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# Shanghai World Financial Center: Without Compromise……

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**Paul Katz**

Paul Katz, Managing Principal with Kohn Pedersen Fox, joined the firm 1984, focusing his work on the planning, design, and development of office, mixed-use and high rise buildings. He has senior responsibilities in all aspects of commercial architecture, including business development, management, and design. In addition, he has been instrumental in establishing KPF's presence in Japan, Hong Kong, and the firm's operations in Shanghai.

Presently, Mr. Katz has several projects in both design and construction phases including the KPMG headquarters at Canary Wharf, London, the Marina Bay Financial Centre in Singapore, the Shanghai World Financial Center, the International Commerce Center and the Landmark in Hong Kong.

Some of the hotel work that Mr. Katz's has been responsible for includes the award-winning Tokyo Grand Hyatt at Roppongi Hills, Mohegan Sun in Connecticut, and the Nagoya Marriott at JR Central Towers, the firm now has ten hotels in design and construction internationally such as the Conrad in Shanghai, and the Mandarin Orientals in Las Vegas and Macau.

Mr. Katz has degrees in architecture from both the Israel Institute of Technology and Princeton University, is a registered architect in New York, Delaware, Nevada and Connecticut, and is a member of several architectural boards.

**Leslie Robertson**

Amongst many other structures, Dr. Robertson is responsible for the structural design of the World Trade Center (New York), the United States Steel Headquarters (Pittsburgh), the Bank of China Tower (Hong Kong), and the Puerta de Europa (Madrid) as well as exceptional museums and the award-winning Miho Museum Bridge (Japan).

He is an Honorary Member of the American Society of Civil Engineers and has received the IStructE Gold Medal, the Gengo Matsui Prize as the outstanding Structural Engineer in the world, the AIA Institute Honor; and was recognized as ENR's Construction 'Man of the Year'. Dr. Robertson is a member of the National Academy of Engineering as well as an Honorary and Advisory Board Member of the Center of Sustainability, Accountability and Eco-Affordability for Large Structures. He has been awarded four honorary doctorates, currently is teaching at Princeton University, and is Distinguished Engineering Alumnus of the University of California, Berkeley. He received ASCE's Outstanding Projects and Leaders (OPAL) Award, AISC's J. Lloyd Kimbrough Award, Tokyo Society of Architects Honorary Fellowship and Medal, and is the first recipient of the Henry C. Turner Award and of the Fazlur Rahman Kahn Medal.

Dr. Robertson is currently working with I.M. Pei and the Pei Partnership on the Macao Science Center in Macao, China, and has completed designs for the Suzhou Museum in Suzhou, China and the Museum for Islamic Art in Doha, Qatar. He is also working with Kohn Pedersen Fox on the Shanghai World Financial Center, which will extend to a height of 492 meters (1614 feet). Additionally, Dr. Robertson is collaborating with Dynamic Architecture of Florence, Italy to develop prototypical designs for the Rotating Tower.

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**Abstract**
Located in the Lujiazui district of Pudong, the Shanghai World Financial Center combines creative architecture and structural engineering to create a mixed-use building 492 meters in height. It will be recognized by the CTBUH as the world's tallest in two of its four categories when completed in April 2008; as the "Highest Occupied Floor" and "Top of Roof".

**Keywords**: Shanghai World Financial Center

## Introduction

Strategically located in the heart of Pudong's Lujiazui district, an area that has emerged as China's commercial and financial capital, the extraordinary 492-meter Shanghai World Financial Center 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 business opportunities.

Now nearing completion, the structure was topped-out in September 2007 (See *Figure 1*.). Anticipated to be completed in April 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, 58meters on a side, intersected by two sweeping arcs to form an ever-changing six-sided shape in plan, ultimately tapering into a single diagonal line at the apex, 492meters above the base.

The building will be mixed-use, with a museum and sophisticated urban retail spaces at the base, a 300-room luxurious five-star hotel at the top, and seventy 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 three floors below grade is devoted to mechanized parking.

Figure 1. Shanghai World Financial Center nearing completion.

## A Bit of History

The original designs began in 1993, with development by Mori Building Company, and with Kohn Pedersen Fox Associates (KPF) as the Design Architect.

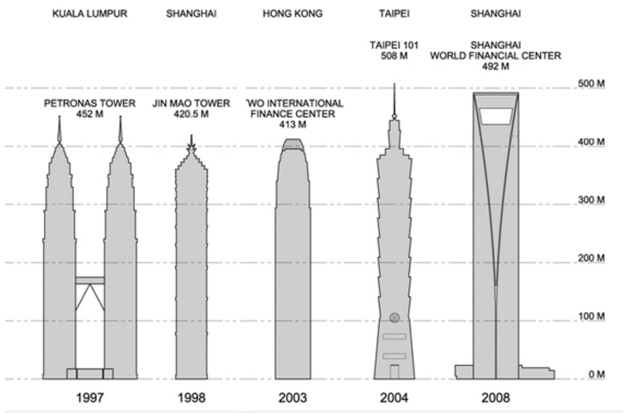



Figure 2. Shanghai World Financial Center in comparison with some of the world's current tallest buildings.

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 by Shimizu Corporation.

By 1995, the piling had been tendered and installed, and the structural package had been completed. In preparation for tendering of structural steel, 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. Structural designs were completed by LERA in sufficient detail for tendering; however the project then went on hold.

In 1999, with KPF remaining as Design Architect, and with the foundation piling in place, the height of the building had been increased from 460meters (1,509feet) to 492meters (1,614feet) and the base dimension had been increased from 55.8meters (183feet) to 58.0meters (190feet). The exterior appearance of the proposed building remained essentially unchanged.

Making use of reusable followers, about two hundred concrete-filled steel pipe friction piles at minimum spacing (under the tower to a length of 78meters), had been driven from the ground surface. Pile cut-off was at the anticipated bottom elevation of the mat [-17.5meters (-58feet)]. To be used later for top-down construction, providing temporary vertical support for the below-grade concrete floors, steel H-piles extended from some of the piling to the ground surface.

With the re-birth of the project, Mori Building Company approached LERA seeking an alternative design to that contained in the original 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.

**The New Structural System**

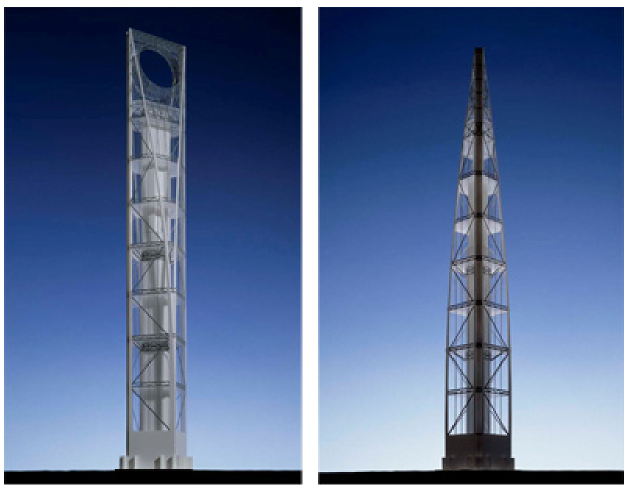
In order to decrease the weight of the building, the majority of that decrease had to be found in a reduction of the thickness of the concrete shear walls of the services core. This reduction was achieved by decreasing the wind and earthquake-induced lateral forces resisted by those walls. That decrease 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 for the perimeter framing (that of a Vierendeel moment-resisting space frame), LERA 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.

**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:

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



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.

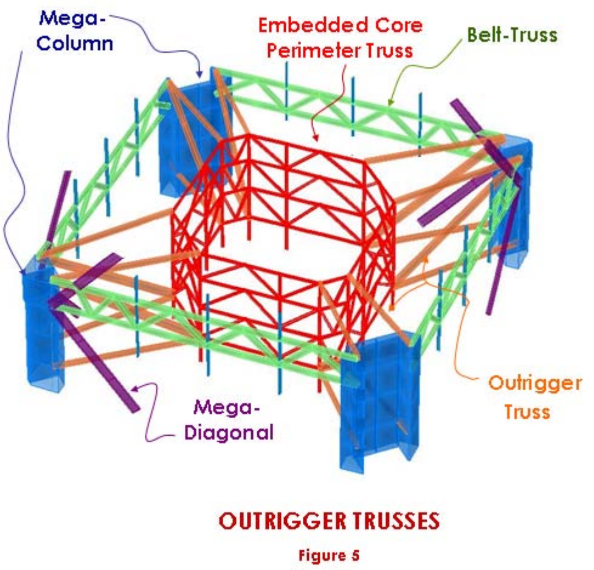



Figure 5. Outrigger trusses tie columns, diagonals and belt trusses to the concrete shear walls of the service core.

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

Driven by the beauty of the architecture 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 skylobby floors.

Seeking to improve the quality of the office spaces, 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, for the two sloping faces, there are either none or 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 wonderful elegance of the architectural form.

**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 of welded boxes of structural steel. These steel boxes are in-filled with concrete, thus providing increased stiffness, non-linear structural behavior, and structural damping. As well, in the upper reaches of the building, enhanced with stud shear connectors, the concrete is used to stabilize against buckling the thin steel plates of the diagonals.

**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 of the Building Codes.

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

**Robustness and Redundancy**

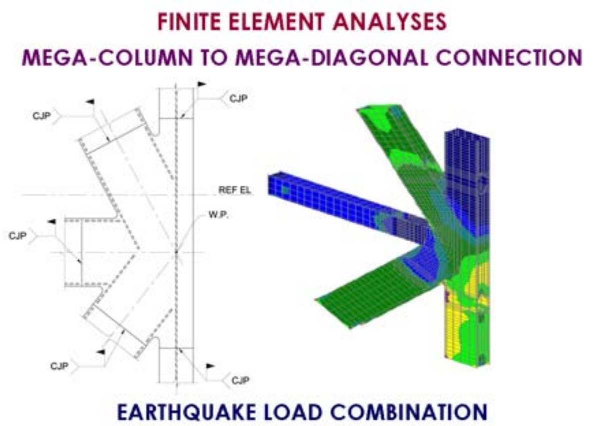



Figure 7. Finite element analysis of a mega-column to mega-diagonal connection.

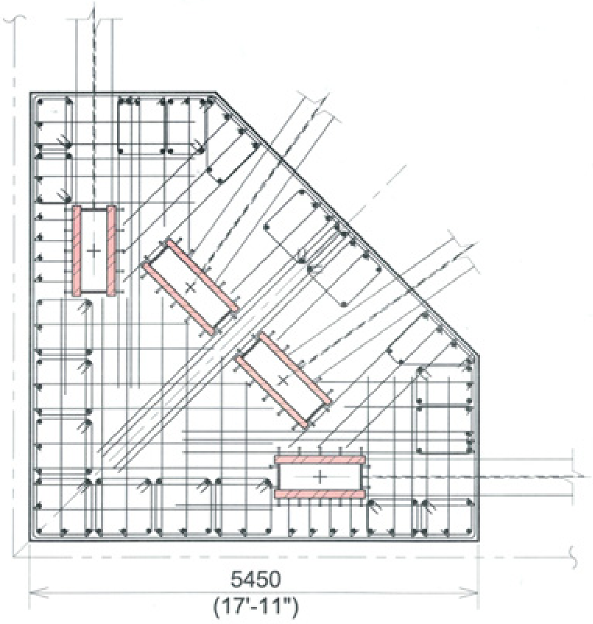



Figure 8. Plan of a corner mega-column.

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.

**Lateral Forces**

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.

**Wind Engineering**

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:

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

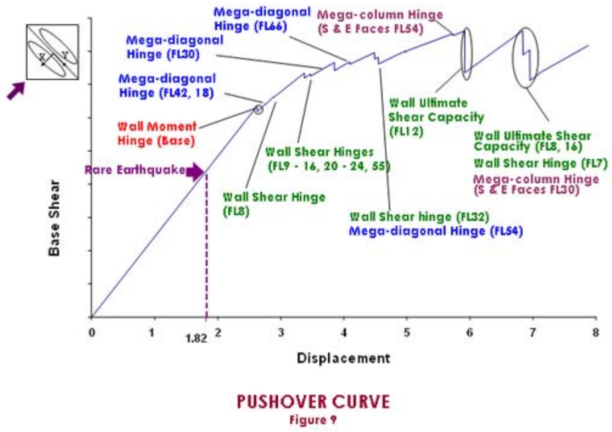



Figure 9. Pushover curve, showing the structure remaining in elastic mode throughout the life of the building.

**Earthquake Engineering**

Because of the unusual nature of the structural system, considerable attention was given to resistance to the moving earth. The required analyses included:

* Dynamic Response Spectrum Analyses
* Time History Analyses, accomplished for six histories.
* Non-Linear 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.

**A Concluding Thought**

The Shanghai World Financial is the fruit of 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...of providing an urban venue, spaces and environments, in which the future will be created.

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 KPF; and to the many talented and resourceful men and women of LERA.