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An Overview of Structural and Aesthetic Developments in Tall Buildings Using Exterior Bracing and Diagrid Systems

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Abstract

There is much architectural and engineering literature which discusses the virtues of exterior bracing and diagrid systems in regards to sustainability - two systems which generally reduce building materials, enhance structural performance, and decrease overall construction cost. By surveying past, present as well as possible future towers, this paper examines another attribute of these structural systems - the blend of structural functionality and aesthetics. Given the external nature of these structural systems, diagrids and exterior bracings can visually communicate the inherent structural logic of a building while also serving as a medium for artistic effect. Viewed in this light, the visual appeal of these systems can be enhanced to give a tower a more distinct urban identity. This entails the creation of structural elements that are aesthetically pleasing, geometrically coherent and that demonstrate dexterity of application in regards to a building's composition, while also respecting the laws of physics and mechanics. In this fashion, an artistic approach can exhibit structural systems as not just purely rational features that enable the construction of tall buildings, but as important visual components that afford opportunities for creative expression. This paper, therefore, synthesizes the concepts of structural performance and creative artistry to facilitate a better understanding of the aesthetic developments in skyscrapers worldwide.

Keywords: Tall buildings, Structural expressionism, Exterior bracing, Diagrids, Aesthetics

1. Introduction

In regards to form, and given the large number of multi-disciplinary and often conflicting design requirements they demand, tall buildings are some of the most complex human-made structures on earth. Although tall buildings may be viewed through many different lenses, this analysis focuses on towers that exhibit powerful structural expressions. In these structures expression does not merely arise by satisfying the basic functional requirements of the building, but rather is achieved through fulfilling the aesthetic vision of the architect. The goal of this paper is to identify this expression and call attention to its form and details. It should also be noted that most towers are designed with economy in mind, which demonstrates one of the dominant ideas of Structural Expressionism - that economics spur the creation of elegant forms through efficient uses of capital. However, a building's form, even when incorporating the most economical structural system, may not be socially acceptable unless it is simple, ordered and pleasant to look at. With this said, the aesthetics of tall buildings are not merely subjective, but also dependent on a viewer's perception in a given context at a given time.

In the building profession, while much emphasis has generally been placed on the architectural expression of form, far fewer considerations have been given to the *structural* expression of a building. In nature, animal bone structures – the shell of a snail or the encasing of an egg, for instance – are all intrinsically related to the principle of structural optimization, where stress flows and distributions find harmony in accordance with the evolutionary logic of nature. In manmade forms, structural integrity must also respect the principles of structural optimization, where materials are well-balanced, stresses are evenly distributed, and the architectural form is given a unity of purpose while also fulfilling its functional requirements.

A truly American building type, the high-rise, evolved differently on the East Coast than elsewhere in the nation. After the construction of Chicago's Home Insurance Building in 1885, with its skeletal frame becoming the impetus of building tall across the country, its stylistic expression as a structural aesthetic set the precedent for many tall buildings going forward, especially in America. While New York and East Coast architects looked to European historical precedents for tall building aesthetics, Chicago architects were less constrained by public opinion, European values, and the historical imagery of European culture, recognizing that the new technology of struc-

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tural frames warranted a new architectural style altogether, giving rise to what came to be known as Structural Expressionism. According to the tenets of Structural Expressionism, when a structure is completed it is expected to look elegant, appealing and, above all else, structurally correct. With this in mind, it is the harmony between architectural form and structure that is key to a building's successful aesthetic expression, rather than pure ornamentation or stylistic embellishment.

2. Structural Expressionism versus Aesthetics

Many tall buildings bring attention to themselves by showing how they were built, or how they remain stable. They may also champion technology, exploration, or innovation by embodying certain physical forms. The proliferation of new structural systems and advanced technologies, combined with Modernism's principles of structural clarity, helped to give birth to the movement of Structural Expressionism (Beedle et al., 2007). This movement began in the 1960s and flourished throughout the 1970s, and tailed off in the 1980s, during the architectural period known as Late Modernism. Many Modernist high-rises have been bestowed with an explicit trait of structural expression, given that they were vigorously attempting to "honestly" display their structural systems. However, in Structural Expressionism, aesthetic quality has been redefined to emphasize the role of new structural systems and innovative building materials (Ali and Armstrong, 1995; Curtis, 1996). In this way, structural expression dominates the design of façades, becoming synonymous with the architectural expression of the building as a whole. Such expression was also fully compatible with the International Style and its formalism, another movement that arose during the Modern era.

The notion of structural expression, which was not necessarily recognized as such early on, is rooted in bridges employing concrete as the structural material - a substance that is amenable to the creation of unique forms, particularly in regards to bridges, which are essentially utilitarian structures that have traditionally been devoid of aesthetic quality. Most bridge designs have historically been under the control of structural engineers, who paid little or no attention to aesthetics. However, some aesthetically sensitive engineers in the past like Robert Maillart and Christian Menn felt that bridges should have aesthetic quality in their natural settings conforming to the landscape. They had taken it upon themselves to design bridges that were remarkably attuned to their surroundings, displaying their structural functions in an aesthetically intriguing way. Architects Felix Candela and Heinz Isler have been inspired by the aesthetics of seashells and the structural logic that they follow, manifesting both elegance and strength. Similarly, Pier Luigi Nervi has designed many interesting structures that follow this same approach, including vaulted structural forms that display a building's load paths, and that match stress flows with physical outputs to create distinct, large-spanning, "ribbed" designs. These structural visionaries view buildings as art forms that are made possible through their intention as functional objects and that can be artistically honed by the constraints of mechanics and physics.

In a similar vein, the tradition of structural expressionism in buildings in a nascent form has been a long one, beginning with the Gothic cathedrals of middle ages and continuing with the theories of French architect Viollet-le-Duc. During the 20th century, engineers and architects have carried on the tradition with a variety of new forms and structural expression (Ali and Armstrong, 1995; Beedle et al., 2007). Such expression in tall buildings has its roots in the work of William Le Baron Jenney and John Wellborn Root in the late nineteenth century. Both had engineering backgrounds, but they practiced as architects in Chicago. Both were concerned with visual effects of buildings that they designed and were influenced by Viollet-le-Duc. They avoided ornamentation and decoration in the façade. Jenney used the skeleton frame in the Home Insurance Building, but did not express it since it was clad with masonry façade in vaguely Romanesque revival style. Although structural expression was in an embryonic form at that time, their projects were the harbinger of what followed in the 1960s and 1970s, when Fazlur R. Khan and Bruce Graham designed a number of buildings in steel and concrete that were structurally expressive. Chicago architect Mies van der Rohe had a profound influence on them, in the same way as Viollet-le-Duc had on Jenney and Root. Fazlur R. Khan, influenced by the minimalist designs of Mies van der Rohe, and the collaborations of architect/engineer Myron Goldsmith and architect Bruce Graham at Skidmore, Owings & Merrill (SOM), had helped define the concept of tall buildings as art forms, by developing tubular structural designs, achieving these conceptual breakthroughs during the height of Modernism, in the late 1970s (Billington, 1983; Ali, 2001).

Khan's exposure to the architectural/engineering practices at SOM, and his opportunity to teach in the Architecture Department at Illinois Institute of Technology (IIT), helped shape him for a remarkable career path in the 1960s and 1970s, and allowed him to be involved in a number of major tall building projects during this time. He quickly realized that with the increasing heights of buildings, the status quo of structural systems was no longer acceptable and that optimal form for such colossal and complex structures would be generated from sound engineering principles rather than from architectural function and aesthetics alone. In other words, Louis Sullivan's architectural tenet that "form must follow function" could be viewed from a different perspective. Force flow in a structural system should be determined by the form. Thus, "form controls the forces … this means that function follows form and not the reverse" (Billington, 1983). Khan recognized that placing the lateral-force-resisting supports away from the building's center would create a large moment arm to resist overturning of the building. Additionally, it would allow the structure to respond to lateral loads, providing the most efficient performance while consuming the least amount of physical materials. In 1953, under the supervision of Mies van der Rohe, Myron Goldsmith wrote his Master's thesis at IIT exploring the "scale effect" of tall buildings in regards to aesthetic expression (Blaser, 1987). Taking the concept a step further, Khan also recognized that when a tall building's structural system is scaled vertically, the loads created by its heavier weight and the increased wind forces of higher altitudes are magnified exponentially. As a result, Khan carried out elaborate studies on the scale effect and eventually articulated his findings as the "premium for height," a notion that led to revolutionary developments in height-based structural system charts for the use of steel and concrete in tall buildings (Khan, 1969, 1972, 1973; Ali, 2001). This opened the floodgates for various innovative structural systems, causing designers to break away from the conventional rigid frame system employed by many tall buildings during the Modern era.

In addition to the framed tube system that Khan developed for the Dewitt-Cheastnut Apartment Building (1965) in Chicago, he also developed the first braced tube system and applied it to Chicago's John Hancock Center in 1970. The latter project owes its origin to a seminal thesis written by IIT student Mikio Sasaki, who studied under Khan in 1964, that proposed a design for a diagonally braced tower (Ali, 2001). Alternate uses of concrete in exterior bracing were carried out in 1968 by another IIT student named Robin Hodgkison, who also studied under Khan (Ali, 2001). This concept was later applied by Khan on another major project in Chicago, the Ontario Center (Fig. 1), which was completed in 1985. Another example of a concrete tower using exterior braces is New York City's Wang Building of 1984.

All these buildings are exemplars of Structural Expressionism insofar as they vividly display their support systems in an aesthetically appealing way. In these and other similar structures, the structural action which counteracts the natural forces of gravity, wind, and earthquakes, becomes an important aspect of tall building design. In a tower that expresses its ability to stand firm against these natural forces, the form is very much related to its structural efficiency, which in turn dictates the building's economy. The structural function of the building is, in this case, determined by its load-carrying capacity, resistance to lateral sway, and optimally balanced composition. With this in mind, it should be noted that placing "structural" elements in a building's façade is not true structural expression as many may mistakenly assume. Unless such elements follow the structural logic of the building's original design, they may not contribute to the building's sturdiness and, hence, may function only as ornamentation.

Figure 1. The Ontario Center. (Photograph by K. Al-Kodmany)

Figure 2. The Hong Kong and Shanghai Bank Corporation (HSBC) Headquarters Building. (Photograph by K. Al-Kodmany)

The Hong Kong and Shanghai Bank Corporation (HSBC) Headquarters building (Fig. 2) serves a good case in point. Although it has some expressive structural façade elements, these elements have no relationship to the building's overall structural logic and do not necessarily make the building more structurally efficient (Goldsmith, 1986). Structural Expressionism is not necessarily synonymous with the British movement known as High-Tech Architecture, insofar as the High-Tech movement covers a broad range of expressions related to technological innovations in mechanical engineering, electrical engineering and computer science. Structural Expressionism stands on its own and may be characterized as only one aspect of the High-Tech movement. Therefore, a building such as the HSBC, for example, represents a manifestation of the High-Tech movement, but not necessarily of Structural Expressionism.

2.1. Decline and Resurgence of Structural Expressionism

While braced tube and framed tube designs can offer efficient and cost effective structural systems for tall buildings, the large exterior diagonal elements of braced systems and the closely spaced columns of framed tubes inevitably obstruct views, a major drawback of this design style. Therefore, architects have investigated alternate structural systems that liberate the façade from these obstructive supports. In the late 1970s and early 1980s, discussions continued amongst architects and engineers in regards to the structural expressionism and aesthetics of tall buildings. Some engineers and architects have argued that Mies van der Rohe sought pure structural expression as an architectural objective, but Pelli (1982) has contended that structural expression is a means to resolve an aesthetic goal, not a goal by itself.

A concurrent factor, which has resulted in the gradual decline of Structural Expressionism, is the disinterest felt by many architects concerning the values of Modernism, especially in light of the Postmodern movement where the strict structural logic of façades was sacrificed in favor of irregular, polychromatic, and flamboyant forms. Architects of the Postmodern era sought to distinguish their work from the International Style "boxes," which characterized much of the world's architecture in the wake of World War II. Monolithic flat-top glass boxes gave way to alternative pluralistic architectural styles, a shift which greatly appealed to developers and the public (Goldberger, 1981). These new buildings restored the vivid tripartite relationship of base, shaft, and crown, evoking historical motifs in structures at a monumental scale; a bold realignment of Modernist architecture with the architectural and aesthetic principles of Classicism. Khan (1982) lamented this loss of architecture based on physical and mechanical law, believing that the aesthetics engendered by Modernism possessed a transcendental beauty. He argued that such "*a priori* architectural façades, unrelated to natural and efficient structural systems, are not only a waste of natural resources, but will also have difficulty in standing the test of time" (Khan, 1982). He predicted that the pendulum of change would continue swinging, implying that the structural logic of Modernism would eventually return.

As a consequence of the Postmodern movement, the structural support systems of tall buildings began moving from the exterior to the interior. The system ideally suited for this shift has been the core-outrigger system. This was not a novel concept, as the core-outrigger system had been used in some buildings during the Modern period (Beedle et al., 2007). In this structural type, the building's core is centrally located with outriggers extending to perimeter belt trusses or large columns. In steel structures, outriggers generally take the form of trusses, while in concrete structures they effectively act as stiff headers inducing a tension-compression couple in the outer belt trusses or columns. This system is also well suited for mixed steel-concrete, i.e., composite structures. The core-outrigger system minimizes the obstruction created by large exterior structural frames, allowing the architect to freely articulate the façade's design.

Because of these functional benefits, and the fact that they offered architects flexibility in exterior column spacing and design, the outrigger system grew in popularity for tall buildings worldwide. Taking note of this and other similar developments, Ali and Moon (2007) presented a new height-based classification system that broadly categorizes the exterior and interior structural systems of both steel and concrete tall buildings. This classification is comprehensive, incorporating other popular structural systems that reached beyond the hierarchy of structural systems created by Khan's seminal classification scheme. During the Modern period, it is worth noting that earlier versions of prismatic and rectilinear forms made it possible for a single identifiable structural system to be developed. However, given the changes of architectural form in the Postmodern era, many innovative structural ideas were introduced to meet the new architectural requirements of the time and, in the process, the ideal of structural expression cherished by structural artists had essentially been lost.

In recent years, however, as had been predicted by Khan (1982), a revival in Structural Expressionism has manifested in two major trends - innovative bracing systems and advanced diagrid systems (Moon, 2015). In the braced systems the exterior columns are widely spaced and connected by "heavy" bracing elements. Viewed from a three-dimensional perspective, the system consists of braces and columns, which effectively work together as a tube. In a diagrid, a lattice-like system which consists of "light" diagonal elements, its structural efficacy operates irrespective of the building's columns. This revival of Structural Expressionism is consistent with the current green movement, which advocates structural efficiency and the minimum consumption of physical materials. Overall, when a structure discloses itself in a logical manner, it often provides opportunities to create interesting visual expressions. This paper focuses on two types of structural systems, namely bracing and diagrids, and presents illustrative examples of both as they have been used in tall buildings around the world.

3. Braced and Diagrid Systems

An early system used to support the lateral loads of tall buildings is the braced frame, which has historically used various types of bracing elements such as X-braces, K-braces, Chevron braces, and eccentric braces, to create distinct structural expressions. These different types of bracing are used to satisfy the criteria determined by building's height, slenderness, architectural program, and seismic and wind load conditions in a geographic location. Braced systems have been extensively discussed in past literature (e.g., Taranath, 1988; Schueller, 1990; Ali and Armstrong, 1995; Ali, 2001).

In recent years, the diagrid (diagonal grid) structural system has become increasingly popular. A diagrid system consists of series of triangles and horizontal rings of beams which provide the structure support against gravity and lateral forces, while also making a building stiffer and often lighter than a traditional high-rise. Diagrids are usually composed of steel, because of its high strength and ability to resist both tensile and compressive forces. The diagrid can suffer from problems of implementation due to its complicated steel joints, but recent advances in joint detailing and prefabrication are helping to address this issue. Due to their triangular configuration, diagrids can efficiently carry the shear and moment caused by lateral loads and gravity (Ali and Moon, 2007). They are effective in minimizing shear deformation, providing maximum resistance against torsion. Ian Volner (2011) cites Cantor Seinuk's definition of a diagrid system as: "A series of triangles that combine gravity and lateral support into one, making the building stiff, efficient, and lighter than a traditional high-rise." As such, the diagrid system has an advantage over bracing systems in that it reduces, or even eliminates, the need for vertical columns along the building's perimeters. Both tubular bracing and the diagrid systems have the potential to eliminate the need for interior columns, facilitating more flexible interior layout designs and increasing openness.

In regards to structural performance, both braced and diagrid systems are effective at carrying the large lateral loads of tall buildings given their three dimensional tubular behavior by virtue of their being exterior systems. The braced tube system tends to be more efficient than the diagrid system for ultra-tall buildings with large height-to-width aspect ratios. However, compared to braces, as alluded to before, the diagrid elements are lighter and less obtrusive. Additionally, diagrids possess greater structural flexibility than bracing systems given that diagrids can be configured, with some desirable adjustment in the modules and angle(s) of the diagonals, to meet architectural and structural requirements. The angles of the diagrid can be adjusted to optimize structural performance, offering more possibilities of structural expression as a result.

It should not be forgotten that the bracing systems of many early tall buildings were antecedent to the diagrid. For example, Fazlur Khan's X-braced John Hancock Center (Fig. 3) is considered a major milestone in the development of braced systems, serving as inspiration for later diagrid designs. However, in the 1980s it was Norman

Figure 3. John Hancock Center. (Photograph by K. Al-Kodmany)

Foster who more directly popularized the diagrid system, proposing that the Humana Headquarters should implement this structural typology (Huxtable, 1984). In the 2000s, Foster successfully employed the diagrid system in several buildings including London's iconic 30 St. Mary Axe (2004) and New York's Hearst Tower (2006) and Calgary's The Bow (2010). These towers are, in many ways, poster-children for the diagrid system, popularizing the technique and making it more palatable for the tall building industry as a whole (Moon, 2015).

4. Critical Aesthetic Elements

By highlighting the prime aesthetic qualities to better understand their relationship with Structural Expressionism, this section attempts to explain the trends and possible directions that these structural systems can take. It will also make visual observations with the intent of identifying critical aesthetic elements. The discussion is divided into three sub-sections: 1) Structural and Architectural Attributes, 2) Form-giving and Aesthetic Expression, and 3) Complexity and Contradiction. The first sub-section examines specific elements that contribute to the architectural-structural integration of external bracing and diagrid systems. It focuses on specific aesthetic issues pertaining to structural systems (e.g., scale, profile, structural details) and façades (e.g., design, color, and lighting). The second sub-section examines tripartite designs by analyzing the three parts of a tall building: top, shaft, and base. The third sub-section addresses the issue of complexity and identifies a new trend that contradicts the initial intention of Structural Expressionism that promotes structural clarity and simplicity. It explains innovative ways to increase complexity while enhancing structural stability using tech-

Figure 4. Bank of China Tower. (Photograph by K. Al-Kodmany)

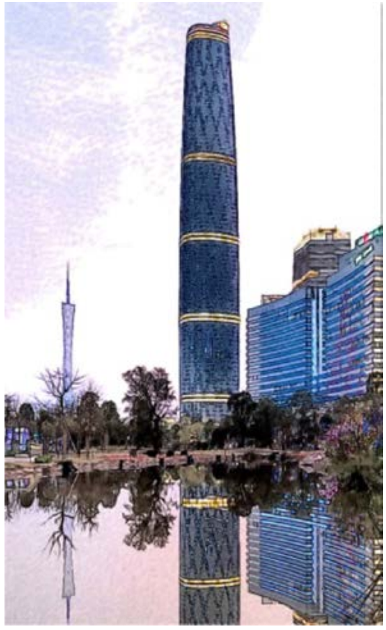

Figure 5. Guangzhou International Finance Center. (Sketch by K. Al-Kodmany)

niques such as: varied grid pattern, aerodynamic form, three-dimensional diagrids, three-dimensional geometric patterns, and irregular diagrids.

4.1. Structural and Architectural Attributes

4.1.1. Structure

Scale. Mega-scale bracing elements and patterns can better suit large-scale buildings because they tend to divide these buildings into smaller components, which may help to mitigate a large building's overwhelming visual impact on the skyline. The 344 m (1,128 ft.) John Hancock Tower (Fig. 3) employs several mega diagonal trusses that help make this 100-story supertall more visually comprehensible. The 305 m (1,000 ft.) Bank of China Tower (Fig. 4) and the 438 m (1,435 ft.) Guangzhou International Finance Center (Fig. 5) provide additional illustrative examples where mega bracings mitigate their monumental scales. Moreover, these mega-diagonal bracings allow their respective towers to be distinguishable from a far distance, qualifying them as major urban landmarks.

Historically, braced systems have been employed in taller buildings with more frequency than diagrids. However, diagrids are becoming more common as the height of tall buildings increases (Korsavi and Maqhareh, 2014). Therefore, within diagrid systems we may distinguish between two types: the large and the small. The flexibility of the diagrid enables buildings to accommodate the size with ease in a particular context. For example, diagrids in the Bow Tower (Fig. 6) span a 6-story height, making this large building particularly distinct from far distances. A similar case exists for Al Dar Headquarters (Fig. 7), where its diagrids also span 6-stories heights.

In contrast, the Capital Gate Building (Fig. 8) employs a finer diagrid that fits this relatively shorter tower 160 m (525 ft.). In this case, the diagrid made construction of this

Figure 6. The Bow Tower. (Sketch by K. Al-Kodmany)

tower possible, given its lean of 18º. Overall, the ability to have smaller diagonal patterns (provided by the diagrids) helps the tower blend in with its surrounding, avoiding "loud" or "brutal" aesthetics.

Profile. While the diagrid generally lends itself to simple outlines in building elevation, the careful articulation of certain elements may introduce visual stimulation, enhancing the identity of the tower. For example, Norman Foster has articulated the corners of the diagrid of the Hearst Tower (Fig. 9) in New York thereby creating diamond

Figure 7. Al Dar Headquarters. (Photograph by K. Al-Kodmany)

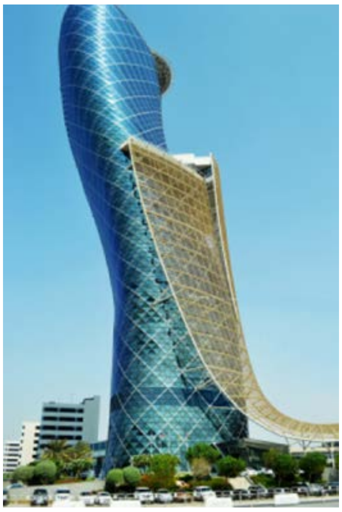

Figure 8. The Capital Gate Building. (Photograph by K. Al-Kodmany)

shapes that taper in and out as the tower ascends, promoting visual interest and giving the tower a more three-dimensional appearance. Similarly, the diagrid of the Shenzhen VC-PE Tower curves around the corner, giving the tower a unique visual appeal (Garai et al., 2015).

Structural Details. Structural details are important and can be used to convey the rationale for a building's overall structural composition. Expressing structural joints artistically, for example, can highlight the ingenuity behind a structural engineering concept. Structural details can also be iconic, having the ability to greatly contribute to the tower's overall visual quality. For example, the NEO Bankside complex utilizes sophisticated details (e.g., hinges, pins, HSS members with triangular plate "fins," clevis connectors) which are used to transfer shear forces, while also making the building's bracing system appear lighter. While the structural joints of many diagrids retain sharp

Figure 9. The Hearst Tower. (Photograph by K. Al-Kodmany)

angles, others introduce curves to soften their visual effect, an example of which can be found in SOM's Shenzhen Rural Commercial Bank Headquarters (under construction at this writing).

4.1.2. Façade

Design. The articulation of the building's facade provides additional opportunities for diversifying a building's visual expression. For example, the Swiss Re Building uses small triangular windows while the Hearst Tower uses large diamond-shaped windows. Most importantly, when a structural system is made distinct from the curtain wall, it is likely to have a greater visual impact. For example, the exoskeleton of SOM's 44-story Hotel Arts (1994) (also known as Villa Olympic Hotel Tower) in Barcelona, Spain, protrudes from the curtain wall, making the building more distinguishable and maximizing its expressiveness. SOM's Shenzhen Rural Commercial Bank Headquarters in Shenzhen (under construction) uses a diagrid structure that is distinct from the façade, thereby also amplifying its structural expressiveness. Additionally, when extended from the façade, exterior bracing and diagrid systems have the ability to provide solar shading, a unique environmental benefit of this structural type.

Color. The effective use of color can be extremely important in highlighting structural systems. For example, the diagrid system of Calgary's Bow is accentuated by the building's dark blue/grey curtain wall, giving the tower elegance despite its relatively massive size. Similarly, the dark blue portion of the curtain wall of the Indigo Icon Tower (Fig. 10) in Dubai highlights the structural system's "A" frame, giving the tower a distinctive look. The NEO Bankside complex (Fig. 11) uses inviting, warm, industrial colors for its curtain walls, which complement the build-

Figure 10. The Indigo Icon Tower. (Photograph by K. Al-Kodmany)

Figure 11. The NEO Bankside. (Photograph by K. Al-Kodmany)

ing's integrated X-bracing and give the complex a unique feel and appearance.

Interestingly, common to early towers that employed braced structural systems was the utilization of darker colors, as can be seen in the cases of One Maritime Plaza (1964), the John Hancock Center (1970), and One US Bank Plaza (1976). As such, these towers take on a bold industrial appearance, which may even be described as "brutal," echoing the Miesian architecture of the International Style. They were revolutionary in their time as towers that were particularly distinct, both visually and structurally. Consequently, these towers have become landmarks in their respective cities (Ali and Moon, 2007). In contrast, diagonally-braced towers (since late 1980s) have mostly employed the use of lighter colors. Examples

Figure 12. The Tornado Tower, daytime (left), nighttime (right). (Sketch by K. Al-Kodmany)

that illustrate this shift in color preference can be seen in the Bank of China Building (1989), Millennium Tower (2006), Poly International Plaza (2007), Indigo Icon Tower (2007), Broadgate Tower and 201 Bishopsgate Tower (2008), and NEO Bankside (2012). In many of these instances the bracings are clad in aluminum or stainless steel sheets, allowing the diagonal patterns to stand out from the rest of the building. Aesthetically, these towers have departed from the International Style, communicating a contemporary look that is appropriate for the times (Garai et al., 2015).

Lighting. At night, a lighting system may be used to accentuate the diagonal elements of a diagrid, making a building's structural system appear more pronounced; see for example the Tornado Tower (Fig. 12) in Doha, Qatar. Also, the Guangzhou International Finance Center employs a lighting system that emphasizes the tower's diagrid (placed immediately behind its curtain wall), making it more visible at night (Fig. 12). In the case of the SOM's Lotte Super Tower (unbuilt), its lighting scheme was designed to simulate a torch light, with white lights illuminating both the diagrid along the building and the sky above. China's proposed Kunming Spring Eye Tower (also known as The Kunming Junfa Dongfeng Square project) will reportedly have a distinctive lighting system.

4.2. Form-giving

An important and early aspect of design is the generation of forms to satisfy site constraints, meet functional and structural requirements, and deliver an aesthetic statement based on the architect's intent and owner's agreement. Factors like evolution of the structural frame, core design, site limitations and regulations, and economic considerations dictating program, volume, material, and detail-

Figure 13. The Vivaldi Tower. (Sketch by K. Al-Kodmany)

Figure 14. Hotel Kapok Shenzhen Bay. (Sketch by K. Al-Kodmany)

ing have influenced the development of form. Progressive architects like Sullivan and Mies van der Rohe have believed that the skyscraper's aesthetic expression should grow 'honestly" from its structure and materials. On the other hand, architects like Burnham and Burgee tend to focus on historicist skyscrapers portraying their symbolism and iconography.

Tripartite design concept originating in the late 19^{th} century, best exemplified in New York City's Chrysler Building, suggests that a skyscraper should have a distinct top (crown), middle (shaft), and base (podium). However, tripartite design was not valued by Modernists who commonly designed monolithic skyscrapers with flat tops and indistinct bases. For example, Chicago's Aon Center of 1973 resembles a giant column with no top and no base. Modern approaches have emphasized simple forms, visually inexpressive structural systems and bland curtain walls, often referring to these as "skin and bone architecture." In later years, the Postmodernists reverted to a tripartite design, examples of which can be found in New York's Sony Building (Formerly AT&T Building) and Chicago's 311 South Wacker Building.

Externally-braced and diagrid systems carry on the Modernists' principles of simplicity and "honesty" in visual expression insofar as they are functional and "ignore" embellishment in distinct tops and bases. The aforementioned examples illustrate this notion. For example, the Bow, Tornado Tower (Fig. 12) and Vivaldi Tower (Fig. 13) all have flat tops. Goettsch Partners recently completed Hotel Kapok Shenzhen Bay (Fig. 14) in Shenzhen, China, a diagrid building that also features a flat top.

However, there are exceptions. For example, the recently completed D2 Tower (Fig. 15) in Paris, France, has a distinctive diagrid top. Also, a proposed tower in New York City, by Perkins and Will, will feature a slanted diagrid top. SOM's Lotte Super Tower (unbuilt) had a distinctive crown that extends the diagrid upward, beyond the building's top, and emphasized the "perforated" diagrid effect. Furthermore, the proposed Kunming Spring Eye Tower possesses a distinctive void at its top that resembles an eye. In addition to its visual impact, the "Eye of Spring" acts as an eco-chimney, providing free cooling for half of the year through a buoyancy-driven natural ventilation system. The "eye" also reduces wind forces on the tower.

At the ground level, it is important that the tower's base caters to the pedestrian environment. Some diagrid towers have prioritized this issue. For example, the base of London's Swiss Re Building features a cut-out that reveals the diagrid, creating a pedestrian arcade at the ground floor. Such a change in the building façade gives the base a distinct look and makes the entryway easily identifiable. At a larger scale, London's Leadenhall Building designed by Richard Rogers, features a large void toward the base extending to 30 m (100 ft.) height. There, the tower exposes its structural system and creates a large protected pedestrian space. The public plaza that has been engendered is particularly inviting and makes the entryway easily recognizable from far distances. In the case of Broadgate Tower and 201 Bishopsgate, among their most stunning features is an arcaded gallery, where structural elements are used to bridge the two edifices. In the case of the unbuilt SOM's Lotte Super Tower, the base is distinguished by a recessed curtain wall that is highlighted by blue uplighters and a deep red color scheme, creating a feeling of depth and harmony.

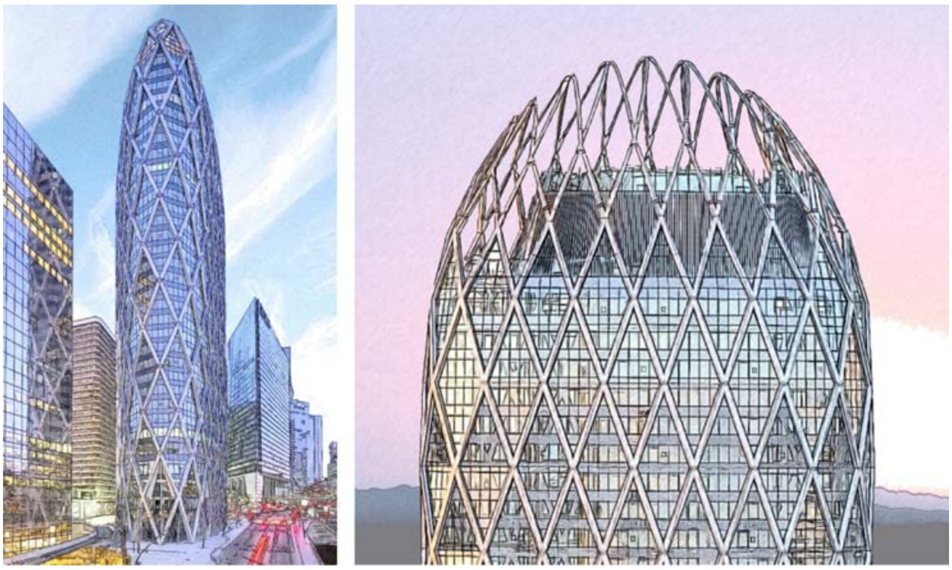

Figure 15. D2 Tower, sideview (left), front and top (right). (Sketch by K. Al-Kodmany)

4.3. Complexity and Contradiction

As discussed earlier, simplicity is a key design principle of Modernism and Structural Expressionism. Simplicity is also commonly manifested in externally-braced and diagrid structures, which tend to feature logical, bold outlines on the façade. These systems often provide equal spacing, balance, rational composition, and harmony. The absence of décor and showiness further reinforces simplicity, examples of which can be found in The Bow Tower (Fig. 6), Al Dar Headquarters (Fig. 7), Vivaldi Tower (Fig. 13), and Hotel Kapok Shenzhen (Fig. 14). In this regard, Khan (1981, p. 41) has argued that "efficient structures possess the natural elegance of slenderness and reason, and have possibly a higher value than the whims of *a priori* aesthetics imposed by architects who do not know how to work closely with engineers, and who do not have an inner feeling for natural structural forms."

While the majority of bracing and diagrid systems exhibit qualities of simplicity, some new towers have begun to exhibit added layers of complexity. It is often the case that when architects, structural engineers and the public at large become overexposed to a design, that new forms and novel aesthetics will arise. Despite the fact that the braces and diagrids may exhibit the structure, the natural load path is not necessarily manifested in some of these complex forms. Such desgn contradicts the earlier Modernist emphasis on rectilinear glass-box paradigm. Complexity in bracing and diagrid systems is being pursued in multiple ways, and may be categorized as follows:

Grid Variation. Some new towers are altering the angles of their diagrids to more effectively respond to varying structural loads. For example, the unbuilt Seoul's 555-m (182-ft.) tall Lotte Super Tower desgned by SOM had a diagrid that gradually changed its vertical angles from approximately 60ºat the top to 79º at the base. This variation provides more structural efficiency where steeper angles are placed toward the bottom, to increase resistance against bending moments, and shallower angles are placed toward the top. Diversifying vertical angles can also provide new visual expressions that makes the tower more unique.

It is also possible to vary the horizontal angles of the diagrid system. For example, the diagrid of the Shenzhen VC-PE Tower becomes steeper toward the tower's corners, giving it greater structural strength and making it more visually expressive. Of course, it is also possible to design a diagrid system as a varied combination of horizontal and vertical angles (Moon, 2015). Furthermore, the diagrid system may also variegate the overall density of its grid so that it may better respond to varying structural loads, as is the case of Beijing's CCTV building. Surely, the CCTV building's varying diagrid system is the most distinctive feature of the tower (Fig. 16). Also, a proposed skyscraper by Zaha Hadid – a design that arose out of a Swedish competition – shows an intricately varied diagrid system. Interestingly, SOM's proposed West Bay Office Tower, in Dubai, utilizes a varied diagrid that gets narrower and denser as the tower ascends. Similarly, the proposed 60-story Nanning Tower in Nanning, China, would alternate its diagrid pattern between diamonds and triangles, creating increased visual interest.

Aerodynamic Forms. Increasingly, architects and engineers are interested in creating aerodynamic forms that streamline the wind flow to improve a tall building's performance in regards to wind resistance, particularly at higher altitudes where wind forces become amplified. When diagrids are applied to these forms they provide new and dynamic visual expressions. One illustrative example

Figure 16. CCTV Building. (Photograph by K. Al-Kodmany)

is the Swiss Re Building (Fig. 17). By having the diagrid wrap around its cylindrical shape, a spiral pattern emerges. In the case of The Bow, the diagrid is applied on a crescent-shaped plan, creating an interesting pattern along the tower's façade. Usually architects have to adjust the functions to complement these forms.

Three-Dimensional Diagrids and Patterns. In a recent article titled "Three-dimensional Exterior Bracing Systems for Tall Buildings," Garai et al. (2015, p. 2) argue that "… bracing systems such as 'diagrids' that link together on the façades of buildings to form three-dimensionally integrated patterns, provide an excellent alternative to outrigger solutions…. [And] offer the prospect of greater resilience, post-earthquake recoverability and sustainability." The authors have illustrated their argument by examining Paris's D2 Tower (Fig. 15). In addition to sustainability and structural features (e.g., employing an aerodynamic form), this new system adds three-dimensional qualities that make it more visually complex.

Another way to increase the visual impact of a building's structural bracings and diagrids is by introducing a three-dimensional geometric pattern. Examples of this design approach have been illustrated by SOM's proposed Diamond Tower in Seoul, the recently completed SOM's Poly International Plaza T2 (Fig. 18) in Beijing, China, HOK's Capital Market Authority (CMA) Tower (Fig. 19) in Riyadh, Saudi Arabia (under construction), Foster's World Trade Center submission for Lower Manhattan, Adrian Smith + Gordon Gill Architecture's proposed Diamond Tower in India and Chengdu Greenland Tower in China, and Norman Foster's proposed tower for Sowwah Island, Abu Dhabi. These towers exhibit intriguing multi-faceted, crystal-like cuts and bold three-dimensional geometric patterns, which have the potential to make them both memorable and iconic.

Exotic Forms. Diagrid systems are more amenable to the application of complex forms. This is clearly demonstrated in the cases of the CCTV building (Fig. 16) and the Capital Gate building (Fig. 8). The diagrid of Al Dar Headquarters (Fig. 7) has made its extraordinary cantilevers possible and allowed the building to take on a spherical form. Dubai's proposed Cypertecture Sphere (also known as Technosphere) and Mumbai's proposed Cybertech Egg would both utilize diagrid systems (Fig. 20). In this regard, Sepideh Korsavi (2014) has explained thus, "The steel diagrid, in its ability to create a 'mesh,' is capable of conforming to almost any shape that can be created using

Figure 17. The Swiss Re Building (left), revealing the diagrid at entrance (right). (Photograph by K. Al-Kodmany)

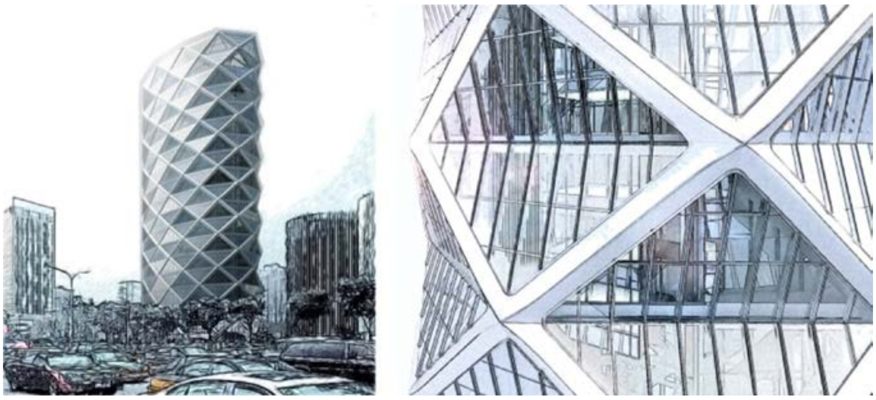

Figure 18. Poly International Plaza T2 (left); detail of "3D" pattern (right). (Sketch by K. Al-Kodmany)

Figure 19. Capital Market Authority Tower. (Sketch by K. Al-Kodmany)

modern 3-D modeling software." Unusual structures and complex geometries have been made possible because of the diagrid, providing enough support to withstand seismic disturbances. Therefore, in addition to structural efficiencies, diagrids are enabling engineers to build the "unbuildable," creating unprecedented visual aesthetics in the process.

Irregular Diagrid. Some "futuristic" towers have attempted to break away from the "homogeneous" diagrid, to more irregular diagrid configuration that promotes artistic expression. Parametric modeling and new software tools have been vital in this regard. For example, the design of Zaha Hadid's City of Dreams Hotel Tower (under construction at this writing) in Macau, China, has employed parametric modeling to create a particularly intriguing diagrid (Fig. 21). The 40-story building features diverse physical qualities that liberate the diagrid from uniformity, allowing for a more complex structure that is almost sculptural in its composition. Kuala Lumpur's proposed Sunrise Tower, also by Zaha Hadid, employs a similar diagrid design. Interestingly, the proposed Bionic Tower of Abu Dhabi features an "organic" diagrid that can be created by using parametric modeling tools. The structure would exhibit lightness, efficiency, and elegance akin to what may be

Figure 20. Cypertecture Sphere (left) and Cybertech Egg (right). (Sketch by K. Al-Kodmany)

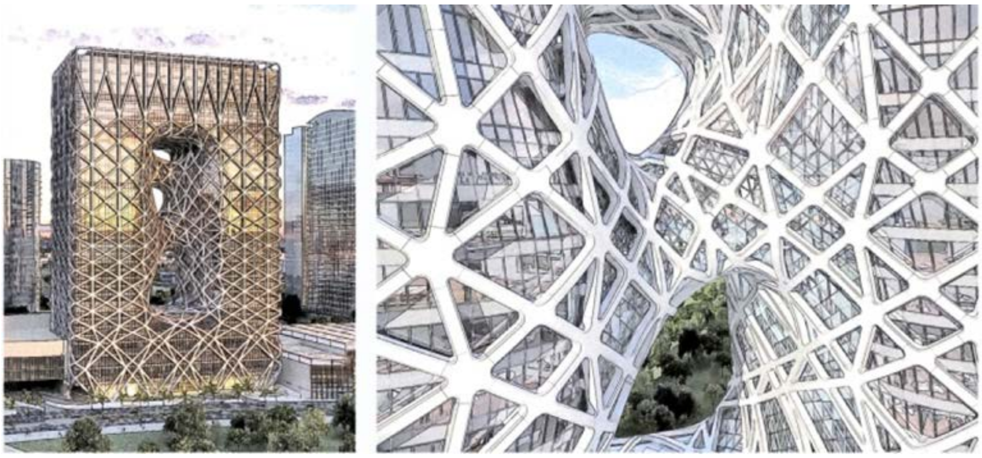

Figure 21. City of Dreams Hotel Tower (left), detail of "irregular" diagrid (right). (Sketch by K. Al-Kodmany)

found in nature.

An interesting and innovative proposal that has used parametric diagrids can be found in Zaha Hadid's 200-m (656-ft) tall Dorobanti Tower (Fig. 22), which would be built in the heart of Bucharest, Romania. The tower uses intricate ornamental patterns to form a structural lattice on its façade, creating a unique blend of structure and decor. In concert with changing structural forces, the façade's structural pattern would adjust as it rises, vividly displaying the flow of forces in the structure. This would make the façade's pattern not only ornate, but also structurally meaningful. The building's shape and tapering profile would also make it aerodynamically efficient, making it a particularly distinct structure within Bucharest's skyline.

5. Illustrative Examples

The following tall building examples illustrate in some detail some structural and aesthetic principles underlying the bracing and diagrid systems employed in them. As will be noted, these systems are amenable to application to tall buildings in varied geometric patterns. Diagrids fare better in this regard because, unlike braces, they can be used for finer grid patterns. Most of these buildings serve as landmarks in their respective cities and neighborhoods by virtue of their displaying the arresting features created by the braces and diagrids.

5.1. Bracing Systems

5.1.1. One Maritime Plaza

One Maritime Plaza (also known as the Alcoa Building), completed in 1964, is located in the central business district (CBD) of San Francisco and provides an early example of a building that utilizes seismic bracing along its exterior. This 27-story, 121 m (398 ft.) tall structure was designed by Skidmore, Owings & Merrill (SOM), (King,

Figure 22. Dorobanti Tower. (Courtesy: Zaha Hadid Architects)

Figure 23. One Maritime Plaza. (Photograph by K. Al-Kodmany)

2011). Aesthetically, the most distinctive features of the tower are: simple, definite, and bold geometry; a grid of multi-story-high X-braces stacked seamlessly atop one another; dark bronze color that appears in the glass curtainwall and painted X-braces. Collectively, given its structural expression and Modernist façade, this landmark tower has been viewed as one of the more popular buildings in the city (Fig. 23).

5.1.2. John Hancock Center

The John Hancock Center in Chicago is a 100-story, 342 m (1,127 ft.) supertall building designed as the first braced tube building by SOM. Completed in 1970, the tower features an expressive structural system, distinctive X-bracing and sloping façades, making it a remarkably iconic structure (Fig. 3). The tower employs a braced tube structural system, with a taper that measures 32 m (105 ft.) on the east and west sides and 20 m (65 ft.) on the north and south sides. Aesthetically, the mega scale X-bracing, the bronze glass window panes, and the dark color of paint used over structural elements give the tower a strong identity. The building projects the "gutsy, masculine, industrial tradition of Chicago where structure is the essence" (Dean, 1980, p. 17). The tower visually expresses the efficiency and economy of the structure and offered a new meaning by its highly visible and unique structural expression. The look of strength and stability accentuated by the larger-than-life diagonals defines undisguised and rational architecture (Ali, 2001). Overall, the John Hancock Center establishes harmony between structure and architectural form, making it an efficient, iconic, and a remarkable example of structural expressionism.

The John Hancock Center is a mixed use tower that offers residential and offices, recreation spaces, hospitality, a conference center, and grocery stores. In some ways, it is a city in itself, representing sky-high living and exemplifying the megastructure concept of a tower where people can live, work and play (Ali, 2001). The tower integrates abundant amenities, recreational spaces, and services. For example, the tower has even its own election precinct, post office, and FedEx office, so that people who live there do not even have to leave the building to vote or to mail a letter. This is most appreciated in the cold and snowy weather of Chicago. Remarkably, it was the first supertall building to be erected after the Empire State Building, which was built in 1931 (Lepik, 2008). At one stage of the development of building form, because of owner's concerns, the architectural team wanted to remove the diagonals above the 90th floor to make the view to the outside unobstructive near the top. But Fazlur Khan, the structural designer, argued against it, wanted to maintain the structural expression throughout the building height, and won (Ali, 2001).

5.1.3. One US Bank Plaza

One US Bank Plaza (also known as the Thompson Coburn Building), completed in 1976, is a 35-story, 152 m (484 ft.) tall office tower located in the heart of downtown Saint Louis, Missouri. The steel frame building is an early example of structural K-bracing, vividly expressed on the building's chamfered corners. In addition to provoking an intriguing visual effect, the K-bracing provides shear resistance and facilitates large, open, column-free interior spaces. Anchoring the north end of the downtown, the tower exhibits clean and bold lines that help to distinguish it from the city's skyline (Fig. 24). Designed by Thompson, Ventulett, Stainback & Associates, Inc., One US Bank Plaza is one of St. Louis' most popular buildings and, until the completion of One AT&T Center in 1986, it was the city's tallest building (Sharoff, 2011).

Figure 24. One US Bank Plaza. (Photograph by K. Al-Kodmany)

5.1.4. Bank of China

The Bank of China building is one of the most recognizable towers in Hong Kong and at 367 m (1,205 ft.) tall it was the first skyscraper outside of the United States to break the 305 m (1,000 ft.) mark. Completed in 1989 and designed by I. M. Pei & Partners and structured by Robertson, Fowler & Associates, the Bank of China building continues to act as a potent symbol for Hong Kong (Dupré, 2008). The building's elegant form arises out of a harmony between the tower's volumetric expression and its structural system, which consists of three-dimensional triangular trusses that are visible along the façade (Ali and Moon, 2007). The building starts as a cube at the well-defined base and diminishes in quarters until a single triangular prism remains at the top. All vertical loads are delivered by diagonal members that transfer loads to four concrete megacolumns, one in each corner. A fifth column extends through the center of the tower to the 25th floor,

Figure 25. Millennium Tower. (Photograph by K. Al-Kodmany)

where it transfers the accumulated loads diagonally to the other four columns (Beedle et al., 2007). The Bank of China building is therefore a composite structure, meaning that it is composed of large steel I-Beams encased in reinforced concrete. These members are expressed externally with naturally anodized aluminum panels.

Aesthetically, the bold X-bracing, the dynamic geometric change of the tower's form that takes place as it rises, and its reflective/glowing glass that mirrors the changing sky are the most prominent aspects of the tower (Fig. 4). The angles and sharp points are aesthetically intriguing, which provide a strong contrast with the surrounding plain, orthogonal buildings. It is noted that the Structural Expressionism adopted in the design of this tower echoes the growing bamboo shoots, an important symbol of hope, revitalization, and prosperity in the Chinese culture. Overall, the tower is a spectacular example of architectural geometry through creative artistry and complimenting efficient structural composition.

5.1.5. Millennium Tower

The 60-story, 285 m (935 ft.) tall Millennium Tower was designed by Atkins and completed in 2006 (Binder, 2006). It occupies a prominent spot near Sheikh Zayed Road in Dubai's new downtown. The tower features unobstructed views in all directions and is, therefore, visible from many vantage points within the city. The structural system is boldly revealed on the tower's east and west façades where these supports are further dramatized by the tower's protruding sides, creating a "sliding" composition. Its middle section is distinguished by dark, nonreflective glass, which contrasts well with the white structural exterior. Atop the middle section is a slim protrusion (containing service functions) which rises to hold a tall spire (Fig. 25). A multi-story podium also serves as a parking garage, with the roof accommodating recreational facilities and a 25 m (82 ft.) long swimming pool. Collectively, between its structural system, composition, and slender profile, the Millennium Tower possesses a strong identity.

5.1.6. Indigo Icon Tower

The 35-story, 123 m (402 ft.) tall Indigo Icon Tower is located in the Jumeirah Lakes Towers (JLT) district of Dubai. Designed by WS Atkins & Partners and completed in 2009 it is a mixed-use tower containing office space, residential apartments and four underground floors. Similar to the Millennium Tower, the Indigo Icon Tower is most recognizable for its external X-bracings - on opposing façades - except that for the latter these are contained within an arched, structural frame that resembles an "A" with its apex pointing to the sky (Fig. 10). This creates a unique iconic character fitting with its name. In both cases the bracing elements are positioned in the two opposing protuberant sides. The tower also extensively uses indigo colored glass to complement its light grey exterior, facilitating an interesting dialogue between the structural system and the building's cladding, giving the tower a strong identity and landmark quality. Interestingly, the Indigo Icon Tower is identical to the Indigo Tower of 2007 in the same JLT development (Roh, 2008).

5.1.7. Broadgate Tower and 201 Bishopsgate Tower

Shortly after the completion of Poly International Plaza, SOM applied X-bracing designs to their 35-story Broadgate Tower and the 13-story 201 Bishopsgate (its shorter counterpart), in the central business district (CBD) of London, U.K. Completed in 2008, the project was built on a 0.847 hectare (2.3 acre) site above rail tracks that run to Liverpool Street Station (Wright, 2006). The diamond-shaped bracings are the buildings' most prominent feature and can be seen from afar. The geometry of the outer wall of Broadgate Tower is based on six-story modules, while the lower portion of the building is arranged as a three-story module (Fig. 26). Broadgate Tower and 201 Bishopsgate are unified by a glamorized industrial appearance, where their steel has been coated with silvery-grey finish. The two towers are also united by a glazed galleria that provides a covered passageway between the two buildings. Structural steel struts cross the glass façades of the two buildings, evoking a strong structural expression. The galleria accommodates a variety of services, including shops and cafes that cater to the buildings' tenants and the public at large. Access to daylight is facilitated by the towers' structural system and their relatively slender, column-free floor plans.

5.1.8. NEO Bankside

NEO Bankside is a 0.607-hectare (1.5-acre) residential complex that lies at the heart of the Bankside area of London, U.K. and is adjacent to the Tate Modern (modern art gallery), overlooking the River Thames. Completed in 2012, the complex consists of four towers in varying multiples of six story increments; two are 12 stories tall,

Figure 26. Broadgate Tower and 201 Bishopsgate Tower (left), pedestrian gallery (right). (Photograph by K. Al-Kodmany)

a third is 18 stories tall, and the fourth is 24 stories tall. In this iconic residential development, Rogers Stirk Harbour + Partners has designed a highly visible structural system comprising X-bracing by employing an elliptical hollow section, which has improved the buildings' structural efficiency while evoking a novel aesthetic. The elliptical section crisscrosses the buildings' façades following a diagonal pattern every six stories, giving the towers an elegant appearance resulting from the soft interplay of light along the steel braces. Furthermore, the visual effect is reinforced by having the steel X-bracing protrude slightly from the façade. Offsetting the structural steel in this way also improves the buildings' safety; that is, in case of fire, the structural steel will be less exposed to heat and, hence, less prone to buckling.

Interestingly, the buildings' façades utilize red and brown colors to reference London's industrial heritage. These colors also create a splendid contrast with the chrome color of the structural bracing. The diagonal pattern of the X-bracing is further emphasized at the ground level through the implementation of elongated hexagons in the pavement and landscaping. Programmatically, the buildings house over two hundred apartments, as well as several penthouses. The buildings' bold X-braced structural system and its colorful façade create a visually memorable work of architecture (Fig. 11).

5.2. Diagrid Systems

5.2.1. Hearst Tower

Hearst Tower is a 46-story, 182 m (597 ft.) tall tower located in Midtown Manhattan. It sits atop the six-story cast stone base of the 1928's Hearst Magazine Building, which has been remodeled to serve its current function; a podium and entrance (Fig. 9). All that remains of the Hearst Magazine Building is its historic façade. The tower's form is essentially driven by its structural logic. The tower employs a diagrid system – a triangulated steel frame – where each of the façade's four-story triangles measures 16.5 m (54 ft.) tall. The building's exterior, diamond-shaped pattern provides a constant shift in its visual relationship to the skyline. This is most apparent when the tower is viewed against the backdrop of Manhattan's taller and blander towers. Overall, the diagrid system gives the tower a bold yet elegant appearance. Furthermore, its heavy historic base and its elegant contemporary shaft create a splendid contrast (Moon, 2008). Designed by Foster + Partners, the Hearst Tower won the prestigious 2008 International High-Rise Award and the coveted Emporis Skyscraper Award of 2006, the same year it was completed (Moon, 2008).

5.2.2. Poly International Plaza

Built in Guangzhou, China, Poly International Plaza is a mixed-use office and retail complex that consists of two towers that stand upon two different podiums, each of which houses retail and exhibition space. Designed by SOM and completed in 2007, the two 35-story towers rise 150 m (492 ft.). The towers' most distinctive features are expressive and bold exterior diagrids. These mammoth diagrids protrude outside the building lines creating a three-dimensional exoskeletal system (Fig. 27). The towers' perimeter structural system results in the merging of both architectural and structural expressions. Each of these towers has an innovative structural spine that supports large open floor plates and a glassy core. Poly International Plaza has received a large number of awards including the AIA-Hong Kong Honor Award, the Architectural Record/Business Week Award, and Award of Merit

Figure 27. Poly International Plaza (left); details of diagrid (right). (Sketch by K. Al-Kodmany)

for Excellence in Structural Engineering.

5.2.3. Capital Gate

Tall buildings, by definition, must possess the attribute of verticality and for this reason are conventionally assumed to be upright. However, when a certain degree of incline is introduced, a building can be made more noticeable and pictorial. Completed in 2010 and designed by RMJM Architects, the 35-story Capital Gate tower located in Abu Dhabi rises to 160 m (525 ft.) above the ground (Schofield, 2012). This luxury hotel has become an important icon for the Emirate of Abu Dhabi. The building employs a diagrid system that creates perhaps the world's most intensely leaning tower. The tower appears to boldly defy gravity as it leans at an 18° angle (Fig. 8). In comparison, Pisa's famous tower leans at only 3.99°. Viewed from the narrow side this colorful sculpted tower akin to a piece of art with its sleek skin exhibits an elongated "S" shape resembling the mathematical integral symbol.

Traditional orthogonal structural systems would not perform well given the unusual shape of this tower. Instead, a large number of small steel diagrids along the perimeter, in combination with a reinforced concrete core, has been employed to hold the building together. In addition to providing the building with greater structural strength, the diagrid system in its triangular patterns has also facilitated the tower's construction without compromising its original form.

5.2.4. Al Dar Headquarters

Al Dar Headquarters is a 23-story, 110 m, (361 ft.) tall commercial office building located in the exclusive Al Raha Beach development of Abu Dhabi. Built in 2010, MZ Architects conceived this iconic landmark by employing a pure and bold geometric form - a large disk emerging from the ground, simulating the rising sun (Fig. 7). Viewed from the side, the semispherical building appears as a clam shell, being comprised of two convexed façades joined by a narrow strip of indented glazing. Structurally, the simple, yet bold design of the tower employs a diagrid structural system, enabling a cantilever of 25 m (82 ft.) in each longitudinal direction. The circular form and diamond patterns give the building a monumental quality, while its monolithic appearance is further reinforced by the fusing of its façade to the roof. And yet, even though the building's overall design concept is rather simple, its façade still follows a complex spatial pattern based on the golden ratio. Al Dar Headquarters puts forth a striking and iconic shape, making it easily one of the most recognizable buildings in Abu Dhabi (Bellini and Daglio, 2010).

5.2.5. Tornado Tower

The 52-story, 200 m (656 ft.) tall Tornado Tower is located in the West Bay district of Doha, Qatar. Completed in 2008, the tower's concept was developed through the collaboration of CICO Consulting Architects and Engineers and SIAT, a German-based architectural firm.The tower features a distinctive hyperboloid shape, its name being derived from the desert whirlwind the hyperboloid tries to mimic; a rotating vertical column of air resembling a tornado. The tower has a gentle concave cross section where the middle bows inward relative to the top and the bottom. This dynamic shape is achieved through the use of a steel diagrid external envelope – the structure's support system – with a diamond-shaped pattern applied throughout (Fig. 12). Not only does this dynamic shape create an intriguing aesthetic, it helps to disperse and deflect wind pressure. The building's primary use is that of an office tower, though it also offers a ground floor restaurant, support facilities, and a bank. Three underground levels serve as parking garages. In 2009, it received the Best Tall Building Middle East and Africa Award by CTBUH (Parker and Wood, 2013).

5.2.6. The Bow

The 58-story Bow office tower rises to a height of 238 m

(779 ft.) and is currently the tallest tower in Calgary, Alberta, and the tallest building in Canada outside of Toronto. Designed by Foster + Partners and completed in 2012, the shape of the tower's floor plan resembles that of a bow, achieving this unique appearance by employing a mega diagrid along a curved elevation. The diagrid is composed of six stories tall structural units, which enhance the aesthetic of the tower by avoiding a monolithic appearance (Fig. 6). To increase the building's structural stability, the triangular "diagrids" have been connected to horizontal beams, making the bow-shape possible. This distinct shape also provides an aerodynamic effect (with the convex façade positioned against the prevailing wind) mitigating the impact of Calgary's strong wind, and decreasing the building's required structural support. Interestingly, the curved triangular diagrid is the first to be applied to a tall building (Parker and Wood, 2013). More efficient than the conventional diagrids applied to rectangular buildings, given that it takes advantage of the natural structural strength provided by the curve, the tower's aerodynamic form, orientation, and diagrid system, have collectively reduced structural steel requirements by 30%. The Bow received the CTBUH Best Tall Building Award for the Americas Region in 2013 (Al-Kodmany, 2015; Goncalves, 2012).

5.2.7. The Guangzhou International Finance Center

The Guangzhou International Finance Center is a supertall tower located along the central axis of the Pearl River New City CBD in Guangzhou, China. Completed in 2010, the mixed-use finance center was designed by Wilkinson Eyre and engineered by Arup. Also known as West Tower, the 103-story, 438 m (1,435 ft.) tall skyscraper employs one of the tallest diagrid structures in the world (Binder, 2015). The diagrid system is subtly exposed behind the edifice's glass curtain wall façade (Fig. 5). At night, a lighting system accentuates the diagrid system, which contrasts well with the building's smooth glass. This slender and crystalline tower features a triangular floor plan with round corners, resembling a guitar pick. The tower possesses a dynamic profile, bowing outward from the ground level for about a third of the way up, where it then tapers back to the top (Moon, 2015). In 2001, the building received the CTBUH Best Tall Building Award for the Asia and Australia Region.

6. Braced and Diagrid Towers in Concrete

Most braced and diagrid towers are made of steel, a material that can be used to clearly and vividly express the structural elements of the façade. However, reinforced concrete may also be utilized toward this end, having the potential to create new architectural aesthetic expressions given its relative fluidity. For example, the COR Building in Miami by Chad Oppenheim Architecture and Ysrael Seinuk of YAS Consulting Engineers, and the O-14 Building in Dubai by RUR Architecture have employed reinforced concrete diagrids as their primary lateral load-resisting systems (Fig. 28). Due to the properties of concrete, the structural diagrid patterns, which are directly expressed as building façade aesthetics, are more fluid and irregular in these buildings, and different from the explicitly pristine features of steel diagrids (Ali and Moon, 2007).

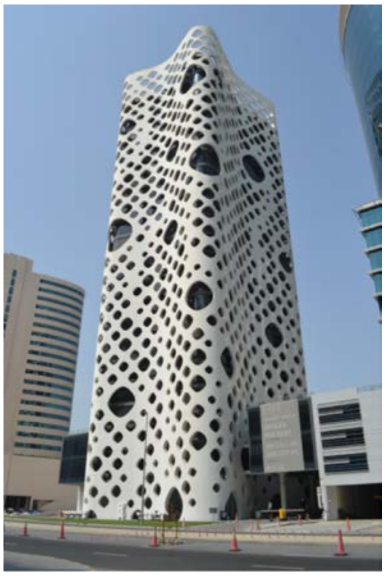

Figure 28. O-14 Building. (Photograph by K. Al-Kodmany)

The recently completed Mikimoto Ginza 2 uses a creatively designed external composite shell made of concrete and steel plates (12 mm thick) which have been placed in an "irregular" diagrid pattern. Interestingly, the perforated façades of these towers are especially captivating at night, with the building's lighting systems being used to accentuate the perforations (Fig. 29). A simpler application of the concrete bracing and diagrid system can be observed in two early towers: Chicago's Ontario Building (1985), and New York's Wang Building (1984). A recent one using diagrids is 170 Amsterdam Avenue (2014), (Fig. 30).

In both Onterie Center (Fig. 1) and Wang Building the structural framework on the exterior are fully exposed. The structural systems are braced framed tube. The diagonals on the façade are created by filling in windows with reinforced concrete. For the Wang Building, these are X's and the long side and zigzag forms on the short side of the rectangular building. For the Onterie Center, the X bracing is thinner and more delicate in appearance. The central parts on the long sides are set back without any diagonals; the remaining two parts are braced with zigzag-shaped diagonals. The two short sides of this building employ X bracing. Although the setback tends to separate the building in two halves, a solid top story reunites them together, capping the building and visually holding

Figure 29. Mikimoto Ginza 2, daytime (left); nighttime (right). (Sketch by K. Al-Kodmany)

Figure 30. 170 Amsterdam Avenue. (Sketch by K. Al-Kodmany)

them together. The apartment building at 170 Amsterdam Avenue in New York is one of the most attractive new buildings. Its exoskeleton form composed of diagrids offers an expression of structural clarity. The 20-story slab tower was designed by Gary Handel for Equity Residential, and contains 239 rental apartments.

7. Conclusion

This paper has analyzed externally braced and diagrid systems in order to facilitate a better visual understanding of these systems. As extremely complex feats of engineering, design and planning, tall buildings lend themselves well to artistic enhancement in structural design. Through their distinctive character, tall buildings may bring attention to themselves by showing how they are built, how they remain stable and how they function. Overall, when a structure presents its façade in a logical manner, both architects and structural engineers work as artists in achieving the same goal; they craft something that is both functional and beautiful where the structure becomes a dominant component of the architecture. As such, this paper has attempted to provide an overview of the structural and artistic principles which may be used to shape tall buildings in the future. In this way, it may be concluded that a well-articulated skyscraper with structural expression – "a structural art form" – with careful considerations to the surrounding context, may improve the overall aesthetic quality of a place.

Therefore, in addition to their structural efficiency, diagonally-braced and diagrid towers have the potential to provide exciting aesthetics and visual interest. These systems vary from the very simple to the extremely complex. A building's design and appearance should be determined by the collaborative decisions of the interdisciplinary team, and discretion should be used in regards to the level of boldness or subtlety expressed in the structural system in a given context. Through an iterative process, and with the help of powerful computer modeling tools, design teams may decide on how specific elements, such as shading, decoration, color, curtain walls, patterns, scale, structural details, lighting systems, etc. can be applied. In the authors' opinion complex and iconic forms should not be used just for their novelty or fashion of a time, but also keeping in mind their cost effectiveness and rational quality that will transcend and pass the test of time.

Future research should examine the relationship between the towers studied in this analysis, and their respective physical contexts. It is important to conduct contextual examinations that assess the contribution these towers provide in regards to placemaking. It would also be beneficial to know what image they project as urban spaces and space markers, and how they are perceived by the public. Future research of this kind could be conducted via public surveys, and should specifically assess the aesthetic impacts of braced and diagrid towers. It is important to understand public opinion over extended periods of time, and while there has been significant work in evaluating buildings in general, research on public opinion in this regard is lacking. In the authors' opinion, complex, contradictory and iconic forms should not be used just for the sake of their novelty, but also keeping in mind the significance of their cost-effectiveness and rational as well as transcendental quality that will stand the test of time. This paper hopes to have provided a theoretical groundwork from which further research may be conducted.

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