From Orthographic to Eccentric: Tall Architecture of Extremes

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DEFINING PROGRESS

"Progress" can be defined in varying ways as a function of point of view and preoccupations. The ability to surpass the feats of the past is thought by some to represent architectural progress. In doing this, designers have attempted mastery over the forces, historically of nature – be they forces of gravity, seismicity or wind. Resistance to terrorism has more recently been added to this list. Architectural progress during the last century has been closely tied to the interweaving of material advances/invention, fabrication, engineering and computer aided design.

Architecture has long been a competitive game. From Roman and Gothic times, striving against the forces of gravity to build the highest vault, to the skyscraper wars of this century that must additionally contend with extreme wind loading, architecture has been reliant upon technical invention to fuel the game. Building height has been a measure of advances in technology and technical achievement of civilizations. In spite of the terror attack on the World Trade Center, tall buildings continue to be a focal point in current culture. The age of the Internet has seen an unprecedented number of web sites (professional and fan based) and blogs devoted to discussing and watching the progress of skyscrapers. Threads related to tracking progress on the construction of the Freedom Tower in New York City, for instance, date back more than half a decade and serve as one of the best repositories for progress construction photos, all uploaded by "fans". Tall building construction progress has become a spectator sport in this respect. Interest in the next tall tower and broken records feeds the news.[1]

Advancement in construction has also been tied to our ability to represent, and subsequently construct, the objects of our desire. Methods of representation are also the children of technological progress. The abandonment of "trial and error" building processes for predictive construction due to the advances in stereometry and mensuration during the Enlightenment resulted in an architecture that was significantly more precise and less prone to failure.[2] Engineering and architecture became separate disciplines in a new science based world where structural failures were less acceptable. Stereometric representation and early applications of statics still limited creativity and were incapable of easily providing solutions to assist in the construction of extreme, irregular, or non-geometrically derived shapes.

In parallel with new materials, methods of representation, communication and structural engineering have either accelerated or hindered progress in both the design of architecture and the ability to exploit the characteristics of materials. Architectural and engineering practices of the 19th and 20th centuries were primarily limited to orthographic representation. Hand drafting combined with slide rule based calculation limited the incorporation of creative geometries, particularly in steel construction. Curvilinear shapes became the trademark of cast in place concrete expression of the 1960s and 1970s, making use of methods of calculation for indeterminate systems. Steel buildings of the period continued to rely on repetitive, simple geometries to retain a measure of economy in production and detailing. Radical change in design methods and urban form is a direct result of the widespread adoption of iron and steel in the 19th century and the current use of advanced computing programs and their ability to solve complex structural problems.

The complete course of architectural history as relates to construction and urban form has changed as the direct result of transformations due to the incorporation of steel as a primary building material. Steel, as a structural material, became an icon for technological progress during the 19th century, and modernity in the 20th century. As a new structural material with immense tensile capabilities, steel allowed for the creation of architecture conceived in lightness and suspension. It was, in fact, the tensile capabilities of steel that challenged design in reinforced concrete to aspire to free itself from its inherent compressive conceptuality. The tensile strength of steel has also allowed for the creation of forms that are capable of resisting extreme forces of wind and eccentric loads due to gravity. These include vertical cantilevers, also known as towers. The invention of iron, and subsequently steel, was responsible for completely changing both the process and the product of architectural design. *Its incorporation fuelled competitive change in the architecture of the last century.*

The introduction of digital design and computer assisted structural engineering supported the inclusion of wildly varying geometries, allowing for a marked change in the nature of steel structures. This is due in part to the ability of steel to handle tensile forces that result from eccentric loading, and in part due to ease of analysis of the same with modern software systems. In the case of eccentric loading and oddly shaped buildings, this would include the benefits of Computational Fluid Dynamics in conjunction with traditional Boundary Layer Wind Tunnel testing.

Technological progress has radically altered the traditional role of the architect as master designer or master builder. It challenges even the rather complete professional divide between architects and engineers. A higher level of proficiency is required in understanding materials and construction processes as well as communicating with engineers, fabricators and consultants in a more collaborative way.

Where early 20th century steel structures used a limited palette of standard steel forms such as angles and plates, from which more complex built up members would be fabricated, contemporary architecture has a wider range of shapes and sizes at hand, as well as fabrication expertise that is capable of creating a myriad of custom shapes. This ability has made possible new methods of structuring tall and eccentrically shaped buildings with various diagonally braced systems. Members are strategically designed rather than "hobbled together" out of dozens of smaller pieces.

EXTREME HEIGHT

Steel has enabled serious competition in the world architectural forum. The tensile capabilities of steel have facilitated the design of structures that were unimaginable in 1912. When the Woolworth Build-

Figure 1. The Eiffel Tower, 1889, was fabricated from members that were built up from plates and angles. The Bow Encana Tower in Calgary, Foster + Partners, 2011, used a wider variety of members from which to fabricate the large custom steel sections of its double glazed façade.

ing was opened in 1913 in New York City, it was at 241m/792 feet, the tallest building in the world. Its steel portal frame supported traditional looking terra cotta cladding and the setback style of its Gothic motif predated bundled tube skyscraper construction that would permit the Willis (former Sears) Tower in Chicago reach a height of 1,451 feet when it was opened in 1973, making it the tallest building in the world. Its title was stripped by the World Trade Center towers in 1977 (the title can be debated whether or not you take into account the height of the highest occupied floor or the top of the antenna). When the new One World Trade Center (Freedom Tower) is completed in 2013, at 1,776 feet, it will replace Willis as the tallest U.S. tower. It will not compete in the global arena for tallest building as concern that it may become a terrorist target curtailed such plans. It will be the tallest office tower. The height of occupied floors has been limited to match the height of its ill fated predecessor.

It is interesting to note that structural progress in the design of steel skyscrapers was reflected in a confidence in high strength steel, structural engineering and construction that led to the elimination of redundant systems. A description of the 1913 Woolworth Building notes:

> "The arched frame of the Woolworth tower extends up to the twenty-eighth floor; above this, to the forty-second floor, bracing is secured through a double system of knee braces in which the knees are located on the top and bottom of the girder and its supporting columns. The Woolworth frame could easily withstand hurricanes of maximum intensity; however, this lavish distribution of steel in deep fillets and braces came to be regarded as an expensive redundancy of metal with an unnecessary sacrifice of the vertical space between the floors. The development of high strength steel, welded connections and new techniques of riveting and bolting made it possible to eliminate these additional shapes in buildings even higher than the Woolworth."[3]

The Empire State Building, completed in 1931, simplified the type of extensive bracing used in the Woolworth tower, eliminating much of the redundant steel that was used to reinforce the connections. In this frame the girders were simply riveted throughout their depth to the supporting column, and the beams riveted throughout their depth to the girders. Triangular braces at the connections were eliminated as these interfered with the clear floor to floor height. The core structure that housed the elevators and exit stairs was framed in steel. A reduction in floor to floor height could allow for increased density on an urban site meaning more rental income.

Skyscraper construction stayed with this model, save for the replacement of rivets by bolts, until the construction of the 100 storey John Hancock Tower in Chicago, designed by SOM, in 1965. Here the braced tubular cantilever was introduced. In order to permit larger expanses of glass and less frequent vertical columns, large diagonal members were overlaid to brace the entire length of the structure.[4,5] Variations on this system of braced tube framing are still widely used in contemporary skyscrapers around the world.

The Willis (formerly Sears) Tower, also designed by SOM from 1970 to 1975, worked with a new type of vertical cantilever system referred to as a bundled tube. Here nine smaller towers whose frames were constructed from heavy Vierendeel trusses were grouped together. Reminiscent of the set back style, the tubes progressively truncate towards the top. Diagonal bracing is not necessary due to the load sharing of the tubes and the minimized surface area and wind load offered by the smaller floor area at the top of the tower. The Willis Tower is said to use 40% less steel than would have been required with a heavier portal system of framing that would make each of the connections moment resistant. As the cost of installed steel is proportional to its tonnage, and this in turn puts loads on the foundations, less steel is an objective in tall building design. Different strategies of framing work towards being lighter while not compromising lateral stability.

The World Trade Center Twin Towers were under construction from 1968 to 1973, under the direction of Minoru Yamasaki Architect and Leslie E. Robertson Engineering. Here a far denser Vierendeel truss was chosen to support the walls on a single tower model. The rigidity of the Vierendeel truss was relied on to resist wind sway without using the method of bundled tubes as in Willis or diagonalized bracing as in the John Hancock Tower.

The tragic events of 9/11 gave rise to reflection and rethinking the design of Supertall buildings[8]. It had to be ascertained if the design of the World Trade Center tower was a contributing factor to the collapse, and if so, how future building design might be modified to create a more resistant design. This study is curious from an architectural and engineer-

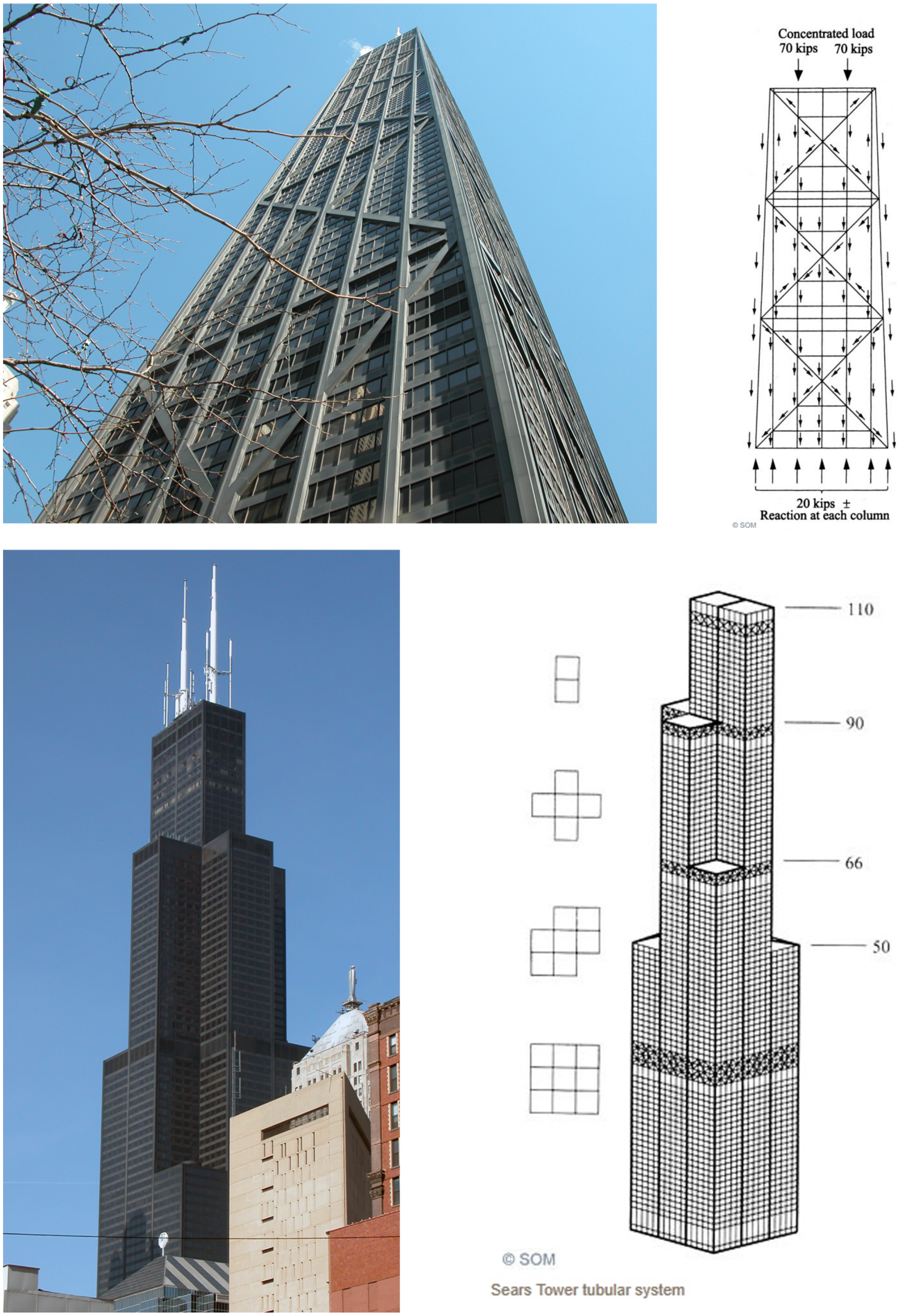


Figure 2. Diagonal bracing system of the John Hancock Tower in Chicago, Illinois. (top images) In addition to reinforcing the tubular steel frame, the diagonals provided for alternate load paths.[6] The Willis Tower (bottom images) uses a bundled tube system to resist wind loading of the cantilevered form. This structural arrangement does not allow significant areas for open office planning, particularly towards the top of the tower. Stepping back the top decreases wind resistance.[7]

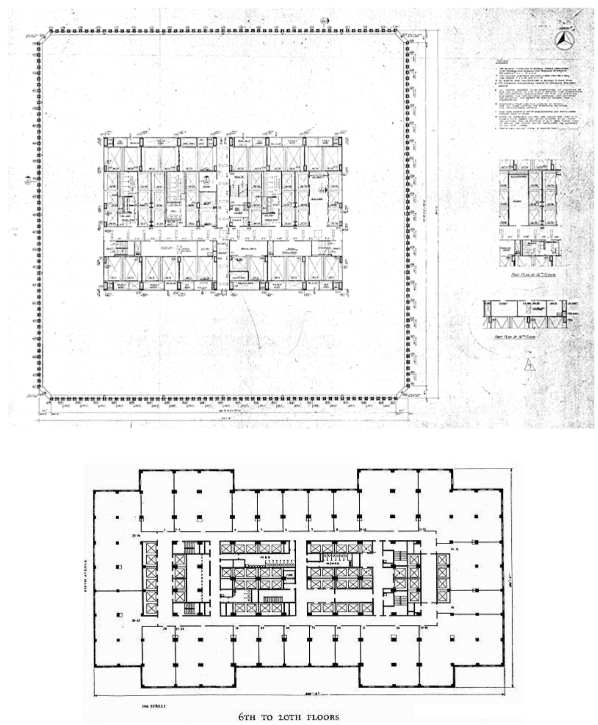


Figure 3. Typical floor plan of the North Tower of the WTC[9] showing the free span between the exterior load bearing system and the columns of the core in contrast with the plan of the Empire State Building[10] whose structure relied on a fairly tight grid of columns. The column grid of the ESB worked well with office planning of the time, where the drive to eliminate interstitial columns in the WTC was in response to marked changes in office planning and the way that office dynamics worked. Both use steel columns to support the core of the building. Elevator and stair walls are made from non load bearing materials

ing perspective as forensics were being carried out on a building that was close to 30 years old at the time of its destruction, and that used an innovative method of construction that had not received widespread adoption in the industry. The assessment of life safety systems and exiting strategies was relevant as these had not changed substantially in the interim. The ensuing recommendations are being used to inform completely different systems of skyscraper design that have already progressed well past the state of construction in 1973.

The National Institute of Standards and Technology (NIST) was charged with the examination[11], although parallel studies were carried out by the steel industry as the materiality and specific nature of the design of the steel structural system were immediately called into question after the collapse. The framing system for the WTC was innovative for its period of construction. The outer load bearing wall was constructed from a series of prefabricated structural steel panels with a vertical support system at 39 inches on center. A lighter weight steel truss system spanned from these exterior walls to the central core, eliminating interstitial columns and providing the desired open office space. The steel was protected with a spray fireproofing. The core design of the WTC was different than many tall structures that tend to use a reinforced concrete core to house the elevators, stairs and services. The concrete core is also relied on for lateral stability and shear resistance for the structure. The WTC core was comprised of a grid of very large steel columns, some measuring 52” by 22”. Steel cores were the norm for New York City tall building construction.

The major question arising out of 9/11 focused on the possibility of designing a skyscraper, or any building, strong enough to resist a similar attack. Buildings to this point had been designed to resist natural forces such as high winds and seismic events, but never “acts of war” or manmade events. Notwithstanding, given an incident in 1945 where a stray fog bound aircraft struck the Empire State Building[13], the World Trade Towers were designed to withstand the impact of a Boeing 707, although not fully loaded with fuel. Although the NIST report makes a multitude of safety recommendations for future skyscraper design, two stand out as having the most impact on future progress in American skyscraper design. Firstly,

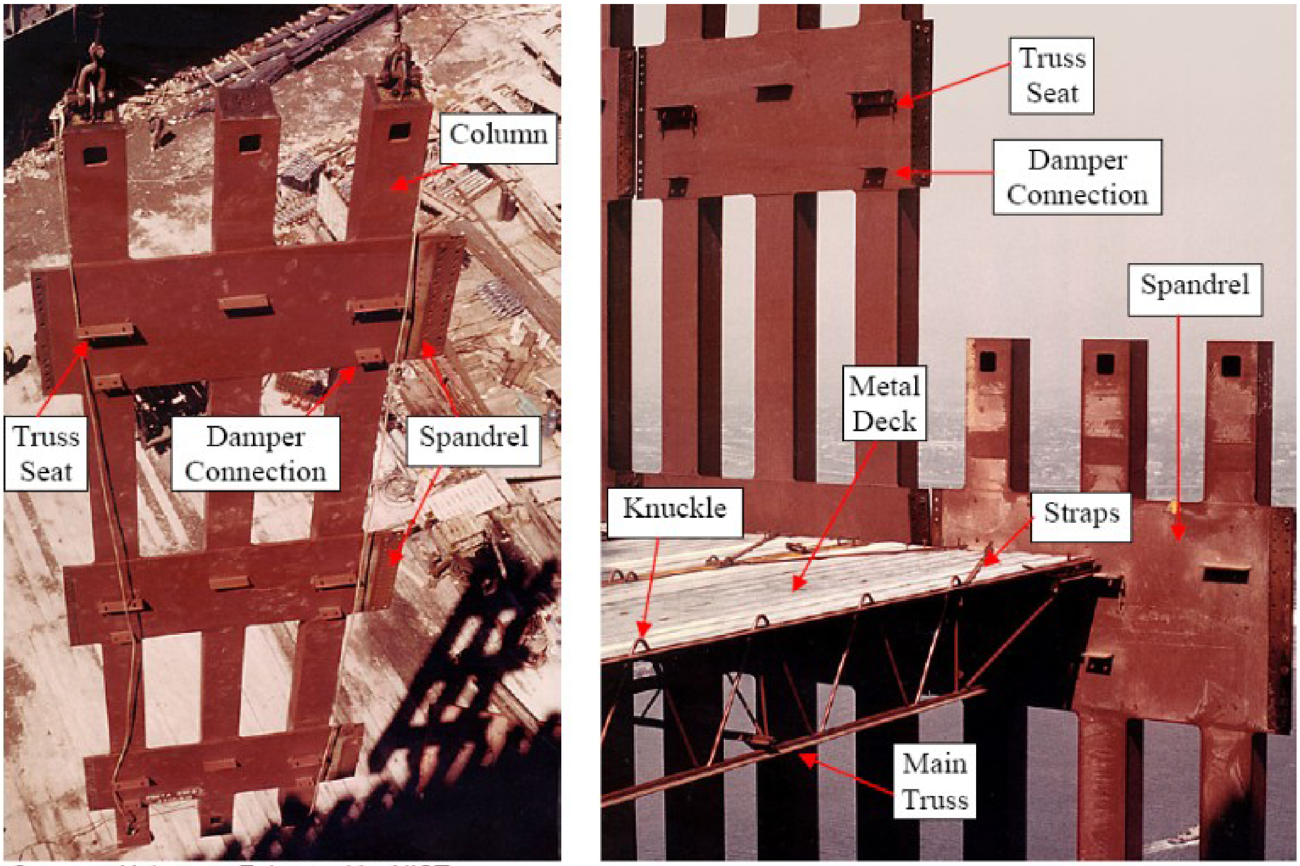
> “Public officials and building owners will need to determine appropriate performance requirements for **buildings that are at *higher risk* due to their iconic status, critical function, or design.”[14]**

This puts the onus on the design team and client to decide upon strategies that exceed local code requirements or construction norms for the type, size and height of tower based on risk assessment.

Secondly,

> Adopt and use ***“structural frame” approach*** (structural members connected to the columns carry the high fire resistance rating of the columns).”[15]

This arises from concerns regarding the lightness of connection of the floor framing system in the WTC to the exterior Vierendeel truss walls. Due in part to the instantaneous destruction of the fire proofing on the steel combined with extreme heat, the



Source: Unknown. Enhanced by NIST.

Figure 4. The exterior steel came in prefabricated panels, installed in a staggered pattern in places so that all of the connection points did not line up, for added rigidity. A truss system spanned from the exterior walls to the steel core.[12]

light weight floor framing in the WTC sagged, pulling in the exterior walls, which resulted in the snapping of the exterior columns. Ensuring a uniformly high resistance to fire should decrease risk. Earlier suspicions that failed connections between the floor trusses and the exterior tube structure that caused progressive collapse were debunked by forensic study of video of the wall failures. However the entire structural system, including the lightweight floor trusses and their connections has not been used again in any subsequent tall building construction.

In response to the suggestions, The Port Authority has stated regarding the construction of the new World Trade Tower:

> "New safety features will include 3 feet (91 cm) thick reinforced concrete walls for all stairwells, elevator shafts, risers, and sprinkler systems; extremely wide "emergency stairs"; a dedicated set of stairwells exclusively for the use of firefighters; and biological and chemical filters throughout its ventilation system." ...

> "Its structure is designed around a strong, redundant steel moment frame consisting of beams and columns connected by a combination of welding and bolting. Paired with a concrete-core shear wall, the moment frame lends substantial rigidity and *redundancy* to the overall building structure while providing column-free interior spans for maximum flexibility."[16]

> "These skyscrapers have steel connections capable of redirecting the path of the upper floors' load downward through other structural members if one should fail. And sprinkler supply lines have been located within an impact-resistant core--a major difference from the Twin Towers. Both innovations are now part of New York City building codes."[17]

So in light of increased concerns for human safety in light of the threat of terrorist attacks, structural redundancy, such as was eliminated shortly after the construction of the Woolworth Building, again becomes part of the approach to the design of super tall buildings. But in light of the recommendations of NIST, the degree of redundancy can be selectively increased proportionate to the likelihood of terrorist attack. Hence not all towers are built with 3 foot thick steel reinforced concrete core walls in addition to steel framing.

Where modified core design may not have overtly architectural design implications, safety concerns that impact the lobby building do. The lower floors of the Freedom Tower have been designed in concrete for better blast resistance, but due to aesthetic concerns, have been clad in a crystalline glass skin. New innovations in blast resistant glazing support systems, such as cable net systems[18], are also being employed in lobbies with lower level security issues.

WIND TESTING

Wind tunnel testing has been around for more than 100 years. The Wright Brothers used a simple wind tunnel to test their airplane as early as 1901. However, wind tunnels were primarily used by the auto and aviation industry to study vehicle performance. It was not until the mid 1960s that wind testing of buildings was even considered as a potential aspect of the design of buildings. At this point only buildings that were very tall or might have unusual snow drifting patterns would have considered testing. This would have been upon the advice of the structural engineer and would not have been mandatory.

The NIST WTC Disaster study cited inconsistency in the predictive wind testing of the failed towers. During its investigation of the collapses of the WTC towers, NIST found that wind load estimates from three separate wind tunnel tests on WTC models differed greatly. As a result NIST has proposed a code change that would require the use of a nationally accepted standard for conducting wind tunnel tests routinely used for determining wind loads in the design of tall buildings.[19]

Regardless of NIST recommendations and spotty adoption into mandatory codes, testing for the effects of wind on buildings is now routinely carried out for all tall buildings and particularly those with unusual geometry that would adversely affect human comfort at grade or result in excessive snow loading. Levels of innovation in the shape of towers make wind design a significant design factor. Developing a working relationship with the wind engineering consultant is part of the technological progress in design associated with managing complex projects.

At present the Burj Khalifa stands as the tallest structure, at 828m/ 2,717 feet, triple the height of the Woolworth Building. Increased height has necessitated the creation of a different approach to the creation of the structure. Where the Woolworth, Willis and the Burj Khalifa towers have a similar massing, their internal design is remarkably different. In common is the increased base area of the tower, stepping back in sections to the top. Where the Woolworth and Willis towers use a steel frame, the Burj Khalifa only uses steel for its uppermost portion, the balance of the building being constructed from highly specialized cast in place concrete using unusual steel reinforcing. The shape of the tower was in part derived from precedent in the design of bundled tubes (Skidmore, Owings and Merrill being responsible for Willis and the Burj Khalifa) as well as from the more than 40 wind tunnel tests that were carried out on the tower. Biomimicry is cited as the source for the use of the Hymenocallis flower form which informed the triangulated setback that included a spiral variation in the height of the subsections. The spiral form is able to "fool the wind". This is scientifically termed "vortex shedding" where uneven geometries are used to prevent the vortexes on the leeward side of the structure from aligning, which if in tune with the natural resonance of the building, could cause catastrophic failure.[20] Such tests are now a routine part of tall building design and are used to both inform as well as suggest modifications to the shape of the tower.

THE EMERGENCE OF THE DIAGRID

Not all tall buildings have competed on the basis of pure height. Where height is not possible, be it for reasons of potential for natural disaster (seismic, hurricane, monsoon), cost or terrorist fears, unusual geometries have been sought after to create a progressive type of signature architecture. A steel diagrid has emerged as the structural system of choice due to its ability to support eccentric geometries, not possible through the use of standard portal/moment frames, tubes, bundled tubes or even diagonalized cores. Structurally it also can provide a redundant system that is capable of providing alternate load paths.

There are a number of structural advantages that can be attributed to the use of a diagrid system over the typical moment frame tube or bundled tube system for a tall building. Where the original diagonalized core system laid a series of diagonal bracing members over a framed exterior support system (John Hancock in Chicago), the current (standard high rise) diagrid system uses an exclusive exterior frame comprised entirely of diagonal members. This type of structure carries lateral wind loads more efficiently, creating stiffness that is complemented by the axial action of the diagonal member. If tightly engineered, these systems can use less steel than conventionally framed tall buildings.

A diagrid tower is modeled as a vertical cantilever. The size of the diagonal grid is determined by dividing the height of the tower into a series of modules. Ideally the height of the base module of the diamond grid will extend over several stories. In this way the beams that define the edge of the floors can frame into the diagonal members providing both connection to the core, support for the floor edge beams, and stiffness to the unsupported length of the diagonal member. This aspect of the diagrid is often expressed in the cladding of the building. The modu-

Figure 5. Aldar Headquarters in Abu Dhabi (2010)(top left) uses a diagrid to create the only circular tower (in elevation) in the world. Capital Gate in Dubai (2011) (top middle) is the most backwards leaning tower. At 18° its lean exceeds that of the Leaning Tower of Pisa. CCTV in Beijing (2010)(top right) is strictly speaking not a pure diagrid tower as it also relies on vertical columns for support. But the diagrid was essential in constructing the remarkable cantilevered sections without aid of shoring.[22] The digital images created by the fabricator[23] for the Bow Encana in Calgary, AB, Canada reveal the complexity of the construction of a diagrid node (bottom left) as well as the staging and shoring for the installation of the long diagonals (bottom right). Erection in eccentrically loaded diagrid buildings is far more difficult than in more historic orthographic towers.

larity of the curtain wall normally will scale down the dimensions of the diamonds or triangulated shapes to suit the height of the floors and requirements for both fixed and operable windows.[21] As with any deviation from standard framing techniques, constructability is an important issue. Both the engineering and fabrication of the joints are more complex than for an orthogonal structure and this incurs additional costs. The precision of the geometry of the connection nodes is critical making it advantageous to maximize shop fabrication to reduce difficulties associated with job site work.

There are two schools of thought as to the rigidity of the construction of the nodes themselves. Technically, if designing a purely triangulated 'truss like' structure, the center of the node need not be rigid and be can constructed as a hinge connection. Where this may work well for symmetrical structures having well balanced loads, eccentrically loaded structures will need some rigidity in the node to assist in self support during the construction process. In many of the diagrid projects constructed to date the nodes have been prefabricated as rigid elements in the shop allowing for incoming straight members to be either bolted or welded on site more easily. As this type of structure is more expensive to fabricate, cost savings are to be realized if there is a high degree of repetition in the design and fabrication of the nodes.[24]

The triangulation of the diagrid "tube" itself is not sufficient to achieve full rigidity in the structure. Ring beams at the floor edges are normally tied into the diagrid to integrate the structural action into a coherent tube. As there are normally multiple floors intersecting with each long diagonal of the grid, this intersection will occur at the node as well as at several instances along the diagonal. The angle of the diagonals allows for a natural flow of loads through the structure and down to the foundation of the building. Steel has been the predominant material of choice for all diagrid buildings constructed to date.[25] The steel diagrid has facilitated a parallel competition in tall buildings. Each vies for claim to some unique shape, geometry or feat in contest against the natural forces of gravity.

These new structures rely extensively on digital drawings to translate the intentions of the complex geometry from design, through to detailing and erection.

BEYOND 2012: THE CHANGING DEFINITION OF PROGRESS

Skyscrapers have traditionally been such optimistic structures, and symbols of architectural and cultural progress. Their design and construction has constantly stretched the limits of traditional methods in engineering and design. The construction methods of 20th century towers have given way to a variety of 21st century methods of composite construction for towers of varying shapes and increasing heights. There is substantial world wealth and pride invested in these towers. How they are designed, constructed, demolished or renovated can truly be seen as a measure of architectural progress over the past 100 years.

Architectural *progress* has often resulted in the demolition of one building to make way for a newer, bigger, better one. Such was the fate of the Singer Building in New York City. At 47 stories it held the title of Tallest Building in the World in 1908. However in 1967, in spite of protests that would have designated it a landmark, a designation that saved the Woolworth Building, it was demolished. It remains the tallest building ever to be peacefully demolished. As a steel structure, it was able to be dismantled, and its remains sent to salvage.

The voluntary destruction of skyscrapers is rare. However, permission to destroy by implosion is being requested by MGM to remove the Harmon Building in Las Vegas, Nevada. The tower, designed by Foster + Partners and never occupied has been declared structurally unsound. The original height of the tower was to be 49 floors. Due to concerns about deficiencies with the steel reinforcing in the concrete structure, the design was lowered to its present 28 floors. Claims are that it is still unsound and would fall during a 100 year earthquake. Although there are arguments between interested parties that would prefer to "fix" the building, the economic downturn seems more likely to result in demolition.[26]

Moving forward, progress environmental thinking values the materials of the world as finite resources, and in search for a cradle to cradle methodology, prefers deconstruction (for reuse) to demolition, ostensibly, for landfill or scrap – although it is possible to magnetically sort through the rubble to separate rebar from concrete, and this is routinely done. When one tall building is removed to allow for the construction of a Supertall building, implosion is the preferred method of demolition as it is faster, if less sustainable. Countless tall buildings that were constructed during the tall building boom of the 1960s and 1970s are presently undergoing re-skinning as a more environmentally and affordable alternate to demolition and new construction. Zerofootprint has launched the second year of "Re-skinning Awards" to encourage more development in this arena. As future progress of the tall building, this should prove interesting to track.[27]

However, more than 10 years after the Twin Towers fell, articles are still being written and people are still concerned that skyscrapers are not able to withstand a similar terror attack. [28]This is more of a concern in the United States than other places. Yet concerned as all may be, the bottom line is a lack of funding to retrofit existing tall buildings or even to voluntarily construct new buildings to improved standards. Building codes will work with technology to create architecture that can resist 100 year natural incidents, but man-made force still belies a credible plan.

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