The Shanghai World Financial Center

Welding Brilliant Architecture To Imaginative Engineering

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This is an extraordinary building, one that will attract the eye of all in Shanghai. Making use of a composite, steel and concrete mega-structure, the structural system is organized to respond to the beauty of the architecture while meeting extraordinary engineering challenges. While no two floors are identical, considerable repetition is found in the concrete walls and steel framing.

The building will be mixed-use, with a museum at the base, a hotel at the top, and office spaces in between. Above the hotel will be a visitor's center, while much of the area below grade will house mechanical parking.

History

With development by Mori Building Company and Kohn Pedersen Fox as the Architect, designs for the Shanghai World Financial Center began in New York in 1993. 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, Leslie E. Robertson Associates (LERA) were approached by Nippon Steel Corporation with the goal of providing a lower-cost, faster-to-construct structural system. LERA completed designs in sufficient detail for tendering; however, the project then went on hold.

In 1999, Mori Building approached us seeking an alternative design to that which we had prepared in 1995. With the foundation piling in place, the height of the building had been increased from 460 meters (1,509 feet) to 492 meters (1,614 feet), and the base dimension had been increased from 55.8 meters (183 feet) to 58.0 meters (190 feet). The overall exterior appearance of the proposed building remained nearly unchanged.

The decision to increase the size of the building resulted in an increase in gross area of approximately 15%, and an increase in overturning moment from wind forces of approximately 25%.

Making use of reusable followers, concrete-filled steel pipe friction piles at minimum spacing had been driven from the ground surface, with the top of piling at the anticipated bottom elevation of the mat [17.5 meters (-58 feet)]. Providing temporary support for the mat and below-grade concrete floors, for top-down construction, steel H-piles extended from some of the piling to the ground surface. In part because the pile cut-off was well below grade, the cost of reinforcing the existing piling was high. LERA determined that the installed pile foundation system could accept a larger building, only by decreasing the weight of the original building by more than 10% and by redistributing the loads to the piling so as to accept the increased lateral loads from wind and earthquake.

This project, anticipated to be one of the tallest buildings in the world, demanded a high-level of reliability in all aspects of the structural design (*Figure 1*).

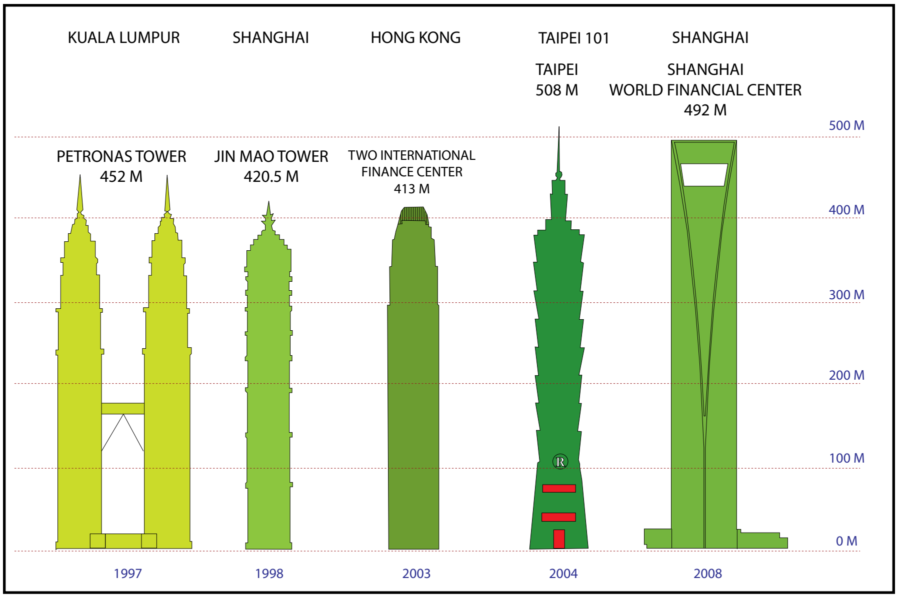

Figure 1: Diagram of Building Heights.

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 could be achieved only by decreasing the wind- and earthquake-induced lateral forces resisted by those walls. That decrease could be found only by increasing the stiffness of the lateral force resisting system of the perimeter wall.

Accordingly, abandoning the Developer's design for the perimeter framing (that of a Vierendeel moment-resisting space frame), LERA resurrected its 1995 design: a diagonal-braced frame with added outrigger trusses. This 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, an additional reduction was realized.

These conceptual changes made possible the ability to design an efficient and economical structural system while still responding to the constraints of the existing piling.

The Mega-Structure

The Mega-Structure concept is shown in *Figures 2* and *3* (both Figures omit intermediate floors). To resist the forces from typhoon (hurricane) winds and earthquakes, three parallel and interacting structural systems were incorporated:

1) The mega-structure, consisting of the major structural columns, the major diagonals, and the belt trusses.
2) The concrete walls of the services core.
3) The interaction between the concrete walls of the services core and the mega-columns, as created by the outrigger trusses.

Figure 2: Structural Model – Omitting Intermediate Floors. Courtesy of Jock Pottle.

The concept for the structural system reduced the cost of the structural system while responding to the essence of the architecture, as well as successfully responding to the limitations of the existing foundation piling. At the same time, the new structural system provided for speedier construction.

Seeking to improve the quality of the office spaces, on each of the four orthogonal faces, the new structural system decreases the perimeter framing from seventeen wide columns to just three narrow columns. Hence, building occupants will be provided an extraordinary sense of openness and unparalleled views of the surrounding city of Shanghai.

By adjusting the stiffness of the perimeter mega-structure and the outrigger trusses, both the shears and the overturning moments resisted by the concrete walls of the services core can be either increased or decreased. In this way, the weight of the services core is subject to control by the structural engineer. The design both controlled the thickness of the services core concrete walls and optimized the design of the outrigger trusses.

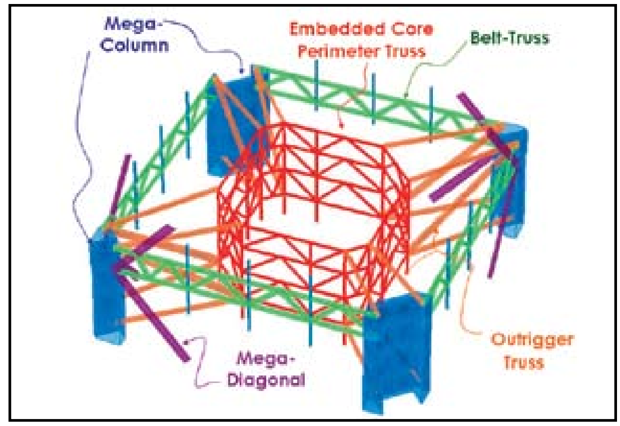

Figure 3: Outrigger Trusses.

The mega-structure is only subtly displayed behind the windows 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 Mori Building Company to communicate these two attributes, while displaying the wonderful elegance of the building form.

The Diagonals of the Mega-Structure

Turning more to the engineering detail, as shown in *Figure 4*, 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 and enhanced with stud shear connectors, the concrete is used to stabilize against buckling the thin steel plates of the diagonals.

Only the side plates of the steel box diagonals are connected at the space-frame nodes. In this way, complex, three-dimensional connections are avoided. The detail is depicted in *Figure 5 (see page 34)*. Also, the structural systems of most very tall buildings are driven more by the performance aspects of the structure than by the need for strength. The simplification associated with connecting only the side plates in the vertical plane more than compensates for the very modest loss in tensile strength; there is no loss in compressive strength.

Figure 4: Mega Column/Mega Diagonal.

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, the steel column 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 column transfers load to the surrounding concrete, the steel column only

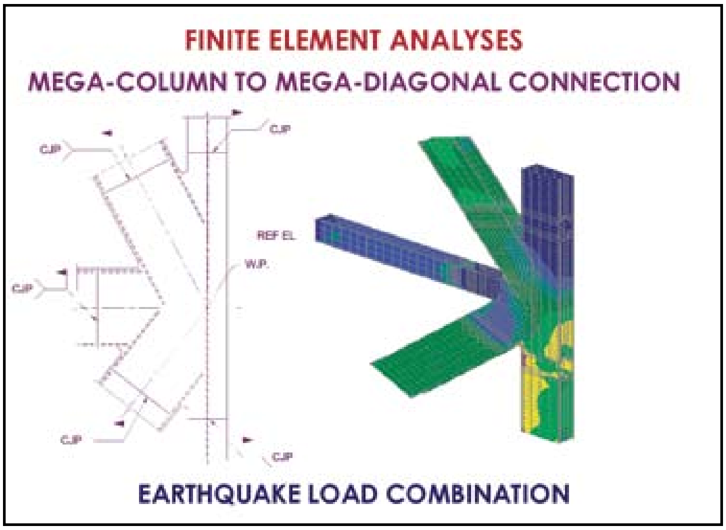

Figure 5: Finite Element Analyses.

needs to be strong enough to carry the construction load of the steelwork above.

As shown in *Figure 6*, in the lower reaches of the building the composite columns are of impressive size. Reinforcing steel must necessarily be 50mm (2 inches) in diameter, the largest size available, and bundled into sets of four bars.

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.

Lateral Forces

The lateral-load resisting system is the primary determinant in the selection and the proportioning of a suitable structural system for any very tall building.

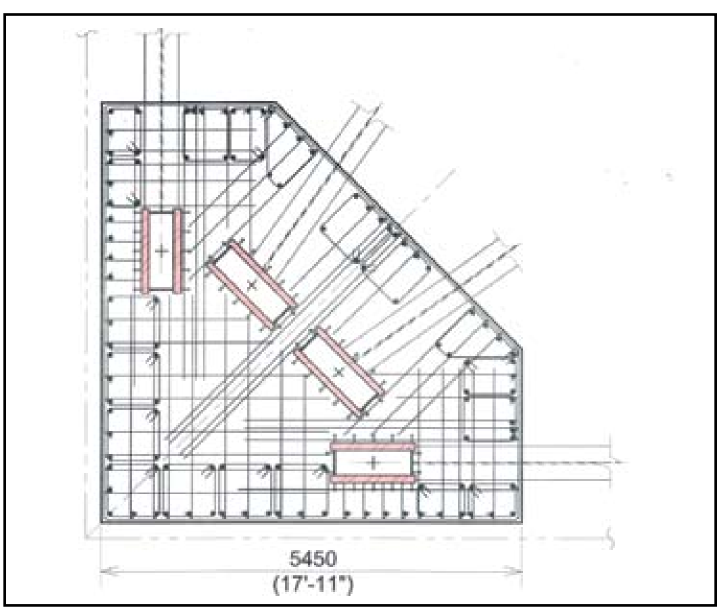

Figure 6: Mega Column at Base.

Wind Engineering

It is not uncommon for the gradient wind speed stipulated by the Building Code to be deliberately and properly conservative. These wind speeds, with their resulting loads and pressures, are used for those projects wherein detailed wind engineering evaluations are not accomplished.

For this project, a detailed analysis of the wind climate for Shanghai was completed, as well as a report examining the relationship between the reliability of a supplementary damping system and the design wind speed.

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.

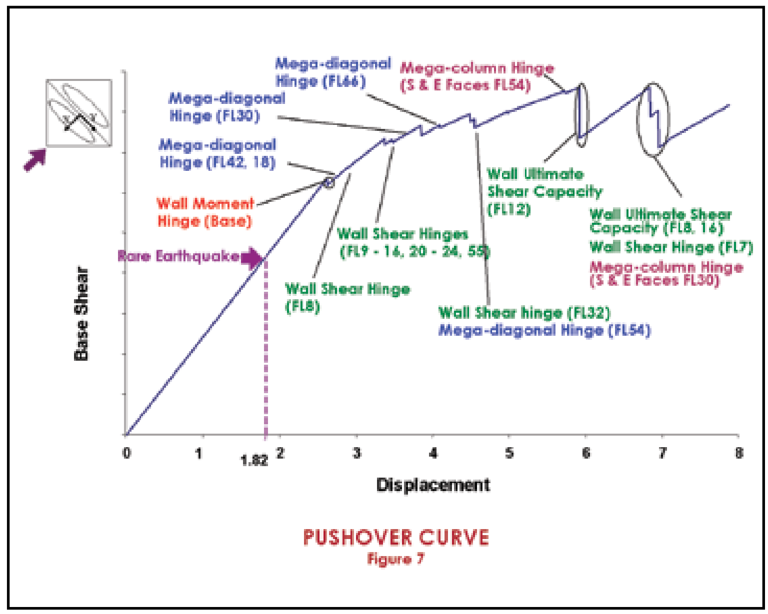

Figure 7: Pushover Curve.

Further, a study was completed examining the relationship between the reliability of a supplementary damping system and the design wind speed. The conclusion of the study was that a properly designed damper may be considered as 100% reliable to reduce the strength of the structure required for wind loading. However, based on the superior structural characteristics of the design, it was concluded that a damper was not required.

Earthquake Engineering

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

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

As can be seen from *Figure 7*, the structure is designed to remain in the elastic mode throughout the life of the building. The design procedures followed, being outside of the scope of the building regulations of the People's Republic of China, was in keeping with much of United States practice, aided by the thoughtful input of the seismic experts from many regions of China.

Shanghai World Financial Center. Courtesy of Kohn Pedersen Fox.

Optimization

Recognizing that there are two basic materials (reinforced concrete and structural steel), adding considerations of the speed of construction, and recognizing that structural detail is perhaps more important than are structural quantities, the optimization of this structure relies in part on experience and in part on judgment. The determination of the proper distributions of lateral shear and overturning moment between these three parallel systems, then, is not subject to precise analysis.

Concluding Thoughts

For this project, there is another primary goal of particular significance: that of preserving the grace, dignity and beauty of the architectural design...all as conceived by the Architects.

Special thanks need be given to Messrs William Pedersen, Paul Katz, and David Malott of Kohn Pedersen Fox Associates, who conceived this wonderful building; to Mr. Minoru Mori, who provided the vision for its construction; and to the talented and resourceful men and women of LERA.▪

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