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Organic and Natural Forms in Building Design

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ABSTRACT

Safe, efficient structural forms are abundant in nature. The challenge, however, is to quantify these forms and to derive behavior that is adaptable, constructible and cost effective. Adaptations and mathematical derivations that use nature's mechanics in structural design have led to innovations in structural systems. These organically-inspired structural systems typically exhibit interesting aesthetic qualities which are not necessarily intuitive. Natural structural systems may also incorporate devices that understand and respond to demand, alter behavior, and ensure optimal performance. Three conceptual structural systems are considered which example the use of organic and natural forms in building design. First, bamboo geometric properties as they relate to structural efficiency are examined and applied to the China World Trade Center Tower Competition. Second, organic growth patterns form the perimeter structural framework of the Transbay Transit Tower Competition. Third, nature-inspired genetic algorithms are used to optimize the perimeter cable filigree of the Al Sharq Tower.

INTRODUCTION

The study of biological organisms and systems has long fascinated the scientific community. Intrinsic rules and relationships shape how elementary components can comprise complex organisms and systems. These rules and relationships often orchestrate growth of the higher-level system without global oversight or guidance. Scientists have observed that these systems are organized, stable and complex. Emergence is a theme observed in nature which suggests that complex, organized, and stable organisms and systems arise from relatively simple sub-components and their interactions without external guidance.

An example of an emergent system is the ant colony. Although the queen ant is the only member creating children, she does not direct the ant colony as a whole. The success of the colony is entirely dependent on basic relationships between ants without supervising guidance, yet they are known to be highly organized. Also, the structures ants build are the result of an emergent process as they are built based on basic rules and regulations, but without a master plan. In spite of this, ants can build very tall and stable structures with self-cooling characteristics, as shown in Figure 1a. Another example of an emergent system is the bone structure of a bird's wing. Bird bones are to be light and structurally efficient to improve the capabilities of the host

a. Ant Colony b. Bird Wing c. Honeycomb

Figure 1. Examples of Emergence in Nature

bird. Over time, bird wings have developed light-weight truss systems inside their wing bones, as shown in Figure 1b. Bone framework is the result of small, unguided changes over time, and therefore is an example of emergence. A third example of emergence is the honeycomb. Bees build individual hexagonal compartments based on instinct and a highly efficient structural and storage system emerges, as shown in Figure 1c.

An intriguing example of emergence is a piece of artwork created by David Nash called *Ash Dome* (2007) (Figure 2). *Ash Dome* is a set of 22 trees set in a circular pattern. The trees were grown under typical conditions except David Nash tied the tree to the ground every few years at various locations causing them to grow at a stepped incline. This example shows that emergence can be purely natural, man-made, or a combination. Emergent organisms respond to constraints using basic materials related by intrinsic rules to create a solution in equilibrium. The result can be functional, aesthetic, or both.

Figure 2. *Ash Dome***, by David Nash (2007)**

The concept of emergence can be used by engineers when they seek organically-inspired solutions. The current study investigates some of these concepts. First, bamboo geometric properties as they relate to structural efficiency are examined and applied to the China World Trade Center Tower Competition. Second, organic growth patterns form the perimeter structural framework of the Transbay Transit Tower Competition. Third, nature-inspired genetic algorithms are used to optimize perimeter cable filigree of the Al Sharq Tower.

CHINA WORLD TRADE CENTER TOWER COMPETITION

The natural formation of bamboo reveals unique structural characteristics. Long, narrow bamboo stems provide support for large foliage during its growing life while providing strong and predictable support for man-made structures after harvesting (Figure 3). Even when subjected to Tsunamis, bamboo behaves effectively and efficiently to lateral loads exhibiting the genius of natural structural properties and geometric proportioning. The growth characteristics are not random. Diaphragm elements are not evenly spaced over the bamboo's height, but are is mathematically predicable.

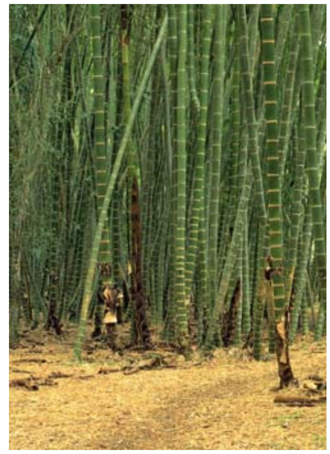


Figure 3. Bamboo

Bamboo consists of a culm, or stem, comprised of nodes and internodes as illustrated in Figure 4. 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. The diaphragms provide resistance to culm wall buckling over the height of the culm. 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.

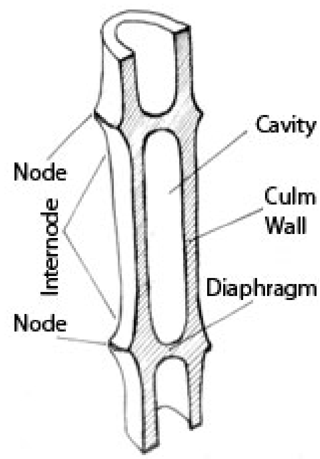


Figure 4. Bamboo Cross Section

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.

Internode Number

$$x_n = n * \frac{100}{N} \tag{1}$$

Internode Length

$$y_{n1} = 25.13 + 4.8080 x_n - 0.0774 x_n^2 \text{ (below mid-height)} \tag{2a}$$

$$y_{n2} = 178.84 - 2.3927 x_n + 0.0068 x_n^2 \text{ (above mid-height)} \tag{2b}$$

Internode Diameter

$$d_{n1} = 97.5 - 0.212 x_n + 0.016 x_n^2 \text{ (below mid-height)} \tag{3a}$$

$$d_{n2} = 178.84 - 2.3927 x_n + 0.0068 x_n^2 \text{ (above mid-height)} \tag{3b}$$

Wall Thickness

$$t = 35 + 0.0181 (x_n - 35)^{1.9} \tag{4}$$

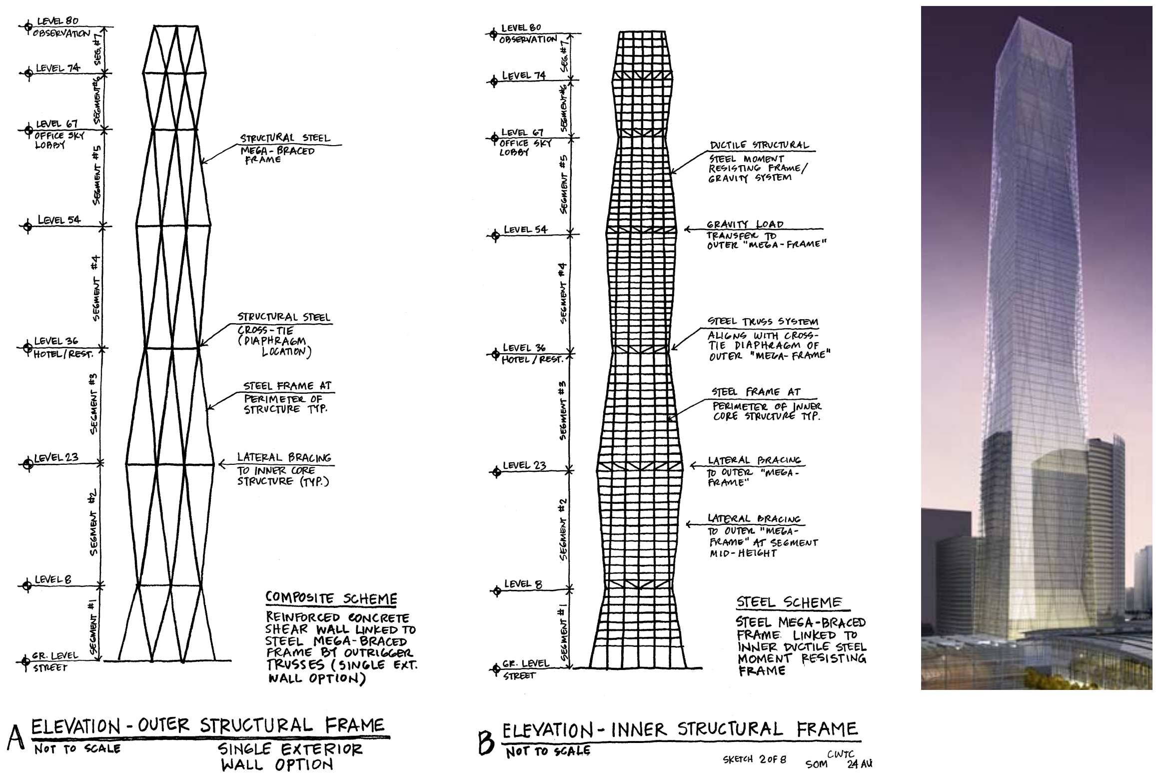


Figure 5. Tower Elevations

Geometric relationships such as length, culm diameter, and wall thickness of many bamboo species have been previously discussed by Janssen (1991). Equations 1 through 4 define the bamboo form as discussed by Janssen (1991). Coefficients are an average of several cited species.

Here x_n is the internode number, n is a shaping parameter specified by the architectural design team to be 80 based on number of floors; N is the height of the structure (320m); y_n is the internode length; d_n is the internode diameter; t is the wall thickness. For the internode length and diameter a nonlinear relationship is observed by the transition from y_{n1} to y_{n2} and d_{n1} to d_{n2} at x_n. Thus, two polynomial equations are provided.

The relationships are shared among inner and outer structural systems shown in Figure 5. The outer structural system follows the internode length (Equation 2) with respect to mega-brace heights and mimics the culm wall fibers. The inner structural system also follows specified bamboo characteristics. Outriggers are taken as the "diaphragm" in bamboo since outriggers tie perimeter structural systems in a similar manor to diaphragms in bamboo. Internode lengths are largest at mid-height and smallest at the base and top. Diaphragm diameter is also varied over the height at outrigger levels as specified by Equation 3. Finally, member sizes are proportioned to follow the wall thickness relationship shown in Equation 4.

TRANSBAY TRANSIT TOWER COMPETITION

The proposed design for the Transbay Transit Tower Competition in San Francisco California is inspired by natural forms. These mathematically-derived forms define systems that are safe, sustainable, cost-effective to construct, and provide optimal performance in seismic events. The logarithmic spiral—found in forms ranging all the way from shells, seeds, and plants to spider webs, hurricanes, and galaxies—is interpreted and applied to the ultra-tall tower, scientifically mimicking natural force flows of a cantilevered structure to its foundation (Figure 6).

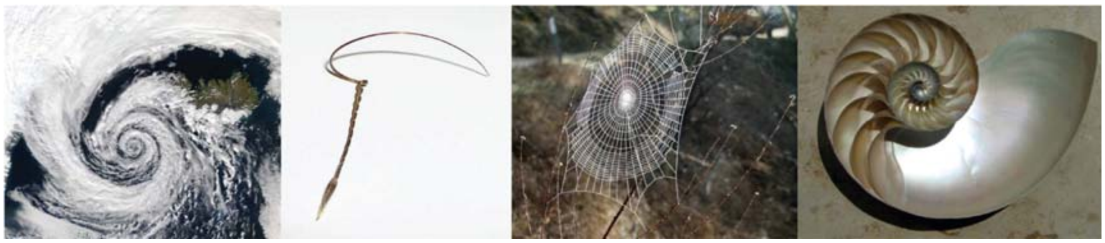
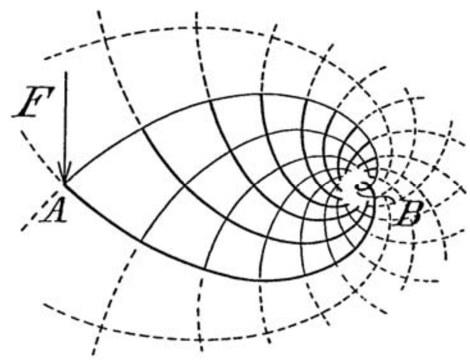


Figure 6. Weather Systems, Storksbill Seed, Spider Web, Nautilus Shell

The spiral inherent in these natural forms traverses 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 fixed support to the tip of the cantilever (Figure 7, Michell, 1904). The result is the most efficient cantilever system with the least material.

The Michell Truss Diagram is mathematically interpreted and overlaid on the tower form defining an optimal perimeter bracing configuration (Figure 8).



A single force F applied at A, and acting at right angles to the line AB, is balanced by an equal and opposite force and a couple, of moment F x AB, applied at B. The minimum frame is formed of two similar equiangular spirals having their origin at B and intersecting orthogonally at A, together with all other spirals orthogonal to these and enclosed between them.

Figure 7. Michell Truss Diagram

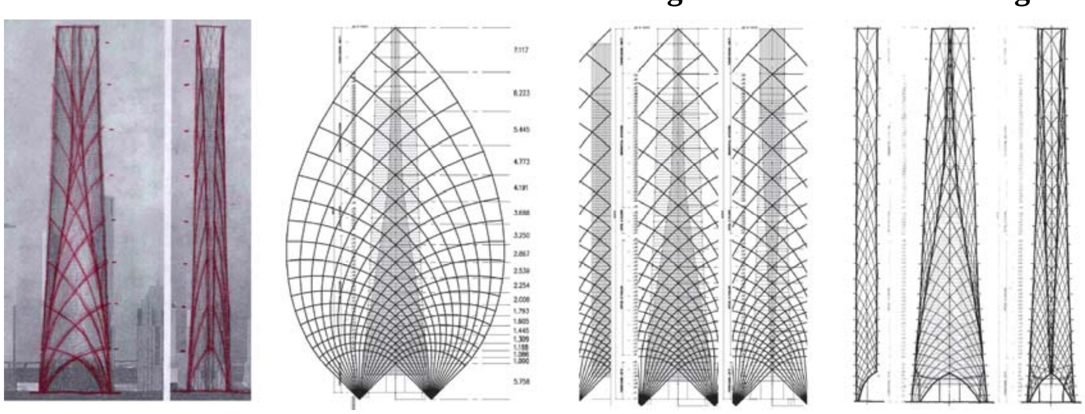


Figure 8. Michell Truss Diagram Applied to the Tower Elevations

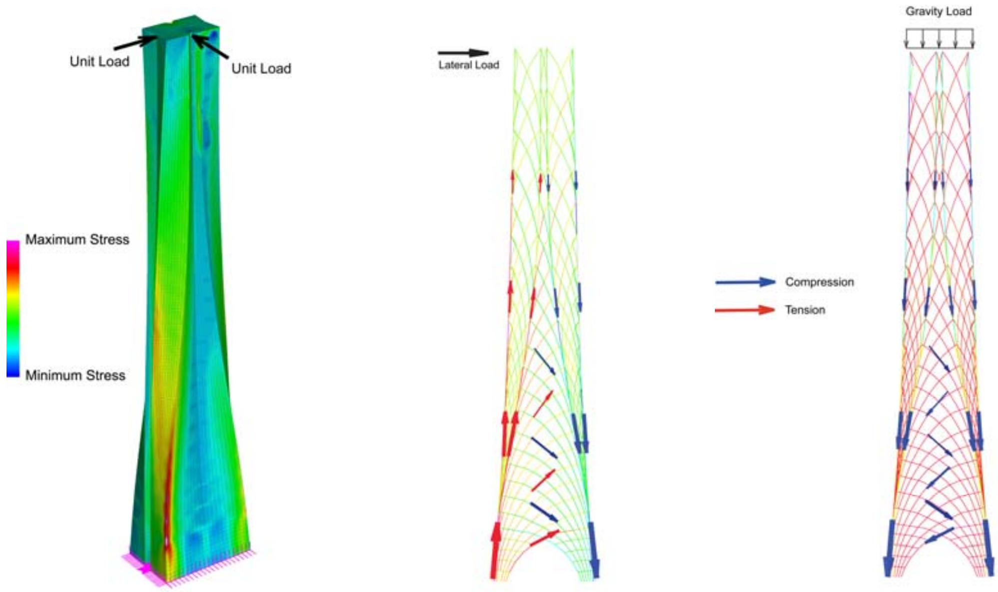


Figure 9. Initial Finite Element Analysis and Force Flow Diagrams

The structure at the base of the tower is designed to accommodate a "gateway" to the adjacent Terminal Building. The structural bracing responds to the openings in the structure, where demand is least, while mimicking gravity and lateral load force flows (Figure 9).

The exterior shell of the tower is robust by design, much like the spider web. It is able to self-heal in the unlikely event that a member is violated by a fire or other catastrophic event. Forces would flow to neighboring members down through the structure and ultimately into the foundations as shown in Figure 10. Should the structure's perimeter come under attack, the exterior composite (steel combined with concrete) bracing acts to disrupt or "shred" projectiles.

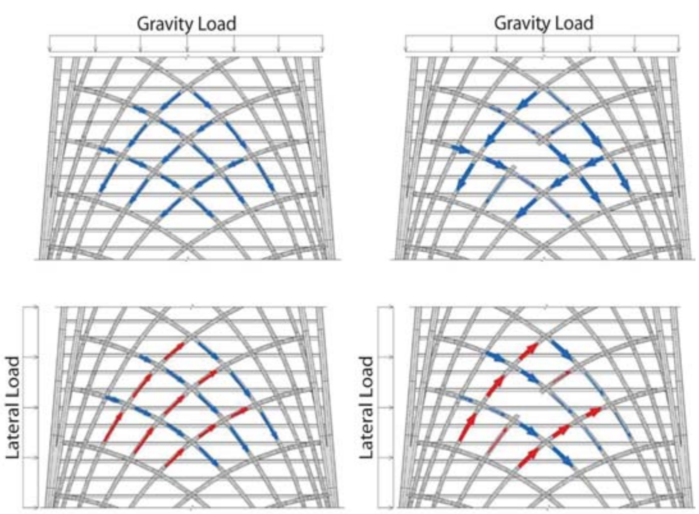
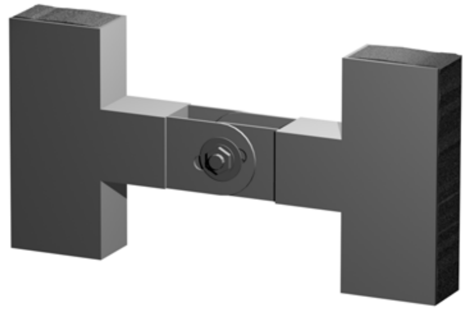


Figure 10. Alternate Force Flow Diagrams

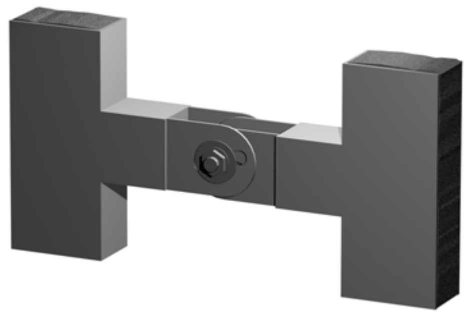
The core of the tower is designed to protect inhabitants and guarantee a safe path of egress in the event of an emergency. The core walls are hardened with a cellular structural concept derived from maritime construction. This "double hull" wall includes a steel plate shell filled with concrete and provides an armored barrier for elevators, stairs, and primary mechanical life safety systems. This barrier also provides optimal fire resistance.

The tower is designed to resist the most extreme earthquakes and remain operational in tandem with the essential Terminal facility. The tower incorporates an innovative array of seismic fuses designed to slide during extreme seismic events. This Link Fuse™ System (Figure 11) allows the building core to dissipate energy at wall link locations (where openings are required to enter the core) while protecting the rest of the structure from damage. After the earthquake subsides and the building comes to rest, the fuses maintain their load carrying capacity and the building can immediately be put back into service.

The structural topology conceived at the perimeter combined with the fused core could provide what may be the most efficient structural system for a tall building anywhere in the world, reducing material quantities required for construction and providing a truly sustainable structure designed not only to survive but also to remain in service after even the most significant natural and unnatural disasters.



a. Undisplaced Shape



b. Displaced Shape

Figure 11. Link-Fuse Joint ™

(U.S. patent pending)

Figure 12. Transbay Tower Competition, San Francisco, California

Figure 13. Al Sharq Tower

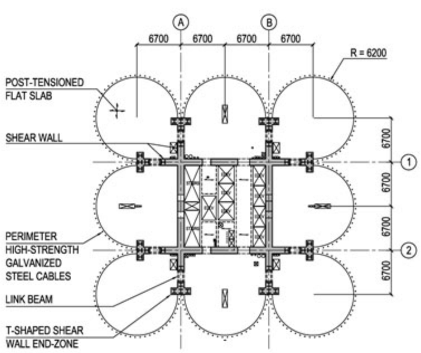


Figure 14. Floor Framing

AL SHARQ TOWER

The Al Sharq Tower is to be located in Dubai, United Arab Emirates (Figure 13). The plan form of the structure is based on nine-adjoining cylinders. Since traditional perimeter columns are not desired, the design teams considered a cable-supported perimeter. Early efforts by the architectural and structural design teams to generate an aesthetically appealing profile followed classic geometric definitions such as that of a helix.

The 102-story residential tower has 39m x 39m floor plan, a height of 365m, and therefore an aspect ratio nearing 10:1. The proposed structural system consists of reinforced concrete systems with perimeter spiraling high-strength galvanized steel cables. The lateral system is composed of intersecting sets of parallel shear walls and perimeter high-strength galvanized steel cables. A typical floor framing plan is shown in Figure 14. The perimeter cable system consists of approximately 70 kilometers (44 miles) of high-strength galvanized steel cables. Initial cable profiles suggested a helical formulation for each. The initial helix definition is propagated to each perimeter cylinder and shown in Figure 15.

Cable Profile Study

Observation of principle stress as a means of form generation is well established in nature. This is demonstrated by the growth patterns of nautilus shells, fiber-reinforcement of palm tree branches and structure of bones which mimic the flow of applied forces. Principle stress observation is undertaken for the preliminary identification of the optimal cable profile for the Al Sharq Tower.

An investigation of principle stresses over the building's perimeter skin is conducted to determine how the form of the building might react to lateral loads. Analysis results show that for the bundled cylinder plan the corner modules exhibit vertical tension (or compression) at the base and transition to 45º (shear) near the top.

Since cables are tension-only members, their most efficient orientation is in alignment with the direction of principle stress. Thus, a cable profile based on observed principle stress trajectories is needed. To define transition of principle stress trajectories, a modified helical formulation is employed. The modified-helical formation is shown in Equations 5 through 7 where z_{Total} is the total height of the building, and n is an adjustable parameter that defines the rate of pitch transition over the height of the structure. The ratio of current to total height raised to the power n alters the cable pitch as a function of tower height. A value of n = 0 yields no transition of pitch, n = 1, yields a linear transition from vertical to 45° over the height of the structure, n = 2 yields a parabolic transition, etc. From observation of the principle stresses, it is determined that the transition of principle stress orientation over the face of the windward corner modules is approximately parabolic (n=2). Thus, a parabolic-tapered helix definition could be used to fully define the cable profile at each perimeter cylinder over the height of the structure as illustrated in Figure 16. As can be observed, the illustrated parabolic-taper helix definition closely matches that of the corner module of the windward face of the principle stress contours.

$$X(z) = r\cos(t) \qquad (5)$$

$$Y(z) = r\sin(t) \qquad (6)$$

$$t = z\left(\frac{z}{z_{Total}}\right)^{n} \qquad (7)$$

Observation of principle stresses at the building perimeter for the determination of cable profile is reasonable if the exterior were monolithic and homogenous. The perimeter is actually a series of discrete tension-only cables. Thus, the principle stress investigation may provide a rational basis of global-perimeter load paths, but further investigation is needed to determine an optimal cable profile.

Cable Profile Optimization

With a rational basis of perimeter load path established, further investigation is sought to develop an efficient cable profile for the resistance of lateral loads. Improved performance is pursued through the employment of a genetic algorithm (GA) optimization routine. GA optimization considers a pitch which varies over the height of the tower. In what follows, a general description of the employed GA is provided.

Genetic algorithms have been used in a wide-range of applications for improved performance in numerous trades such as the aerospace, automobile, and medical industries. This simple, yet robust algorithm facilitates multi-variable and multi-objective searches in large, often poorly defined, search spaces. Early investigations of evolutionary algorithms were conducted by

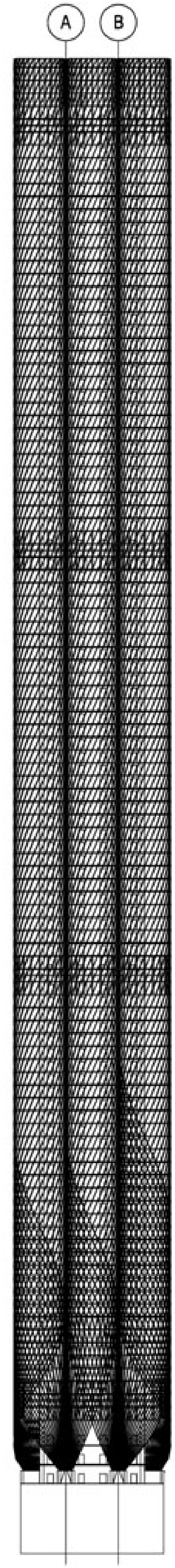


Figure 15. Elevation

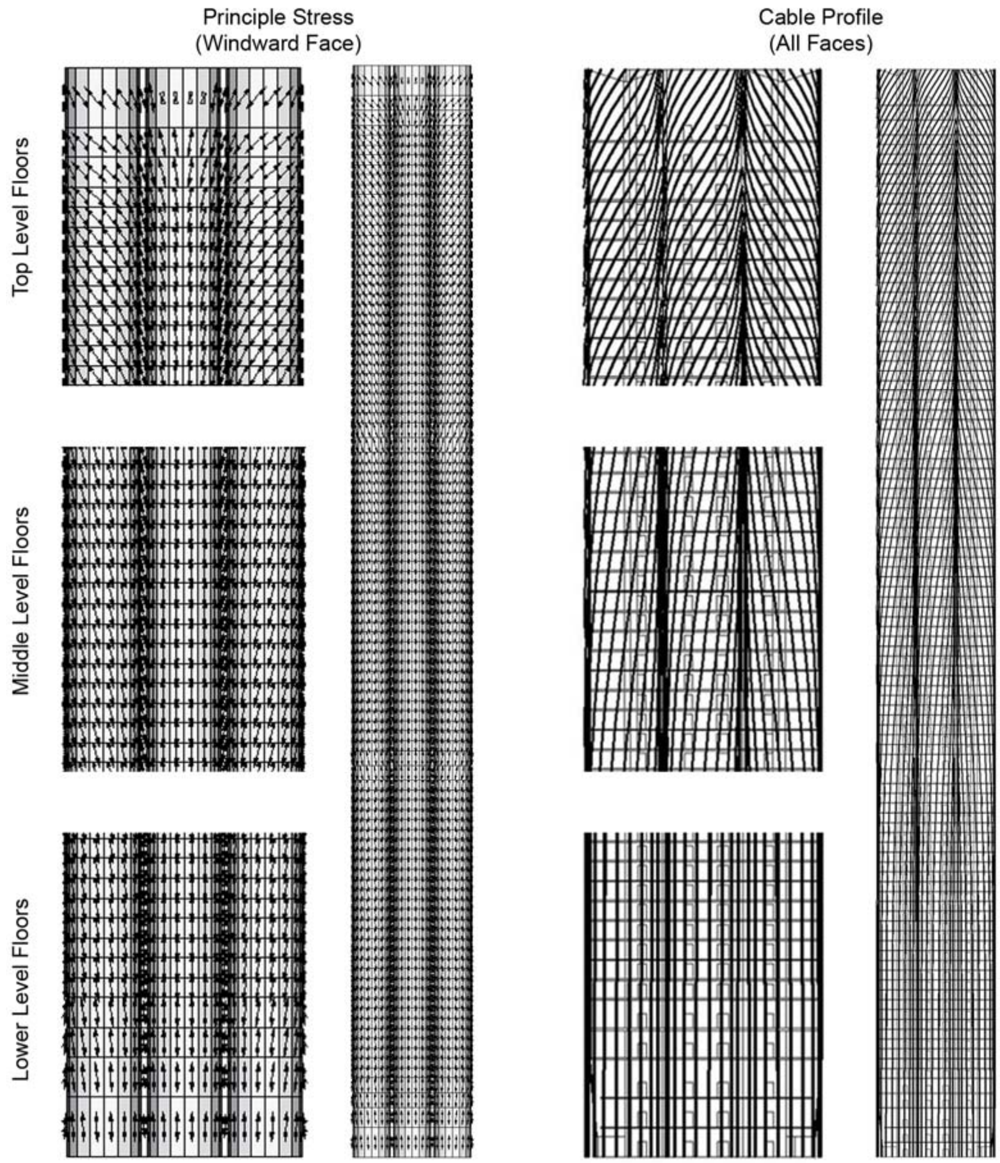


Figure 15. Principle Stress Analysis and Cable Profile

Holland (1975) and inspired from observations made by Darwin (1859). GA is a heuristic optimization method which utilizes trial-and-error of mass populations as a basis of optimization. To demonstrate GA concepts, a simple truss optimization problem is illustrated in the following text.

For GA optimization to begin, an initial population must first be generated. A population is a group of candidate-solutions. For the example truss problem, a population would consist of a set of potential truss configurations. Each truss would have a different member configuration but the loading and boundary conditions would be the same. This concept is illustrated in Figure 17.

With an initial population generated, candidate-solutions are evaluated. Their fitness, or score, is determined by a fitness function. For this example a truss's fitness is the sum of normalized deflection and normalized weight. This GA is a minimization algorithm, thus the sum of the normalized values is taken for the fitness. Both deflection and weight must each be normalized to minimize bias in the fitness score. Analysis software can be used to quickly determine the deflection and weight of each truss in the population. Increased weight and deflection increase the fitness of a candidate-truss and therefore diminish its chances to be selected by the GA for inclusion into future generations.

The initial population is the first parent population and is used to generate the child population. The child population is a new set of candidate-solutions which are derived from the parent population. The child population is to be the same size as the parent population. Each member of the child population is to be generated using GA-operators. Parameters to be optimized by the GA are contained in a vector of values termed a chromosome as illustrated in Figure 17.

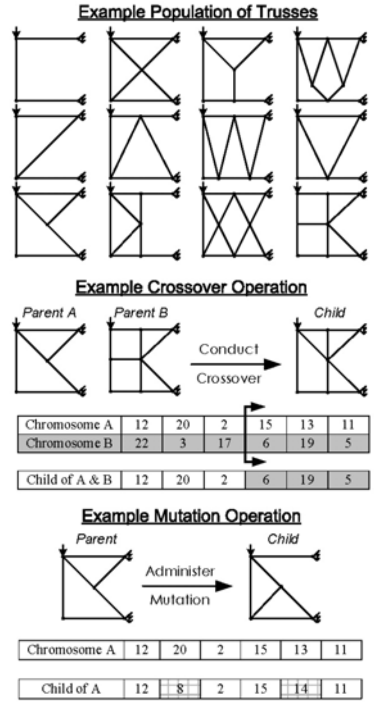


Figure 17. Example GA Illustrations

The first type of GA operation is called ‘crossover’. A crossover operation takes two parents and combines characteristics from each parent to form a child. The second type of GA operation is called ‘mutation’. A mutation operation takes one parent and alters one or more characteristics of the parent to form a child. These concepts are illustrated in Figure 17.

After the child population is generated, each child is evaluated and fitness determined. Next, parent and child populations are combined into a single pool of candidate-solutions. The pooled set is ranked according to each member’s fitness score. For the truss example problem, the truss with lowest fitness score is considered best and the truss with highest fitness score is considered worst. With the pooled parent and child populations ranked, the top 50% are elected to be the parent population for the next generation. The remaining trusses are discarded.

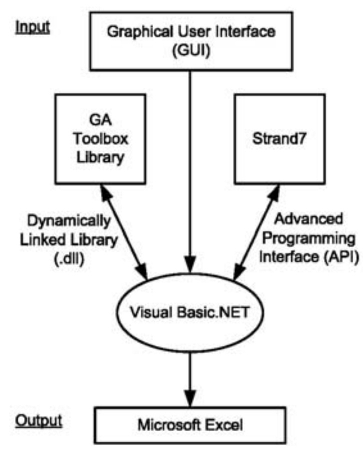


Figure 18. Implementation of GA

To implement GA for the optimization of Al Sharq cable filigree, several tools are needed. Visual Basic .NET is a general purpose programming environment well-suited for conducting GA-operations, interaction with finite element software, and collection of results. Finite element analysis software Strand7 is utilized for analysis of GA-generated cable profiles. An illustration of GA tools and their relationships is provided in Figure 18.

With the concepts of the genetic algorithm described, its application to the optimization of cable filigree of the Al Sharq Tower is now considered. GA operations are to optimize cable pitch at each floor. As already observed in the principle stress analysis, optimal cable pitch may vary over the height of the tower. With this in mind, GA optimization allows pitch at each floor to be varied. Thus, 102 variables are concurrently optimized. Fitness function is the normalized roof drift.

A total of 500 generation-cycles are conducted with a population size of 10, thus evaluating a total of 5000 potential cable filigree configurations. Fitness scores steadily improve until approximately generation 350. The top performing solution from generation 500 reveals a cable profile which is very similar to the parabolic profile determined in the previously discussed principle stress-based cable profile study.

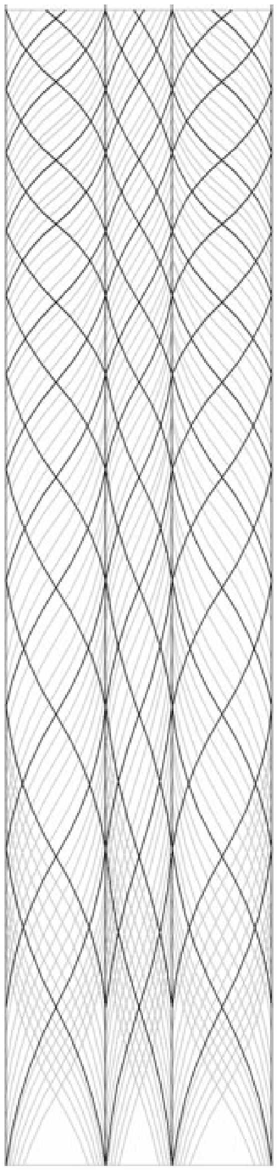


Figure 19. Final Interpreted Cable Profile

Results of Study

Early efforts to determine an efficient and rational cable profile in response to lateral loads have yielded a cable profile derived from the observation of principle stress contours and confirmed by GA optimization. The optimal cable profile follows a parabolic-helical definition which closely matches the principle stress contours observed; vertical at the base transitioning to 45° at the top. A final interpreted cable profile is shown in Figure 19.

CONCLUSION

As demonstrated in the cited examples, emergence is a key theme observed in nature and can be used to understand existing and novel forms resulting in efficient structures. Identified structural systems and forms can be expressed in the architecture to achieve a rational and provocative solution.

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