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The Rational Optimization and Evolution of the Structural Diagonal Aesthetic in Super-Tall Towers

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Abstract

In the design of super-tall towers, engineers often find the conventional frame systems used in countless buildings in the past decades incapable of providing the required form, performance and constructability demanded by super-tall heights. The strength of the diagrid as a structural system in high-rise towers is the total flexibility it affords the designer as an adaptable, efficient and buildable scheme. Using fundamental engineering principles combined with modern computational tools, designers can take minimum load path forms to create rationalized diagrid geometries to create optimized, highly efficient towers. The use of diagrid frames at SOM has evolved as a structural typology beginning with the large braced frames on the John Hancock Center and continued in modern applications proving to be a powerful system in meeting the demands of super-tall buildings.

Keywords: Diagrids, Tall buildings, Rationalized geometry, Optimization

1. Introduction

The use of diagrid geometries in tall towers has a strong legacy at the design offices of Skidmore, Owings & Merrill LLP (SOM), the genesis of which can be traced to the John Hancock Center with its bold expression of diagonal braced frames opening the doors for the pure, column-free diagrid systems of the modern day. As the diagrid has matured as a structural system in the decades since the John Hancock Center and the pioneering work of Dr. Fazlur Khan, Myron Goldsmith and others, it has been clearly established that what it represents is an adaptable system which the designer can modify, shape and form to create and optimum, rationalized scheme in response to the particular conditions of each individual tower.

The ability of a system to distribute lateral loads equally across all elements in its perimeter frame is a key indicator of structural efficiency and it is here where the diagrid demonstrates its superiority as an optimal lateral load resisting system when compared to conventional frames. Where a perimeter tube frame struggles to distribute axial wind loads into all of its vertical elements, a phenomenon known as shear lag, the force distribution provided by diagonalized members in the diagrid frame creates a system with near total efficiency.

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2. Diagrids in Tall Structures

The use of diagonalization on the Rural Commercial Bank is the purest expression of a diagrid structure. The design is a clean, repetitive system with all the performance benefits of a diagrid combined with the connection economy of moment frame systems. The diagrid exoskeleton stands outside of the building, beyond the extent of the finished glazing presenting a powerful synthesis of architecture and structure. This design decision enables a completely column free zone throughout the floor plan allowing for maximum programmatic flexibility. Due to the simplicity of the diagrid, tower nodes are identical throughout the height of the structure, varying only in material thicknesses.

The Cyber City tower presents again a clean expression of structure where the triangular geometry is maintained throughout the tower but intermediate members are added inside the triangles at lower floors in response to the accumulation of lateral demand at the base of the tower. The addition of intermediate members within the diagrids serves to reduce the demand on individual members and also shortens the unbraced length of primary diagonals and thereby improving their buckling capacity.

When the trajectories of the principle stresses in a solid cantilever under wind loads are broken down, one can see that the forces at the base are primarily axial loads and thus want to be more vertical while the stresses at the top of the building are controlled by shear and thus want to be more horizontal, a reflection of minimum load path



Figure 1. Evolution of diagonal frames in tall towers.

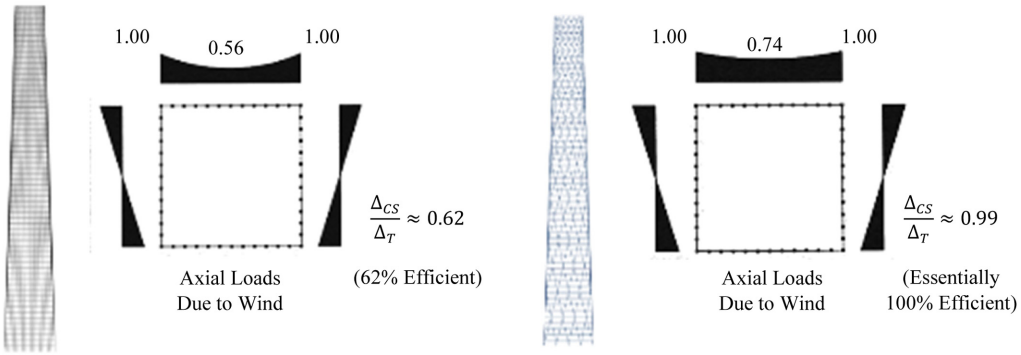


Figure 2. Efficiency of conventional frames vs. diagonal frames under wind load.

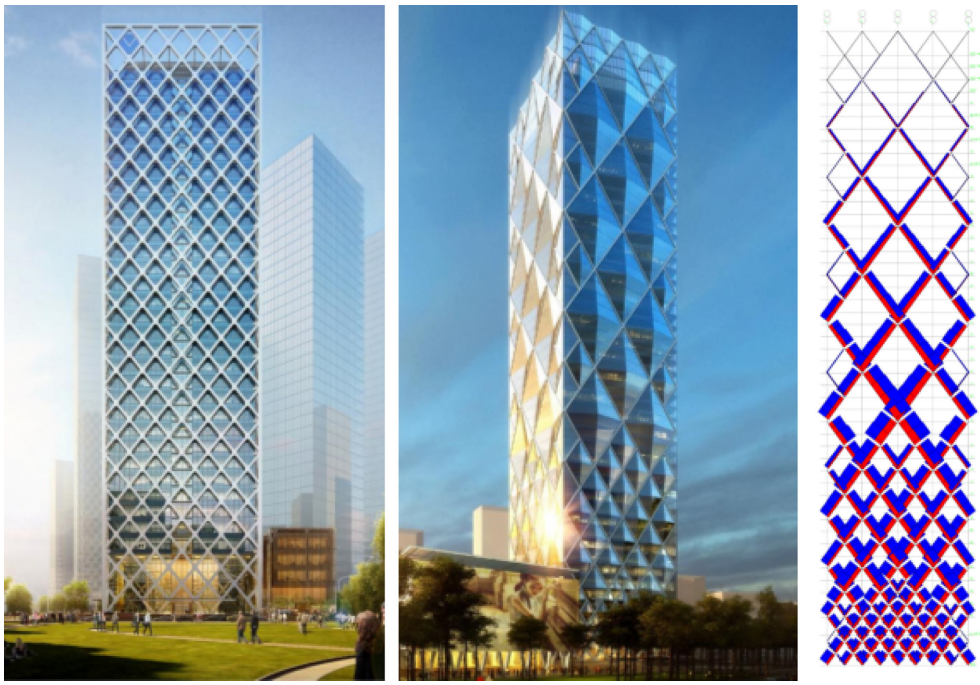


Figure 3. Rural Commercial Bank (left), Tian'an Cyber City (center) and load paths in Cyber City (right).

Michell trusses. Applying this simple concept to a tall tower, the optimum angles for the primary structural member are calculated to strategically place the appropriate steel material at the proper location and angle. When coupled with a reinforced concrete core wall system to provide building mass and additional stiffness, the structural steel diagrid completes a balanced structural system to resist the lateral loads in a very efficient manner.

If the Rural Bank and Cyber City towers are illustrations of the diagrid in its most pure form with consistent grid geometry repeated on all faces over the entire height of the structure, the 555m super-tall Korean tower is an illustration of the diagrid as a totally adaptable system capable of responding to an array of tower geometries. The super-tall tower in Korea features geometry which transforms from a square, 70-meter square footprint to a 39-meter circle at 555 meters above ground. A structural diagrid defines the form from bottom to top. The individual, planar triangles of the diagrid are clad with taught glass surfaces, revealed from their adjacent glass surfaces. Plating the diagrid structure in a geometrically defined, planar surface enhances the transforming geometry from a relatively smooth surface at the square base to a more complex, faceted texture at the crown. This marriage of structure and form is inherent in the building imagery. The tapering profile of the building in combination with the modeled surface at higher elevations creates a highly efficient structural form. The composite system established by the steel diagrid and concrete core, enhanced by the tapered and faceted profile, creates a highly efficient high-rise structure.

$$A\cdot\Delta=\frac{1+\cos^2(\theta)}{N\cdot\cos^2(\theta)\cdot\sin^2(\theta)}+\frac{L\cdot x\cdot(1+\cos^2(\theta))}{D^2}\cdot\left[\frac{1}{\sin^4(\theta)}+\frac{1}{\tan^2(\theta)\cdot\sin^2(\theta)}\right]$$

where:

q : an angle of the columns in the story
Δ : drift of the top of the building due to deformation of the story
A : a constant describing the stiffness of the story
D^2 : property of the locations of the columns in the story
N : number of columns
L : moment arm (M/V)
x : distance of the story being optimized to the top of the building

The lateral loads in the perimeter steel diagrid are resisted by a perimeter network of diagonals and horizontals in which the angles have been optimized to limit wind deformation and overall shear forces. The diagonals carry both wind and gravity loads to the base of the structure. Because the diagonals utilize their entire cross sections to resist the loads, they are very efficient. The diagonals are also efficiently utilized by resisting the loads in direct compression without bending. The diagonals are rigidly connected to major horizontal spandrel beams on multi-floor modules occurring at the intersection of adjacent diagonals and participate in the lateral system by transferring lateral loads between the diagrid and floor slab. The form

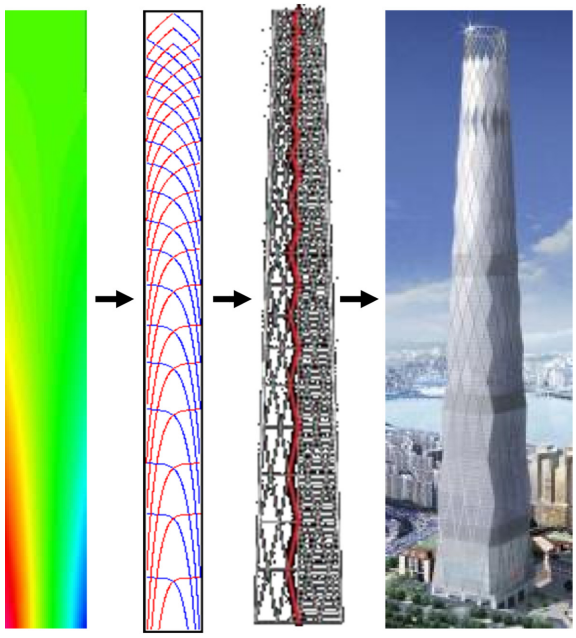


Figure 4. Stress trajectories informing diagrid geometry in super-talls.

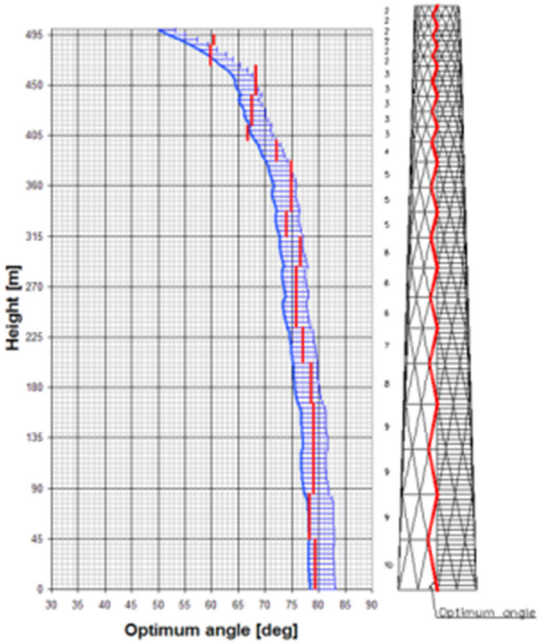


Figure 5. Graph of diagrid angle optimization in 555 m super-tall and associated equations.



Figure 6. 555m super-tall diagrid system.

of the tower was influenced by intensive collaboration between architects and engineers to provide an efficient form to resist both wind and seismic forces.

An advantage in designing a diagrid structure is the availability of helical axial load paths for resisting gravity and lateral loads (Fig. 7) which allow for column-free interiors and long-span framing without compromising effective global stiffness. In a structure with a conventional perimeter moment frame system, a continuous floor slab diaphragm is needed to transmit lateral forces to the frames at each level. The loads then travel down each respective plane of frames to the building base. In a diagrid system. However, lateral loads are transmitted to the base in a helical manner not relying on a continuous diaphragm slab at the building ends (Fig. 7). The exoskeletal diagrid system on the perimeter acts in tandem with concrete walls at the building's core to provide a dual gravity and lateral load resisting system with multiple continuous and

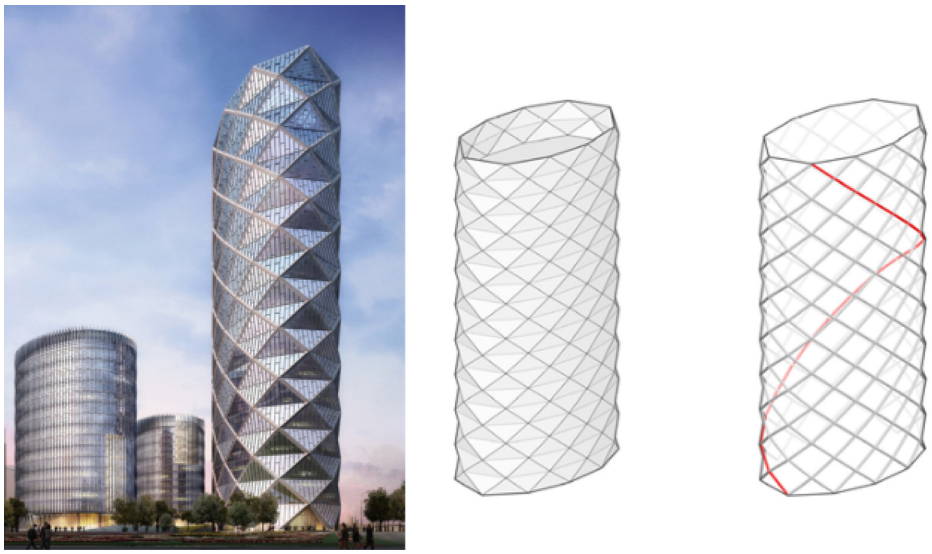


Figure 7. Poly International Tower and helical load paths.

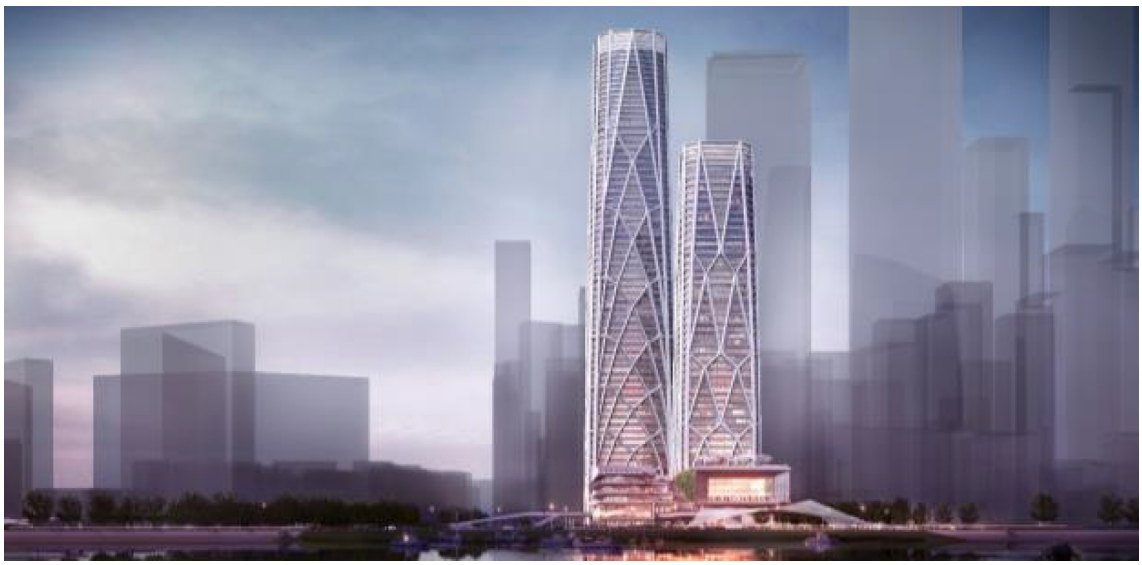


Figure 8. CITIC Towers.

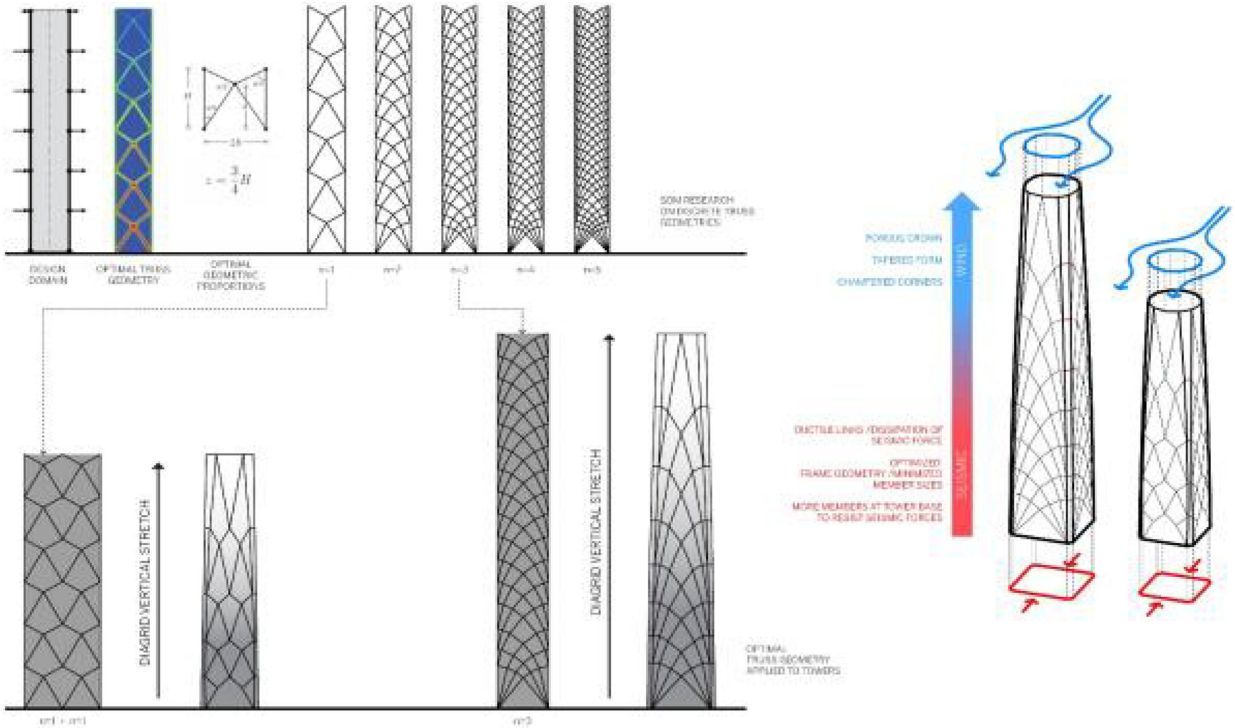


Figure 9. Optimal trusses and diagrid rationalization in CITIC Towers.

redundant load paths.

The SOM designed CITIC Towers in China represent a further progression of diagrids tall structures where the advance of technology in the area of digital computation has made the creation and analysis of complex, optimized geometries accessible to the design community. SOM research in optimization of discrete and continuum typologies has led to a novel diagrid geometry where the density of diagonals is higher and their angle is shallower at the base where seismic forces govern design before reducing in count and increasing in angle towards the top of the tower where wind pressures are more significant than seismic forces. This ability to parametrically design for multiple performance objectives and constraints while observing

visual and analytical outcomes in real time with sophisticated computational tools previously unavailaible to engineers has led to numerous optimal solutions for diagrid towers. The design of the CITIC Towers began with the most efficient cantilever form in a bound Michell truss and was stretched over its height to achieve a rationalized frame system and a prominent expression of the modern diagrid.

3. Performance

Establishing the structural behavior of the diagrid system is paramount to its successful application in real projects. Conventional tower framing systems (core walls, braced cores, moment frames) have been comprehensively analyzed, tested and implemented in countless buildings for decades and as such their behavior is a relatively known quantity. While there are precedents for diagrid systems in tall structures the body of work concerning their behavior is not as established as conventional systems and as a result projects implementing these systems often require bespoke analysis. With experience on several diagrid tower structures, SOM has had the opportunity to contribute to this body of work.

3.1. Wind Engineering

While prescriptive methods for analyzing wind loads and resulting building response exist in current design manuals, the influence of wind on super-tall structures most often requires specific analysis and scaled testing of physical models in wind tunnel laboratories. For any super-tall building, the effects of wind will near always control the design of the structural lateral system. Wind induced vortex shedding or crosswind building movements can cause intolerable building accelerations that can resulting in occupants experiencing motion sickness.

Three major strategies were employed early on in the design process of the 555m tower to address the effects of wind. First, tapering of the tower from a 70m square base to a 39m circular top was done to limit the total wind load on the tower. A total reduction of 28% in wind force at the top of the structure was achieved by manipulating the tower form using the tapered profile and open top. Second, an open trellis at the top of the building was employed to limit vortex shedding. Lastly, a reinforced concrete core was utilized to provide appropriate mass to the tower. All of these early decisions were tested in a scaled wind tunnel model considering both typhoon and non-typhoon wind conditions and proved to be an incredibly efficient means to limit the effects of the wind. Wind tunnel loads were found to be approximately 60% of those calculated by the relevant building code. In addition, the effects of building accelerations were found to be well below internationally accepted criteria. As a result, no artificial means were required to reduce accelerations, such as motion dampers.

3.2. Seismic Engineering

According to site-specific seismology, earthquake-induced inertial forces may have significant influence on the design of a tower's superstructure. Like in wind engineering, diagrid systems are not typically included in prescriptive methods for seismic design and hence their performance must be assessed on a case-by-case basis. In an attempt to limit the volume of tedious calculations future diagrid tower designers must perform when using the sys-

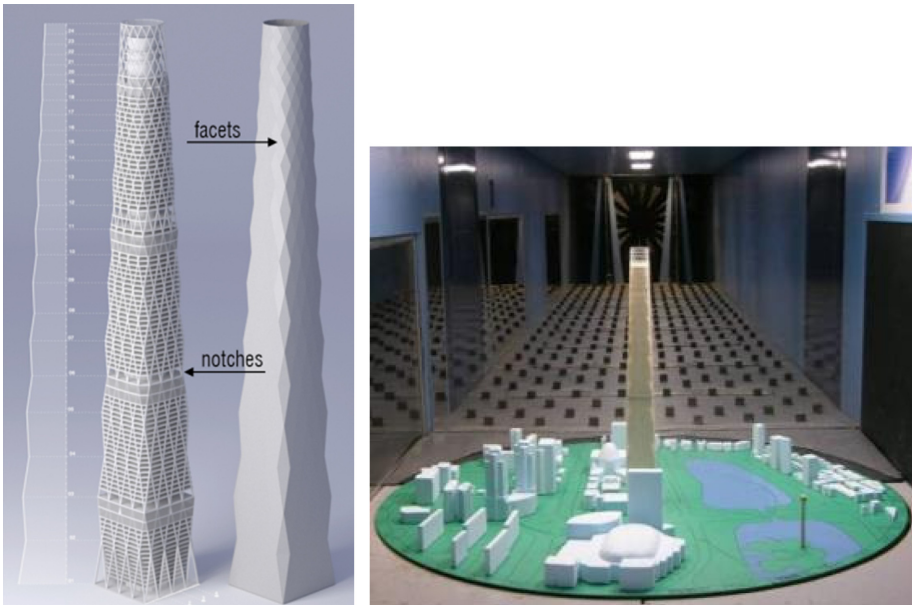


Figure 10. Wind response mitigation and wind tunnel testing.

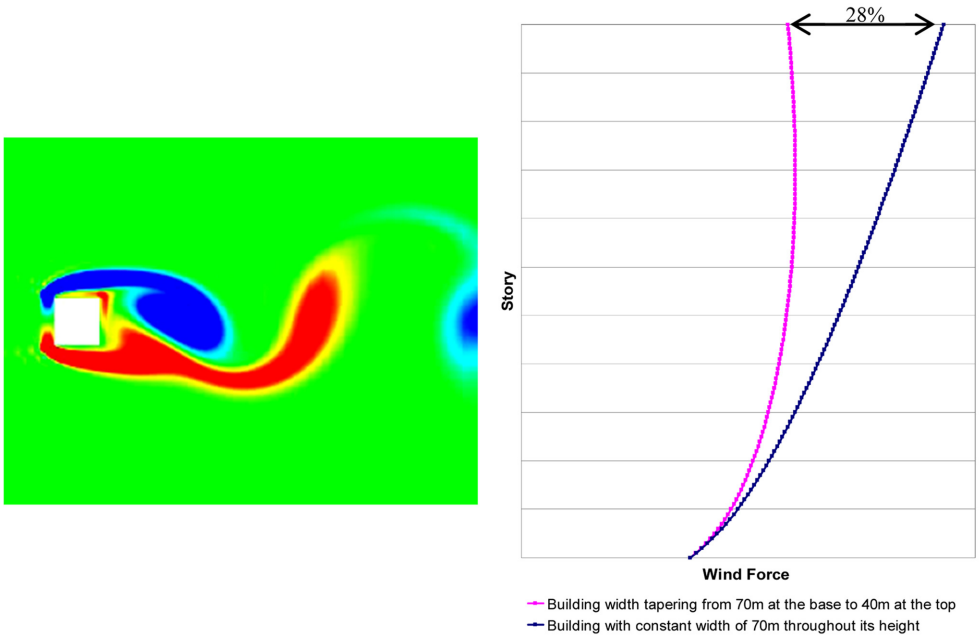


Figure 11. Vortex shedding (left) and reducing wind pressures from tapering tower form (right).

tem in future structures, SOM has conducted several studies seeking to quantify both the distribution of seismic shear in dual grid-core systems, as well as the level ductility availed to the design engineer by the diagrid system.

Typically, steel diagrid framed systems are configured as a dual system for the seismic force-resisting system and their response modification coefficients (*R*-factors) are selected from 5.5 to 8.0 without further justification since the systems are typically composed of exterior steel diagrid frames in combination with ductile reinforced concrete core-wall frames. However, for a diagrid system that is not combined with a ductile core-wall frame as a dual system, the exterior diagrid frames become a standalone lateral force-resisting system. Therefore, as an undefined system, it is necessary to establish a methodology per the approach in ATC-63 to determine appropriate seismic performance factors using a more rigorous and reliable procedure. To this end, SOM conducted extensive analytical studies on an array of diagrid orientations and building dimensions. The investigation suggested an overall approach that allows a significant reduction in computational effort through an iterative approach to establish R-Factors based on a nonlinear static analysis rather than a more cumbersome iterative approach using nonlinear dynamic response history analysis and established an R-Factor of approximately 4.0 in the 555 m Korean tower.

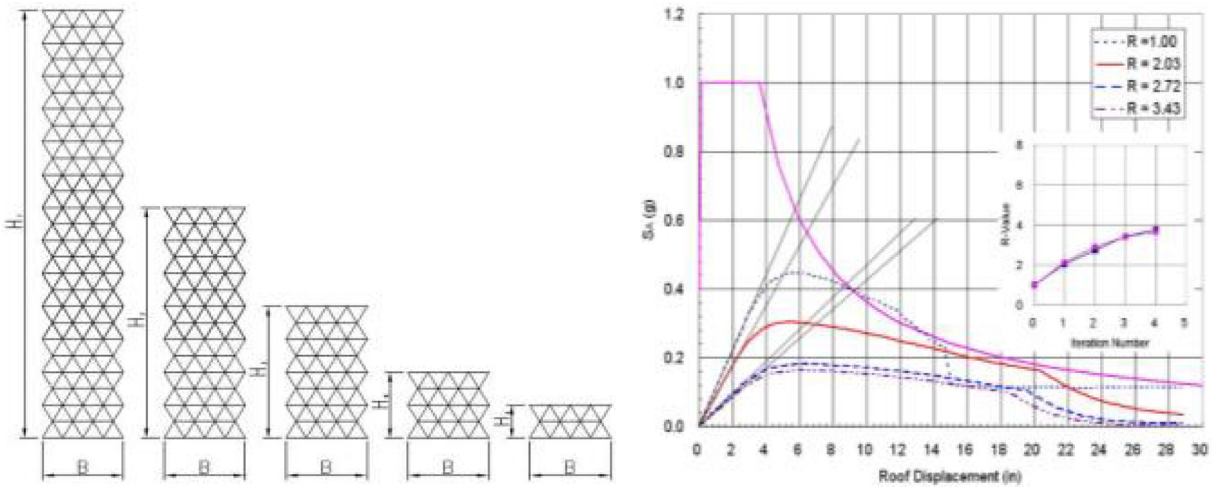


Figure 12. Archetype diagrid models (left) and R-Factor results for diagrid systems (right).

As a tube-in-tube dual lateral system consisting of the a perimeter diagrid and shear wall core, nodal floors are able to distribute their seismic mass laterally to both the core walls and diagrid, while the intermediate non-nodal floor diaphragms are connected only to the core walls. The seismic shear distribution within the tube-in-tube system was evaluated in the Poly International Tower to verify that the diagrid and core walls reasonably shared the lateral loads. Comparing story shears at every level in both directions, it was found the diagrid to take a minimum of 20% of the transverse shear, and a minimum of 37% of the longitudinal shear. Because the diagrid is stiffer than a traditional perimeter moment frame, a larger percentage of the lateral load is resisted by the diagrid than is usual in a conventional perimeter frame, indicating a well behaved and efficient structure.

4. Constructability

One of the most critical aspects of producing a diagrid super-tall structure is creating a simple diagrid geometry that can be fabricated with conventional methods, without an onerous amount of unique nodes, and can be erected in an efficient manner. The key component of a constructible diagrid tower is simplified nodal geometry, being the factor requiring the most attention in terms of analysis, design, fabrication, testing, and installation. The effort to create a buildable super-tall is often an iterative process where multiple parameters are held in the balance to converge upon a desirable design. Parameters include material economy, design aesthetic, local construction methods and tolerances, fabricator sophistication, structural performance and more. There is no single solution to creating a diagrid tower that can be built, with each project featuring unique constraints demanding their own solution. Different node types in diagrid towers designed at SOM shown in Fig. 13 demonstrate the range of geometries possible as a design responds to its unique set of constraints in an effort to rationalize diagrid geometry with floor spacing, fabrication complexity, and structural efficiency.

The nodal geometry in the Rural Bank tower represents the simplest solution, a result of the rectangular building plan and consistent diagrid dimensions. This configuration is the most advantageous for simplicity of construction as a single node can be applied to each building face, though plate thicknesses may vary in response to the changing demand across the height of the tower. The Cyber City tower, also rectangular in plan, features two unique nodes per face, one for the primary diagonal nodes and a second for the intermediate nodes at the lower floors.

As the complexity of a building's diagrid geometry increases, further efforts are required to rationalize the framing system to arrive at a constructable design. In the Poly Int'l Tower the resolution of diagrid spacing, nodal simplicity and architectural programming led to a solution involving two separate nodal floor types repeated throughout the building with intermediate floors between node elevations being suspended from the nodal floor type

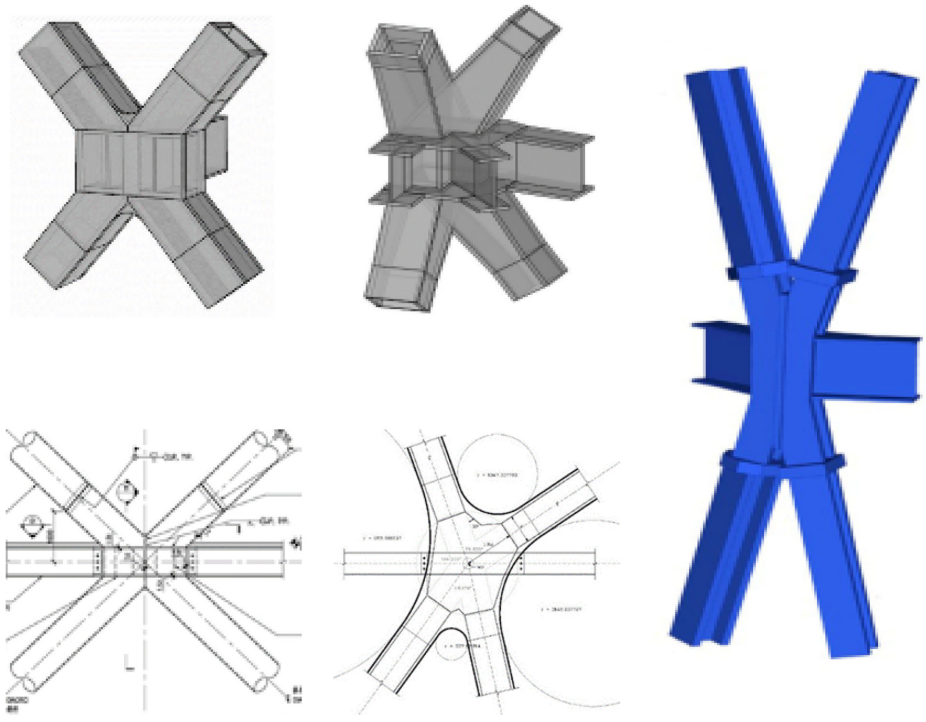


Figure 13. Nodal geometry in the Rural Bank (top left), Cyber City (top center), Poly Int'l (bottom left), Poly International (bottom center) and 555m super-tall (right).



Figure 14. Single node type on Rural Bank (left) and two node types on Cyber City (right).

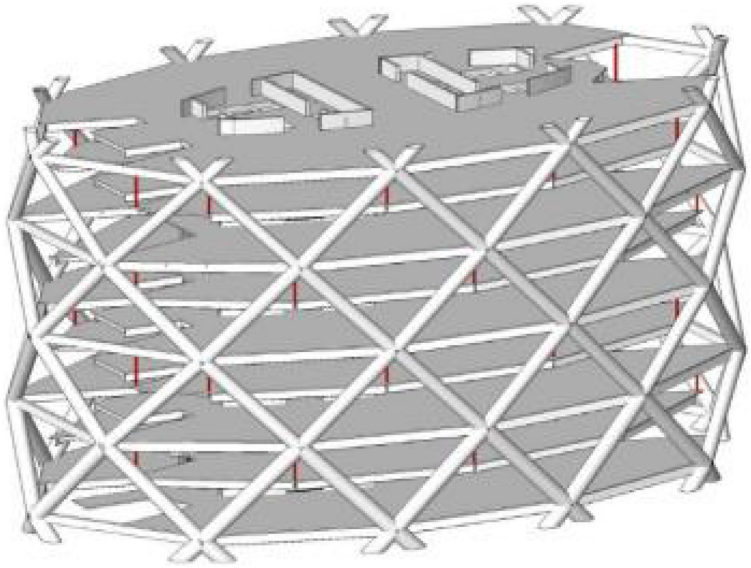


Figure 15. Nodal geometry and suspended floors in the Poly Int'l Tower.

above. The resulting tower geometry to be constructed is then simple, functional and efficient.

The importance of a clearly rationalized diagrid in improving the constructability of complex geometries is evidenced by the 555m super-tall. Fig. 16 illustrates the methodology behind defining the diagrid over the height of the structure in a clear manner for the benefit of the builder. There are a total of 16 nodes at each of the 27 primary levels. At each primary level there are either two or three unique nodes depending on whether the diagrid members are coming together or spreading out at the corners of the building. This leads to a total of 68 unique nodal designs. Each unique node requires two angle changes and a rotation for each member coming into it. Therefore, it was important to set all the geometry in the tower based on 432 nodes that established all angle changes and rotations in order to simplify the design and construction.

Comparisons were made between this diagrid solution and a more conventional perimeter moment frame solution. It was found that the total structural steel quantities could be reduced by nearly 27%. The diagrid provides the added advantage of limiting the number of physical moment connections from approximately 9600 to 432, resulting in additional savings during fabrication and construction. This example once again illustrates the effective-

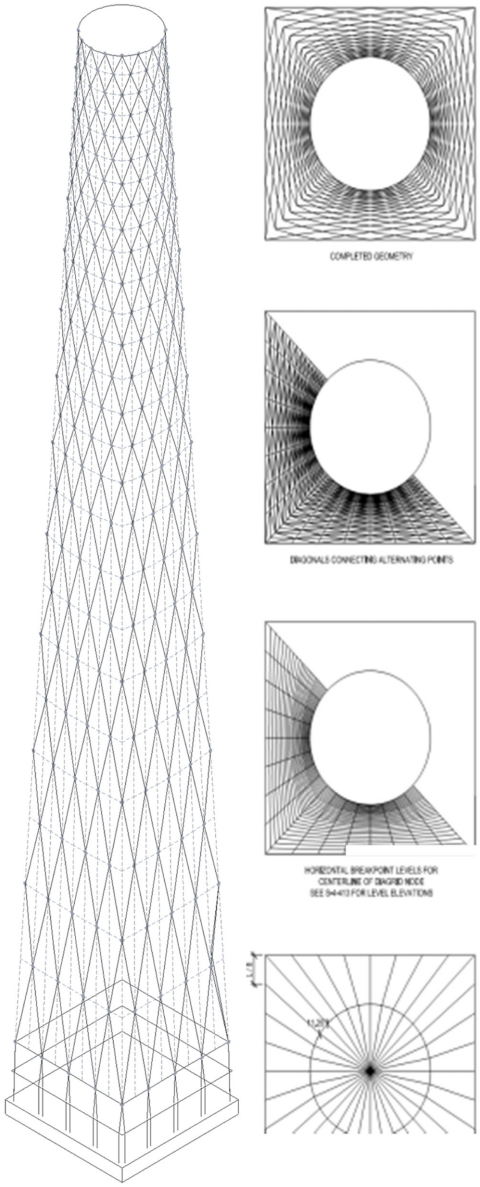
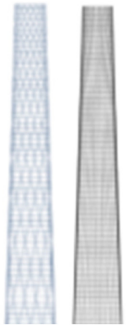


Figure 16. Simplifying nodal arrangements for transformative tower geometries.



	MOMENT FRAME	DIAGRID
NO. NODES	9600	384
STRUCTURAL STEEL	1.27	1.00
COMPARISON OF TOTAL COST	1.30	1.00
COMPARISON OF COST PER SQ.M.	1.34	1.00

Figure 17. Tower node comparison in moment frames vs. diagrids.

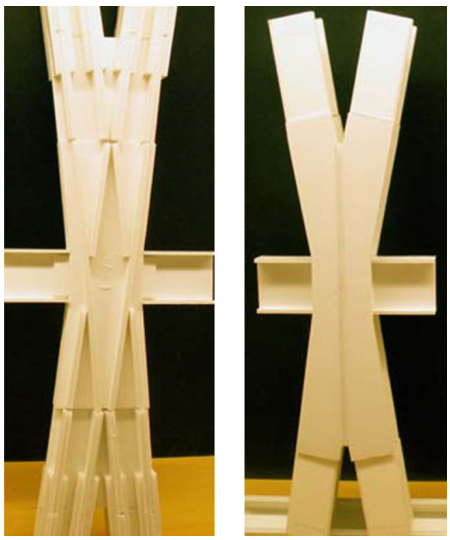


Figure 18. Member orientations for 555m super-tall diagrid nodes.

ness of the diagrid as a flexible, constructable system.

Early on in the design of the 555m super-tall tower many hand-built study models of different configurations were used to come up with the optimum solution. As shown in Fig. 18 the conventional configuration with the orientation of flanges in line with the moment frame was very large leading to extremely heavy nodes. It was necessary to make the nodes as compact as possible to limit the weight to around 35 tonnes for placement by a crane. The solution was to rotate the members by 90 degrees which allowed a significantly more compact and lighter node assembly as shown in Fig. 19. Three-dimensional solid models of each node was created to fully understand the angles, welds and assembly weights. This 3D solid information is easily forwarded to a fabrication shop to eliminate errors in fabrication. Typical detailing for nodal elements includes parts that would be fabricated and welded in the shop with all appropriate angles built into it and the diagrid member between the joints that would be perfectly straight and set in the field on pre-drilled bolted plates.

Nodal diagrid connections can be realized through a variety of member shapes and materials. Connections in the Poly International Tower were envisioned as concrete filled tubes (CFT) nodes fabricated using either castings or welded steel plates. The lower cost, efficiency and modular possibilities available using welded steel plates ultimately led to their selection for use in the node connections. The integrity of the diagrid structural system depends on the performance of the welded nodes. Although the CFT sections of the diagrid element vary over the height, the shape of the node was modularized to be the same size throughout the structure. As shown in Fig. 21 the typical welded node consists of two horizontal steel

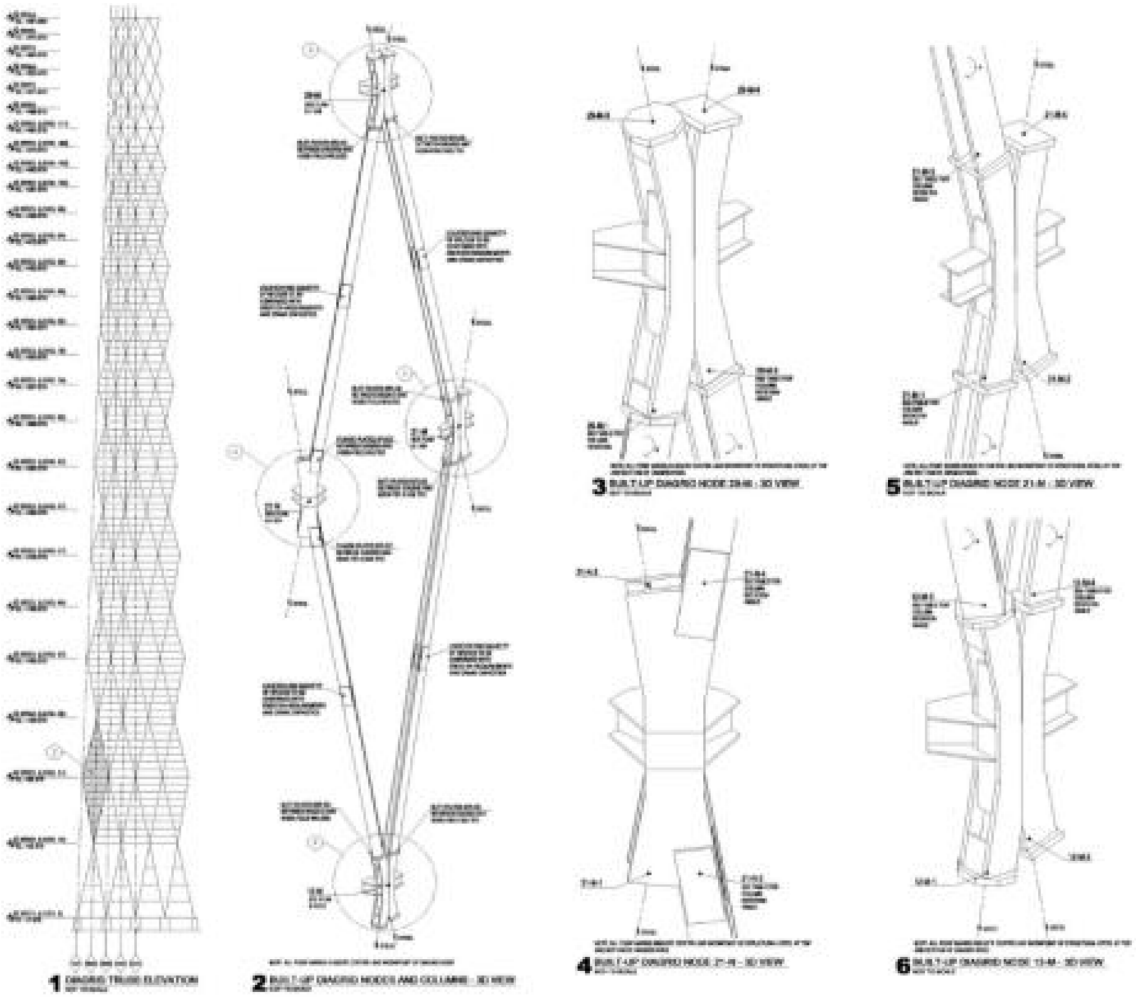


Figure 19. Detailing of diagrid nodes.



Figure 20. Installation of CFT diagrid nodes in Poly International.

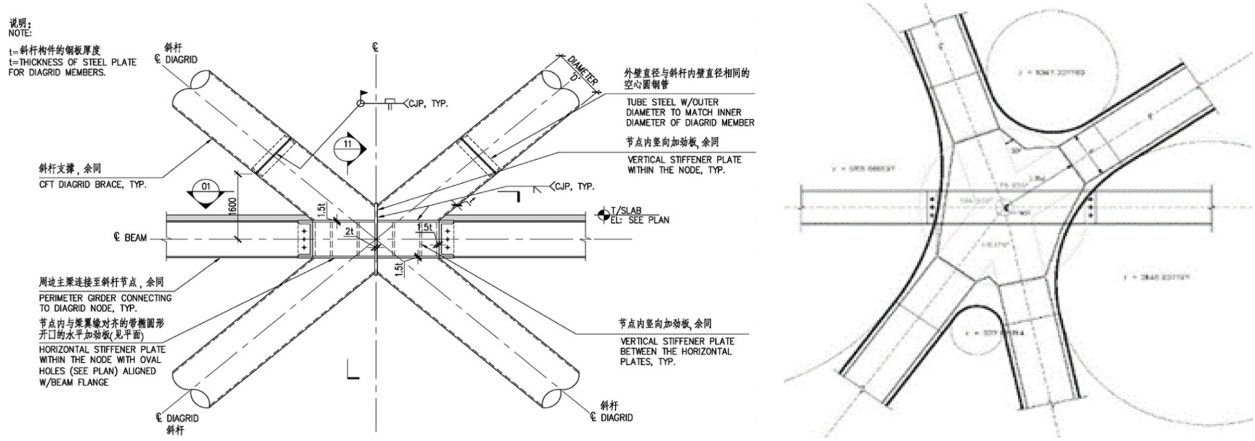


Figure 21. Detailing of CFT welded nodes in Poly International.

plates in line with the perimeter beam flanges and one vertical steel plate at the middle of the node in addition to the outer curved plates projecting from the CFT sections. The use of materials and the simplicity of nodal geometries in the Poly Int'l created a successful, constructable design.

Once a level of comfort is reached with connection detailing, three-dimensional solid analytical models are created and analyzed in FEA software to confirm that plates stresses meet all the design criteria. Linear and nonlinear analysis is performed for service and ultimate loads conditions. With analytical modeling of complex geometry designers can quickly assess stress concentrations, areas requiring supplemental reinforcement and whether the node can be relied upon to provide strength and ductility as required.

A unique modeling technique was required for the accurate assessment of connection behavior for diagrid nodes in the 555m Korean tower. Raw FE member forces from each element framing into the connection are applied at their own node coinciding with the connection work point, resulting in multiple nodes sharing the same location. Rigid links were used between the loaded node and the connection face to reflect the true flow of forces through the elements into the work point. In this way equili-

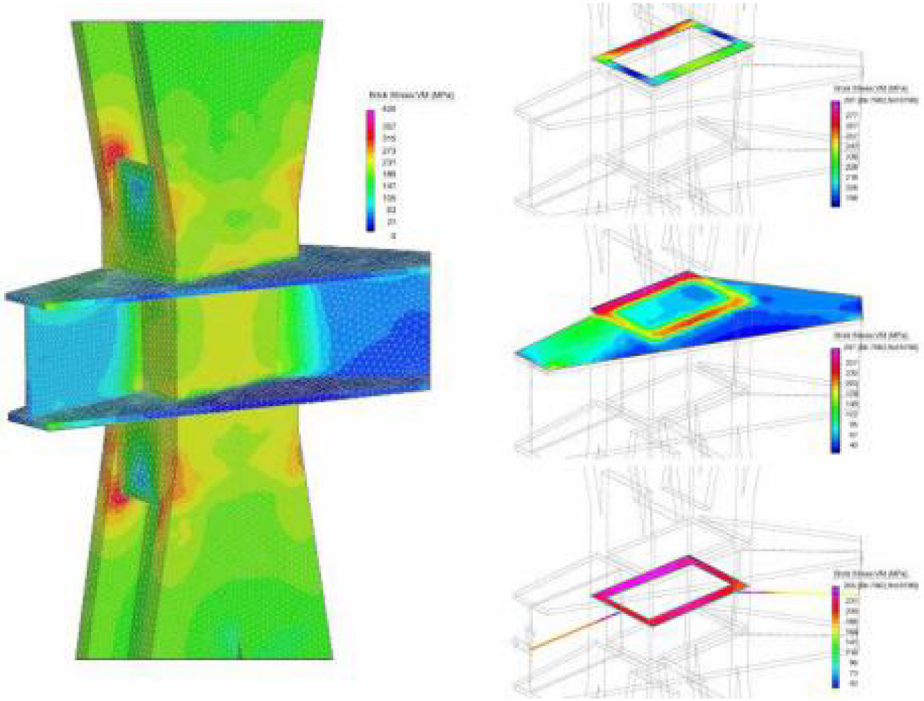


Figure 22. FE modeling of corner nodes in 555m super-tall.

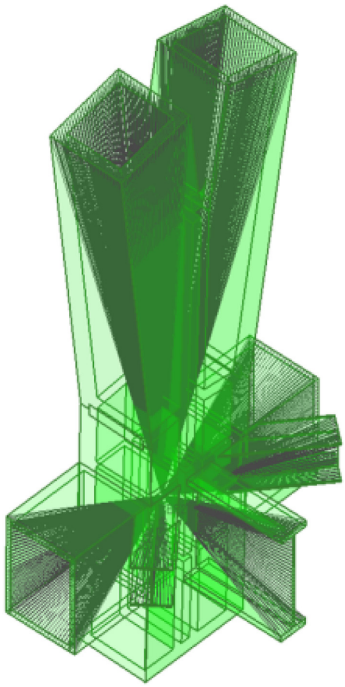


Figure 23. Node FE modeling of raw forces linked to loaded connection faces.

brium of the joint is assured and the resulting response of the stand-alone FE model reflects the actual stressed state of the built connection in the context of the entire structure.

Physical testing of full or partial scale specimens may be undertaken where further understanding of nodal behavior and structural properties is required. Whereas the performance of traditional moment connections in high-rise structures using wide flange beams has been thoroughly researched and well-documented with prescriptive measures for design in steel and concrete design manuals, the use of diagrid nodes in super-tall structures is not as comprehensive and certain geometries may have limited precedents from which to draw upon for design assistance. Areas of high seismic activity often require special attention as diagrid frames are an essential component of the lateral force resisting system, indeed they may be thought of as their own system working simultaneously with the interior core as a tube-in-tube system. Cyclic testing of nodes allows designers to assess the load-deformation relationship of the particular node and quantify the available ductility. Connection design and detailing may be iterated and refined during analysis of testing results to arrive at an end product with established properties that satisfics performance objectives.

5. Conclusion

The use of diagrid typology in super-tall structures shows tremendous promise as a viable system capable of achieving performance objective and providing a more efficient alternative to conventional tower systems. As an emerging structural system in tall towers the diagrid is appearing more frequently in projects all the time as engineers become increasingly familiar with its perform-

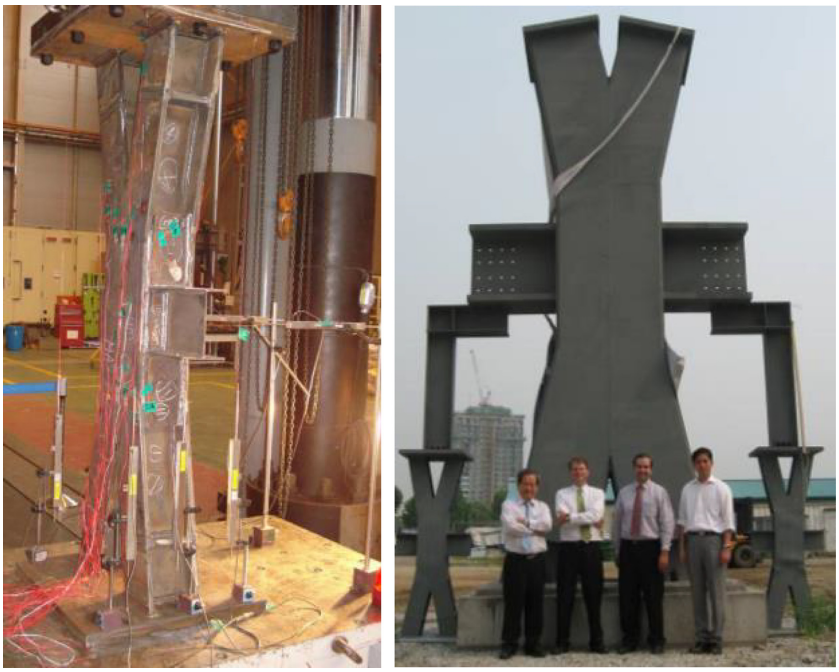


Figure 24. Physical testing of diagrid nodes at RIST in Korea, (left) and node mock-up (right).

ance and as architects become exposed to the wide range of new design possibilities made available by this system. As demonstrated in the design of a 555m Korean tower, the use of diagonalized perimeter framing presents new opportunities to explore unique geometries which respond to the structural demands of high-rise construction and can result in drastically improved performance. Acting as a stand-alone system to resist lateral loading the geometry of a diagrid perimeter framing has inherent bending and torsional stiffness creating a building with maximum occupancy comfort during wind events.

As a recently developed system for tall structures the diagrid may not be as exhaustively researched as more conventional systems, however the performance of the system in super-talls has been proven to be robust as shown through analytical and physical investigations at SOM. Through extensive studies on the seismic performance of a wide range of diagrid structures the system is proven to be provide resilient response during earthquake events.

In addition to its performance merits, the diagrid system is an entirely constructible design with potential for significant cost savings. The SOM designed diagrid supertall managed to reduce the number of moment connections by an order of magnitude to vastly simplify erection and fabrication cost and complexity. Rationalizing diagonal angles and nodal geometry to produce a constructible system requires extra care and attention, particularly for buildings non-orthogonal in plan, however this effort is rewarded handsomely by improved building performance and aesthetic. Overall the diagrid system presents an exciting opportunity for the expression of structure in a novel, meaningful form.

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