wood timber structures and their connections rely on proven design standards and methods which include "condition of use" design factors that account for short-term and long-term load duration, volume, curvature, and beam/column stability.

SITE SEISMICITY AND GROUND MOTIONS

The Cathedral of Christ the Light is located in the City of Oakland, California on Harrison Street, bounded by Grand Avenue on the north and 21st Street on the south, directly west and adjacent to the city park areas along the northwest shore of Lake Merritt. The site is located approximately 4.6 km from the Hayward Fault (Type A) and 25.4 km from the San Andreas Fault (Type A).

Two levels of site-specific probabilistic earthquake hazard ground motion criteria consistent with California Building Code (CBC) requirements were provided by the project geotechnical engineer represented by response spectra based on CBC seismic Zone 4 ($Z = 0.4$) with a site classification soil profile Type S_C.

"Near fault" effects were considered based on CBC site near-source factors of 1.24 and 1.65 for Na and Nv as defined by UBC 1997 fault map criteria. CBC design criteria included both lower bound and upper bound ground motions. The lower bound CBC Design Basis Earthquake (DBE) is defined as an event with a 10-percent chance of exceedance in 50 years based on a 475-year return period with a peak ground acceleration of 0.683g. The upper bound Maximum Capable Earthquake (MCE) is defined as an event with 10-percent chance of exceedance in 100 years based on a 972-year return period with a peak ground acceleration of 0.827g.

Important design aspects of the Cathedral of Christ the Light include 1) a site location in close proximity to faults, 2) the uniqueness of the design of the superstructure, and 3) the use of a seismic isolation system to achieve enhanced seismic performance objectives. In consideration of these design aspects, particular care was undertaken in the development of site-specific spectra with input from the seismic isolation peer review panel for the project. An emphasis on state-of-the-art ground motion criteria addressed proximity to near-faults, directivity effects, depth to rock, and, vertical ground accelerations.

SEISMIC PERFORMANCE OBJECTIVES

Seismic performance objectives are identified for both the CBC defined "design basis earthquake" (DBE) and "maximum capable earthquake" (MCE) levels of ground shaking. These performance objectives are used to define further the anticipated levels of performance with expected levels of seismic ground motions.

For the main Cathedral superstructure, the owner elected to provide "enhanced" seismic performance objectives. An "enhanced" seismic performance objective provides better performance, or lower risk, than minimum "life-safety," or "collapse prevention" objectives of the CBC. This enhanced seismic performance is achieved by employing a seismic base isolation system and limiting the response of superstructure and substructure elements to achieve elastic behavior under the DBE with negligible structural damage, and, essentially elastic behavior under the MCE with minimal structural damage. To ensure elastic behavior under the DBE with negligible structural damage, the isolated superstructure was designed using maximum force demands calculated based on maximum stiffness (upper bound friction) of the isolation system and R_I=1. The superstructure drift was limited to 0.010/R_I = 0.01 vs. a CBC limit of 0.020/R_I = 0.02. To ensure essentially elastic behavior under the MCE, ductility demands were limited to be less than 1.0 and the superstructure drift was limited to 0.020/R_I = 0.02. Non-structural components and exterior wall elements are designed and detailed to accommodate the MCE movement without damage or permanent deformation.

For seismic demands greater than the MCE, the analysis and design of the superstructure demonstrates a low probability of collapse with reserve strength and ductility capacities as well as energy dissipation and redundant alternate load path system characteristics. This is established by a controlled failure hierarchy initiated by yielding in the diagonal steel rods while the primary gravity load carrying elements maintain significant reserve overstrength and ductile capacity.

SUMMARY AND CONCLUSIONS

The Diocese challenged the design team to create a building allowing for structural light and longevity for the ages. Through the use of its innovative hybrid structural system, including base isolation, the Cathedral was designed using advanced seismic techniques to withstand a 1,000-year earthquake. While wood provides an important unifying architectural, structural, and spiritual design element, its use as a primary structural element of the Cathedral's glue laminated superstructure was tantamount to the desired long-term performance objectives. As a result, the Cathedral of Christ the Light will endure for centuries rather than decades.

Figure 8. Interior View from altar looking south

REFERENCES

California Building Standards Commission. (2001). *2001 California building code*, Sacramento, California.

Fenz, D. Constantinou, M. (2006). "Behavior of double concave friction pendulum bearing", *Earthquake Engineering and Structural Dynamics*, Vol. 35(11), 1403-1424.

International Conference of Building Officials (ICBO). (1997). *Uniform building code*, Whittier, California.

Glass and Steel: Transparent and Lightweight Enclosure Structures in China

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ABSTRACT

The recent surge of construction in China has seen many exciting and innovative structures built. Architects, engineers and builders from all over the world have joined their counterparts in China to participate in what is arguably one of the most significant bursts of creative endeavor in the history of building. Skidmore, Owings & Merrill LLP has been fortunate since the early 1990s to have had the opportunity to be part of this phenomenon. Transparent and lightweight enclosures of public spaces in four recently completed projects in Beijing, China, are described. Each enclosure includes façade and / or roof elements that uniquely respond to specific design issues. The four projects highlight the particular ways in which innovative structural engineering concepts have been used to realize the aspirations of the architects making these atria and pavilions special places.

BACKGROUND

SOM established a track record of major building projects in China with the Industrial and Commercial Bank of China headquarters in Beijing (completed 1998) consisting of a dual system of steel eccentric braced frames and moment resisting frames, and the Jin Mao Tower in Shanghai (completed 1999) consisting of a composite system of reinforced concrete core walls, perimeter composite mega-columns and structural steel floor framing. At 420m tall, the Jin Mao Tower was, till recently, the tallest building in China. As the Chinese market for international class buildings has continued to grow, SOM has embraced the opportunity to design high quality buildings in this developing market.

TRANSPARENT AND LIGHTWEIGHT ENCLOSURE STRUCTURES

The four atrium / pavilion projects described highlight particular ways in which innovative structural engineering concepts have actualized the architectural aspirations of lightness and transparency to make these structures special places. The structural systems employed push technological boundaries, break new ground, or represent refinements and developments on similar previous efforts. “Transparent” and “lightweight” are evocative terms that describe both the architectural effect realized in these designs and the structural engineering challenges that were overcome in achieving these results.

"*Transparent Gateway*" **Beijing Finance Street – B7 Office Towers, Beijing**

The Beijing Finance Street development is an urban district in the southwest quadrant of Beijing, five blocks west of the Forbidden City in the city's historic core. The new plan for Beijing Finance Street is conceived of as an interwoven set of indoor/outdoor rooms and courtyards linked by pathways which penetrate parks, indoor public spaces and the buildings themselves. The result is a highly permeable urban district of interwoven connections, which, when complete, will provide a vibrant urban setting in which the boundaries of inside/outside and public/private are blurred. The Beijing Finance Street - B7 office towers represent the landmark gateway to the development, and the B7 "All Seasons Garden" is an important visual and physical connection between the Second Ring Road to the west, and Finance Street and the park that is the core of the development to the east (Figure 1).

Figure 1. B7 from the Second Ring Road.

Figure 2. B7 "All Seasons Garden".

Given the importance of the transparency of the B7 All Seasons Garden in achieving the architectural link between the west entry and the heart of the Finance Street development, the structural design of the enclosure became a study in minimalist efficiency. Efficiency measured not only in terms of minimal use of structural materials, but also in the simplicity of design to provide the cleanest most transparent solution. This was achieved by minimizing the number and simplifying the layout of structural elements. The All Seasons Garden roof system employs a series of rod-stayed kingpost trusses that have the visual appearance of slender beams spanning 27 meters between adjacent building structures (Figure 2). Visual clutter associated with traditional steel trusses is eliminated by localizing connectivity between the top and bottom chords to the centre of the span only (Figures 3 and 4). Rather than providing additional structural elements as an independent gravity and lateral system to support the roof of the All Seasons Garden, gravitational and lateral forces are transferred to the adjacent concrete building structures. This approach eliminated the need for any atrium columns, reinforcing the concept of a transparent public space between the B7 building structures. Glass end walls complete the transparent box. Vertical wind braces in the glass end walls are pin-connected to the roof and the ground floor slab, and rack to accommodate movements of the roof diaphragm. Lateral forces from the roof sections are transferred to the lateral force resisting systems of the adjacent building structures through tie-rod diaphragm bracing in the plane of the glass roof.

As the glass roof system spans between seismically independent structures a system of fixed and sliding supports is employed to accommodate their differential movements.

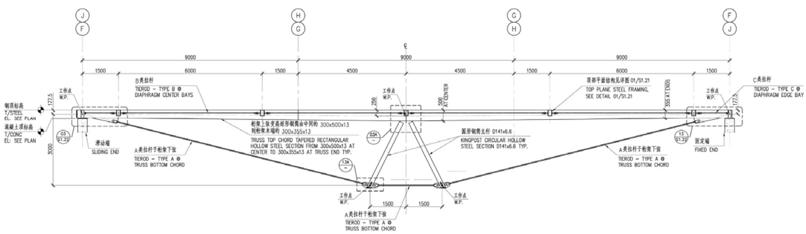


Figure 3. Elevation of typical king-post truss.

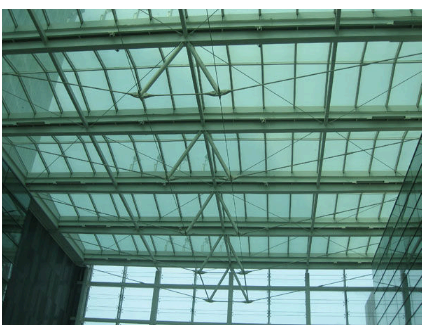


Figure 4. B7 All Season Garden Trusses.

The roof system is designed to be fixed to one of the adjacent building structures along one edge in order to transfer its diaphragm loads into it. Sliding supports are provided at the opposite edge where the roof is supported on a seismically independent building structure.

"Butterfly Trusses" Beijing Finance Street – F9 Retail Project, Beijing

The buildings in this carefully planned development are decidedly modern, reflecting Beijing's strong position in international commerce. Beijing Finance Street's many architectural and landscape elements are all clustered around a park, which is the project's core. Opening on to the park is the Great Urban Atrium. This circular segment shaped building (Figure 5)—the most engaging component of the project with a sharply slanting roof and exposed diagonal trusses—provides a vibrant indoor urban space (Figure 6), and being adjacent to the park, enhances the complex's role as a gathering place.

The roof of the cavernous 300 meter-long atrium retail space, continues the language of transparency that was established with the B7 All Seasons Garden Roof. The supporting reinforced concrete retail buildings are subdivided into independent structures with a maximum dimension of 90m. The structures were also subdivided by the natural building break that occurs across the atrium. As a result, the roof needs to span between six independent building structures. Given the roof spans, the potential relative movement between supports (Figure 7) prohibited the use of the sliding details similar to those used at the B7 roof. The high end of the sloped roof trusses are supported atop free-standing columns that extend up to 11m above the roof of the supporting concrete structure, further reducing the applicability of a sliding detail at one end. However, the high end columns were also the source of the design solution to the 'dynamic' support issue. By providing articulated ball-and-socket joints at the top and bottom of the high-end columns, the columns and trusses become components in a three-pinned arch roof system (Figure 8).

Figure 5. BFS development.

Figure 6. Retail atrium interior.

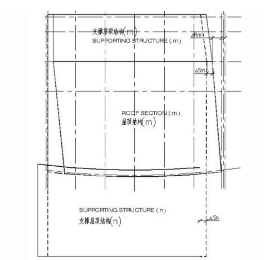


Figure 7. Relative movement diagram.

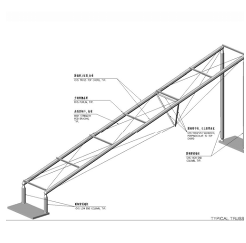


Figure 8. 3D 'butterfly' truss diagram.

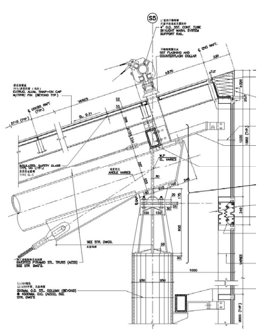


Figure 9. Apex joint detail.

When the supports move closer together and further apart along the axis of the roof trusses, the enclosed angle at the apex of the roof closes and opens. The glazing system is jointed to allow this rotation without damage (Figure 9). When the relative movement between supports is perpendicular to the axis of the trusses, the tops of the high-end columns effectively move with the low-end support points due to the diaphragm bracing, while the bottoms of the high-end columns move with the high-end support points. This causes the vertical wall of the roof system to rack in-plane. The glazing for the vertical wall is supported in horizontal courses that are allowed to slide relative to each other as the columns rack. Due in part to the dynamic nature of the support conditions, the kingpost truss arrangement was modified to result in a three-dimensional truss configuration that has additional out-of-plane stiffness. The language of the inverted “V” kingposts on the planar B7 trusses is maintained by tipping two planar single kingpost trusses towards each other, resulting in a three dimensional “V” kingpost ‘butterfly’ truss. The lack of bracing elements between the top and bottom chords, as well as the visual weight of the 457mm diameter pipe truss top chords relative to the 25-37mm diameter cable bottom chords, results in the appearance of slender parallel beam elements spanning the atrium (Figure 6). Similar to the B7 All Seasons Garden Roof, lateral forces induced in each of the roof sections are transferred to the supporting structures at only one end of the trusses (through the low end columns) with the use of in-plane diaphragm bracing rods.

“Suspended Pavilion” **Legend Raycom Phase II, Beijing**

The Legend Raycom Phase II development consists of twin 17 storey office towers connected at grade with a transparent glass pavilion that is suspended from attachment points on the tower superstructures.

The structural design of the pavilion takes advantage of the strength and stiffness of the concrete cores of the adjacent twin towers, which are used as anchor blocks for four 105mm diameter primary cables which span 63m between the towers (Figures 11 and 12). An array of built-up beam elements spans across the primary cables. These elements act both as spacers and supporting elements for the side walls of the pavilion.

The pavilion side walls are vertical one-way cable-nets that span between the built-up beam elements and the reinforced concrete framing at ground level (Figure 12). The vertical cables carry the gravity loads from the wall glazing to the beam elements above, resist out-of-plane deflections of the walls due to wind and seismic loading, and also act as tie-downs for the primary suspension cables. Relatively constant tension in the vertical cables is maintained through the use of springs located at the underside of the level 1 slab. The configuration allows the vertical cables and primary suspension cables to effectively be pre-stressed against each other, providing enhanced stability to the system.

Lateral loads are induced in the glass roof plane both from seismic loading on the roof elements, and from seismic and wind loads that are transferred to the roof plane through the vertical cables. These lateral loads are resisted through the use of lateral ‘fish’ cables that lie in the plane of the roof and transfer lateral forces directly to the adjacent concrete building cores (Figure 11).

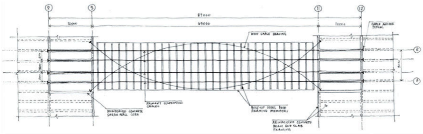


Figure 11. Pavilion Roof – Plan.

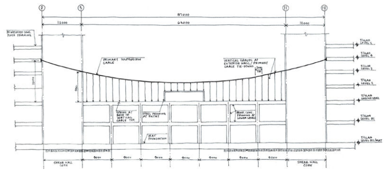


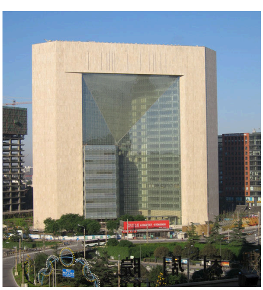
Fig. 12: Pavilion Roof – Section.

Figure 13. Exterior view of suspended pavilion.

Figure 14. Interior view of suspended pavilion.

"The Rocker Mechanism" **The New Beijing Poly Plaza, Beijing**

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 towards the intersection and beyond to the client's existing headquarters building. The 100 m tall building's triangular form minimizes the perimeter exposed to the elements, whilst a series of interior atria provides the office spaces with 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 in order to maximize visual and solar transparency (Figures 15 and 16).



Figures 15. Northeast Elevation.

Fig. 16: Upward view from atrium floor.

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. Out-of-plane 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. A deflection limit of L/45 is generally set for the serviceability 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.

The project's atrium is enclosed by a cable-net glass wall, 90m high by 60m wide. The scale of this wall greatly exceeds anything that has been built before, introducing specific challenges that are not critical in smaller walls. Preliminary analysis showed that the cable-net spans were too large to be economically achieved using a simple two-way cable-net design. It was 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 (Figure 20), 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 lines, large diameter cable under significant pre-stress that support a "hanging" museum structure are used The largest of these primary cables is 275mm in diameter and consists of a parallel strand cable bundle of 199 individual 1x7 strands, each strand being 15.2mm in diameter. The largest cable is pre-stressed to 17,000kN, and experiences a maximum in service loading of 18,300kN during a 100 year strength design wind event. Using the faceted design solution, the typical horizontal and vertical cables are limited in diameter to 34mm and 26mm respectively.

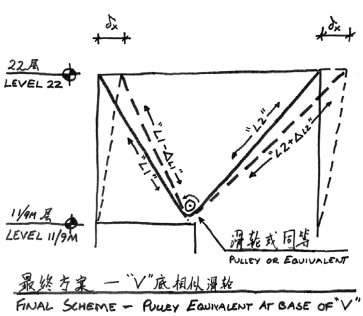


Figure 17. Pulley equivalent concept.

Figure 18. The 'Rocker Mechanism'.

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-storey drifts as any building structure does. By connecting a point on one floor slab with an axially stiff element diagonally to another point 45m higher up the structure, the diagonal cable elements behave as brace elements and try to resist base building drift. Thus analyzed, the forces in the main cables become too great to be resisted by the main cables, or the base building structure. A "rocker mechanism" arrangement that mimics pulley action (Figures 17 through 19) was introduced to address this issue. This allows the base building to drift without significantly increasing or decreasing the level of pre-stress in the main cables.

Figure 19. "Rocker Mechanism".

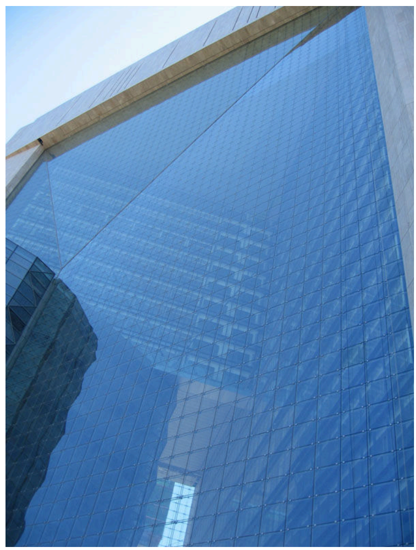


Figure 20. Faceted Cable-Net Wall.

SUMMARY

The present day construction climate in China offers clients and designers the opportunity to realize exciting advancements in architecture. The rapid and sustained growth of the Chinese economy, the desire of enlightened clients to create signature buildings, and the ability of Chinese domestic fabricators to produce high quality architectural components at a fraction of the cost of those available in the developed US and European markets, have all coalesced into an unprecedented period of design opportunity. The highlighted projects show SOM's resolve, through the quality of design work to ensure that this period is seen in retrospect as one where opportunities were realized rather than lost.

** Images courtesy of SOM. Figures 5 and 6 © Tim Griffith.*