NATURE | STRUCTURE
Structural Efficiency Through Natural Geometries

SKIDMORE, OWINGS & MERRILL LLP
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Inspired by the efficiency and adaptability of natural organisms, the SOM San Francisco Structural Engineering Studio develops sustainable structural solutions for some of the world’s tallest buildings. “Forms found in nature have superior engineering, inherent memory, and a great deal of elasticity,” says Director Mark Sarkisian, PE, SE, LEED® AP. Amalgamating engineering with biology enables high-rises to be super-efficient and durable. The benefits of using organic precedents for SOM projects has had a resonating effect throughout a design, improving the overall quality.

For nearly a decade, many of SOM’s most iconic tower designs have synthesized biomimicry (derived from the words bios, meaning life, and mimic, meaning imitate) and structural system design. Biological influences have led to innovative strategies in SOM architecture, yielding elegant, sustainable tower designs with high value in the global development market. Sarkisian began by investigating the cross-section of natural structures that exhibit an exponential growth pattern with mathematically predictable segmentations that brace the form, considering the growth patterns of bamboo and the fractal geometry of the chambered nautilus shell for clues about natural strength. The high-rise applications of these principles borrow specific sequences of the organic structures to replicate their most attractive attributes: a high strength-to-weight ratio, elasticity, long-term endurance, and a highly efficient form that resists loads and maximizes stability. As building structure, organic bracing is capable of fragmenting forces by sharing loads more uniformly within the structure and transferring them into the building foundation.

SOM’s building systems like the Pin-fuse Joint® and the New Beijing Poly Plaza’s rocker mechanism use the agility of systems found in nature to enhance their ability to cope with large forces. Applied to buildings in areas of high seismicity, these systems supply superior longevity to the structure. “The performance, reliability, and repairability of structural elements in the seismic force resisting system contribute to sustainable design. Time and cost savings can also be achieved since the building will be less disrupted for repair or rebuilding after an earthquake,” reports SEADNC’s Sustainable Design Committee.

New organic structural strategies rely on biological precedents to manage resource consumption and have a global impact on climate preservation. By integrating biomimicry into high-rises, SOM has increasingly refined and economized many structural forms, yielding multiple environmental benefits to the local microclimate over conventional structures. The use of efficient structural forms similar to those found in nature reduces the overall volume of materials required and eliminates large quantities of waste. Less building mass allows more ventilation to penetrate the urban landscape and prevents the urban degradation of natural wind flows which aid ventilation and cooling. It also increases the opportunities for natural daylight through enhanced connectivity to the outdoors. Additionally, reducing the surface area of the built mass minimizes thermal exchanges with the urban environment that disrupt its natural state.

**Introduction**

Biomimicry: Structural Efficiency Through Natural Geometries

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GROWTH PATTERNS
China World Trade Center Competition
While SOM developed the competition scheme for the China World Trade Center, Beijing, interest in bamboo as an architectural form led to the discovery of the properties of bamboo and how they might relate to the extreme high-rise. The natural formation of bamboo reveals unique structural characteristics. Long, narrow stems provide support for large foliage during its growing life while providing strong and predictable support for man-made structures after harvesting. Even when subjected to tsunamis, bamboo responds effectively and efficiently to lateral loads exhibiting the genius of natural structural properties and geometric proportioning. The nodes or diaphragms, as seen in rings over the height of the culm or stack, are not evenly spaced—closer at the base, further apart through the mid-height, and close again near the top. These diaphragm locations are not random and can be predicted mathematically. They are positioned to prevent buckling of the thin bamboo walls when subjected to gravity and lateral loads. This growth pattern is common to all bamboo. The nodes mark the location of diaphragms and provide the location for new growth. A slight change in diameter exists at node locations. Internodes exist between nodes. Internodes are hollow creating an inner cavity surrounded by a culm wall. Material in the culm is located at the farthest point from the stem’s neutral axis, providing greatest bending resistance, allowing gravity loads to exist only in the outside skin which impedes uplift due to lateral loads and minimizes overall weight. The cellular structure of the bamboo wall reveals tighter cellular density near the outer surface of the wall and less density near the inner wall. Again reinforcing the idea of maximum material efficiency when subjected to bending loads.

Bamboo consists of a culm, or stem, comprised of nodes and internodes. Nodes mark the location of diaphragms and provide the location for new growth. A slight change in diameter exists at node locations. Internodes exist between nodes. Internodes are hollow creating an inner cavity surrounded by a culm wall. Material in the culm is located at the farthest point from the stem’s neutral axis, providing greatest bending resistance, allowing gravity loads to exist only in the outside skin which impedes uplift due to lateral loads and minimizes overall weight. The cellular structure of the bamboo wall reveals tighter cellular density near the outer surface of the wall and less density near the inner wall. Again reinforcing the idea of maximum material efficiency when subjected to bending loads.

The geometric characteristics of bamboo are applied to the structural systems of the China World Trade Center Tower Competition submission. The tower is divided into eight segments along its height. The structural demand from lateral load is highest at the base of the culm (or tower) therefore internode heights are smaller compared to the mid-height. Smaller spacing increases moment capacity and buckling resistance. Beyond the mid-height of the culm (or tower) the heights of the internodes decrease proportionally with the diaphragm diameter. Thus, the form of the culm (tower) responds to structural demands due to lateral loads. The competition scheme for the China World Trade Center Superstructure developed with an internal core interconnected to a perimeter tube at mathematically defined locations to brace the frame against buckling in accordance with the growth pattern of bamboo are extremely efficient.
Drawing upon biology for structural concept for the Jinling Hotel Tower Competition in Nanjing, China enabled substantial reductions to be made in the amount of structural material and size of the structural members required for the perimeter frame. The spacing of the horizontal and vertical members in the frame of the tower utilize an efficient ratio. A smaller material mass for the structural frame allowed the SOM design team to enhance the quality of the interior spaces with natural daylight access, views, and natural ventilation while lowering its carbon footprint and environmental impact.

The mesh tube structure for this innovative tower is a hybrid of previously developed orthogonal structural systems and recently developed organic systems. The grid, which provides the outer structural frame, replicates the strong mesh of biological cell structures. This frame consists of a closely spaced diagonal membrane that is much tighter than a conventional diagrid form. “To resist lateral loads and achieve the goal of 100% structural efficiency, the verticals and the horizontals in the lateral system are combined to create a fine diagonal mesh, where every member is in tension or compression without bending, resulting in a structure that is optimally efficient with the strength and stiffness for a tall building,” explains Mark Sarkisian. The external structure doubles as an integrated shading device, mitigating energy-intensive cooling loads from solar heat gains on the glazed façade. The structural grid members are designed to be manufactured off-site to minimize construction waste and reduce on-site construction time.

As the building height increases, the concentric floor plates rotate to give the tower mass its organic structural stability. The spacing between the four vertical massing elements gets tighter at mid-height then the forms converge at the base so that the ground floors provide rigidity and balance while the upper floors are able to be less rigid where the wind forces are naturally greatest.
DIAGONAL SCREEN FRAMES
POLY INTERNATIONAL PLAZA
In 2007, natural forms and the goal of minimizing a structure's carbon footprint lead to SOM’s structural advancements in the design of the multi-award-winning Poly International Plaza in Guangzhou, China. The design for this tower uses principles of the natural segmented structural bracing found in plant organisms to form the innovative double lattice structural screen frame. External braces were engineered to support the loads of the column-free floor plates in the exceptionally slender, almost “billboard-like” towers. “The south working frame has two levels of diagonalization, working with the vertical piers to manage loads,” Mark Sarkisian explains of this perimeter structure. With the introduction of only three two-story diagonal steel members at the mid-height and top of the building, the south-braced frame was engaged with the north conventional frame in resisting lateral loads in the narrow dimension of the towers.

The super-efficient structures of Poly International Plaza provide a high degree of openness and minimize the use of virgin materials to achieve a dramatically lower carbon footprint. The planar external bracing structure on the south facades, which Sarkisian says, “was purposely pulled forward off the external wall to control temperatures,” acts as an integrated self-shading device controlling excessive heat gain and glare, especially in the summer months when sun angles are high. The spacing between the bracing structure permits low winter sun angles to bring daylight and warmth to the interior spaces during the cooler months. The design team implemented a shallow floor plan concept, which enhances natural daylight penetration in the building, improving the quality of the interior spaces, increasing productivity, and lowering energy demands for lighting. The bracing system on the south façade allows for a conventional orthogonal frame on the north façade resulting in open views to the Pearl River.
HURRICANE STRENGTH
TRANSBAY TOWER COMPETITION
Designed to exceptional standards of structural safety and environmental consciousness, the Transbay Tower Competition design for San Francisco, a city of high seismic risk, was an evolution of the external structural designs developed for the Jinling Tower and Poly International projects. The groundbreaking structural form, which is the result of the elegant adaptation of natural forces to the building structure, has an inherent organic symbolism and creates a unique design derived from the forces experienced in San Francisco.

The structural grid composition was based on the specific mathematical derivation of the perfect cantilever originally developed by Anthony Mitchell in 1904, offering an exceptionally strong and efficient geometry. Contrary to conventional belief, the purest cantilever is one with a bulbous shape, composed of radial force flow lines. Founded in the Fibonacci sequence and proportional to the spiral patterns of a nautilus shell or a hurricane, the structural grid was developed with a scaling factor that is most concentrated at a point and spirals out, becoming less concentrated. “The inner areas of the hurricane have the highest level of force with the forces reducing along the spiralling arms,” describes Mark Sarkisian of the energy that’s created by the natural forces of a hurricane.

Influenced by the hurricane, Sarkisian and his team developed a structure that would respond to the natural concentration of force in this super-tall tower. According to Sarkisian:

“The spiralling form provides the resistance and is based on the idea that every reaction has an equal and opposite reaction. The spiral, which has the greatest resistance at the center and the least resistance at the outer arms, was translated into bracing that would resist the lateral loads where they were naturally the highest with the tightest part of the spiral and lowest where the bracing was more open. The diagonals radiate from the corners of the tower where forces are the highest and transform to more open geometries near the top where forces are lowest. The applied wind load increases with height, therefore it is best to reduce the building plan size to reduce the surface area that will be subjected to wind. Integral forces generated by ground motions during an earthquake are collected within the superstructure and transmitted back into the ground. They too are attracted to supports in a radial fashion.”

This bold structural move allowed the design team to use the bracing for control of heat gain through shading of the façade while allowing for natural daylight and ventilation.
SACRED GEOMETRIES
THE CATHEDRAL OF CHRIST THE LIGHT
Two interlocking spheres create the principal geometry for The Cathedral of Christ the Light. The planar section of the geometry results in the sacred “vesica piscis” form, evoking the symbol of a fish. The shape recalls the ancient symbol of congregation, implements a sign of Christianity, and responds to the site’s close proximity to water. These interpenetrating circles are related to one another through the square roots of 2, 3, and 5, the first three digits of the Fibonacci sequence (other than binary digits). The height and the shape resulting from the intersecting circles are related by the square root of 3. The height, or the longitudinal length of the cathedral, is equal to the diameter times the square root of 3, or 1.7305, and the width or the transverse length of the cathedral is equal to the longitudinal length divided by the square root of 3. The geometric and mathematical applications of the resulting shape are the same as those commonly occurring in nature and in the order of the universe itself. Many natural phenomena express this sequence in their geometric structure, including the sunflower seedpod and the shape of hurricane patterns.

As an extension of the Cathedral’s fundamental architectural concept, the Great Doors are inscribed with adjoining circles. When closed, the doors form the vesica piscis shape. The Fibonacci sequence orders their vertical articulation. Custom door pulls emerge directly from the vesica piscis, their surface texture a topographic map of the spiraling Fibonacci sequence.

Many natural phenomena express this Fibonacci Sequence in their geometric structure, including the sunflower seedpod and the shape of hurricane patterns.
PIVOTAL MOVEMENT

THE PIN-FUSE JOINT®
While structural grid systems successfully provide exceptional strength and rigidity to SOM towers, resisting the shear forces of earthquakes also demand elasticity. Explains Sarkisian, “These buildings need to move, and where you find the need for movement the most is in certain areas of high seismicity.” Incorporating his patented Pin-fuse Joints®, the internal structural elements of towers are designed to have superior ductile strength. Pin-fuse Joints® emulate the pivotal movements of a human shoulder joint to work with the shear stress forces. This joint uses materials that allow engineers to define a certain coefficient of friction, so the joint remains fixed and then it slips during high loads. As soon as the load gets large enough, the joints start to move. By using this joint to provide localized flexibility, the earthquake forces can be dissipated and damage to the structure minimized. The increased durability of the materials in SOM structural designs provides the environmental benefits of a lower initial carbon footprint and the economization of lower life-cycle costs.
THE ROCKER
THE NEW BEIJING POLY PLAZA
The New Beijing Poly Plaza is located in an area of high seismicity, similar to San Francisco. SOM pursued a design concept that would allow the building to be displaced when subjected to a major earthquake. As part of the design, the eight-story museum element was suspended by diagonal cables in the lofty 295-foot-tall daylit atrium space. To prevent overstress in the cables during a large earthquake, a cast-steel rocker mechanism was devised to allow the building to move without inducing force into the cables. “You are able to design for a force level that is much lower than it would have been if you fixed this connection,” says Mark Sarkisian, whose inspiration for the three-story tall rocker mechanism came from the multi-direction rotation capabilities of the human arm. Staticlly the rocker mechanism stays in place, and then during an earthquake, the rocker moves. The rocker, which looks like a giant pulley system, is similar to the Pin-fuse Joint® concept.

*The natural response of the joint in the body is to release itself; the muscles respond to the different configurations but ultimately keep a fairly modest size allowing that rotation arm movement to happen,” Sarkisian explains.

Inspiration for the three-story tall rocker mechanism came from the multi-direction rotation capabilities of the human arm.
THE WEB

THE NEW BEIJING POLY PLAZA
The world’s largest cable-net supported glass wall enables daylight and views into the main atrium enclosure of The New Beijing Poly Plaza building. According to Sarkissian, this wall, which moves with the wind loads in Beijing, shares its principles of flexibility with spider webs that move considerably when exposed to loads. “They have to be very elastic because otherwise they’ll fracture,” says Sarkissian in reference to the delicate structure of spider webs. “It would be as if you took a spider web and filled glass panels over the top of individual cells and allowed for relative movement between those panels,” he explains.

The cable net is stiffened by two V-shaped cables that are counterweighted by the suspended museum. This expansive glazed cable-net system resists gravity and lateral loads using the giant rocker mechanism to return to its original position after deformation.

The flexibility of the web-like mesh system prevents fracturing under large loads, which eliminates future material waste. In this building, structural biomimicry helped SOM to advance structural innovation, create an iconic building, greatly reduce material quantities, and be sustainable in the process.