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Authors: Paul Katz, Principal, Kohn Pedersen Fox Associates
Leslie Robertson, Principal, Leslie E. Robertson Associates

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Case Study: Shanghai World Financial Center

From the onset of the Shanghai World Financial Center project, its developers targeted a cutting-edge, mixed use mega-complex that would serve a multitude of tenant lifestyle demands. When a desire to change the building size surfaced after the foundation was put in place, it was up to the structural designer to come up with a new approach to the building systems in order to keep the project on track. Following a substantial and fast-paced reconfiguration of the building's structural design, the project team achieved a taller building without compromising the capability of the original foundation to support it. A discussion of the design process of the building and its cutting edge features follows.



Paul Katz



Leslie E. Robertson

Authors

¹Paul Katz, FAIA

²Leslie Earl Robertson, NAE, Dist.M.ASCE, F.IStructE, CE, PE, SE,

²SawTeen See, Dist.M.ASCE, CE, PE

¹Kohn Pedersen Fox Associates

111 West 57th Street

New York, NY 10019

t: +1 212 977 6500

f: +1 212 956 2526

e: info@kpf.com

²Leslie E. Robertson Associates

30 Broad Street, 47th Floor

New York, NY 10004

t: +1 212 750 9000

f: +1 212 750 2002

e: info@lera.com

Paul Katz, *Principal*

Paul Katz, Managing Principal with Kohn Pedersen Fox, is a leader in the planning, design, and development of office, mixed-use and high-rise buildings. In addition to the Shanghai World Financial Center, Mr. Katz presently has several projects in design or construction around the world, including the KPMG headquarters at Canary Wharf in London, the Marina Bay Business and Financial Centre in Singapore, and the International Commerce Center in Hong Kong.

Leslie E. Robertson, *Principal*

Responsible for the structural design and construction of some of the world's tallest buildings, Leslie E. Robertson has been at the forefront of structural engineering design for more than 50 years. In addition to the Shanghai World Financial Center, Dr. Robertson is responsible for the structural design of the World Trade Center in New York, the Puerta de Europa Towers in Madrid, and the award-winning Miho Museum Bridge in Shigaraki, Japan.



Figure 1. Shanghai World Financial Center nearing completion.

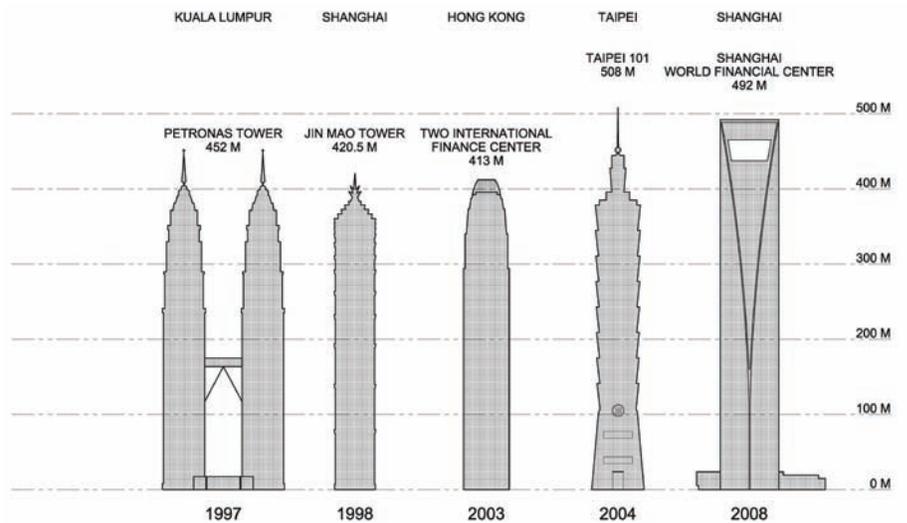


Figure 2. Shanghai World Financial Center in comparison with some of the world's current tallest buildings.

1. Introduction

Strategically located in the heart of Pudong's Lujiazui district, an area that has emerged as China's commercial and financial capital, the 492 meter Shanghai World Financial Center (SWFC) is destined to become a symbolic icon of Shanghai. This 21st century vertical city will symbolize Shanghai's status, China's arrival, and a new era unfolding in Asia. It will become a destination where people from around the world come together to enjoy and to share a wealth of information, knowledge, and culture, as well as a place to explore new business opportunities.

In an effort to reduce commuting time and urban sprawl, projects like SWFC increase density and conserve valuable land. People can live, work, and play within the same area. Vertical complexes can accommodate these urban lifestyles, embodying a density that greatly enhances their accessibility.

Now nearing completion, the structure was topped-out in September 2007 (see Figure 1). Anticipated to be completed in summer 2008, it will be recognized by the CTBUH as the world's tallest in two of its four categories; as the "Highest Occupied Floor" and "Top of Roof" (see Figure 2).

The tower's basic form is that of a square prism, 58 meters on a side, intersected by two sweeping arcs to form a vertically-evolving six-sided shape in plan, ultimately tapering into a

single diagonal line at the apex, 492 meters above the base.

The building will be mixed-use, with a museum and sophisticated urban retail spaces at the base, a 174-room luxurious five-star hotel at the top, and sixty-two office floors with cutting-edge specifications between. Above the hotel, at the 94th to 101st levels, there will be a visitor's center and observatory. Much of the available space on the three floors below grade is devoted to mechanized parking.

According to the developer, Mori Building Company, the anticipated tenants are world-renowned financial institutions. In order to provide these business people with entertainment and recreation opportunities after working long hours, this project will include restaurants, shops, and entertainment facilities. Currently, this area of Lujiazui does not provide these amenities. A multi-use project like SWFC will provide a more human-oriented place for people working in this city within a city'.

2. History

2.1 Early History

The original designs began in 1993, with development by Mori Building Company, and with Kohn Pedersen Fox Associates (KPF) as the Design Architect. Following the completion of conceptual structural designs by Ove Arup &

Partners, New York, all design work, but for Architecture, then moved to Tokyo to be completed locally by the Shimizu Corporation.

By 1995, the piling had been tendered and installed. Making use of reusable followers, about two hundred concrete-filled steel pipe friction piles were driven at minimum spacing to a depth of 78 meters from the ground surface. Pile cut-off was at the anticipated bottom elevation of the mat at 17.5 meters (58 feet) below street level. Steel H-piles extend from some of the piling to the ground surface, which were to be used for subsequent top-down construction, providing temporary vertical support for the below-grade concrete floors.

Whilst the construction documents package for the tower superstructure was largely complete by this time, Leslie E. Robertson Associates R.L.L.P. (LERA) was approached by Nippon Steel Corp. with the goal of providing a lower-cost, faster-to-construct structural system for adoption prior to tendering of the structural steel. Structural designs were completed by LERA in sufficient detail for tendering; however the project was subsequently placed on hold.

With the resurrection of the project in 1999, and with the foundation piling already in place, Mori Building Company initiated an extension to the overall height of the building from the previous 460 meters (1,509 feet) to 492 meters (1,614 feet) and an enlargement ↗

of the base dimension had been increased from 55.8 meters (183 feet) to 58.0 meters (190 feet) square. The exterior appearance of the proposed building remained essentially unchanged in subsequent design iterations.

In order to address the looming challenge of building a taller tower atop an existing piled foundation sized for the previous design, Mori Building Company approached LERA seeking an alternative design to that contained in the preexisting construction documents. In part because the pile cut-off was well below grade and in part due to non-engineering considerations, the cost of reinforcing the existing piling was high. LERA determined that the installed pile foundation could accept a larger building, but only by decreasing by more than 10 % the weight of the original building and by re-distributing the loads to the piling so as to accept the increased lateral loads from wind and earthquake.

2.2 Development of a New Structural System

In order to decrease the weight of the building, the majority of that decrease had to be found in a reduction of the thickness of the concrete shear walls of the services core. This reduction was achieved by decreasing the wind and earthquake-induced lateral forces resisted by those walls. That decrease was found by significantly increasing the stiffness of the lateral force resisting system of the perimeter wall and by decreasing the stiffness of the concrete walls of the services core.

Accordingly, abandoning the Developer's original design which included perimeter framing elements (that of a Vierendeel moment-resisting space frame), LERA instead proposed the resurrection of its 1995 design: a diagonal-braced frame with added outrigger trusses. KPF, LERA, and Mori Building Company worked closely together to incorporate this new structural system into the existing architectural form. The change enabled a decrease in the thickness of the services core shear walls as well as a decrease in the weight of structural steel in the perimeter walls. Further, by making use of outrigger trusses coupled to the columns of the mega-structure, a further reduction was realized.

3 Innovative Building Features and Notable Design Considerations

3.1 The Mega-Structure

The Mega-Structure concept is shown in Figures 3 and 4 (both Figures omit intermediate floors). To resist the forces from typhoon (hurricane) winds and earthquakes, three parallel and interacting structural systems were introduced:

- The mega-structure, consisting of the major structural columns, the diagonals, and the belt trusses.
- The concrete shear walls of the services core.
- As created by the outrigger trusses, the interaction between these concrete walls and the mega-columns (see Figure 5).

Driven by the architectural form and by the limitations of the existing foundation piling, the new structural system reduced the cost of the structure and provided for speedier construction. KPF was able to capitalize on the presence of the outrigger trusses by incorporating them into the architectural design of the sky lobby floors.

Seeking to improve the quality of office spaces located on each of the four orthogonal faces, the new structural system decreased the perimeter framing from the seventeen wide columns of the moment-resisting frame to a maximum of just three narrow columns. Depending on the breadth of the two sloping faces, there is at most only one narrow column along its width. Hence, building occupants will be provided an extraordinary sense of openness and unparalleled views of the surrounding city of Shanghai.

The mega-structure is displayed subtly behind the facade of the building. Architecturally founded on a heavy stone base, the mega-structure gives the impression of both strength and of permanence. Indeed, it is one of the goals of both KPF and Mori Building Company to communicate these two attributes while retaining the elegance of the architectural form.



Figures 3 & 4. Model showing the building's mega-structure system of mega-columns, diagonals and belt trusses along with concrete core walls and outrigger trusses.

3.1.1 The Diagonals of the Mega-Structure

Turning more to the engineering detail, as shown in Figure 6 the diagonals of the mega-structure are formed from welded boxes of structural steel. These steel boxes are in-filled with concrete, thus providing increased stiffness, non-linear structural behavior, and structural damping. The advantages of concrete infill are likewise used in the upper reaches of the building where it is used to enhance shear stud connectors and stabilize against buckling of the thin steel plates comprising the diagonals.

3.1.2 The Columns of the Mega-Structure

The columns of the mega-structure are of mixed structural steel and reinforced concrete. At the connection of the mega-diagonals to the columns (see Figure 7), the steel columns must be of a size capable of fully transferring the vertical component of the load in the diagonals to the composite columns. Above and below this connection, the size of the steel column is reduced. Away from the area where the steel columns transfer loads to the surrounding concrete, the steel columns need only be strong enough to carry the construction load of the steelwork above and to meet specific requirements the building codes that govern and guide tall building design in China.

As shown in Figure 8, in the lower reaches of the building the composite columns are of impressive size. Reinforcing steel must necessarily be 50 mm (2 inches) in diameter, the largest size available, and bundled into sets of four bars each.

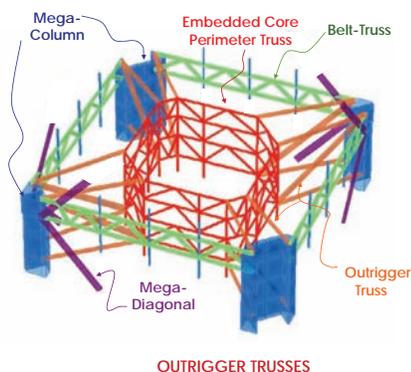


Figure 5. Outrigger trusses tie columns, diagonals and belt trusses to the concrete shear walls of the service core.

3.2 Robustness and Redundancy

In keeping with the underlying philosophy of all of LERA's designs, and as demonstrated by the robustness of the World Trade Center, New York, the structural system is designed to accept the simultaneous loss of a multitude of structural elements.

For example, at any level the small perimeter columns are able to be accidentally removed without the disproportionate collapse of the surrounding construction. Further, members of a perimeter belt truss can be removed without disproportionate collapse. Similarly, accidental removal can be accepted for the steelwork within the services core.

3.3 Lateral Forces and Wind Engineering

For any very tall building, the magnitude of the imposed lateral loads is the primary determinant in the selection and the proportioning of a suitable structural system. A detailed analysis of the wind climate for Shanghai was completed. Further, a four-phase program of wind tunnel testing was completed at the Alan G. Davenport Wind Engineering Group that included:

- Force balance test for structural loads (structure strength) and dynamic response (human comfort);
- Pressure test for the development of steady-state and the dynamic pressures and suctions on the façade (for the design of the façade);
- Environmental test (for windiness in the streets and courtyards); and
- Aeroelastic test for structural loads and dynamic response.



Figure 6. The diagonals of the mega-structure, formed from welded boxes of structural steel.

3.4 Earthquake Engineering

Because of the unusual nature of the structural system, considerable attention was given to the performance of the building under seismic loading. The required analyses included Dynamic Response Spectrum Analyses, Time History Analyses (accomplished for six histories), and Nonlinear Static Pushover Analyses. As can be seen from Figure 9, the structure was designed to remain in the elastic mode throughout the life of the building. Being outside of the scope of the building regulations of the People's Republic of China, aided by the thoughtful input from seismic experts from many regions of China, the design procedures were in keeping with much of United States practice.

3.5 Safety Measures

In a high-rise like SWFC, safety is a major concern. Evacuation floors are located at every twelve floors in the event of emergency. Seniors and disabled persons can be guided to these protected areas and await the arrival of emergency personnel. Normally, elevators are not used in times of emergency. However, Mori is negotiating with the government to find a way of using an emergency power supply for evacuation by elevator.

3.6 Green Technology

At the time that this project was initiated, Green Technology was not mainstream. Currently, it is the guideline of choice. As the project is now advancing, SWFC will apply green technology to its interiors, such as ↗

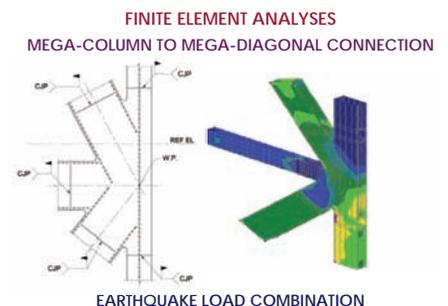


Figure 7. Finite element analysis of a mega-column to mega-diagonal connection.

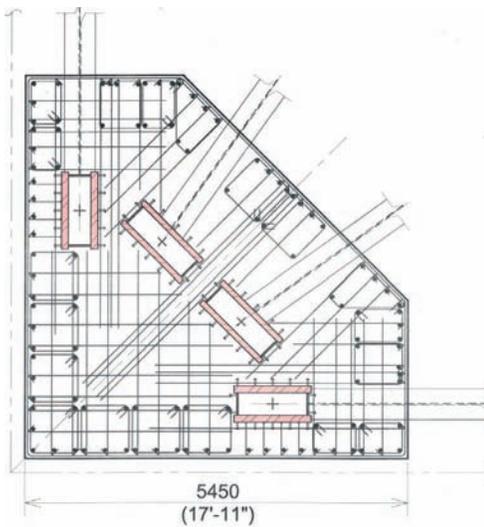


Figure 8. Plan of a corner mega-column.

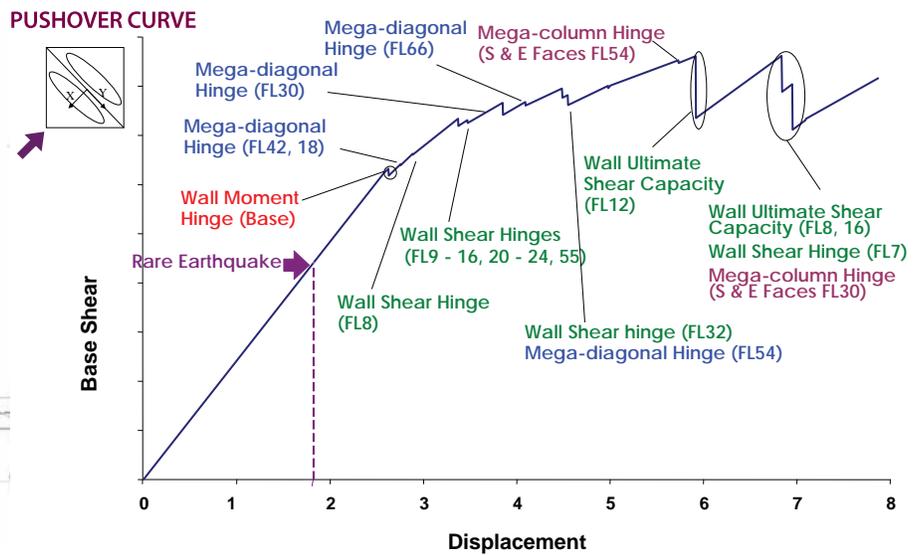


Figure 9. Pushover curve, showing the structure remaining in elastic mode throughout the life of the building.

formaldehyde-free carpet tiles throughout the entire building. A recycling system will be used by the tenants building-wide, along with education on how to become more recycling-conscious. Mori is also negotiating with the government for the provision of a paper recycling plant. The HVAC system will be variable air volume. Each floor will contain multiple zones for tenant comfort along with high efficiency.

4.0 Concluding Thoughts

The Shanghai World Financial Center reflects the creativity and passion of many individuals, all with the common goal of providing a place in which people are encouraged to meet and

mingle, share ideas, and give birth to new knowledge, culture and values. Realization of this project will yield an urban venue: spaces and environments in which the future will be created. These values have been an integral part of the Shanghai World Financial Center development from its inception, however it was through the creative work of many within the design team that facilitated the necessary extension of the high-rise tower above a building foundation that had already been put in place. Success was reached through a substantial reconfiguration of the structural system, which provided the same level of safety, stiffness and redundancy but at greater weight efficiency. East China Architectural Design & Research Institute Co. Ltd. is the

architect and the engineer of record, and Mori Building Company provided detailed architectural assistance.

Special thanks need be given to Mr. Minoru Mori, who provided the vision for its construction; to Mr. William Pedersen who conceived this wonderful building, and to David Malott, Project Architect, both of whom represent KPF; and to the many talented and resourceful men and women of LERA.

To view a video presentation on the design and construction of the Shanghai World Financial Center as presented at the CTBUH 8th World Congress in Dubai by Leslie Robertson and David Mallot, please go to <http://blip.tv/file/1099810>



Shanghai Skyline, China with Shanghai World Financial Center, © KPF