacing of vertical cables is 2000mm with a cable diameter of 25mm. Four 130mm diameter cables spaced approximately 3000mm on-center span with ends embedded in the concrete web walls of the shear wall system. The cable drape from support to midpoint is approximately 3000mm. Suspension cables pass through castellated steel beams spaced to align with vertical cables. Prestress was introduced into the cable system to create initial stiffness, a distribution of point loads along the length of the suspension cable system through the castellated beams, provide support for the exterior glass enclosure system, and to provide resistance to any uplift forces that could be caused by wind.

Lateral displacement perpendicular to the entrance canopy caused by seismic and wind loads are resisted by two 75mm diameter parabolic cables located at and in the plane of the roof level. These cables overlap providing efficient resistance from loads in any direction. Springs were designed and placed below the structure at the entry level to maintain a constant force on each vertical cable accounting for any temporary vertical deformation of the suspension cable system due to snow loads etc. and any long-term deformation due to creep, shrinkage, and elastic shortening of the end piers/shearwalls.

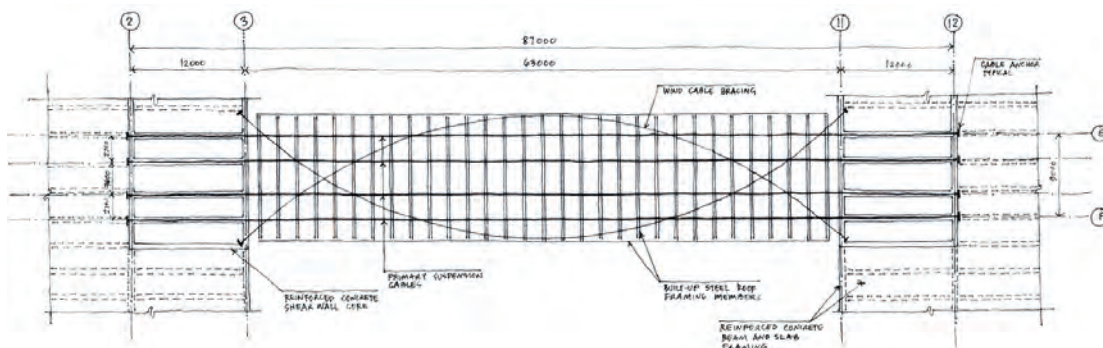


FIGURE 4 – ENTRANCE PAVILION ROOF FRAMING PLAN

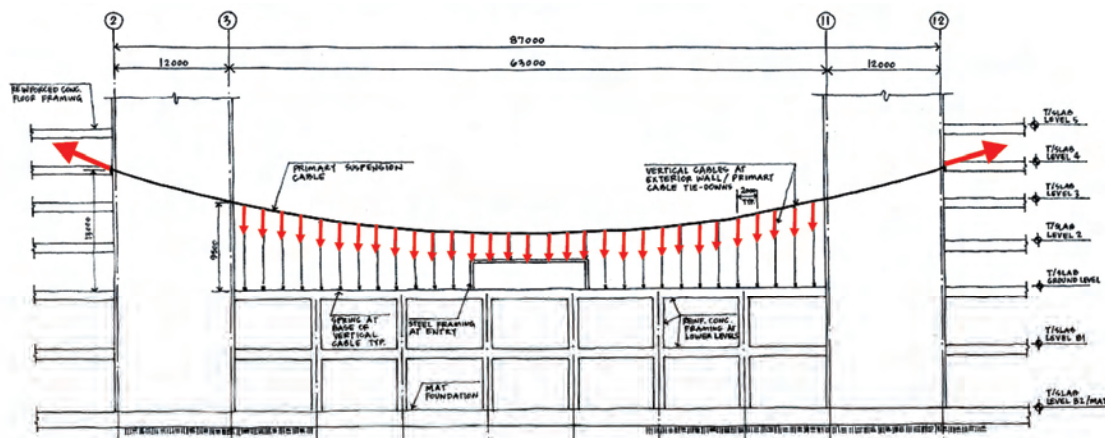


FIGURE 5 – ENTRANCE PAVILION ELEVATION AND FORCE DIAGRAM



FIGURE 6 – LENOVO RAYCOM PHASE II ENTRANCE PAVILION, BEIJING, CHINA

SCREEN WALLS

Screens have been used for centuries to create art forms, control light, and in some cases provide security. One might argue that the most beautiful screens are those that are created from strong frames infilled with delicate and sometimes asymmetrical patterns. The patterns within these screens many times act to brace what would otherwise be weak frames.

The initial architectural concept for the Goldfield International Gardens included what appeared to be elevations that containing a random spacing of transparent and opaque elements. Upon close evaluation, the elevations revealed patterns, albeit asymmetric, but repetitive. The idea of a large scale mega-frame, stiffened to provide enough lateral and gravity resistance using the same concept of the screen was conceived and introduced into the structure. The mega-frame is formed by a structural bay 9m wide and three stories high (12m high or 3 levels at 4m each). Each mega-panel is infilled with an asymmetrical frame only introduced to provide the appropriate lateral stiffness. The frame consists entirely of reinforced concrete with mega-frame section sizes of 1200mm x 1300mm for columns and 1200mm x 700mm for beams. The infill

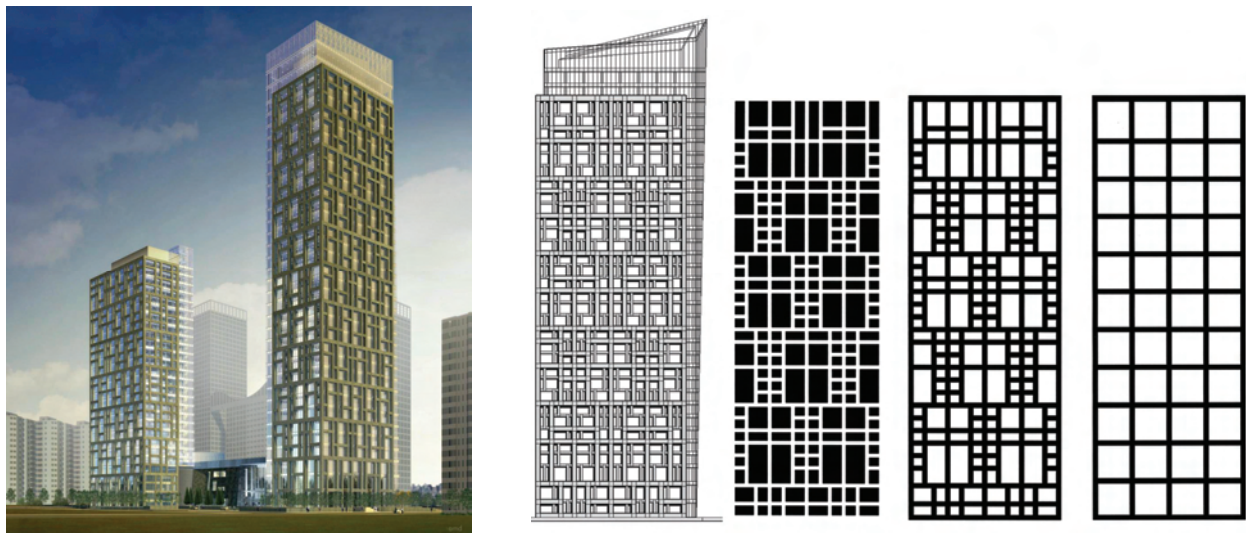


FIGURE 7 – GOLDFIELD INTERNATIONAL GARDENS, BEIJING, CHINA

frames include 900mm x 700mm column and beam elements. The main tower is 150m tall and incorporates the screen frame into two of the four facades with the other two facades regular, incorporating frames with columns typically spaced at 6m on-center. The second tower is 95m tall and also incorporates the screen frame into two of the four facades. These expressed asymmetrical frames incorporated calibrated stiffness to tune the structure so that frames on all sides had similar stiffness avoiding adverse torsional effects. The mega-frames and infill elements required detailing and member sizing to ensure strong column-weak beam behavior and the required ductility to resist strong seismic loadings. Finally, construction joints were introduced into the infill frames to keep any gravity loads from entering into the infill frames during construction as a result of creep, shrinkage, and elastic shortening of the mega-frames.

FOLDED PLANES

Dr. Fazlur Khan understood the limitation of conceiving a tall building as a tube, with solid but thin walls. Introduction of openings for windows was a must. However, he discovered that the placement and portioning of openings could still lead to an efficient structure. He transformed this idealistic concept into a constructible, affordable system by developing closely spaced columns and beams to form a rectilinear grid. Simply introducing diagonal members into the tubular frame achieved greater efficiency with height. This system was conceived for buildings consisting of all-steel and all-concrete.

The Jinao Tower in Nanjing, China, combines the use of local materials (reinforced concrete) and local labor to minimize cost for what would otherwise be a conventional tube-in-tube structure. By introducing a diagonal steel member on each façade with a primary connection every 4 stories on lower floors and every 5 stories on upper floors, 45% of the rebar and concrete required for the lateral system could be eliminated resulting in a 20% decrease in material overall. With the introduction of a single diagonal on each façade (diagonal on opposite façade completes x-bracing through the structure) the reinforced core wall system can be punched with multiple openings making it more frame-like. Loads are managed, optimally shared between the core and the perimeter steel pipe braces. These braces are nominally 500mm in diameter with a wall thickness that does not exceed 40mm. The bracing is inserted in a double wall system. The inner layer of this wall system is conventional and is directly connected to the concrete frame with the folded glass wall separated from the inner wall and connected to the diagonal pipe bracing system.



FIGURE 8 – JINAO TOWER
NANJING, CHINA



FIGURE 9 – CORNER
STUDY MODEL

NATURAL STRUCTURAL RESPONSES

Dr. Khan discovered that bundling tubular frames decreased shear lag. Shear lag is the inability of axial loads to flow around the cross-section of a tube when subjected to lateral load. Bundling the individual tubular frames not only decreases shear lag, but also increases efficiency. Efficiency is the ratio of axial column deformation to total deformation (axial, bending, and shear) in the tower. Khan sought solutions to the perfect tube and was able to increase the efficiency of the tubular frame from 61% to 78% (considering the geometry of the Sears Tower) by bundling the tubes, although he never achieved 100% efficiency.

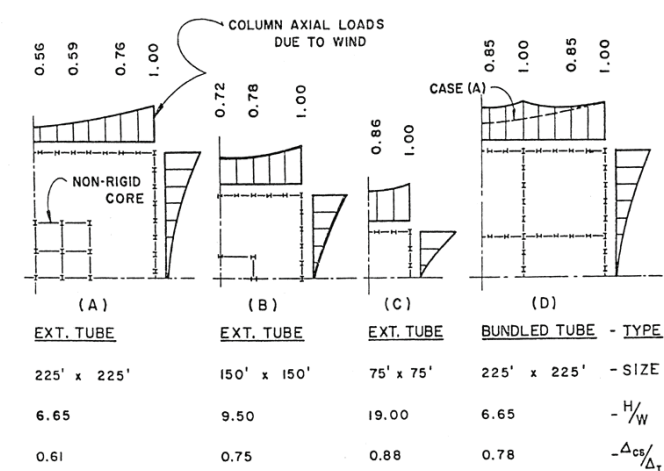


FIGURE 10 – DR. FAZLUR KHAN – TUBULAR FRAME EFFICIENCY

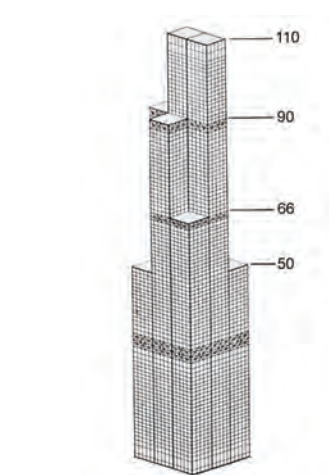


FIGURE 11 – SEARS TOWER BUNDLED TUBE

The Mesh-Tube conceived for the Jinling Hotel, Nanjing, China incorporates a fine diagonal mesh of structure at the perimeter of the building, eliminating any local shear or bending deformations of vertical members, resulting in an essentially 100% efficient structure, a structure that might lead us to expanding further the height limits of the high-rise.

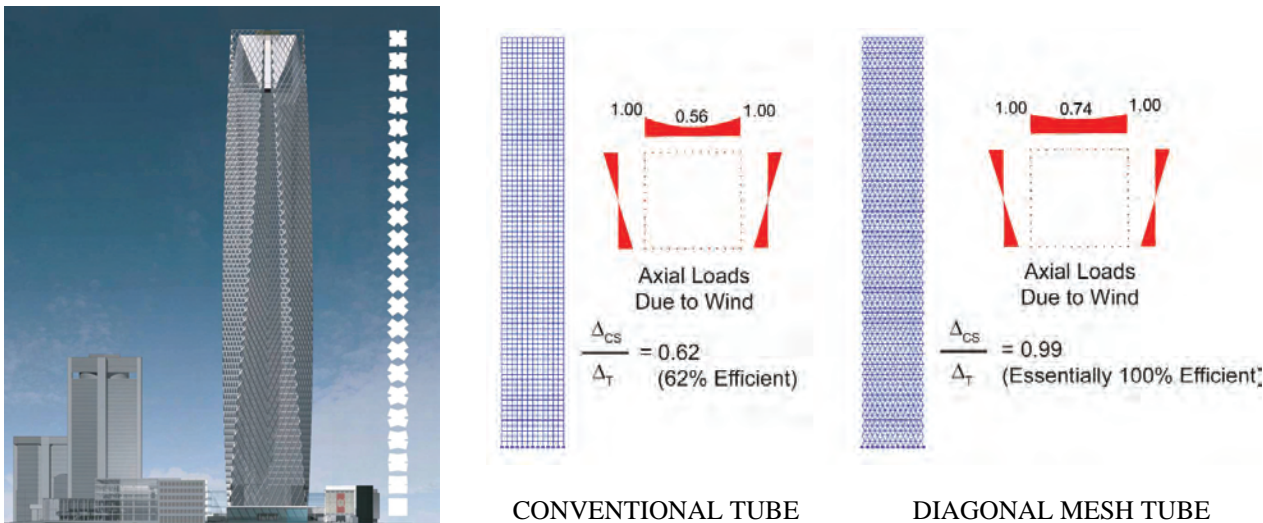


FIGURE 12 – JINLING HOTEL, NANJING, CHINA

Natural forms commonly occurring in nature provide the clues to optimizing structures. The shapes and structural systems are inspired by developing the optimal structural typology. The logarithmic spiral, repetitively occurring in natural forms ranging from plant growth to nautilus shells to weather systems, provides the inspiration for the radiating lines of the exterior structure. Based on derivations such as the Fibonacci Sequence, the logarithmic spiral defines typological lines that directly relate to natural demands on a structure. The golden or logarithmic spiral is constructed by a series of rectangles with length of sides that are based on the Fibonacci sequence with the quotient of each number divided by the previous number in the sequence equal to $\Phi=1.6$. This value is common to all growth patterns and natural forms.

Forms that illustrate the logarithmic spiral such as the hurricane or cut nautilus shell are typically perceived as plan objects. What if this form is projected on a vertical plane and in the case of the hurricane, transformed from a force-producing object to a form-resisting object? The highest wind forces of the hurricane exist along the wall of the eye with forces decreasing proportionally at distances from the eye and through the logarithmic spiral geometry. This concept, transforming a force-producing concept to a force-resisting structure is applied to the circular tower form of Wuxi Times Square.

The building structure separates the system of resisting lateral and gravity load. The gravity system would be built conventionally of steel, concrete, or a combination of the two (composite) with a structural steel mesh, mathematically described with the geometry of the logarithmic spiral, draped around it. Lateral loads travel through the exterior façade.

When a plot of the Fibonacci sequence is developed in elevation, one finds a strong correlation with the bending moment diagram of a cantilever subjected to a constant lateral load. With the plotted diagram converted to structural bracing and the geometry mirrored on top of one another, the form of the structure emerges with efficient resistance to load from any direction.

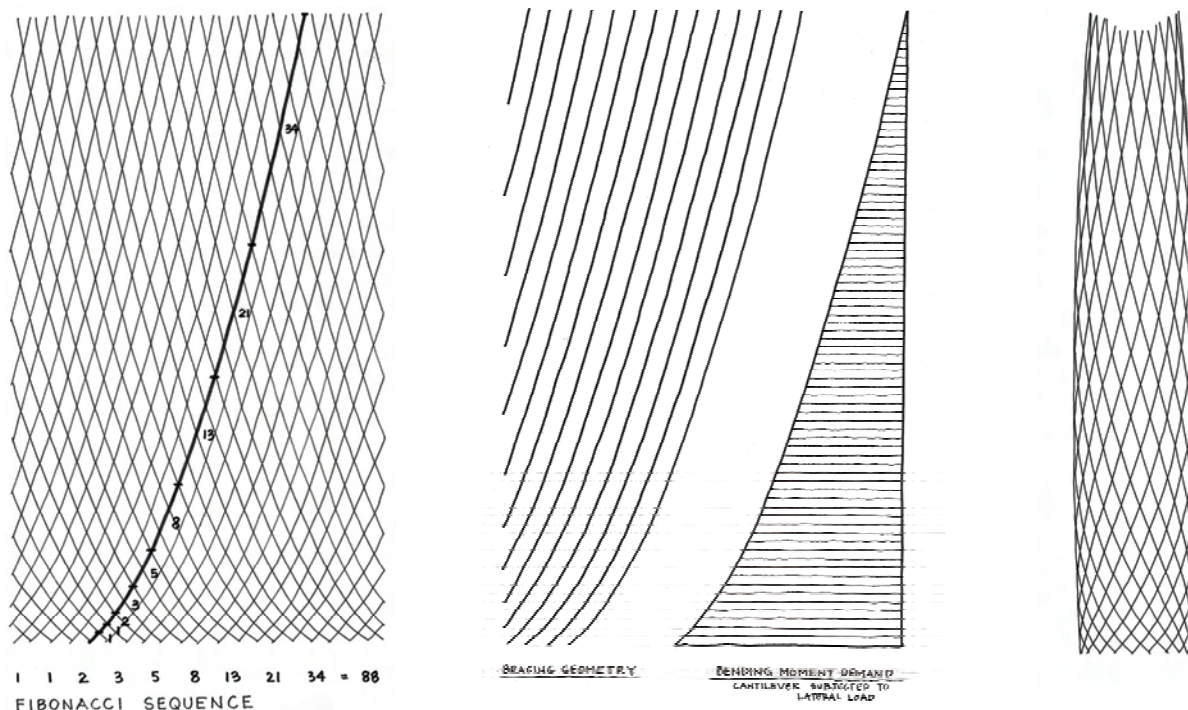


FIGURE 13 – FIBONACCI SEQUENCE AND BENDING MOMENT DIAGRAM – WUXI TIMES SQUARE

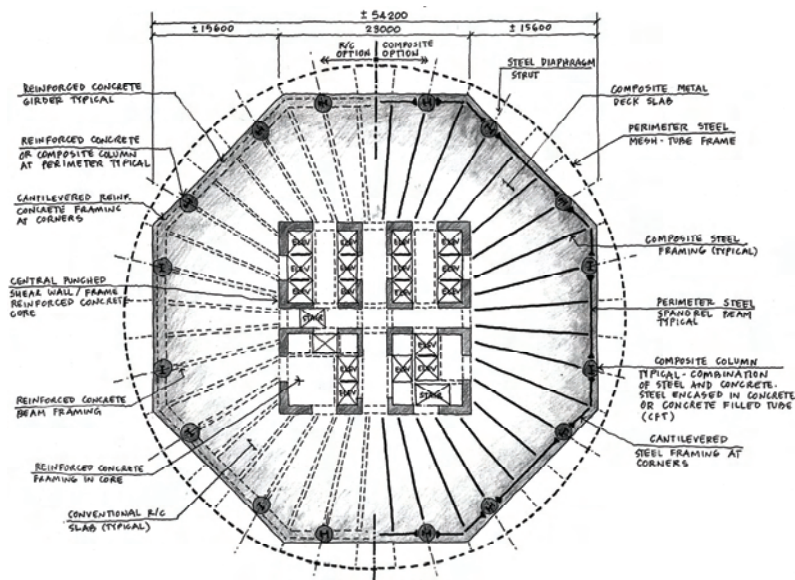


FIGURE 14 – TYPICAL FRAMING PLAN AND RENDERING, WUXI TIMES SQUARE, WUXI, CHINA

The spiral of the hurricane or other natural forms winds around a fixed center and gradually recedes from the center. Engineer Anthony Michell captured this behavior through his research in the early 1900s by describing the radiating lines of a pure cantilever, where force flow lines of equivalent constant stress result in specific spacing and orientations from the base to the tip of the cantilever with his studies based on a cantilevered object with two points of support. The bracing system, mathematically described and overlaid on the building form as developed for the Transbay Tower in San Francisco, provides the optimal structural system considering the boundary conditions of height, width, and the desired base configuration.



FIGURE 15 – WEATHER SYSTEMS

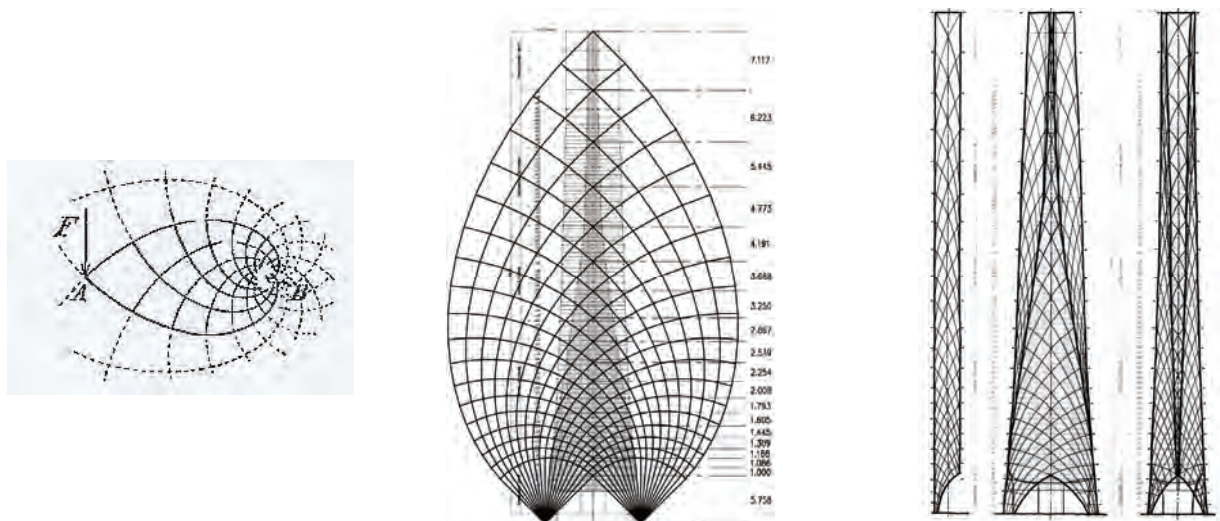


FIGURE 16 – MICHELL TRUSS DIAGRAM APPLIED TO THE TRANSBAY TOWER ELEVATION

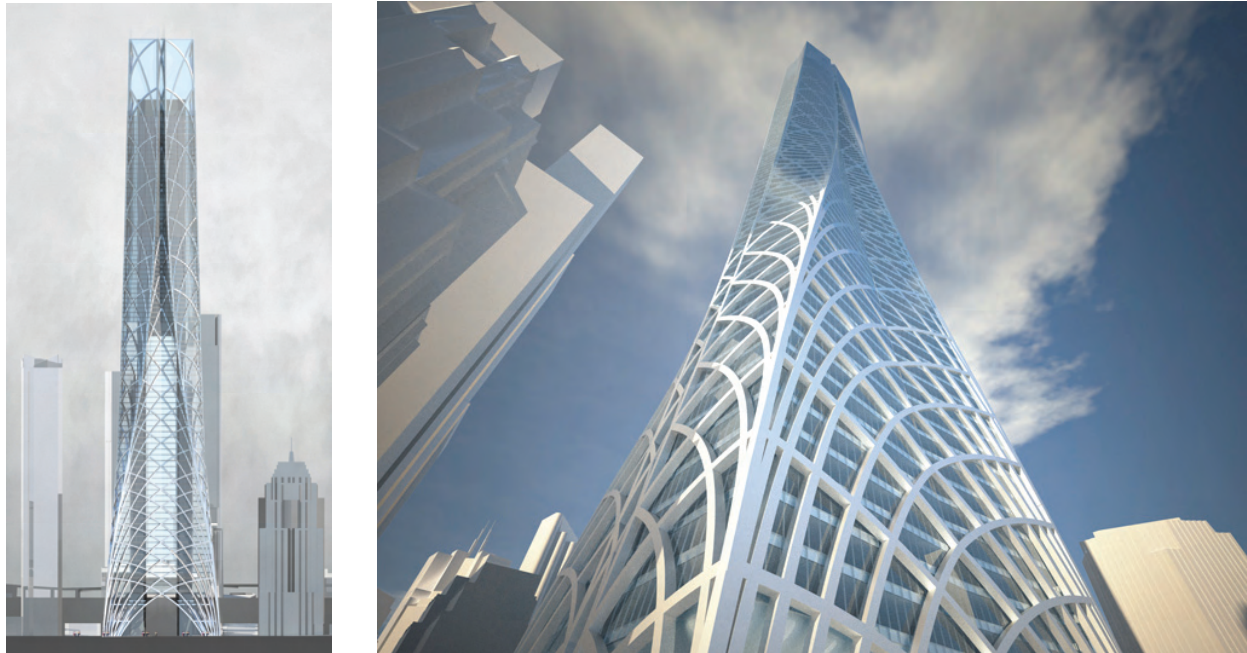


FIGURE 17 – TRANSBAY TOWER COMPETITION, SAN FRANCISCO, CA

10:1 ASPECT RATIO

The Al Sharq Tower with a height of 360 meters and a maximum plan dimension of 36 meters will not only be one of the tallest structures in the world, it will be one of the world's most slender with an overall aspect ratio (height relative to least structural plan width) of 10:1. Eight 12m-diameter tubes, each with an aspect ratio of 30:1 are gathered into a cell-like matrix. The center "tube" or shear wall core exists within the eight other tubes. The shear wall core extends slightly from the central core area between each of the perimeter tubes creating a truncated tic-tac-toe pattern in plan. The shear wall core wall system varies in thickness from 1200mm at the base to 600mm at the top. The entire perimeter of the structure is column-free. Slab edges are suspended with a high-strength, galvanized, spiraling cable system varying in diameter from 70mm at the base to 15mm at the top. Cables are nominally spaced at 1500mm and are anchored back into the core wall system over the entire height of the building. All slabs are designed without any drops and are typically 200mm thick. A structural steel section is incorporated into the slab edge to facilitate the cable connection and to provide collapse prevention in the event of losses of individual or groups of cables by transferring forces directly back to the core largely through cantilever action.

The cable system is used to manage and provide optimal distribution of gravity load throughout the structure and to provide ballast against large uplift forces caused by wind. The exterior wall enclosure for the building is very regular and is placed within and does not interconnect with the spiral cable structure.

Tied to Darwinian Evolution Theory and the science of genetics in living organisms, Genetic Algorithms were used to develop the most optimum structural solution. Information was generated for multiple structural models and stored in separate chromosomes. These chromosomes of information were manipulated through each generation until the algorithm was stopped or converges. Variables controlled in this analysis were:

- Number of Generations (In case of non-convergence)
- Population Size (Number of Chromosomes Per Generation)
- Structural Variables (Genes) Per Chromosome
- Cable Diameter
- Cable Slope
- Cable Spacing

Final results were based on and optimized to weighting functions that considered what conditions were most important to the structure. Since gravity loads were essentially constant within each cable, lateral loads imposed on the cables due to wind loads and overturning formed the basis for optimization. It was determined that it was optimal to have six (6) cables across each half of a circular section in plan. It was also determined that the cable size resulting from the best fitness score was 15mm in diameter unless, and perhaps most appropriately, the roof displacement was given a high weighting factor. With this weighting system, the cable diameter would need to be approximately 70mm. Computer programs used for this analysis include Visual Basic.NET Computer Programming Software and a Genetic Algorithm Toolbox. Strand7 was used for the Structural Analysis Software and Microsoft Windows was used as an interface between Visual Basic and Strand7.

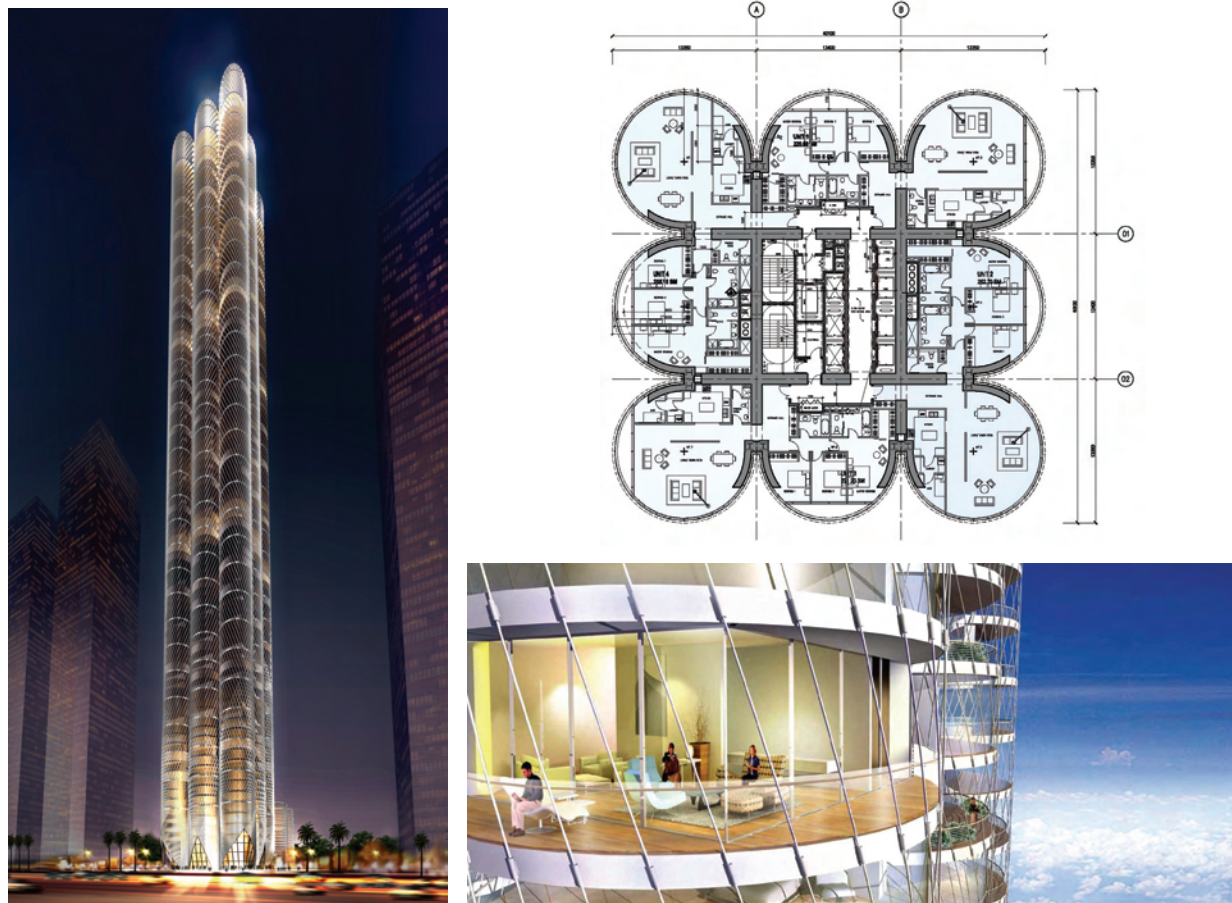


FIGURE 18 – AL SHARQ TOWER, DUBAI, UAE