Title: **Three-dimensional Exterior Bracing Systems for Tall Buildings**

Authors: Rupa Garai, Associate, Skidmore, Owings & Merrill LLP
Mark Sarkisian, Partner, Skidmore, Owings & Merrill LLP
Neville John Mathias, Associate Director, Skidmore, Owings & Merrill LLP
Andrew Krebs, Associate, Skidmore, Owings & Merrill LLP

Subjects: Architectural/Design
Building Case Study
Façade Design
Structural Engineering

Keywords: Façade
Form
Structural Engineering

Publication Date: 2015

Original Publication: Global Interchanges: Resurgence of the Skyscraper City

Paper Type:
1. Book chapter/Part chapter
2. Journal paper
3. **Conference proceeding**
4. Unpublished conference paper
5. Magazine article
6. Unpublished

Three-dimensional Exterior Bracing Systems for Tall Buildings

Rupa Garai
Associate

Skidmore, Owings and Merrill,
San Francisco, USA

Rupa Garai is an Associate with the San Francisco office of Skidmore, Owings and Merrill LLP. She has over 10 years of experience as Structural Engineer working on projects ranging from mixed-use, commercial, airports, courthouses, residential and office towers. She has served as a project engineer for domestic projects – 222 South Main Office Tower, San Diego Courthouse as well as international projects – Poly International Plaza, China, and Pioneer Park, India. Rupa has Master degrees in Structural Engineering from Stanford University.

Mark Sarkisian
Partner

Skidmore, Owings and Merrill,
San Francisco, USA

Mark Sarkisian is a Partner and leads the structural engineering practice at the San Francisco office of Skidmore, Owings & Merrill LLP. He completed his Bachelor's degree at the University of Connecticut and his Master's degree in structural engineering at Lehigh University. Mark has been with SOM since 1985 and has led the design of numerous highly innovative structures all around the world. Mark participates actively in the conferences and seminars, has authored numerous papers and publications, and takes active part in research and teaching with leading Universities. He holds several patents.

Neville Mathias
Associate Director

Skidmore, Owings and Merrill,
San Francisco, USA

Neville J. Mathias is an Associate Director with the San Francisco office of Skidmore, Owings & Merrill LLP (SOM). He got his Bachelor's degree in Civil Engineering from Madras University in India and joined SOM in 1985 after completing Master's degrees in Structural Engineering and Architecture at the University of California, Berkeley, USA. Neville is deeply committed to integration and innovation in structural engineering and has worked extensively on tall and large-scale building projects across the US and around the world. He has helped author numerous papers and publications and has participated in seminars and conferences all over the world.

Andrew Krebs
Associate

Skidmore, Owings and Merrill,
San Francisco, USA

Andrew Krebs is an Associate in the structural group at Skidmore, Owings and Merrill in San Francisco. He joined SOM in 2009 after completing his Bachelor's degree at North Carolina State University and his Master's degree at Stanford University. He has worked on several challenging projects including the Los Angeles Federal Courthouse. Andy was recently recognized for his achievements , receiving the Structural Engineer's Association of California's NabihYoussef Young Engineer Award.

Abstract

The use of outriggers with and without belt trusses has become an expedient of choice for harnessing the three dimensional potential of tall buildings to resist lateral loads. Outrigger components typically link core structures to perimeter structures of buildings, maximizing the use of building dimensions, providing three dimensional action. While efficient, the use of outriggers and belt-trusses can have a significant impact on the use of space, building appearance, and construction time; being complex in detail and often requiring delayed construction techniques. Bracing systems such as "diagrids" that link together on the facades of buildings to form three-dimensionally integrated patterns provide an excellent alternative to outrigger solutions. These systems typically obviate the need for outriggers, and by staying largely elastic over their range of expected response, offer the prospect of greater resilience, post-earthquake recoverability and sustainability. This paper elaborates on this theme using case examples.

Keywords: Diagrid, exterior bracing system, resilience

Introduction

The most appropriate lateral load resisting system for a tall building depends on a number of considerations including: locally available materials and construction technology, building program and function, architectural form, and, very importantly, the type and magnitude of lateral loads. Wind load effects generally tend to govern system selection and material quantities as buildings get taller, even in regions of high seismicity. Engineers have known for a long time that the lateral systems which are appropriate and efficient in buildings of lower heights are not necessarily as successful in buildings of taller heights (see Figure 1).

Ideally, one designs a structure to efficiently support gravity loads, and then considers the lateral system in the most optimal manner; maximizing lateral stiffness with the least amount of additional material. Increased height has consequences that impact efficiency, function and aesthetics. For example, a 10-story building with concrete moment frames with columns 20 feet on-center designed to support gravity loads might be capable of withstanding lateral loads with negligible additional material, but, with increased height, will require material to be added to stiffen it to control drift resulting, larger members and lower utilization of member strength capacities. Added stiffness is better achieved by altering / augmenting the system, for example, by introducing shear walls.

With increased building height, there has been an evolution of appropriate structural systems; tuned to efficiency, compatibility with function, and cultural / aesthetic sensibilities. The burst of high-rise construction over the last two to three decades, particularly in China, has seen the ascendancy of composite structures combining inexpensive concrete and strategic placement of expensive steel into dual systems; consisting of concrete cores and composite exterior frames linked by steel outrigger systems with and without belt-trusses capitalizing on the full widths of the buildings to resist lateral loads. While successful, outrigger and belt-truss systems have their challenges; most significantly impacting space in the building interior at the stories where they occur and the exterior expression of the buildings where belt-trusses are used. Most importantly, the use of outriggers impacts construction as outriggers typically require the use of delayed construction techniques

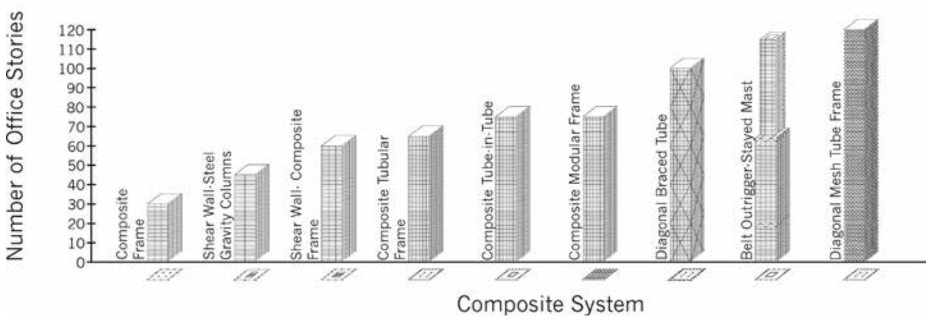


Figure 1. Appropriate Height Limits of Structural Systems (Source: Skidmore, Owings & Merrill)

to mitigate the otherwise excessive forces induced in them by differential shortening of linked vertical elements in the cores and building exteriors.

Three-dimensional exterior bracing systems, in particular "diagrid" systems, offer an attractive alternative to outrigger systems in buildings of comparable height.

The most efficient way to resist lateral loads in tall buildings is to provide the resisting elements with maximum stiffness at the building exterior maximizing the benefit of the overall building plan dimensions. This system is designed to resist gravity and lateral loads while eliminating outriggers. Through the use of exterior diagrid systems, diagonal members support gravity loads but also act as braces to provide very significant lateral stiffness and lateral load resistance.

A challenge of diagrid systems is that members must be designed not to buckle in rare wind and seismic events and typically require explicit performance-based design evaluations to assure safety and code equivalence. These structures tend, as a necessary consequence, to perform more elastically, and with less energy dissipation in large events than the more conventional structural systems. While this might, at first glance, seem at odds with conventional thinking, it is more in tune with the thinking of the future; to have building structures with minimal if any added cost suffer less damage that would require structural repair or replacement along with associated business down-time following major seismic events, consequently maximizing resilience and sustainability. These structures also tend to be very redundant; offering multiple load paths in the event an individual member is lost.

Diagrid systems are not currently well addressed in prescriptive building codes, putting their use beyond the common practice of most structural engineers. Nodal connections require careful detailing consideration and their unique load paths result in "bulging" deformations in plan that, while not large, must be explicitly addressed with tie members and slab reinforcement. The challenges associated with their use, however, pale in comparison with their advantages; particularly those of resilience and sustainability.

The following sections provide examples of the use of diagrid exterior bracing systems.

Poly International Plaza, Beijing, China

Overview

The elliptically shaped plan and faceted exterior of the iconic 161.2 m-tall Poly International Plaza tower in Beijing was inspired by pebbles and ripples in the natural water features that abound in the landscape surrounding the site (see Figure 2). A column-free exterior diagrid system evolved as the most appropriate and best integrated structural system for this design. The primary design goal of the 32-story office building was to provide a unique, high-quality work environment utilizing long-span structural framing to create column-free interior spaces and achieve a light-filled spatial experience throughout the tower.

Structural System Description

The combination of a perimeter diagrid and inner concrete shear wall core create a tube-in-tube lateral force resisting system, sharing a balanced portion of lateral forces between the two systems. The diagrid perimeter structure, with a four-story module and 18 m span between the nodes, is designed to resist gravity and lateral loads axially, with only minor bending effects due to the rigid welded nodal connections. Every alternate floor is connected to nodes and the floor in between the nodal floors is suspended from the nodal floor above. The concrete filled steel tube (CFT) diagrid members serve as effective axial members to resist high compression loads due to gravity and lateral loads and vary from 1300 mm in diameter at the building base to 800 mm at the top. The axial force induced by the lateral and gravity loads in the diagrid members take a helical load path around the perimeter down to the base (see Figure 3) allowing for long spans between nodes while providing global stiffness to distribute lateral forces. The interior reinforced concrete shear

Figure 2. Poly International Plaza (Source: Skidmore, Owings & Merrill)

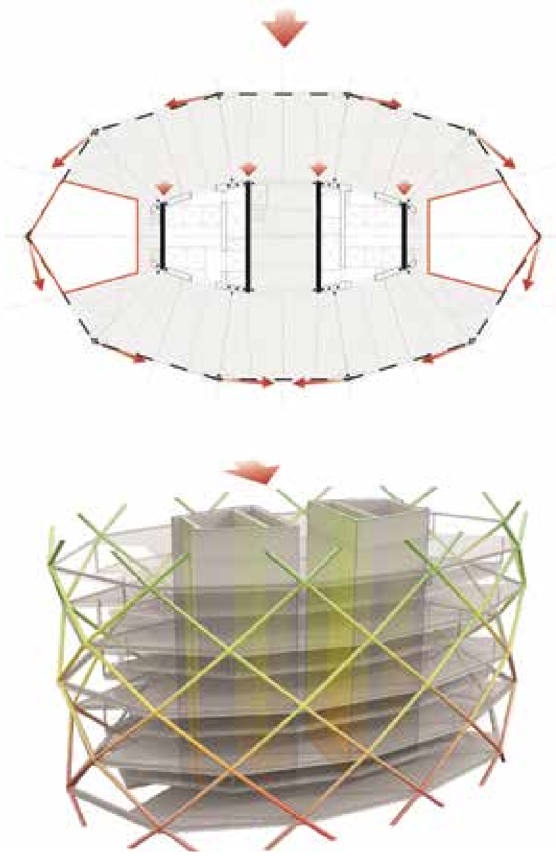


Figure 3. Helical Load Path for Diagrid System (Source: Skidmore, Owings & Merrill)

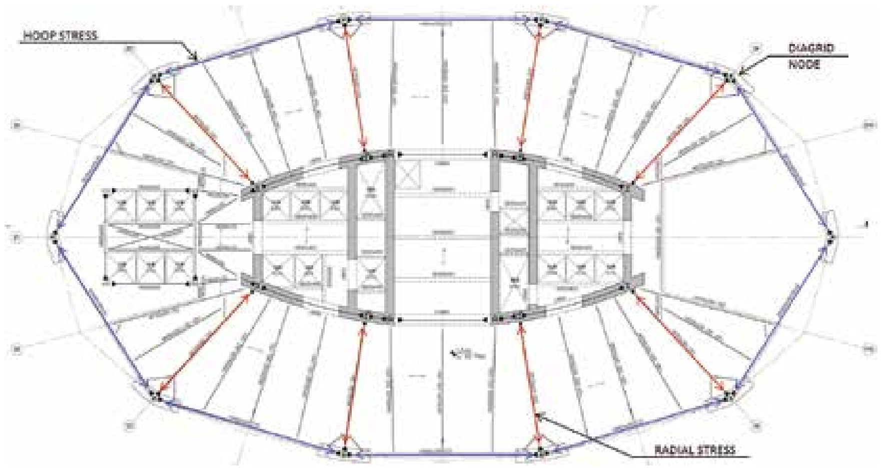


Figure 4. Nodal Floor Plan Showing Hoop and Radial Forces (Source: Skidmore, Owings & Merrill)

walls form an elongated core that follows the same elliptical shape as the exterior façade. The shear walls vary in thickness from 1300 mm thick in the basement to 400 mm at the top.

Key Features of Behavior

While the helical load paths are advantageous in allowing for long perimeter spans and large atriums, the axial forces in the elliptical exterior diagrid result in tensile perimeter hoop and radial floor diaphragm forces (see Figure 4) at nodal floors that were resolved through the use of perimeter steel tie members at nodal levels and radial steel floor framing members that connect the diagrid nodes to the inner concrete core.

With a tube-in-tube lateral force resisting system, the tower behaves laterally as a vertically cantilevered structure, much like a reinforced concrete core-only building. The tower exhibits a single curvature deflected shape with the axial CFT members of the outer diagrid and reinforced concrete shear walls of the inner core sharing lateral loads evenly in proportion to their relative stiffness to each other. The nodes of the diagrid are modular consisting of welded plates such that each node is essentially the same. The typical welded node consists of plate thicknesses at least 1.5 times the thickness of the steel tube sections themselves and have openings to allow for the free flow of concrete through them.

Performance Goals and Special Studies Undertaken

The buildings lateral system resulted in Chinese code requirements being exceeded due to the height of the main roof, slab discontinuities at the atriums, and the unconventional column free perimeter frame. In response to these code-exceeding aspects, the following measures were taken in the design:

- Diagrid members were constructed using CFT sections;
- Steel sections were embedded in the core wall perimeter to enhance connections to radial floor framing members at nodal levels;
- Two software programs, ETABS (main) and SATWE (checking) were used for the analysis of the tower;
- Enhanced seismic performance objectives in moderate as well as rare earthquakes were adopted for critical members and connections, including:
  - Core walls;
  - Diagrid CFT members;
  - Perimeter and perpendicular framed beams that connect to diagrid nodes;
  - Diagrid nodes;
  - Hangers;
  - Diaphragms bounding atrium openings and intermediate levels.
- Thermal analysis was performed;
- Progressive collapse studies considering the removal of critical diagrid CFT members and hangers were completed;
- 3D Finite element analysis was used for typical diagrid nodes to verify the stress distribution;
- Stability / Buckling analysis was performed for the diagrid at the atriums;
- Non-linear time-history analysis was done to verify the structural performance in rare earthquakes.

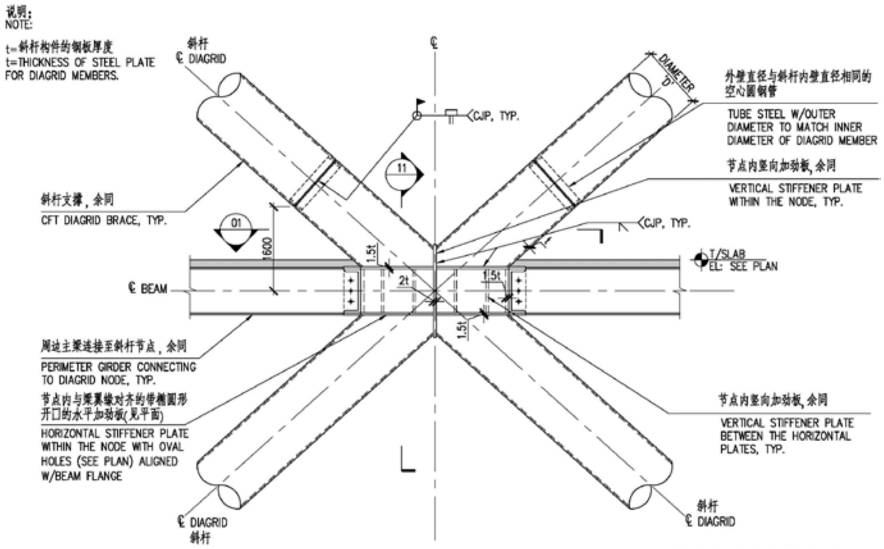


Figure 5. Welded Diagrid Node Detail (Source: Skidmore, Owings & Merrill)

Nodes & Testing

The integrity of the diagrid structural system depends on the performance of the welded modularized nodes. A typical welded node consists of two horizontal steel 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 (see Figure 5). Both horizontal plates and vertical plates have thicknesses at least 1.5 times the thickness of the steel tube sections themselves and have openings to allow for the free flow of the concrete through them. The transition of tube sections occurs within the node element; between the horizontal plates and the projected perimeter of diagrid elements intersecting them.

Finite element analyses were performed for representative diagrid nodes. Additionally, to address the comments of seismic experts during the Expert Panel Review (EPR) process, reduced scale tests were performed on these nodes. The tests were performed at the China Academy of Building Research (CABR) in Beijing. The test set-up is shown in Figure 6. Three sets of tests were performed. Each set consisted of: (1) a welded node section with concrete infill simulating the representative node selected; and (2) a steel only node with

Figure 6. Diagrid Node Test Set-up
(Source: Skidmore, Owings & Merrill)

no concrete infill, but with further increased plate thickness (beyond the 1.5 times member thickness used in concrete in-filled joints).

The specimens were easily able to withstand the code cyclic loading protocol. Monotonic load tests were conducted with increasing loads until failure occurred. For the specimens with the concrete infill, failures occurred at the connection of the node to the diagrid members. Note this is the region where the transition of steel plate thickness occurs. For the specimens with no concrete infill, failure was observed to occur in the node between the horizontal plates. Both the Finite Element Analysis models and the tests showed similar behavior. The tests thus confirmed the importance of sound concrete within the nodes to move the eventual failure location beyond the node and validated the load paths and adequacy of the node design.

Sunline Ningbo Guohua Financial Tower, Ningbo, China

Overview

The Sunline Ningbo Guohua Financial Tower project, currently under construction, is a 45-story office tower, 208 m-tall measured to the top of the parapet. The tower has a rectangular footprint, 62.5 m long by 36.4 m wide, and a total above grade gross floor area of 95,938 m^2 (see Figure 7). The superstructure consists of a composite diagrid braced frame at the building perimeter, and a reinforced concrete core. Composite steel beams supporting composite metal deck floor slabs frame between the core and the perimeter (see Figure 8).

The perimeter diagrid frame utilizes rectangular concrete filled tube diagonals with built-up or rolled steel beams, moment connected at the node levels typically every four floors. The perimeter braced frame

Figure 7. Sunline Ningbo Guohua Financial Tower
(Source: Skidmore, Owings & Merrill)

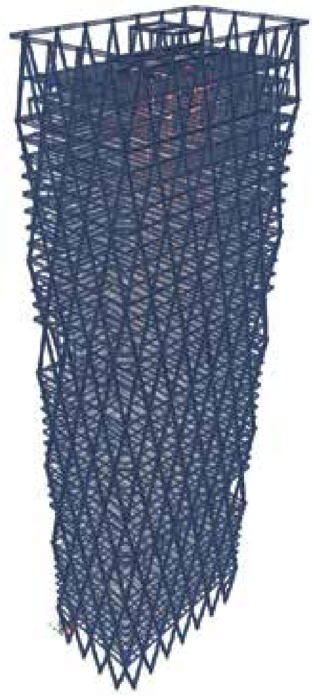


Figure 8. Structural Model of Ningbo Tower
(Source: Skidmore, Owings & Merrill)

extends from grade to the top of the parapet, transferring to a system of columns and shear walls below grade. The shear walls within the core extend from foundation up the height of the building, reducing in extent as the size of the core reduces at the upper levels.

Benefits of the Diagrid System

The perimeter diagrid frame system offers greater structural efficiency than more conventional dual systems since stiff lateral and gravity load resisting brace elements are optimally placed at the perimeter, increasing both the lateral and torsional stiffness of the tower. Figure 9 shows the distribution of overturning moment on the structure between the core and exterior frame over the height of the tower. As can be seen, the exterior frame takes a very significant proportion of the overturning moment on the structure. Accordingly, the amount of the shear walls required in the building core is minimized with the resulting benefit of additional floor space, particularly at the upper levels where the core program is diminished and the shear walls transition to reinforced concrete columns and moment resisting frames.

The use of a perimeter diagrid system with its coherent geometry made it possible for load paths to transfer gravity and lateral loads around the building exterior perimeter corners eliminating the need for corner columns. This, in addition to the large open column-free façades, made the resulting office spaces very desirable.

Construction of the perimeter diagrid is amenable to being simplified through the use of prefabricated node elements to reduce the amount of site welded connections. The one-story high prefabricated nodes will occur at every fourth floor, and be connected to the three-story high diagonal members of the diagrid frame in the field.

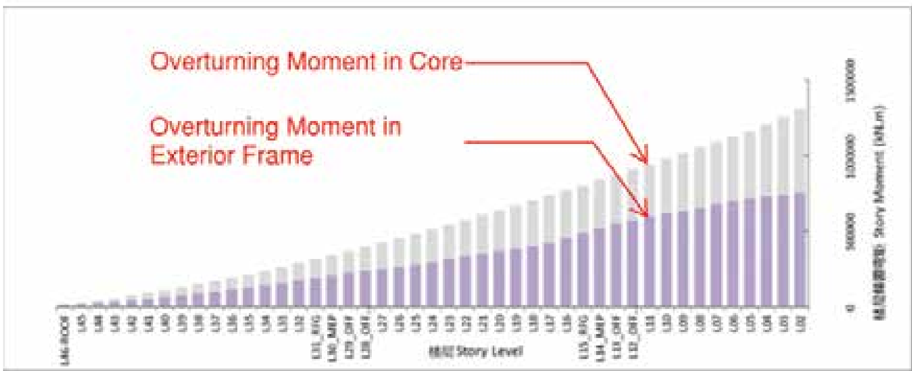


Figure 9. Overturning Moments in Exterior Frame and Core (Source: Skidmore, Owings & Merrill)

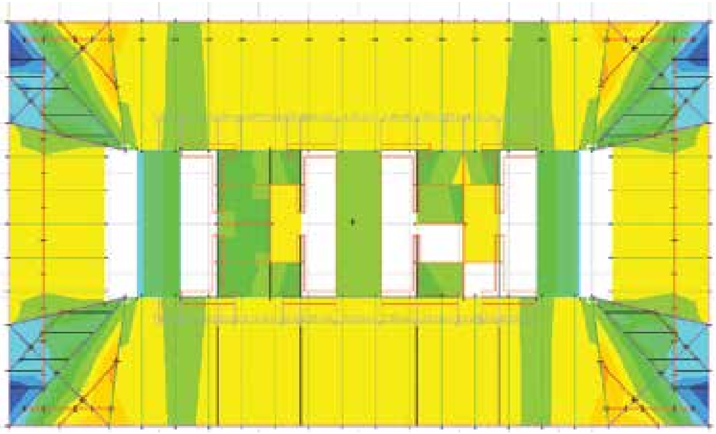


Figure 10. Stresses in the Diaphragm at Nodal Levels (Source: Skidmore, Owings & Merrill)

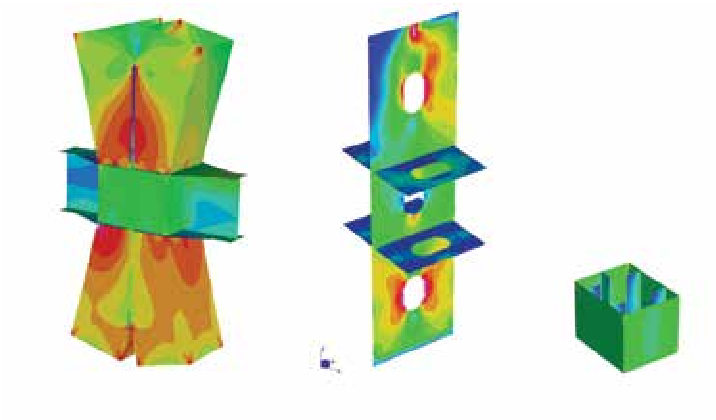


Figure 11. FEA Nodal Stresses (Source: Skidmore, Owings & Merrill)

Challenges

Under gravity loads, the diagrid frame experiences outward in-plane deformations as a result of the crossing diagonal pattern in elevation, particularly at the nodal floors. Despite the fact that tie beams capable of withstanding outward forces without contribution from the slabs are provided, some cracking under service conditions due to deformation is expected. Figure 10 shows a plot of a semi-rigid stress study of a mid-level nodal floor diaphragm slab with stress concentrations particularly at the building corners clearly evident. Slabs at the nodal floors are thickened and additional reinforcement is added to increase capacity and mitigate possible serviceability issues. Additionally, the concrete topping on the metal deck at selected nodal floors is specified to be poured when the tower structure is fully constructed to minimize the possibility of cracking under service conditions.

Diagrid Nodes

No testing of the diagrid nodes was required by the officials for this project. Finite Element Analysis (FEA) was performed on the nodes considering them with and without concrete fill to ensure that the node capacities would be greater than the capacities of the diagrid members framing into them (see Figure 11). The transformed area of material in any node was required to be the same or greater than that in the members framing into it. With the thickness of the vertical stiffeners and plates within the nodes at least 1.5 times the steel thickness of the CFT members framing into them, the equivalent area calculation satisfied the above principle. The FEA studies showed that the nodes would perform well in rare earthquake events.

Shenzhen CITIC Financial Center

Overview

The proposed development in the city of Shenzhen, China, currently in design, will include a 312.0 m-tall office tower and a 212.0 m-tall hotel tower both designed to have optimized perimeter bracing systems on their exteriors acting in tandem with concrete cores without outriggers to resist gravity and lateral loads (see Figure 12).

The 65-story office tower is 299.8 m above grade to the main roof, and 312.0 m to the top of the parapet with a typical floor-to-floor height of 4.5 m (3.6 m at the upper levels). The tower has an approximately square footprint, 52.0 m on the side, and a total above-grade gross floor area of 143,175 m^2.

The 44-story hotel tower is 199.5 m above grade to the main roof, and 212.0 m to the top of the parapet with a typical floor-to-floor height of 4.2 m at the lower levels and 4.5 m at the upper levels. The tower has an approximately square footprint, 42 m on the side, and a total above-grade gross floor area of 75,871 m^2.

The lateral system for both towers consists of a continuous composite steel / concrete braced frame at the building perimeter and reinforced concrete shear walls within the building core. In each tower, the perimeter braced frame extends from grade to the top of the parapet, transferring to a system of columns and shear walls below grade which will be coordinated with the basement program. The shear walls within the core extend from the foundation up the height of the building, reducing in extent as the size of the core reduces at the upper levels. At the four corners of each tower, pairs of adjacent columns at the adjoining façades will be connected by ductile steel moment connected beams (links) at each floor level. These links will be sized to remain elastic for wind and frequent seismic loading and to yield in the rare seismic event. Moment connections will also be utilized at the perimeter frame girders to create a continuum band at levels bounding nodes experiencing tensile forces.

The gravity floor framing in both towers consists of steel floor framing beams and girders, spanning between the building core and perimeter. The beams support composite metal deck floor slabs, with which they are designed to act compositely. Within the core, the gravity floor framing consists of reinforced concrete beams and slabs.

The continuous perimeter composite braced frame is designed to support gravity loads in addition to lateral loads. Similarly, the

Figure 12. Shenzhen CITIC Financial Center (Source: Skidmore, Owings & Merrill)

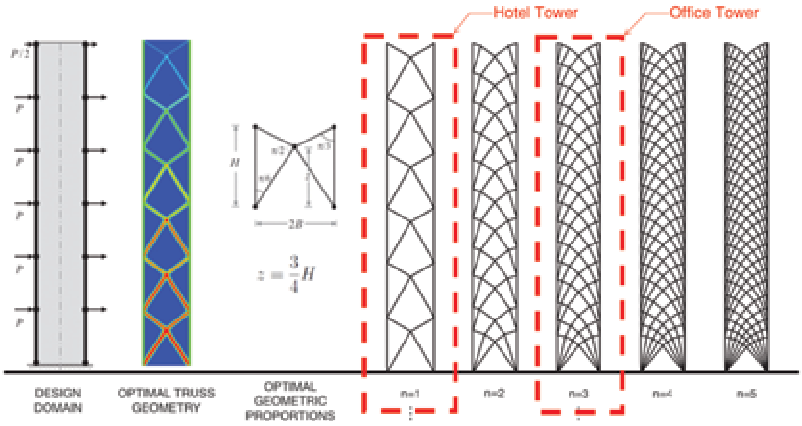
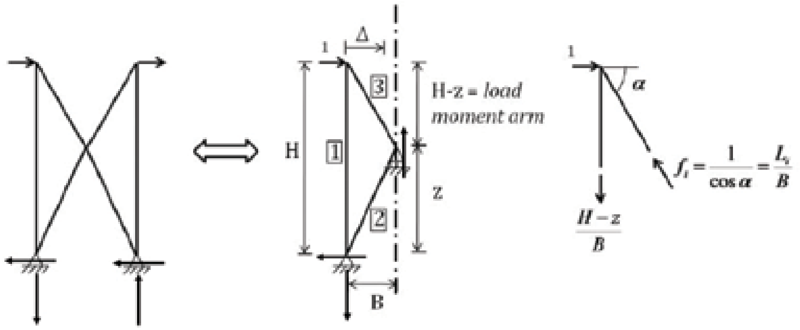


Figure 13. Optimized Braced Geometries (Source: Skidmore, Owings & Merrill)



$$f_1 = \frac{H - z}{B}$$

$$f_2 = \frac{\sqrt{B^2 + z^2}}{B}$$

$$f_3 = \frac{-\sqrt{B^2 + (H - z)^2}}{B}$$

$$\Delta = \frac{F_i}{EA_i}\sum_i f_i L_i = \frac{\sigma B}{E}\sum_i \frac{f_i L_i}{B}$$

$$\frac{\partial \Delta}{\partial z} = \frac{\sigma B}{E}\frac{\partial}{\partial z}\left(\sum_i \frac{f_i L_i}{B}\right) = 0$$

$$\boxed{z = \frac{3}{4}H}$$

Figure 14. Topology Optimization of Truss Geometry (Source: Skidmore, Owings & Merrill)

reinforced concrete shear walls in the building core support gravity and lateral loads. At the upper levels of the building, where the extent of core walls diminishes, columns are introduced where necessary to support the gravity loads.

Exterior Bracing System

The forms of the exterior bracing systems used on the façades of the two towers were generated using the methods of topology optimization; geometric rules characterizing optimal layouts as described by Mazurek et al. 2011 and Henrik 2011. While different in appearance, the bracing configurations of the two towers, selected with constructability of nodes in mind, both evolved from the same geometric principles (see Figure 13). Derivation of the value of "z" used in the optimized geometry is also provided (see Figure 14).

The resulting exterior braced frames which support both gravity and lateral loads are highly efficient in resisting lateral loads. Over 70% of the overturning moment in the office tower is resisted by the exterior frame. This is far in excess of what is typical in structures with more conventional dual systems for the same height.

As the bracing members resist both gravity and lateral loads, they are of necessity designed not to buckle in rare seismic and wind events, rendering their response elastic under most load conditions. While benefiting from this behavior in terms of resilience and sustainability, a modest amount of energy dissipation is effected in moment connected links provided at each of the four building corners.

While very similar to an exterior diagrid system, this exterior bracing system differs in that it has two mega-column members at each of

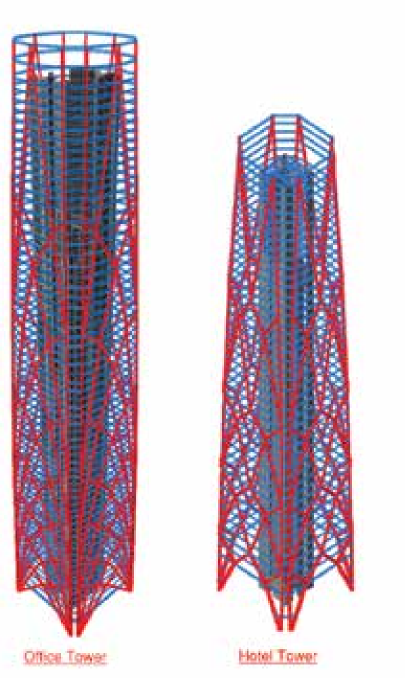


Figure 15. Structural Model of Tower Structures (Source: Skidmore, Owings & Merrill)

the four corners. The use of mega-columns and links at the corners results in less three dimensional behavior in this exterior bracing system than is available in classic diagrid systems, which, however, does not reduce the efficiency of the system (see Figure 15).

Bracing members and mega-columns in this exterior bracing system will be composite square concrete filled tubes and the nodes will be similar to those used in the Sunline Ningbo Guohua Financial Tower described in the preceding section.

Conclusion

Current construction of tall buildings in recent years has favored the use of composite floor framing and dual lateral structural systems comprising concrete cores and composite exterior frames linked together with outriggers and belt-trusses. While successful, the use of outriggers presents challenges during design and construction. Three-dimensional exterior bracing systems, diagrid systems in particular, have shown themselves to be an excellent alternative, obviating the need for outriggers, and providing excellent efficiency with significantly greater opportunities for resilience and sustainability than the more conventional outrigger systems.

References:

Henrik A. (2011). **On the Geometry of Discrete Michell Trusses.** Proceedings of the 2011 IABSE-IASS Symposium.

Mazurek et al. (2011). **Geometrical Aspects of Optimum Truss like Structures.** Struct Multidisc Optim