



CTBUH Research Paper

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Case Study: Shanghai Tower



Jun Xia



Dennis Poon



Douglas C. Mass

"Shanghai Tower, which will anchor the city's Lujiazui district as one of the world's foremost commerce destinations, isn't simply about a single high-rise building. It represents a new way of envisioning and creating cities, and it addresses the tremendous challenges that face designers of supertall buildings today."

As the third tower in the trio of supertall buildings at the heart of Shanghai's new Lujiazui Finance and Trade Zone, Shanghai Tower embodies a new prototype for tall buildings. Placed in close proximity to Jin Mao tower and the World Financial Center, the new tower will rise high above the skyline, its curved façade and spiraling form symbolizing the dynamic emergence of modern China.

More than a landmark, the 632-meter, 121-story mixed-use tower offers a sustainable way of living in vertical cities, with a unique mix of restaurants, shops, offices and hotels spaced through the building. It is a super high-rise building wrapped entirely from top to bottom in public spaces and sky gardens. By emphasizing public space where people can linger and offering a variety of community services placed vertically at strategic intervals, Shanghai Tower envisions a new way of inhabiting supertall buildings.

Planning

Spurred by the Chinese economic reforms that began in the 1980s, the Lujiazui district in Shanghai has transformed from farmland to financial center in two decades. This rapid urbanization has required new planning and design strategies to address the need for high-density development on the one hand and "breathing room" on the other. In the design of Shanghai Tower, Gensler has applied the idea of traditional lane houses found in Beijing's hutongs and Shanghai's shikumen, where families live in close-knit dwellings organized around a communal open space. In the case of Shanghai Tower, the neighborhoods are vertical, each with its own "sky garden" to foster interaction and create a sense of community.

In addition to satisfying the Shanghai government's requirement that 33% of the site be reserved as green space, the site's landscape design draws upon historic Chinese precedents of temples, towers and palaces nestled amidst gardens. The park at its base connects architecture to nature, encouraging people's engagement with a variety of outdoor spaces designed for contemplation and simple enjoyment of the landscape. The park will accommodate diverse activities, from large celebrations to intimate conversations. Park paving patterns reflect modern interpretations of Chinese garden details, lending a human scale to the landscape.

Authors

Jun Xia, Principal and Design Director of Gensler, Shanghai; **Dennis Poon**, Managing Principal at Thornton Tomasetti; **Douglas C. Mass**, PE, LEED AP, President/Principal-in-Charge of Cosentini Associates

Jun Xia¹

Jun Xia, Principal and Design Director of Gensler's Shanghai office, is an award-winning architect. Jun holds a bachelor of architecture degree from Tongji University in Shanghai and a master of architecture in Urban Design from University of Colorado at Denver. He is noted for his ability to render complex building issues into accessible terms for his clients, leading to better design collaboration throughout the construction process. Jun's Chinese projects are noted for their visionary qualities, and include master plans for Shanghai Shipyard and Nanjing Road West, office buildings including ChangAn International Center and China Petrochemical HQ in Beijing, among others.

Dennis Poon²

Dennis Poon is a Managing Principal at Thornton Tomasetti, Inc., a 550-person, privately held structural engineering firm. Mr. Poon has more than 30 years experience in the structural engineering of a wide variety of building types, from super high-rise commercial and mixed-use buildings to long-span sports and entertainment arenas, in both steel and concrete. Mr. Poon played a leading role in the structural engineering team for the design of the Taipei 101 in Taiwan. Currently, Mr. Poon is the Principal-in-Charge for the structural design of the 632 meter tall Shanghai Tower, the 590 meter tall 151 Incheon Twin Tower, and the 600 meter tall Ping An Tower in Shenzhen.

Douglas C. Mass³

Douglas Mass is President of Cosentini Associates, a 370-person international consulting engineering firm headquartered in New York. Mr. Mass' 30 year career in mechanical engineering includes hundreds of projects: major mixed-use developments, world-renowned museums and performing arts centers, hotels/resorts, high-rise commercial office buildings, corporate headquarters and educational facilities throughout the United States and abroad. His recent work in the development of fully integrated underfloor delivery of air, power, and voice/data has earned him a national reputation involving design commissions as well as numerous authoring and lecturing invitations.

Tower Design

By integrating design with technology, Shanghai Tower achieves a new understanding of the supertall building. Gensler's design team anticipated that three important design concepts could reduce typhoon-level wind loads common to Shanghai: the asymmetry of the tower's façade, its tapering shape, and consistently rounded corners. To refine the tower's shape, Gensler worked with partner engineering firms Thornton Tomasetti and RWDI to conduct a series of wind tunnel tests to simulate typhoon-like conditions. Results yielded a structure and shape that reduced the lateral loads to the tower by 24 percent – with each five percent reduction saving about US\$12 million in construction costs.

Shanghai Tower's program is organized into nine vertical zones. Zone 1 is the base-level retail podium of luxury boutiques, high-end dining destinations, cafés and lounges. Zones 2 through 6 are comprised of office floors, each of which acts effectively as a distinct

neighborhood within the tower. Each office zone contains a sky garden to provide identity and community gathering space. A five-star hotel will be located near the top in Zones 7 and 8. The hotel's conference, banquet, and spa facilities share the six-story podium with separate office, housing, and hotel lobbies. The highest of the nine zones houses public amenities: gourmet restaurants and enclosed and open observation decks served by the tallest single-lift elevator in the world. Separate double-decker elevators transport people rapidly between other zones in the tower, and below-grade parking links via walkways to the nearby Jin Mao and World Financial Center towers.

Each of Shanghai Tower's vertical neighborhoods rises from a sky lobby, a light-filled garden atrium that creates a sense of community and supports daily life with a mixed-use program to cater to tenants and visitors. The sky lobbies function much like

...on schedule

“It's a great time to build a building. We can get it done faster and cheaper than during the boom. We're ahead of schedule and under budget.”

Quote from Larry Nichols, Chief Executive of Devon Energy Corp. describes the revival of downtown Oklahoma City, Oklahoma. From the article "Decaying Downtown Becomes Full of Life Again," New York Times, January 27, 2010.

traditional town plazas and squares, bringing people together throughout the day. These civic spaces recall the city's historic open courtyards, which combine indoors and outdoors in a landscaped setting. ↗



Shanghai Tower will be one of the most sustainably-advanced tall buildings in the world. A central aspect of its design is the transparent, second skin that wraps the entire building. The ventilated atriums it encloses conserve energy by modulating the temperature within the void. The space acts as a buffer between inside and outside, warming up the cool outside air in the winter and dissipating heat from the building interior in the summer. Mechanical equipment is spaced strategically throughout each zone of the building to provide optimal flexibility and cost efficiency.

Structure

Shanghai Tower will be the tallest building in China and the second tallest building in the world when completed in 2014. Faced with many challenges – a windy climate, active earthquake zone, and clay-based soils typical of a river delta – the structural engineers sought to simplify the building structure. The heart of the structural system is a concrete core, about 30 meters square (see Figure 1).

The core acts in concert with an outrigger and supercolumn system. There are four paired supercolumns – two at each end of each orthonormal axis (see Figure 2).

In addition, four diagonal supercolumns along each 45-degree axis are required by the long distances at the base between the main orthonormal supercolumns. These distances are approximately 50 meters and reduced to 25 meters to the diagonal columns.

The tower is divided vertically into nine zones, each with 12 to 15 floors. An inner cylindrical tower steps in at each zone, similar to a wedding cake. At the interface of the adjacent zones, a two-story, full floor area is created to house mechanical, electrical and plumbing equipment and also serve as that zone's life safety refuge area. This full-floor platform creates a base for the atrium spaces directly above.

The lateral and vertical resistance of the tower will be provided by the inner cylindrical tower. The primary lateral resistance is provided by the core, outrigger, and supercolumn system.

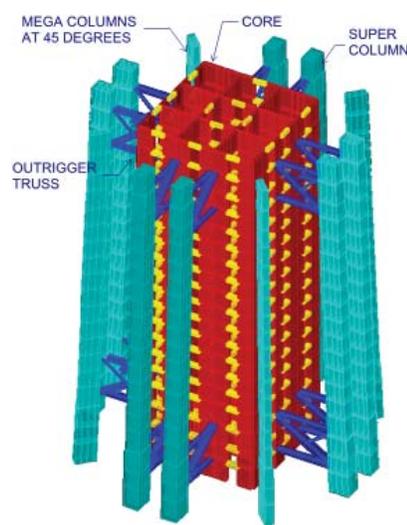


Figure 1. Core profile

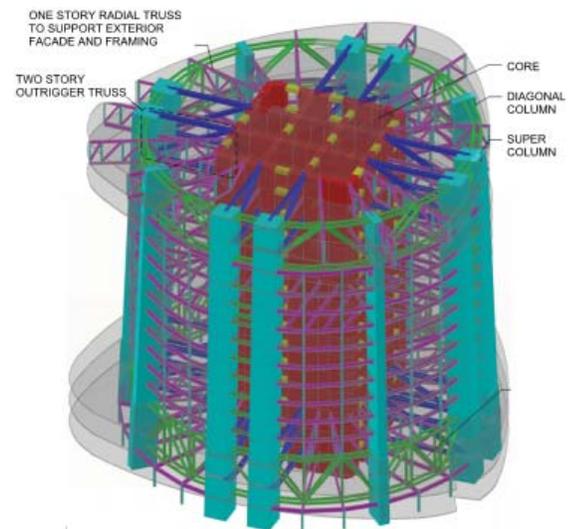


Figure 2. Lateral system for Shanghai Tower

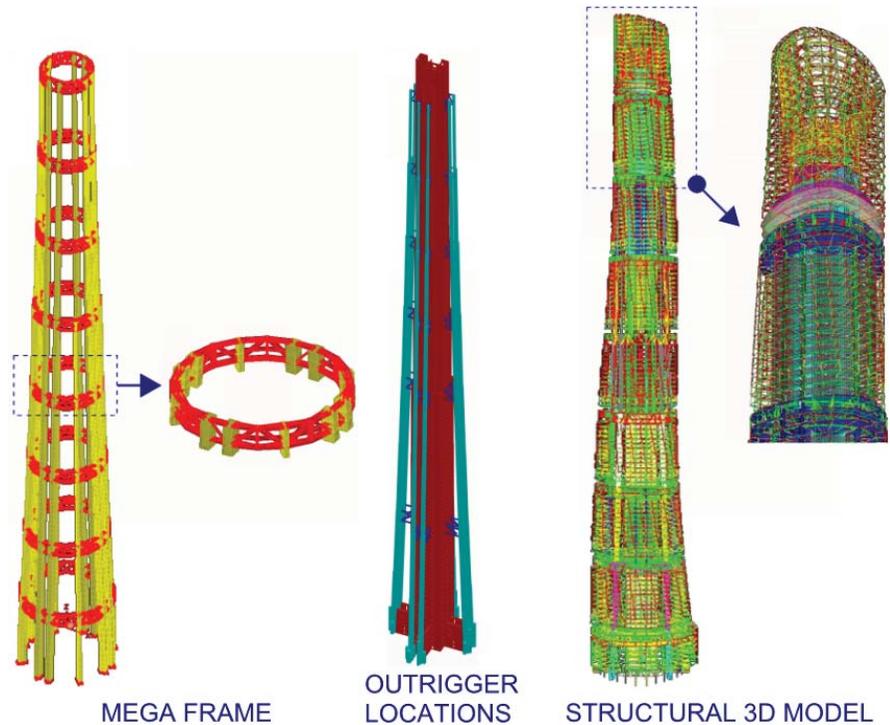


Figure 3. Exterior mega frame, outriggers and structural 3D model

This system is supplemented by a mega frame consisting of all the supercolumns, including the diagonal columns together with a double belt truss at each zone that picks up the intermediate steel columns in each zone and the mechanical and refuge floors (see Figure 3).

The core is concrete, the outrigger and belt trusses are structural steel, and the supercolumns are composite structure with concrete-encased steel vertical sections. The encased steel sections in the supercolumn are the key element to ensure the proper performance of the connections and thus the

performance of the structure. The structure was designed to meet the performance-based design (PBD) requirements as specified in the China Seismic Design Code (GB50011-2008). In order to do this, the non-linear (plastic) behavior of the members and connections had to be determined. This was accomplished via the three-dimensional, finite element program Abaqus, which not only modeled the encased steel element, but also the concrete encasement itself. In Abaqus, the concrete elements are modeled as shell elements and steel elements are modeled as beam elements. The China Code provides the post-elastic behavior of steel and concrete. Figure 4a shows the stress behavior of the concrete as specified by the China Code. Figure 4b provides a similar relationship for the steel.

At the building core, localized vertical steel members are used to facilitate the outrigger connections and a similar, three-dimensional finite element analysis was performed. From these finite element analyses using Abaqus, an M-P-θ (Moment, Axial force and rotational deformation) profile was created. Based on these profiles, using a performance-based program "Perform 3D" and Abaqus, the performance of the primary structure was developed using seismic time history graphs for a similar soil profile as that of the site.

The soil conditions in Shanghai are challenging seismically – defined in the China Building Code as type IV, which approaches the Class F classification in the IBC code. The resulting foundation for the tower consists of bore piles one meter in diameter and 52 to 56 meters long. In total, the tower is supported on a six-meter-deep mat supported by 947 bore piles. Seven sets of seismic time histories that matched Shanghai's soil profile and earthquake intensity were modeled. Table 1 represents the criteria for acceptance under the China Code.

From the performance-based design analysis, the following conclusions were reached.

- The average maximum drift ratio in either axis is less than 1/130. This meets the 1/100 limit specified in the China Building Code.
- The core wall stresses are elastic, except in limited areas. ↻

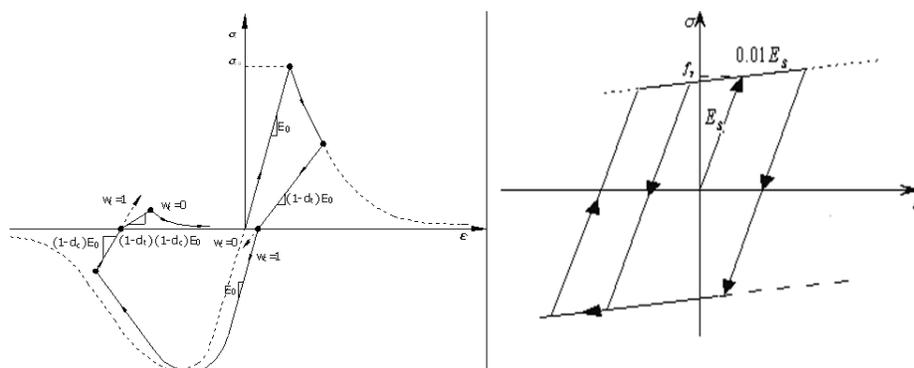


Figure 4a+b. Left: Concrete, Right: Steel

Seismic Hazard Level		Frequent Earthquake	Moderate Earthquake	Severe Earthquake
Return Period		50-year	475-year	2475-year
Performance level description		No damage or negligible damage	Little Damage, Repairable	Serious Damage, No Collapse
Structure Behavior Description		No damage, structure basically in elastic range	Allow minor damages, structure substantially retains original strength and stiffness	Allow serious damage, but no fracture of major connection joint; no shear fracture of super columns and core walls; no partial or global structure collapse;
Story drift ratio limit		h/500; h/2000 (bottom levels)	h/200	h/100
Member performance	Core wall	Elastic, Strength design per code: - factored seismic load - material design strength	Code-based strength design <u>At outrigger floors:</u> - factored seismic load - material design strength <u>At other floors:</u> - unfactored seismic load - material ultimate strength	Plastic hinge rotation: θ<IO at at bottom levels θ<LS at other levels Shear forces<= ultimate shear capacity
	Link beam		Allow plastic hinge; Code-based strength design	Plastic hinge rotation: θ<LS and <=0.02 rad
	Super column		Elastic, Code-based strength design - factored seismic load - material design strength	Plastic hinge rotation: θ<IO at bottom levels θ<LS at other levels Stress in reinf. f > fy but < fu
	Belt truss		Elastic, Code-based strength design - factored seismic load - material design strength	Elastic, steel stress f < fy
	Outrigger		Code-based strength design - unfactored seismic load - material ultimate strength	Plastic deformation: θ<LS and stress f < fu
	Critical Connections		Elastic, Strength design per code: - factored seismic load - material design strength	Special FEM analyses are required and stress f<= fy

Table 1. Performance Target and Acceptance Criteria

- Most core wall link beams exhibit fully plastic deformations, and plastic hinge rotations are still within the limit set for “Life Safety.”
- Most outrigger trusses and belt trusses are in the elastic range.
- Embedded steel elements in super-columns and core walls remained elastic.
- The Shanghai Center achieved the performance levels for “Life Safety” in the China Code.

The connections of the primary structure are critical to the tower’s design. Starting with the supercolumn connections to the outrigger and belt trusses, the emphasis was on continuity of forces (see Figure 5).

The main axis of the supercolumns has an embedded steel built-up section coincident with the axis of the outrigger to simplify the connection. In the orthonormal direction, the belt truss frames into the supercolumn at a slightly non-orthonormal direction due to being in the circumferential direction. In the steel section of the supercolumns, there are perpendicular cross ribs that align with belt trusses. Any slight deviation of the cross ribs with the axis of the belt trusses is resolved by stiffeners within the embedded steel section. A similar detail is used at the intersection of the core and the outrigger. At this location there is a small embedded vertical steel column at the intersection. This small steel column simplified the outrigger connection to the core. Continuity of core reinforcing was a paramount consideration. At the levels of the outriggers, tie plates coincident with the outrigger top and bottom chords pass through the core.

Curtain Wall

The tower has a unique design incorporating two independent curtain wall systems. The exterior skin is cam-shaped in plan, with rounded corners resembling a guitar pick, while the inner skin is circular. The spatial separation between the two skins creates flowing atria every 12 to 15 floors within each of the tower’s zones. To create these atria, a unique enclosure system was developed (see Figure 6).

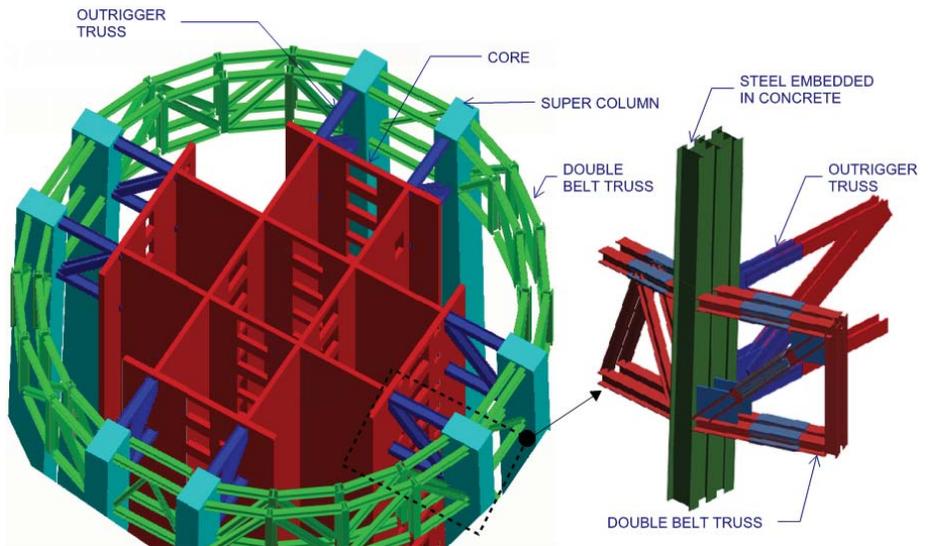


Figure 5. Mega frame for Shanghai Tower and outrigger detail

The outer, cam-shaped plan gradually reduces in size at each higher zone, giving the glass tower an elegant tapered profile. In addition, the cam-shaped plan twists around the inner cylindrical tower at each higher zone, creating the unique spiraling exterior façade that distinguishes the tower’s iconic form.

The outer curtain wall is created by a series of hoop rings that are cam-shaped and rotating

around the circumference of the inner cylindrical tower (see Figure 7). The hoop ring is held away from the cylindrical tower by struts (i.e., horizontal posts) to create the outer, cam-shaped plan. As the levels progress upward, the hoop ring shifts horizontal position around the inner cylinder by a set degree of rotation, creating the unique spiral shape of the tower’s outer façade. In addition, the cam-shaped hoop rings decrease in circumference incrementally as they rise up the tower. This creates the sweeping, tapered shape of the tower that accentuates its height.

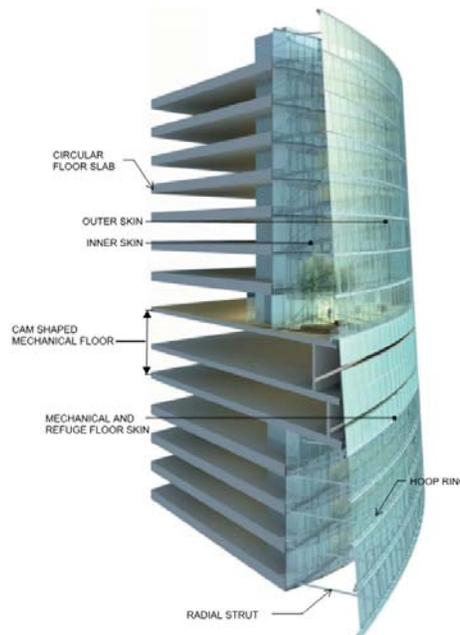


Figure 6. Typical zone section perspective view

Sustainable Technologies

Sustainable design is at the core of Shanghai Tower’s development. From the outset, the design team targeted a LEED Gold rating and a China 3 Star rating. This goal informed the design of the engineered systems by MEP engineers Cosentini Associates throughout the building.

The project features water treatment plants that recycle grey water and storm water for irrigation and toilet flushing. The system features water treatment plants within the tower, podium, and basement level to reduce pumping energy. Further, the domestic water system utilizes interim water storage tanks within the tower, allowing the water pressure

to be maintained by gravity. Low-pressure pumping energy is utilized only to transport the water to each tank in a cascading arrangement. These strategies will result in a 38% source-water consumption reduction.

For a tower of this size, the energy required for transporting energy is significant. The design concept of nine 12- to 15-story buildings stacked vertically is served by the engineered systems as nine separate buildings connected to a central utility infrastructure. The vertical city concept allows for a substantial reduction in transport energy. As designed, the building is estimated to save close to 20 million RMB or 21.59% in annual energy costs compared to the ASHRAE 90.1-2004 baseline.

There are two chiller plants in the building. The Low Zone Chiller Plant, located on the B2 level, consists of 27,000-Ton Hours of ice storage, a natural gas-fired cogeneration system, dual-duty ice making/chilled water chillers, and standard-duty water chillers. This chiller plant serves the facility up to the 65th floor. The High Zone Chiller plant is located on the 82nd and 83rd floor. This plant consists of six high-efficiency, centrifugal water chillers. Having two plants greatly reduces the transport energy required to pump chilled water throughout the facility. It also allows a substantial number of the project's cooling towers to be shifted from a location on grade to the tower roof, thus providing additional green space at ground level. This was a tremendous aid in reaching the 33% green space requirement of the Shanghai government.

The 2,200-kW natural gas-fired cogeneration system provides electricity and heat energy to the Low Zone areas. The system provides site-generated power while producing 640 Tons of refrigeration during the cooling season and heat during the brief winter months. Site-generated power has the advantage of reducing source energy consumption and the carbon footprint of the facility by utilizing clean-burning natural gas in lieu of high-sulfur coal.

The tower's HVAC system utilizes high-pressure steam generated in the Low Zone Central Plant to feed the heating and domestic water

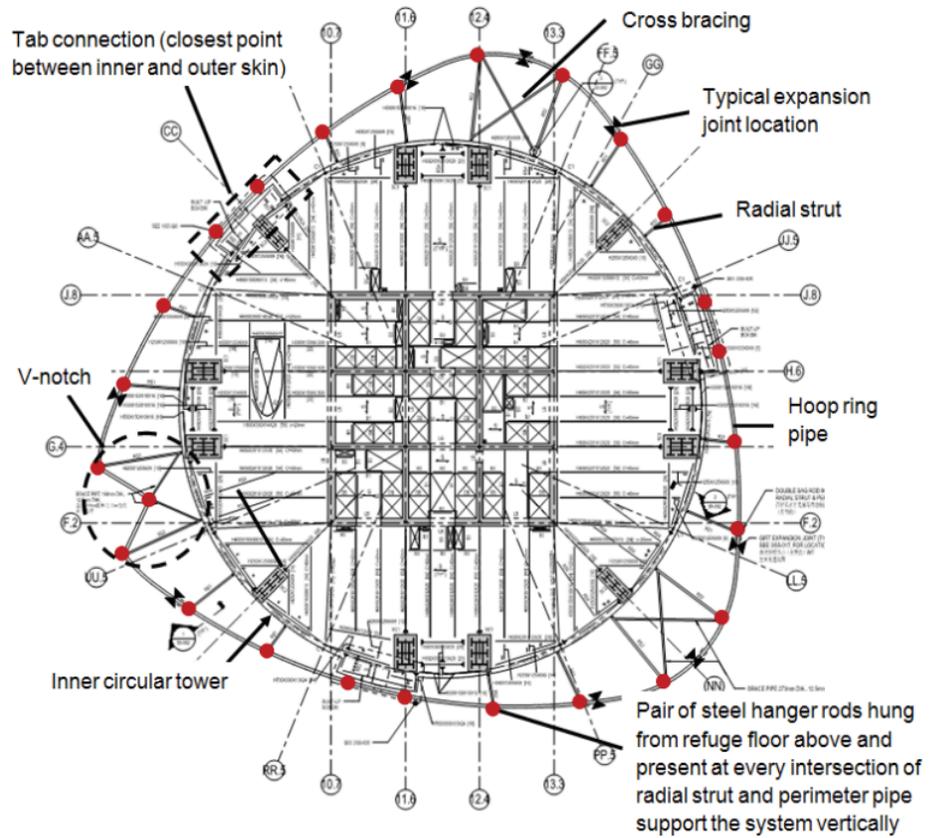
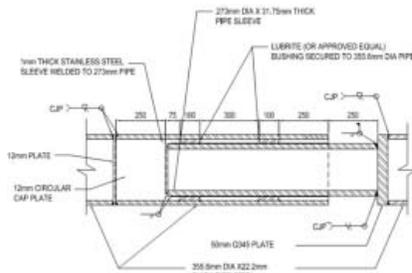
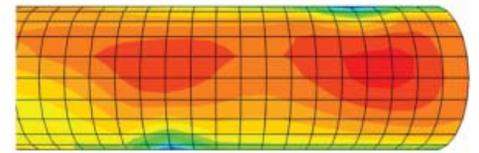


Figure 7. Typical structural floor plan



Curtain wall exterior girt expansion joint detail

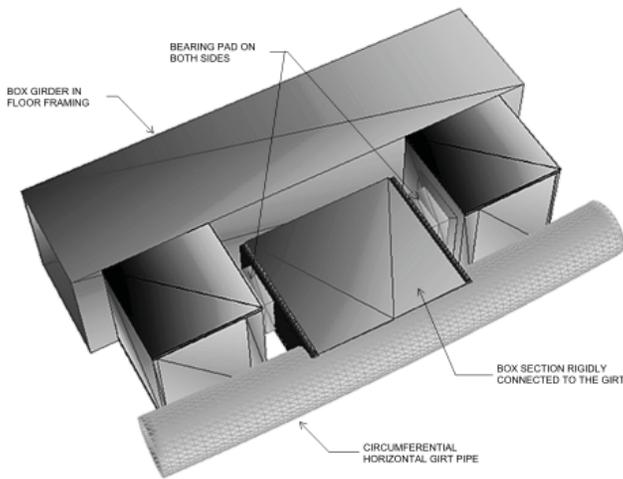


Finite element analysis of expansion joint detail

heating system. The steam system requires no pumping to deliver heat energy to the facility, thus reducing the transport energy.

Each vertical zone is served from mechanical floors above and below the occupied zone. These mechanical floors house the dedicated ventilation systems, electrical transformers, and water systems. Outdoor air is pre-conditioned, filtered, and measured before being supplied to the occupied zones. The ventilation systems

require very low pressure to move the air through the occupied zones, thereby reducing transport energy. Electrostatic filters on the outdoor air systems reduce fan motor horsepower and rotary heat exchangers between the outdoor air and exhaust air streams reduce the heating and cooling energy required to pre-condition the outdoor air. ↻



Curtain wall thrust block detail

The atria are utilized as “buffer zones” around the inner façade on the building. Used indoor air is spilled to each atrium before being exhausted from the building. The result during warm months is the temperature above the occupied level of the atrium is maintained below the ambient outdoor temperature, greatly reducing the cooling load requirements of the office, hotel, and observation zones. Similar advantages are realized during the winter, when the heating load is reduced.

The design of the tower’s two independent curtain walls works hand in hand with the mechanical systems by integrating shading strategies to reduce heating and cooling loads. Considering Shanghai’s relatively mild winters, the outermost curtain wall is designed as a non-thermally broken, aluminum extrusion system encasing 26 mm laminated low-iron glass with a spectrally selective low-E coating. With a solar load on the vertical external glass surface of 230 Btu/hr/ft², several other systems were employed to reduce glare and heat build-up. First is a fritted-glass surface designed to provide sun shading and lower shading coefficient values. Fritting covers 25% of the typical glass panel. In addition, at each floor level, the building geometry creates horizontal ledges extending outward up to 600mm and providing additional shading. Last, vertical aluminum mullions are reinforced with continuous, 350 mm-deep, glass fins that will refract significant amounts of daylight.

The innermost curtain wall is designed as a non-thermally broken, aluminum extrusion system encasing 30 mm insulated clear glass with a spectrally selective low-E coating. In this case, several strategies are employed for sun shading. Partial fritting is proposed on the vision glass from the floor level to chair rail height. Vertical, non-operable shading fins adjacent to the vertical mullion on the exterior of the insulated unit are being considered for possible

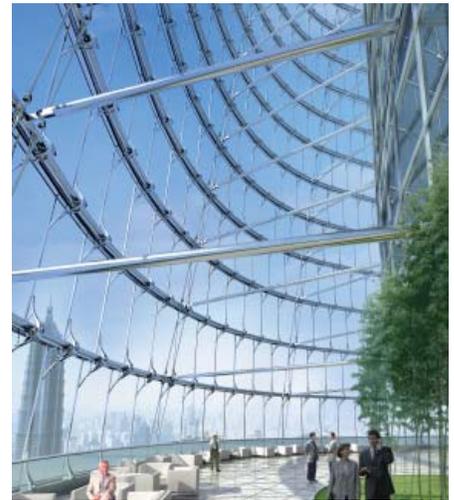
use. Finally, mechanically controlled, interior roller shades will be used.

The design will perform in the middle range for LEED Indoor Environmental Quality points. The HVAC system features outdoor air delivery monitoring, CO₂ monitoring and control, and tobacco smoke control. Operable windows and natural ventilations strategies for the tower were not adopted due to the height of the tower, weather conditions in Shanghai, and the poor quality of the outdoor air.

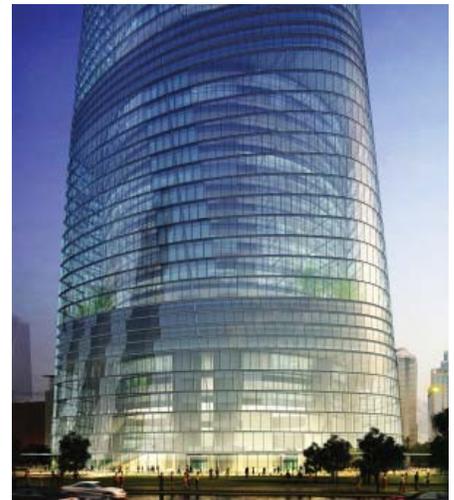
Conclusion

Shanghai Tower, which will anchor the city’s Lujiazui district as one of the world’s foremost commerce destinations, isn’t simply about a single high-rise building. It represents a new way of envisioning and creating cities, and it addresses the tremendous challenges that face designers of supertall buildings today. By incorporating cutting-edge sustainable design, by weaving the building into the urban fabric and drawing community life high into the tower, and by embodying design that is both compelling and high-performing, Shanghai Tower is defining the role of tall buildings for decades to come. ■

Editor’s Note: To further discuss this topic with the author, please join our CTBUH Skyscraper Group at <http://LinkedIn.ctbuh.org>



Atrium, Shanghai Tower



Tower Base, Shanghai Tower

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Letters to the Editor

The Council would like to hear your thoughts and opinions on the papers published in the Journal and CTBUH activities generally. Please send your letters to journal@ctbuh.org

CTBUH 2010 Mumbai Conference



Opening Session at the CTBUH 2010 Mumbai Conference

As the euphoria of CTBUH 2010 settles down, I'd like to take this opportunity to share with your readers my thoughts. First and foremost my kudos to both CTBUH and RoMF [Remaking of Mumbai Federation] for putting up one of the best ever events I have seen in India. I have seen the World Economic Forum (WEF) India Summits, the India Euro Money Conferences, Conferences sponsored by the World Bank/UN agencies et al; and (with the possible exception of the WEF), I must say that CTBUH ranked well ahead of various other mega events hosted in India. The experts that participated were envious; their content was brilliant and thought provoking. Every presentation that I saw was excellent in its relevance and delivery. It was indeed a show where diverse disciplines come together like artists in a choir. At this "choir" every note was right. The composition was an elegant harmony of various messages. And the fusion of different notes was at its collective best. CTBUH 2010 Mumbai for all times to come shall be an inspirational event. Take a bow!

But the job has just begun and that's the key purpose of this note. The messages of CTBUH on what India needs to do while addressing and implementing its drive in the Tall Buildings Habitat needs to be spread in India. RoMF will surely be the greatest beneficiary and the torch bearer in this regard. But we also need to take this message to other states/cities in India, to the policy makers in the concerned Central and State Ministries and the Planning Commission, to the many bureaucrats/technocrats/civic officials involved in this process, etc. Also, the large participation of US based design and build companies was a manifestation of their need to participate in India's urban development efforts. Their participation will hugely help as India needs their know-how and fill-in of the competency gaps within our local talent pool.

Clearly the way forward would be for the US based companies to collaborate with their Indian counterparts.

Anyway, congratulations again on a fantastic event and, hopefully, the start of something major for India. I am willing to provide you all my support!

Girish Bhagat
Euro India Centre and RICS India

Editor's Note: To find out more about the CTBUH 2010 Mumbai Conference, entitled *Remaking Sustainable Cities in the Vertical Age* visit: <http://ctbuh2010.ctbuh.org>

Bruce Graham Passing



The Council on Tall Buildings and Urban Habitat is saddened to learn of the recent passing of architect Bruce Graham, formerly with Skidmore Owings and Merrill LLP. His influence on the

Council's hometown of Chicago was profound; one cannot look upon the city skyline without seeing the influence of Graham's legacy. Once the tallest building in the world, Graham's Sears (now Willis) Tower still endures today as a hallmark of the Chicago skyline while holding the title of the tallest building in North America. Equally, Graham's Hancock Tower still holds its own as a lesson in not only structural efficiency, but elegant form and real mixed-use planning. In his time Bruce was an active member of the Council on Tall Buildings and Urban Habitat and served on the advisory board for much of the 1980's. Few architects have had such an influential career and impact on the design of tall buildings, and Bruce Graham's influence still reverberates today in the Council and its membership.

Council on Tall Buildings and Urban Habitat
Chicago, USA

...Barangaroo

“The Opera House sits on a pier which intrudes deep into the harbor. There are two large and long piers in Pyrmont that would face the proposed pier at Barangaroo. If all those piers were allowed to stay (for good), what is wrong if another one is added? The present scheme by Lord Rogers should be encouraged to proceed for its creativity, courage and design merit.”

John P. Mangraviti, C3D Design shares his thoughts on the proposed Barangaroo development. From "Pier pressure: architects divided on Barangaroo", The Sydney Morning Herald, March 10, 2010

Erratum CTBUH Journal 2010, Issue I

Page 12 included a Global News update on the Digital Media City tower in Seoul. The article incorrectly states the designer of the project. The Digital Media City tower was designed by *Skidmore, Owings & Merrill LLP*.

Page 37 of the article Structural Design of Reinforced Concrete Tall Buildings included the wrong image caption for Figure 9. The correct caption is: *Average weight vs. number of floors for steel framed tall buildings [5]*.

CTBUH Discussions

Editor's Note: Anyone active in the LinkedIn community and involved in the design, development, construction and management of skyscrapers is welcome to join The CTBUH Skyscrapers Group to start discussions to further discuss articles published in the Journal, please visit our CTBUH Skyscraper Group at <http://LinkedIn.ctbuh.org>