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Site | Structure | Architecture - Projects that Create Change

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Abstract

China's rapid growth has created great opportunities for design and construction of projects that not only transform sites but cities. This work combines local, national, and international expertise in developing memorable designs that seek to humanize urban life and emphasize the importance of visionary clients. Innovative examples of work in China will be presented with emphasis on three iconic projects designed and built for Poly Corporation based in China. These projects include developments in Beijing and Guangzhou and introduce the use of locally supplied materials and construction techniques. The Poly Corporate Headquarters, the Poly Real Estate Headquarters, and the Poly International Plaza, and will be described through innovative ideas that integrate urban planning, structure, and architecture.

Keywords: Structural steel, Efficiency, Cable net, Mechanism, Seismic

1. Introduction

The rapid and sustained growth of the Chinese economy, the desire of some enlightened clients to create signature buildings, and the ability of Chinese domestic fabricators to produce quality architectural components have all coalesced into an unprecedented period of design opportunity. In particular, the Poly Corporation has been a champion of supporting high quality design that has not only transformed local development but has influence ideas for other building projects around the world.

The Poly Corporate Headquarters building in Beijing, China was the first to be designed and built. Creating a "window to the world" this unusual mixed-use development includes 24 stories of office space, an eight-story hanging museum 'lantern' structure and a 90 meter-tall atrium enclosed by the world's largest cable-net supported glass wall. The second was the Poly Real Estate Headquarters located in Guangzhou, China. Located on the bank of the Pearl River, this project consists of two slender towers carefully integrated with a ground level landscaped area as well as a podium. This project provides column-free office space, a structure that has a dual purpose of shading the southern facades, and a vertical transportation system that uses translucent and transparent glass. Located approximately half way between the Forbidden City and the Beijing Capital Airport, the third project, Poly International Plaza occupies a prominent position immediately adjacent to the Capital Airport Expressway and the interchange with the Fifth Ring Road. The building offers a unique light-filled spatial experience for entering and moving through the office building, utilizes a long-span structure to open up interior spaces, and employs a highly sustainable architectural/mechanical engineering approach to address climate and air quality issues particular to Beijing.

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2. The Rocker Mechanism and the Tallest Cable Net in the World - Poly Corporate Headquarters

2.1. Architectural Concept

The client's goal for this headquarters building was to represent the company's disparate subsidiaries as a unified whole. The program for the building contains a wide range of spaces including office, retail, restaurants and the Poly Museum. The museum, established by one of the company's subsidiaries, has the unique purpose of repatriating China's cultural antiquities through purchases at international auctions.

The project is prominently located at a major intersection along Beijing's second ring road, northeast of the Forbidden City. The site's primary orientation is northeast toward the intersection and beyond to the client's existing headquarters building. The triangular form minimizes the perimeter length exposed to the elements, while a series of interior atriums provide additional interior surface area to give office areas maximum access to daylight. The result is a simple 'L' shaped office plan that cradles a large atrium (Fig. 1). The exterior walls of the atrium are comprised of minimal glass membranes supported on two-way cable nets to maximize visual and solar transparency.

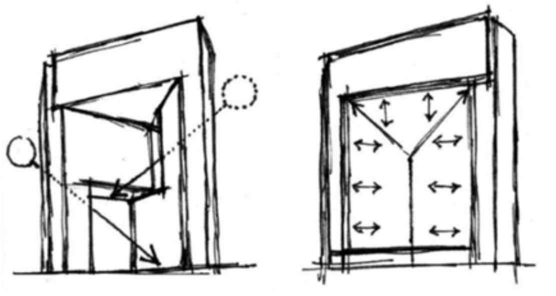


Figure 1. Atrium Concepts.

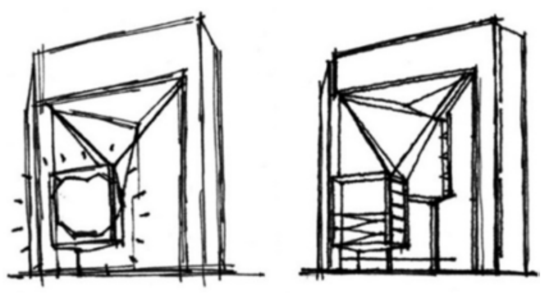


Figure 2. The 'Museum Lantern'.

Forming a unique solution to the unusual mixed-use requirements of this project, the Poly Museum is suspended within a 'Lantern' in the main atrium space (Fig. 2). This defined programmatic volume within the atrium space, is both isolated from and yet enclosed by the main building volume. Its crystalline surface of laminated patterned glass is pleated to increase its light reflecting/refracting qualities. Inside the 'Lantern,' exhibit and lease spaces are enclosed by wood walls which control daylight while common circulation areas occupy the void between the solids and the glazed perimeter walls.

Secondary 'Sunset' and 'All-Day' atriums cut through the west (Fig. 3) and south (Fig. 4) legs of the 'L' to act as daylight chambers for bringing direct sunlight into the main atrium. The exterior walls of these atriums are comprised of minimal glass membranes supported by two way cable nets in order to maximize visual and solar transparency. The main atrium's cable-net is stiffened by two 'V'-cables that are in turn counterweighted and kept in tension by the self-weight of the suspended 'Museum Lantern' (Fig. 5).

The cable-net wall is 90 meters high by 60 meters wide - dimensions making a simple cable-net supported wall uneconomical. The design is achieved by folding the cable-net around diagonal V-shaped, parallel-strand bridge cables, subdividing the wall into three facets and reducing the effective cable spans. The parallel-strand cables also support the 'lantern' as it hangs in the atrium space without any columns extending to grade. Gravity loads from the 'lantern' are used to induce high levels of

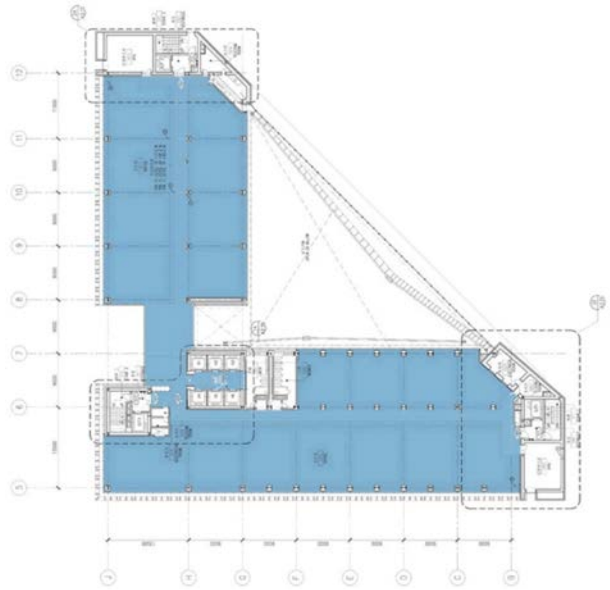


Figure 3. Typical High-Rise Plan.

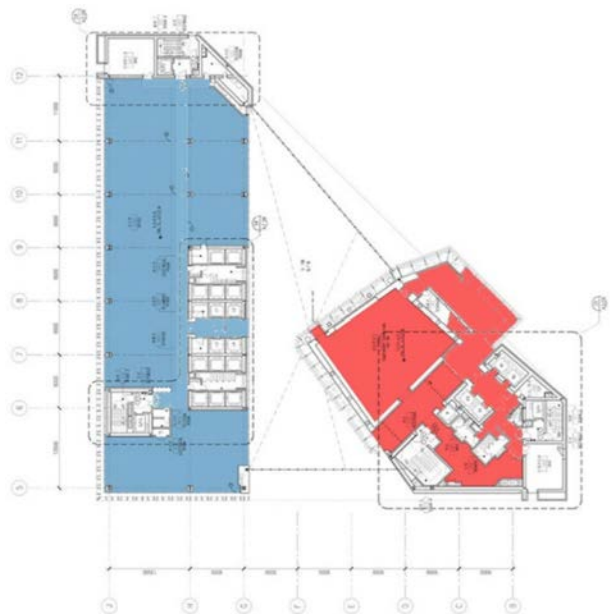


Figure 4. Typical Low-Rise Plan.

pre-tension in the parallel-strand cables. An innovative 'rocker mechanism' is used to isolate the cable hanger system from forces induced by lateral drift. The 'rocker mechanism' is architecturally 'celebrated' - an exposed articulated joint mechanism made of rigid pin-connected castings which perform as a pulley equivalent.

The project is prominently located at a major intersection along Beijing's second ring road, northeast of the Forbidden City. The site's primary orientation is northeast toward the intersection and beyond to the client's existing headquarters building. The triangular form minimizes the

Figure 5. Northeast Elevation Rendering.

Figure 6. Northeast Building Elevation.

Figure 7. Upward View from Atrium Floor.

perimeter exposed to the elements, whilst a series of interior atria provide additional interior surface area to give office areas maximum access to daylight. The result is a simple 'L' shaped office plan that cradles a large atrium. The exterior walls of the atrium are comprised of minimal glass membranes supported on two-way cable nets to maximize visual and solar transparency (Figs. 6 and 7).

2.2. Technology

While conceptually simple, cable-net curtain wall systems may still be considered an exotic solution for the structural support of glass curtain walls. However, the completion of several major walls around the world has established a proven track record of an achievable scale and level of transparency. Planar two-way cable systems support and stabilize glass facades through the resistance to deformation of the two-way pre-stressed net. Gravitational loads from the glass elements are carried through the attachment nodes to the vertical cables, and up to a transfer structure in the base building above. Lateral deformations due to wind and seismic loadings are resisted by the tendency of each of the horizontal and vertical cables to return to its straight-line configuration between supports, while being subject to a perpendicular force. The flexible nature of a planar cable-net under lateral loading means that the critical design goal is limiting deflection through adjusting axial stiffness of the cables, and the cable pre-stress. Deflection limits of L/40 to L/50 are generally set for the design loading condition (typically the 50-year wind event), to protect the integrity of the glass and sealants and to minimize a perception of weakness by the building's occupants.

2.3. Challenge

The Poly Corporate Headquarters project is a 100 m tall composite structure and includes a 90 m tall atrium enclosed by a cable-net glass wall, 90 m high by 60 m wide. The scale of this wall greatly exceeds that which has been built before, introducing specific challenges that are not critical in smaller walls. SOM's preliminary analysis sho-

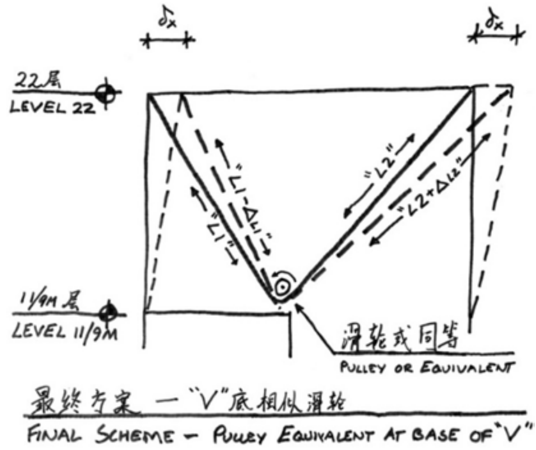


Figure 8. Pully Equivalent Concept.

Figure 9. The 'Rocker Mechanism' Model.

Figure 10. The 'Rocker' Installed.

wed that the cable-net spans were too large to be economically achieved using a simple two-way cable-net design. SOM determined however that the cable-net could be achieved by subdividing the large cable-net area into three smaller zones by folding the cable-net into a faceted surface, and introducing a relatively stiff element along the fold lines. The faceted cable-net solution allows the individual sections of the cable-net to span to a virtual boundary condition at the fold line, effectively shortening the spans. Rather than introduce a beam or truss element to stiffen the fold line, a large diameter cable under significant pre-stress is used. The largest of these primary cables is 275 mm in diameter and consists of a parallel strand cable bundle of 199 individual 1×7 strands, each strand being 15.2 mm in diameter. The largest cable is pre-stressed to 17,000 kN, and experiences a maximum in service loading of 18,300 kN during a 100 year wind event. Using the faceted design solution, the typical horizontal and vertical cables are limited in diameter to 34 mm and 26 mm respectively.

By introducing the large diameter diagonal cables, an issue is created as one is solved. As the base building structure is subject to seismic and wind loads, it experiences inter-story drifts as any building structure does. By connecting a point on one floor slab with an axially stiff element diagonally to another point 45 m higher up the structure, the diagonal cable element behaves as a brace element and tries to resist the base building drift. Thus analyzed, the forces in the main cables were too great to be resisted by the main cables, or the base building structure. However, when the base building drifts in a direction that causes one diagonal cable to go into tension (tries to lengthen) the other cable that forms part of the "V" configuration goes in compression (tries to shorten). A pulley analogy was developed that allowed the "V" cables to be considered as a single element, with rotation at the base of the "V" allowing the length increase of one cable to be offset against the length decrease of the other cable (Fig. 8). This allows the base building to drift without significantly increasing or decreasing the level of prestress in the main cables. The pulley analogy was realized in a buildable form as a cast 'Rocker Mechanism'. By crossing the cables and connecting to the rocker casting arms, the need to provide curved pulley surfaces and curved sections of the main cable were eliminated (Figs. 9 and 10).

2.4. Performance

The critical service level load condition, (the 50 -year wind event) was determined through careful Wind Engin-

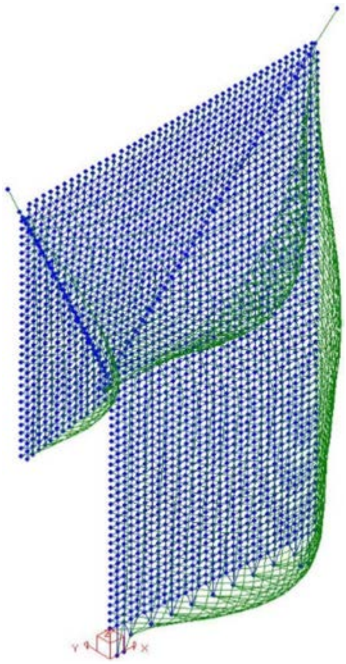


Figure 11. Deflected Shape Under Wind Loading.

Figure 12. Completed 90mx60m Folded Cable-Net.

Table 1. Project Summary Statistics

Overall Parameters			Main Cables		Horizontal Cables		Vertical Cables	
Height	Width	Deflect.	Dia.	Pre-stress	Dia.	Pre-stress	Dia.	Pre-stress
90m	60m	928mm	248mm	17MN	36mm	210kN	26mm	90kN

eering studies performed by Beijing University. The wind studies included a traditional rigid model of the building massing as well as that of the surrounding building fabric, and an aero-elastic wind tunnel study performed on a flexible model of the actual cable-net configuration, using wires and a membrane to replicate the anticipated dynamic response of the cable-net system. This study, likely the first of its kind to be performed on a cable-net curtain wall system was used to verify and modify where appropriate the results of the rigid model. Analysis and testing shows that the New Beijing Poly cable-net wall behaves very much as conceived. The results from the static nonlinear (large displacement) analysis clearly show that the strategy of subdividing the wall into facets with shorter individual spans was successful (Fig. 11). This strategy allows the overall displacements to meet the established for the project, while maintaining the economic viability of the project (Fig. 12).

Table 1 illustrates the key attibutes of the northeast cable net.

3. Braced Concrete Butresses-Poly Real Estate Headquarters

In considering a structure's life and its effects on the environment, structural solutions, building orientation and integrated systems are important considerations. To achieve a high level of sustainability, the structure must allow the entry natural light and natural ventilation, air distribution from below the floor, shaded outdoor spaces, green roofs and minimal material use. The structural concept for the 525 ft (160 m) twin Poly International Plaza Towers (Fig. 13) incorporates a long-span concrete floor framing system with a series of concrete buttress walls to not only resist gravity and lateral loads but provide shading of the south facades (Fig. 14) significantly reducing the need for mechanical cooling of towers over their operational life.

To further enhance the shading effects, two lines of braces were incorporated into the south facades of the towers to provide significant stiffness in the east-west direction of the towers (long direction), but more importantly, act to anchor the structure in the north-south (short direction) of the towers functioning in tandem with the buttress walls as a "stressed skin" through the action of the outriggers. The stressed skin acts as a flange to resist compressive and tensile loads applied in the short direction. See Fig. 15 for the construction of the south façade. See Figs. 16 and 17 for architectural and structural floor plans respectively.

Figure 13. Poly International Plaza, Guangzhou, China.

Figure 14. Shading Effects on South Façade.

Sustained gravity loads are used as ballast within the primary lateral load resisting elements achieved through long-span reinforced concrete framing where compressive loads are placed on both the north and south facade structural systems. Openings were introduced into the mid-height of the two towers to provide an area of refuge during an emergency and to provide an aperture for predominant winds to pass through the structure. The screen enclosures at the top of the towers consist of tilted individual panels, providing open paths for wind to pass through, reducing wind loads on the top of the towers where they would induce the highest demand on the structure.

Through balancing load on the structure by using an

Figure 15. Poly International Plaza Under Construction Illustrated Structural Steel Interconnected with Concrete Elements.

efficient bracing system on the south facades and the openings that allowed for winds to pass through the structure, a 15% savings of structural materials was achieved when compared to conventional structures of the same height (even with slender forms). See Fig. 18 for an exploded view of major building components. See Fig. 19 for the completed building.

4. Combining a Concrete Shear Wall with a Diagrid Frame - Poly International Plaza

The Poly International Plaza Tower (Fig. 20), located at a prominent site approximately half way between the Forbidden City and Beijing Capital Airport, China, incorporates a faceted exoskeleton system to create an iconic exterior envelope highly visible in the surrounding skyline serves as part of the gravity and lateral force resisting system while allowing for long 18 m (60 ft) column-free spans combined with the reinforced concrete central core. A primary design goal of the 32-story office building is to provide a unique, high-quality work environment utilizing long span structural framing to open up interior spaces and achieve a light-filled spatial experience throughout the tower.

The diagrid perimeter structure is designed to resist gravity and lateral loads axially, with only minor bending effects due to the rigid welded nodal connections. The concrete filled steel tube (CFT) diagrid members serve as effective axial members to resist high compression loads due to gravity and lateral overturning, varying from 1300 mm (51”) in diameter at the base to 800 mm (32”) at the top. The load path of the axial force travels around the perimeter diagrid down to the base, allowing for long spans between nodes while providing global stiffness to distribute lateral forces.

While the helical load path is advantageous in allowing

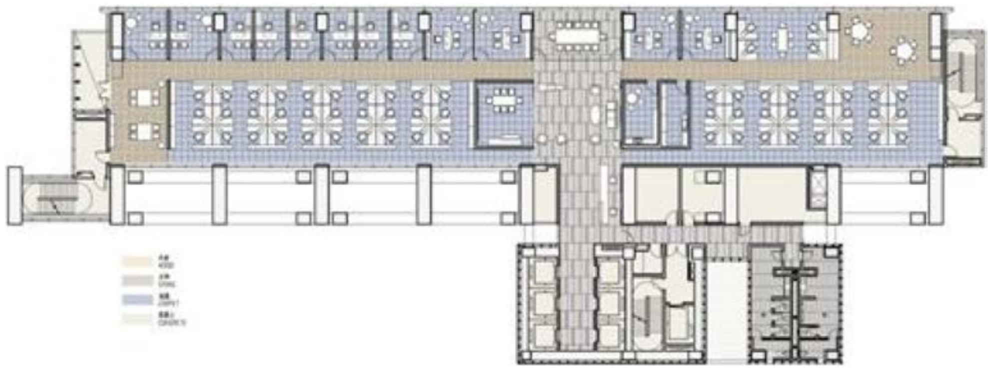


Figure 16. Typical Architectural Floor Plan.

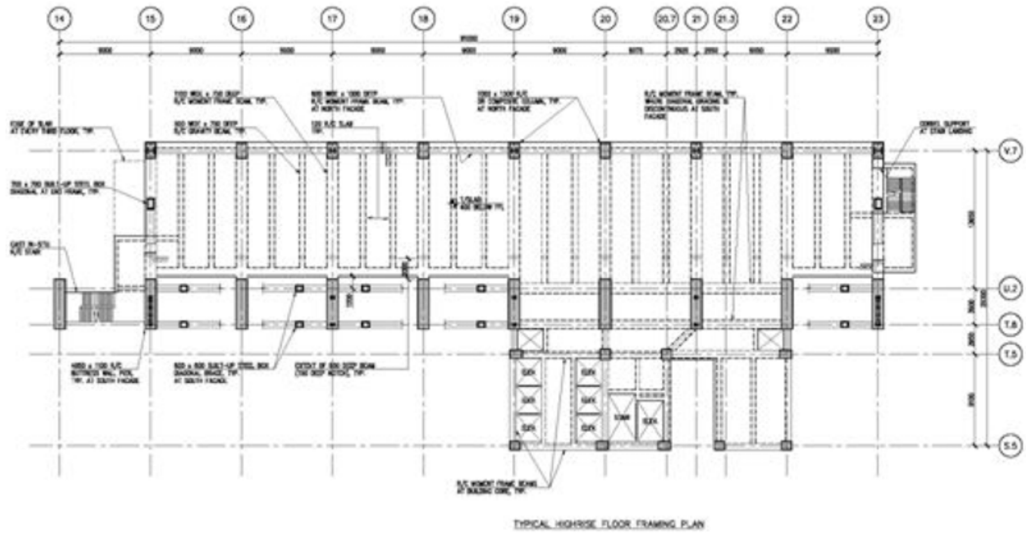


Figure 17. Typical Structural Floor Plan.

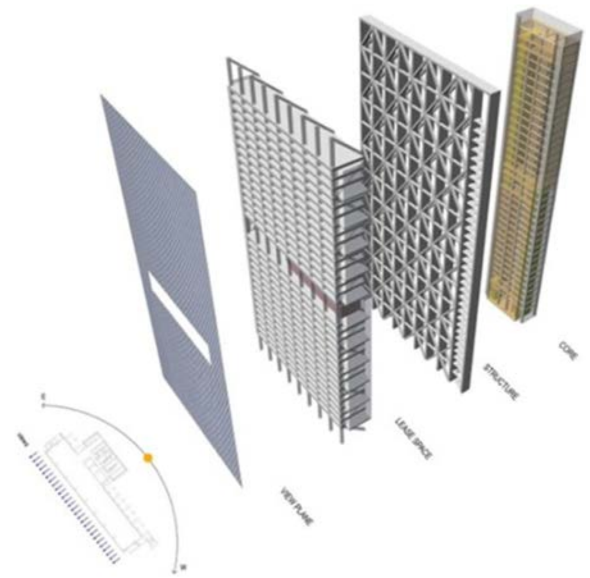
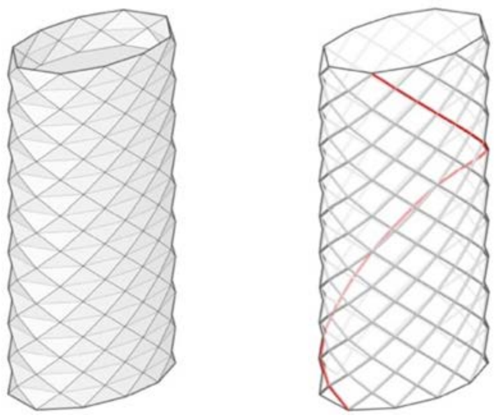


Figure 18. Exploded View Showing Major Building Components.

Figure 19. South Façade and Base of Tower.

for long perimeter spans and large atriums, the axial forces in the elliptical exterior diagrid result in tensile perimeter

Figure 20. Poly International Plaza Tower Rendering (left), Building Under Construction (right).



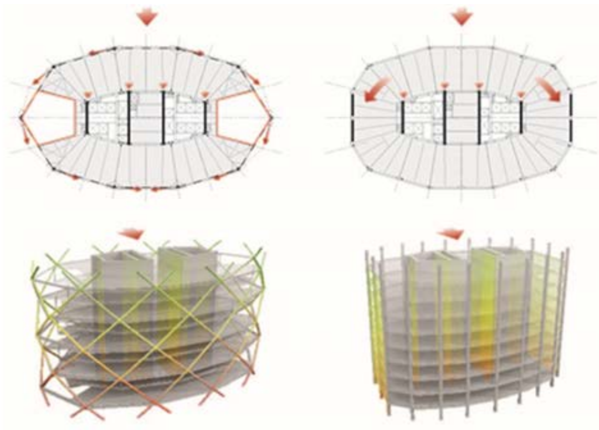
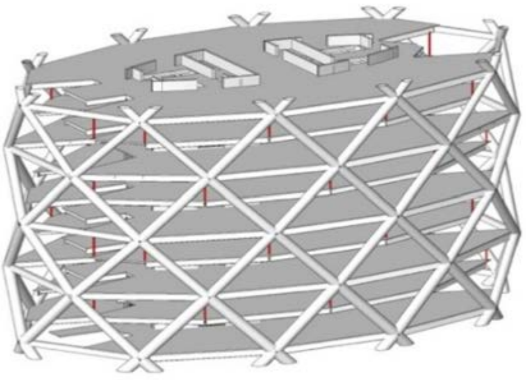


Figure 21. Helical Axial Load Path (left).
Figure 22. Diagrid System Lateral Load Path vs. Conventional System Lateral Load Path (left to right).

hoop and radial floor diaphragm forces that needed to be resolved through the perimeter steel framing members at nodal levels and radial steel floor framing members that connect the diagrid nodes to the inner concrete core. The interior reinforced concrete shear walls form an elongated core that follows the same elliptical shape as the exterior façade. The shear walls vary in thickness from 1300 mm (51") thick in the basement to 400 mm (16") at the top. The varying shear wall thickness and diagrid member diameters were optimized to meet design drift limits using strain energy optimization with ETABS and Excel VBA. The combination of the 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.

An advantage of designing a diagrid structure is the availability of helical axial load paths for resisting gravity and lateral loads (Fig. 21) while allowing for a column-free interior 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. 22). The exoskeletal diagrid system on the perimeter acts in tandem with the concrete walls at the building's core to provide a dual gravity and lateral load resist-



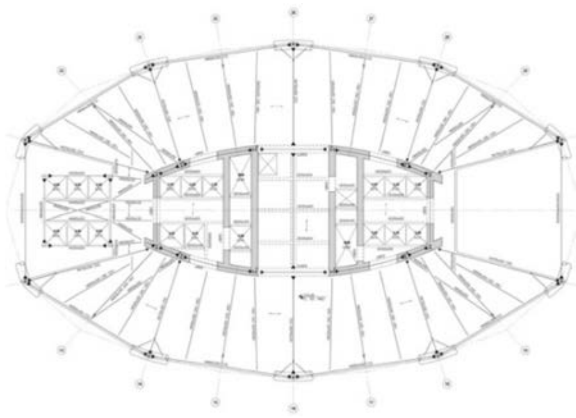


Figure 23. Diagrid Floors Showing Hanger Columns (left).
Figure 24. Typical Structural Floor Plan (right).

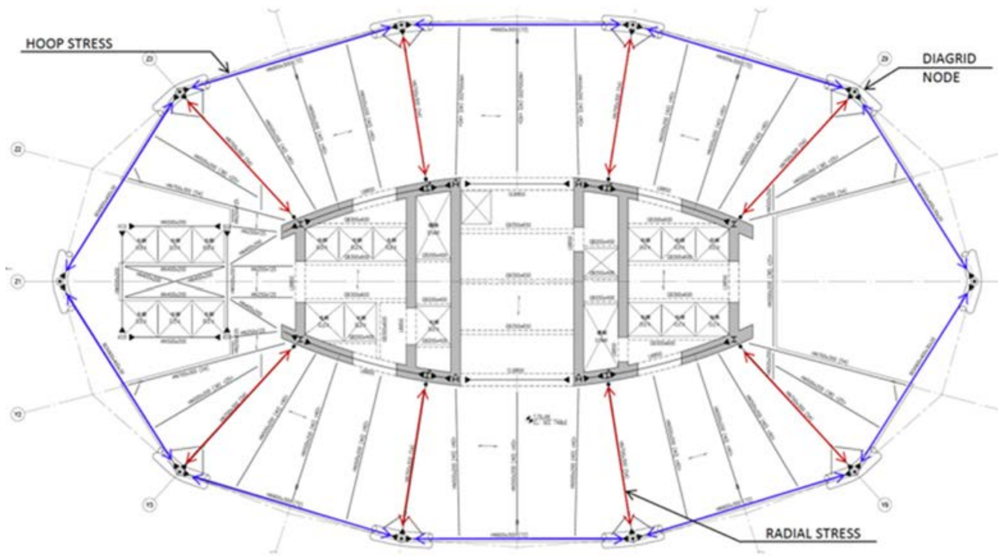


Figure 25. Floor Plan Showing Hoop and Radial Stresses in Diaphragms.

ing system with multiple continuous and redundant load paths.

Since the diagrid members are most efficient as axial members, connections of the floor diaphragms are limited to nodal floors to avoid imposing bending demands at the mid-spans of members. With a four-story tall diagrid module, every alternate floor connects to diagrid nodes and every other intermediate floor requires hangers to connect to members of the nodal floor above (Fig. 23). These hangers at non-nodal floors were incorporated into the enclosure mullions to maintain a column free perimeter. The annular space created between the slab edges of hung floors and the nodal floors above and below made it possible to have a double plane exterior wall, which afforded the building sustainable thermal buffering possibilities.

The typical floor framing plan at a nodal floor is shown in Fig. 24.

Concrete filled steel tubes (CFT) were chosen as the most efficient member type for the diagrid, since gravity forces resulted in high compression loading in the axial members.

A challenge of using concrete filled tubes is ensuring that the connection at the diagrid nodes is stronger than the members framing in. Connections were envisioned for the CFT nodes as either fabricated using 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.

In addition to the axial diagrid forces due to gravity and lateral loads, the nodes also transmit perimeter hoop and radial diaphragm forces that result from the folded diagrid geometry (Fig. 25). Caused by the bulging tendency of the diagrid's form under gravity loads, maximum hoop and radial forces in the diaphragms were noted primarily at the

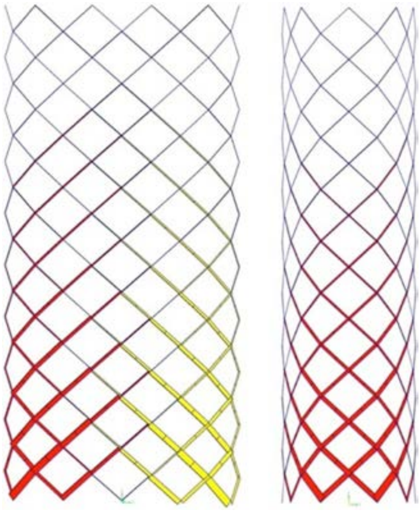


Figure 26. Lateral Axial Force Distribution.

Figure 27. Concrete Shear Wall within Diagrid Frame.

Figure 28. Finished Building Photograph.

Level 6, Level 8 and Level 10 nodal floors. The diaphragm hoop forces are resisted by tension in the steel floor framing members around the perimeter of the floor plan that connect the diagrid nodes. The radial diaphragm forces are resisted using the steel floor framing members that span between the core walls and diagrid nodes. In order to protect the connections of these critical members, additional plate strengthening elements were provided at the diagrid node connections, and embedded steel wide flanged shapes were used to strengthen the connections of the radial members to the core walls. The lateral axial force distribution is shown in Fig. 26.

Suspended intermediate level floor diaphragms do not connect to the perimeter diagrid frame and transfer all their inertial seismic forces to the core walls. These diaphragm slabs thus act as in-plane cantilevers supported at the face of the core walls. They are reinforced to transfer horizontal seismic forces during the moderate earthquake to the core walls without yielding. See Fig. 27 for the concrete cone and diagrid frame under construction and the finished building in Fig. 28.

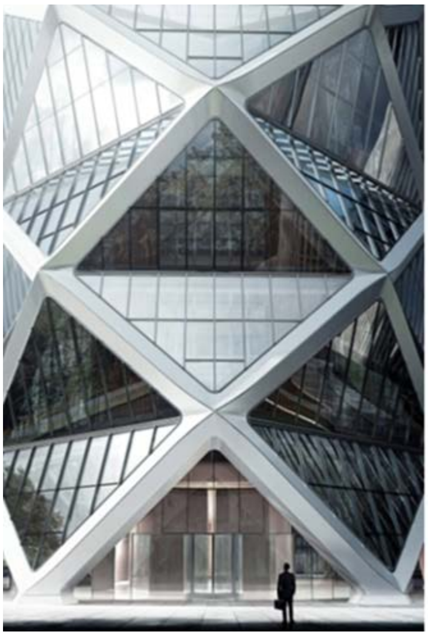
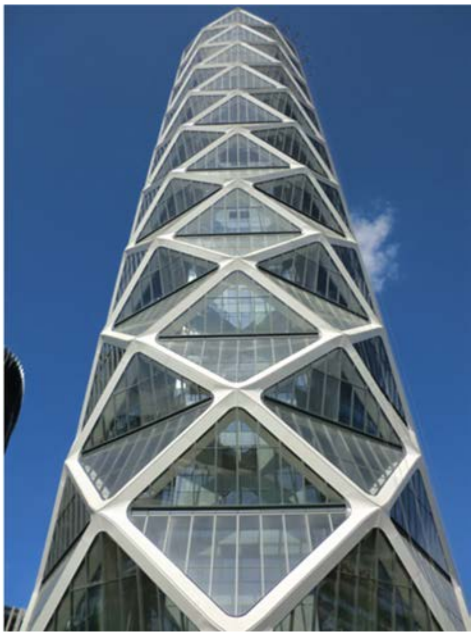



Figure 29. Rendered Elevation at Building Base and Finished Building.

5. Conclusions, Opportunities, and the Future

Each of the Poly projects uniquely responded to their sites and use while creating an integrated design solution. Perhaps in the future projects will refer to this work for new inspirations. See rendered elevation at based and finished Poly International Plaza in Fig. 29. For instance, exterior wall systems for structures represent the single greatest opportunity to consider flow and interaction between structure and building service systems. Hundreds of millions of square feet of occupied area are enclosed each year by a system that essentially provides protection from the elements and internal comfort. A closed loop structural system integrated with the exterior wall system that includes liquid-filled structural elements such as pipes could provide a thermal radiator that when heated during the day could be used for building service systems such as hot water supply or heat for occupied spaces, especially during the evening hours. A solar collection system could be integrated into the network and incorporated into double wall systems where it can be used to heat the internal cavity in cold climates. See Figs. 30 and 31.

Transparent photovoltaic cells could be introduced into the glass and spandrel areas to further capture the energy

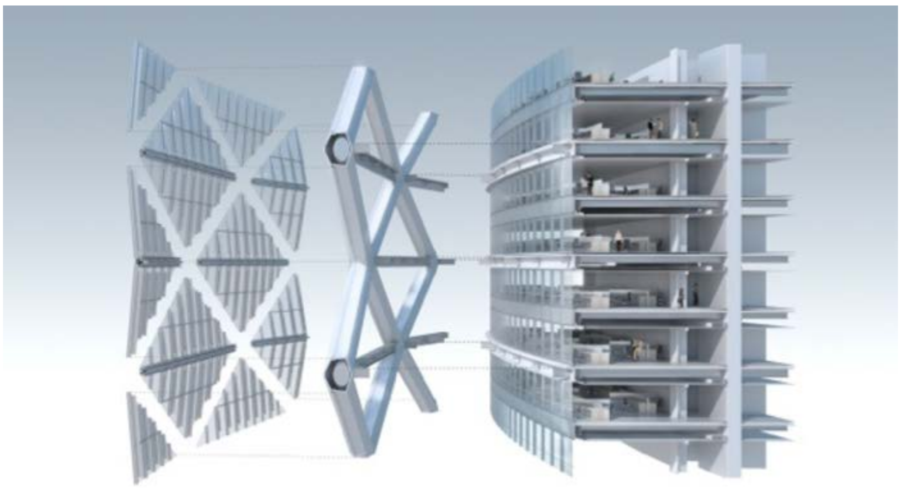


Figure 30. Exploded View of Integrated Systems.

Figure 31. Internal Column-Free Space.

of the sun. When storing fluid in structural systems of great height, pressures within the networked vessel become very large. With this level of pressure, water supply systems to the structure or to neighboring structures of lesser height could easily be supplied without requiring additional energy to move the water. Constant low flow through these systems would prevent the liquid from freezing.

Liquid within the networked system could act to control motion with fluid flow acting to dampen the structure when subjected to lateral loads due wind and earthquake events. In addition, liquids at high pressure could add significantly to the axial stiffness and stability of structural members subjected to compression, increasing capacities without increasing structural material by creating capped compartments. Combining ultra-high strength tensile materials such as carbon fiber fabricated into closed circular forms where loads are primarily resisted by hoop stress with the liquids under ultra-high compressive stress would likely result in greatest efficiency in resisting applied load.

The concept of flow can be further developed into structures that are interactively monitored for movement. Through the measurement of imposed accelerations due to ground motions or wind, structures could respond by changing the state of the liquid within the system. For instance, the structure could use endothermic reactions to change liquids to solids within the closed network. Sensor devices could inform structural elements of imminent demand and initiate a state change in liquids that would be subjected to high compressive loads where buckling could occur. In the simplest sense, water within the system could be frozen for additional structural rigidity.

For example, the Poly International Plaza, Beijing, China, offers a unique insight into towers of the future. The structure makes significant steps in the direction of the most advanced technologies. Because of significant levels of seismicity and the concern for life-cycle seismic performance, concrete was used in the exterior tubular frame. In the future, however, this framed system could be utilized for a fully integrated approach where structure, architecture, and mechanical systems are completely synergetic.

The study of these emerging forms as they interact with the architecture (overtly or covertly) will only yield further opportunities to explore light, space, structure and a new relationship that combines them all in an ephemeral solution. The investigation into the flow of material that can be manipulated to adhere to a seismic, temperature or safety condition can only inform us of new ways to design and build.

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