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Unique Structural Engineering Solutions for China's Tallest Building

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Summary

The site for the Jin Mao Tower located in new Pudong development district of Shanghai, The People's Republic of China, is not naturally conducive to accepting a tall building structure, especially China's tallest. Soil conditions are very poor since the site is located in the flood plain of the Yangtze River, the permanent water table is just below grade, typhoon winds exist, and moderate earthquakes are possible. Unique structural engineering solutions were incorporated into the design with the combined use of structural steel and reinforced concrete; solutions which not only overcame the adverse site conditions but also produced a very efficient structure for this ultra-tall building.

1. The Structural System

The superstructure for the 421 meter-tall, 88-story Jin Mao Tower consists of a mixed use of structural steel and reinforced concrete with major structural members composed of both structural steel and reinforced concrete (composite). Thirty-six (36) stories of hotel spaces exist over 52 stories of office space. The structure is being developed by the China Shanghai Foreign Trade Co., Ltd. and constructed by the Shanghai Jin Mao Contractors, a consortium of the Shanghai Construction Group; Obayashi Corp., Toyko: Campenon Bernard SGE, France; and Chevalier, Hong Kong. The structure was topped-out in August 1997 with an expected overall completion date of August 1998. The structure is the tallest in China and the third tallest in the world behind the Petronas Towers in Kuala Lumpur, Malaysia and the Sears Tower in Chicago, Illinois, USA.

The primary components of the lateral system for this slender Tower, with an overall aspect ratio of 7:1 to the top occupied floor and an overall aspect ratio of 8:1 to the top of the spire, include a central reinforced concrete core wall linked to exterior composite mega-columns by structural steel outrigger trusses. The central core wall houses the primary building service functions, including elevators, mechanical fan rooms for HVAC services, and washrooms. The octagon-shaped core is nominally 27 m deep with flanges varying in thickness from 850 mm at the top of foundations to 450 mm at Level 87 with concrete strength varying from C60 to C40. Four (4) - 450 mm thick interconnecting core web walls exist throughout the office levels with no web walls on the hotel levels, creating an atrium with a total height of 205 m which leads into the spire. The composite mega-columns vary in cross-section from 1500 mm x 5000 mm at the top of foundations to 1000 mm x 3500 mm at Level 87. Concrete strengths vary from C60 at the lowest floors to C40 at the highest floors.

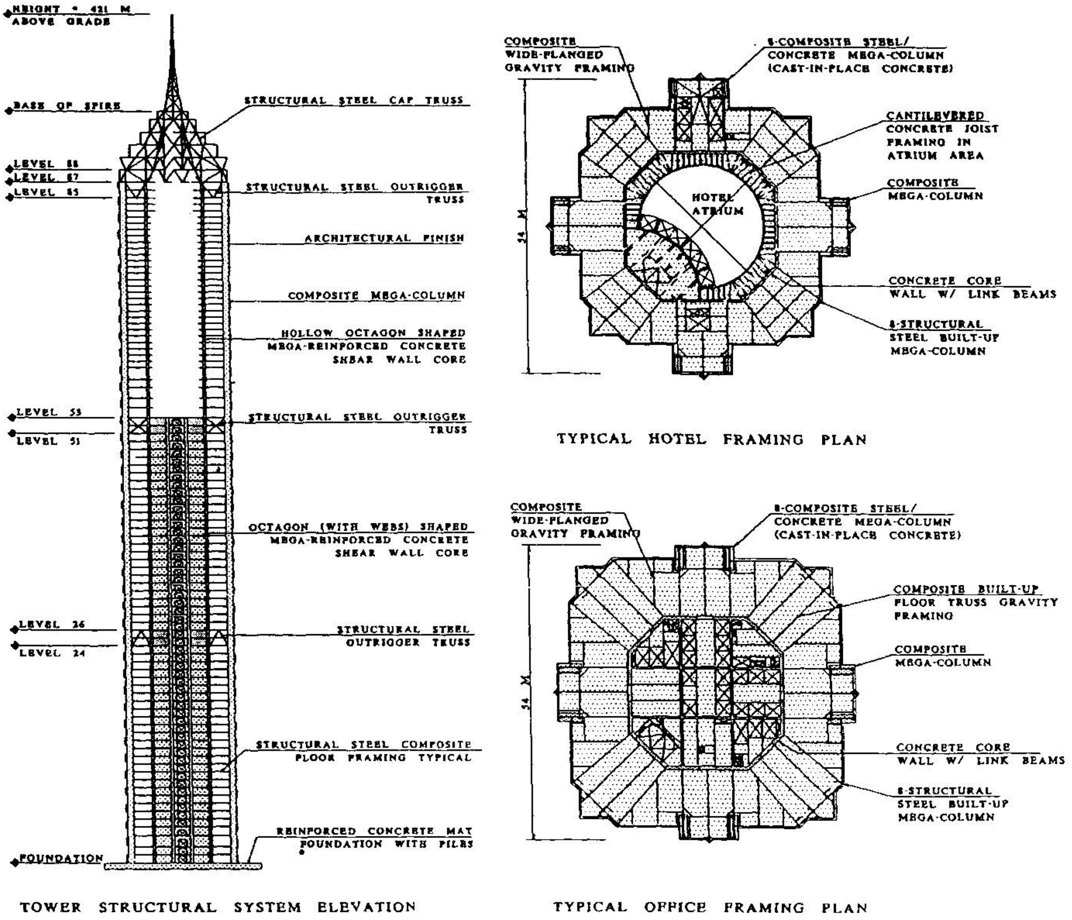

Figure 1 - Structural System Elevation and Framing Plans

Structural steel outrigger trusses interconnect the central core and the composite mega-columns at three 2-story tall levels. The interconnection occurs between Levels 24 & 26, Levels 51 & 53, and Levels 85 & 87. The outrigger trusses between Levels 85 & 87 engage the 3-dimensional structural steel cap truss system. The cap truss system which frames the top of the building between Level 87 and the spire is used to span over the open core, support the gravity load of heavy mechanical spaces, engage the structural steel spire, and resist lateral loads above the top of the central core wall / composite mega-column system.

In addition to resisting lateral loads, the central reinforced concrete core wall and the composite mega-columns carry gravity loads. Eight (8) built-up structural steel mega-columns also carry gravity loads and composite structural steel wide-flanged beams and built-up trusses are used to frame typical floors. The floor framing elements are typically spaced at 4.5 m on-center with a composite metal deck slab (75 mm metal deck topped with 80 mm of normal weight concrete) framing between the steel members. Figure 1 illustrates the components of the superstructure.

2. Poor Soil Conditions

Because of extremely poor upper-strata soil conditions, deep, high-capacity structural steel pipe piles are required to transfer the superstructure loads to the soil by friction. Open structural steel pipe piles are 65 m long with a tip elevation 80 m from existing grade. The tips of the piles rest in very stiff sand and are the deepest ever attempted in China. Pipe piles were installed in three (3) approximately equal segments, having a wall thickness of 20 mm, and having an individual design pile capacity of 750 tonnes. Piles were driven from grade with 15 m long followers before any site retention system construction or excavation had commenced. The pipe piles are typically spaced at 2.7 m on-center under the core and composite mega-columns with a 3.0 m spacing under the other areas. The piles are capped with a 4 m thick reinforced concrete mat comprised of 13,500 m^3 of C50 concrete. The mat was poured continuously, without any cold joints, over a 48 hour period. Concrete temperature was controlled by an internal cooling pipe system with insulating straw blankets used on the top surface to control temperature variations through the depth of the mat and to control cracking.

A reinforced concrete slurry system was designed and constructed around the entire perimeter of the site (0.75 kilometer). The thickness of the slurry wall is 1 m with a concrete design strength of C40 and depth of 33 m. The slurry wall bears on moderately stiff, impervious clay. The slurry wall acts as a temporary retention system wall, a permanent foundation wall, and a temporary / permanent water cut-off system. A tieback ground anchor system was designed and successfully tested to provide lateral support of the slurry wall during construction, however, the contractor chose to construct a locally accepted reinforced concrete cross-lot bracing system for the three (3) full basement levels which extended approximately 15 m below grade. The permanent ground water table is within 1 m of existing grade. Based on the site conditions and the slurry wall depth, a sub-soil drainage system was designed to carry 18.5 liter/sec of water. An overall description of the foundation system is shown in figure 2.

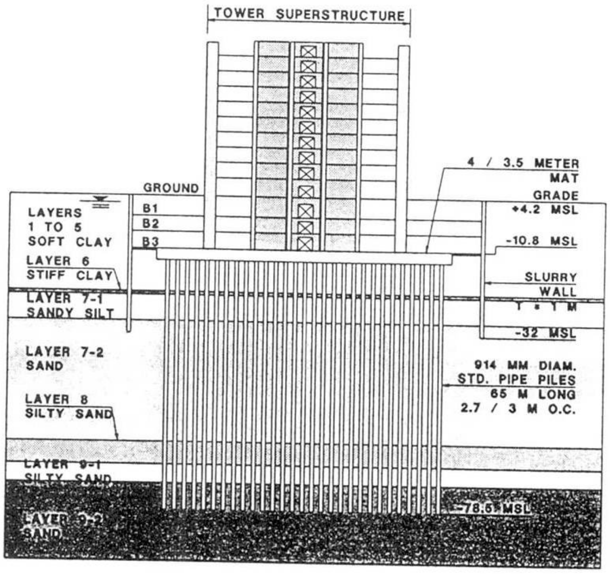

Figure 2 - Tower Foundation Systems

3. Extreme Winds

Typhoon winds as well as strong extratropical winds exist in the local Shanghai environment. Multiple analytical and physical testing techniques were used to evaluate the behavior of the Tower. Since ultra-tall structures had not been previously constructed in China, the Chinese wind design code did not address structures taller than 160 m. Therefore, code requirements were extrapolated for the Tower and wind tunnel studies were performed to confirm Code extrapolations and to study the actual, "rational" local wind climate. Wind tunnel studies, performed under the direction of Dr. Nicholas Isyumov at the University of Western Ontario in conjunction with the Shanghai Climate Center, were conducted for the building located in the existing site condition and considering the future master plan development termed the "developed Pudong" condition. The existing site context essentially consisted of low-rise buildings (3-5 stories in height) with the fully "developed Pudong" environment consisting of 30 - 50 story buildings surrounding the Jin Mao Tower with two (2) ultra-tall towers located within 300 m of Jin Mao. Wind tunnel investigation included a local climate study, construction of proximity models, a force balance test, an aeroelastic test, an exterior pressure test, and a pedestrian-level wind study. All tests considered both typhoon and extratropical winds as well as the existing and "developed Pudong" site conditions.

The final design of the Tower considered both the People's Republic of China Building Code as well as the "rational" wind tunnel studies. Strength design for all lateral load-resisting components is based on the Code-defined 100-year return wind with a basic wind speed of 33 m/s for a 10 minute average time at 10 m above grade. The basic wind speed corresponds to a design wind pressure for the Tower of approximately 0.7 kPa at the bottom of the building and 3.5 kPa at the top of the building. Results from the wind tunnel studies, considering the existing site condition and the "developed Pudong" condition as well as extratropical and typhoon winds confirmed that the Chinese Code requirements for design were conservative.

Serviceability design, including the evaluation of building drift and acceleration, was based on the "rational" wind tunnel study results. Wind tunnel studies were performed for 1-year, 10-year, 30-year, 50-year and 100-year return periods. The studies considered the actual characteristics of the structure. The fundamental translational periods of the structure are 5.7 seconds in each principal direction and the fundamental torsional period is 2.5 seconds. The overall building drift, with comparable inter-story drifts, for the 50-year return wind with 2.5% structural damping is H/1142 for the existing site condition and H/857 for the "developed Pudong" condition. It was determined that the two (2) ultra-tall structures proposed to be located near the Jin Mao Tower would have a significant effect on the dynamic behavior resulting in significantly higher effective structural design pressures. Building drifts are well within the internationally accepted building drift of H/500. Considering 1.5% structural damping and a 10-year return period, the expected building acceleration ranged from 9 - 13 milli-g's for the top floor of the occupied hotel zone. In addition, expected building acceleration ranged from 3 - 5 milli-g's for a 1-year return period considering 1.5% structural damping. The internationally acceptable accelerations for a hotel structure are 15 - 20 milli-g's for a 10-year return period and 7 - 10 milli-g's for a 1-year return period. Because of the favorable serviceability behavior of the building, the passive characteristics alone could be used to control dynamic behavior with no additional mechanical damping required.

Wind tunnel study results determined that the Code requirements for lateral load design was equivalent to a 3000-year return wind. The overall building drift based on this conservative wind loading is H/575 which also meets internationally acceptable standards for drift.

4. Moderate Seismicity

The approach for evaluating seismic loadings for the Jin Mao Tower considers both Chinese Code-defined seismic criteria and actual site-specific geological, tectonic, seismological and soil characteristics. Actual on-site field sampling of the soil strata and engineering evaluations were performed by Woodward-Clyde Consultants, the Shanghai Institute of Geotechnical Investigation and Surveying, and the Shanghai Seismological Bureau.

All lateral load resisting systems, including all individual members, were designed to accommodate forces generated from the Chinese Code-defined response spectrum as well as site specific response spectrums. Extreme event site-specific time history acceleration records (10% probability of occurrence in a 100-year return period) were used in time history analyses to study the dynamic behavior of key structural elements including the composite mega-columns, the central core, and the outrigger trusses.

The site specific response spectrums used to describe the Tower's dynamic behavior included analyses for a most probable earthquake with a 63% probability of occurrence in a 50-year return period and a most credible earthquake with a 10% probability of occurrence in a 100-year return period. In addition, the Tower was evaluated using a 3-dimensional dynamic time history analysis for a most credible earthquake with a 10% probability of occurrence in a 100-year return period.

In all cases, the Chinese-defined code wind requirements governed the overall building behavior and strength design; however, special considerations were given to the outrigger trusses and their connections. In all design cases, these structural steel trusses were designed to remain elastic.

5. Unique Structural Engineering Solutions

The structural design for the Jin Mao Tower created an opportunity to develop unique structural engineering solutions. These solutions included the practical development of theoretical concepts, unusual detailing of large structural building components, and comprehensive monitoring of the in-place structure.

The overall structural system utilizes fundamental physics to resist lateral loads. The slender cantilevering reinforced concrete central core is braced by the outrigger trusses which act as levers to engage perimeter composite mega-columns, maximizing the overall structural depth. The overall structural redundancy is limited by engaging only four (4) composite mega-columns in each primary direction. Structural materials are strategically placed to balance the applied lateral loads with forces due to gravity. Very little structural material premiums were realized because of the structural system used. Lateral system premiums essentially related to material required for the outrigger trusses only without measurable structural material premiums required for central core wall and composite mega-column elements. The combination of structural elements provides a structural system with 75% cantilever efficiency.

Even after equalizing the stress level within the central core and composite mega-columns, the expected relative shortening between the interconnected central core and composite mega-columns was large. By calculation, considering long-term creep, shrinkage, and elastic shortening, the expected relative movement between these elements at Levels 24-26 was as much as 50 mm. The magnitude of relative movement would have induced extremely high stresses into the stiff outrigger truss members weighing as much as 3280 kg/m. Therefore, structural steel pins with diameters up to 250 mm were detailed into the outrigger truss system (see figure 3). These pins were installed into circular holes in horizontal members and slots in diagonal members to allow the outrigger trusses to act as free moving mechanisms for a long period during construction. This allowed a majority of the relative movement to occur free of restrain, therefore, free of stress. After a long period of time, high strength bolts were installed into the outrigger truss connections for the final service condition of the lateral load resisting system. The expected relative movement after the final bolting was performed was a maximum of 15 mm at Levels 24-26. Considering the flexibility of the long composite mega-columns, the final forces attracted to the trusses did not appreciably increase the member and connection sizes.

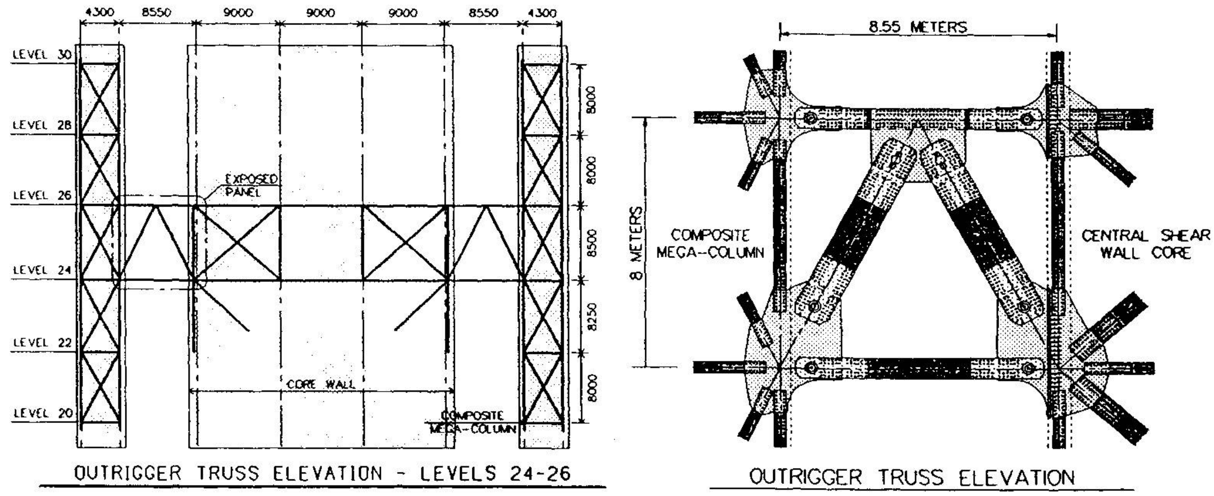

Figure 3 - Elevation and Detail of Outrigger Truss System

A comprehensive structural survey and monitoring program was designed and implemented into the Jin Mao Tower. Extensometers were placed on the reinforced concrete central core and on the reinforced concrete of the composite mega-columns. In addition, strain gages were placed on the built-up structural steel mega-columns as well as on the wide-flanged structural steel columns location within the concrete encasement for the composite mega-columns. Sample results of measured strain versus calculated strain are shown in figure 4. In addition to the gaging of the superstructure, the mat was periodically surveyed for long-term settlement. The mat foundation system under the Tower was initially surveyed just after pour completion in October 1995 and is currently still being surveyed. Based on a sub-structure / soil analysis, the expected maximum long-term Tower mat settlement is 75 mm. The latest Tower mat settlement is shown in figure 5. Laser surveying techniques were used for both lateral and vertical building alignment. Floor levels of the structure were typically built to drawing design elevation, compensating for creep, shrinkage, and elastic shortening which occurred during construction. Lateral position of the Tower was constantly monitored from off-site benchmarks and was found to be well within acceptable tolerances.

6. Conclusions

Incorporating fundamental structural engineering concepts into the final design of the Jin Mao Tower lead to a solution which not only addressed the adverse site conditions but also provided an efficient final design. The final structural quantities included the following for the Tower superstructure from the top of the foundation to the top of the spire (gross framed area = 205,000 m^2):

Structural Concrete	0.37 m^3/m^2
Reinforcing Steel	30.4 kg/m^2
Structural Steel	73.2 kg/m^2

A final evaluation of monitoring and survey data will be performed. Data from the as-built structure subjected to actual imposed loads will be correlated with theoretical results. This comparison will prove to be invaluable for the future design and construction of ultra-tall occupied structures.

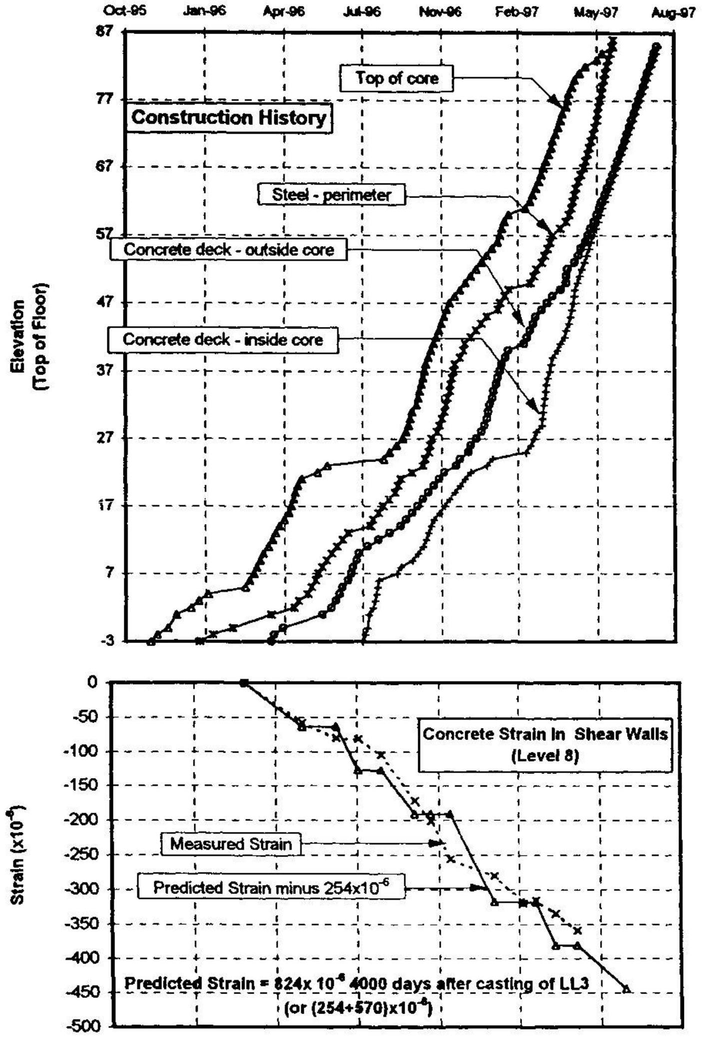

Figure 4 - Comparison of Measured Strain Versus Predicted Strain in Shear Walls (Level 8).

Results of Mat Settlement Analysis as a Function of Construction Sequence

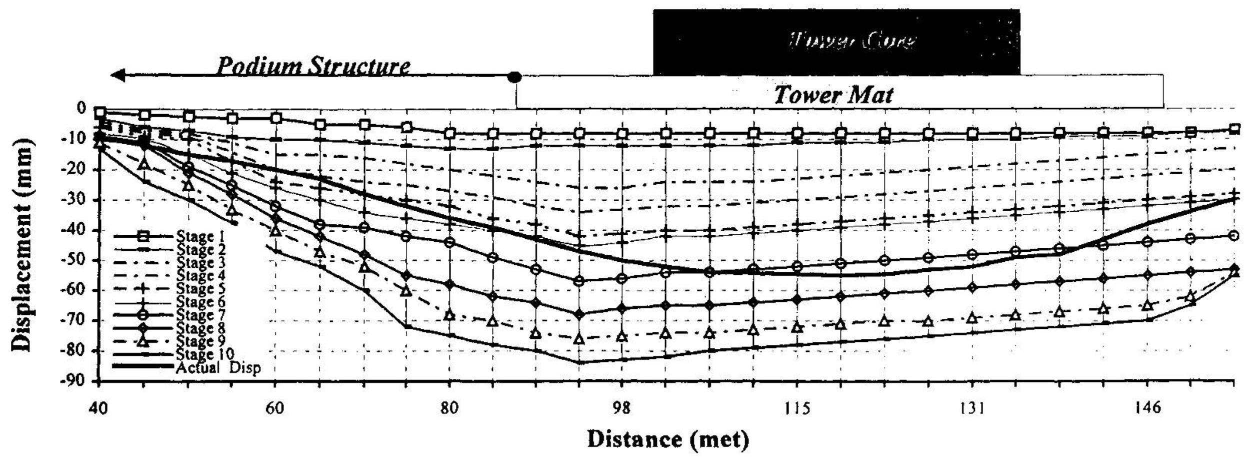

Figure 5 - Comparison of Estimated Versus Actual Tower Mat Settlement