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JIN MAO TOWER'S UNIQUE STRUCTURAL SYSTEM

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Abstract

The composite structural system for the Jin Mao Tower was designed to resist typhoon winds and earthquake forces and accommodate poor soil conditions while providing a very slender tower to be fully occupied for office and hotel uses. Reinforced concrete, structural steel and the combined use of structural steel and reinforced concrete (composite) members are used for the structural system. Reinforced concrete, with its excellent mass, strength, stiffness, and damping characteristics, combined with the strength, speed of construction, long-span capabilities, and lightweight characteristics of structural steel are used in the Jin Mao Tower. The structural system for the Tower responds to the Client's request to utilize local materials and labor expertise related to reinforced concrete, traditionally preferred for buildings in Shanghai. Reinforced concrete is strategically placed to utilize its excellent compression characteristics while structural steel is used for extreme tension conditions. Loads in the Tower are optimally controlled to distribute forces correctly and efficiently.

The structural solution to the Jin Mao Tower illustrates that even with moderately high strength concrete compressive strengths, reinforced concrete is an effective solution to ultra-tall structures. The advantages of concrete pumping technologies related to pumping volumes and pumping heights and advanced self-climbing forming systems have made concrete a strong competitor to structural steel when considering the construction of such towers. Reinforced concrete provides excellent structural behavior characteristics when subjected to extreme wind loadings. The inherent, passive structural characteristics of reinforced concrete provides excellent dynamic properties, reducing building accelerations, and therefore minimizing occupant perception.

This paper addresses an international design approach for a very tall building located in the Far East, specifically in Shanghai, The People's Republic of China, and focuses on the

mixed use of concrete and structural steel with its effect on structural efficiency within the superstructure structural system, concrete material availability, wind and seismic engineering based on local and international standards, and foundation engineering specific to poor local soils. In addition, differential movement due to creep, shrinkage, and elastic shortening will be discussed particularly related to the mixed use of concrete and structural steel within this truly composite structural system.

General System Description

The Jin Mao Building is a 280,000 m^2 (3,000,000 sq.ft.) multi-use development including office, hotel, retail, parking, and service spaces which is currently under construction in the Pudong Development Area of Shanghai. The expected completion of the building is August of 1998.

The development consists of an 88-story, 421 meter (1381 foot) tall tower with an adjacent low-rise building. The use of the space within the Tower includes fifty (50) stories of office space and thirty-eight (38) stories of hotel space with 900 automobile parking spaces and over 1000 bicycle parking spaces within three (3) below grade levels. The adjacent building to the Tower is primarily occupied by retail space with ballroom and pre-function spaces, an auditorium and hotel spaces.

The architectural and structural systems for the Tower make several references to the fortuitous number 8. In addition to the building being 88 stories, the exterior expression at the base of the Tower is 16 stories tall, or 2 times 8. Each succeeding segment of the Tower is one-eighth smaller than the 16-story base, dropping from 14 stories to 12 to 10 to 8. In the upper-most portions of the building, the vertical segments shrink from 8 to 7 to 6 to 5 to 4 to 3 to 2 to 1. The combination of the numbers is 88.

The structural system consists of components which also respect the number 8. The Tower, one of the most slender in the world, has an aspect ratio of 8:1 when considering the full building height (7:1 to the last fully occupied floor). The only vertical elements of the system are an octagon-shaped reinforced mega-concrete core wall, eight exterior composite mega-columns, and eight (8) exterior steel mega-columns. All vertical structural elements are supported by piles capped with a four (4) meter-thick reinforced concrete octagon-shaped mat.

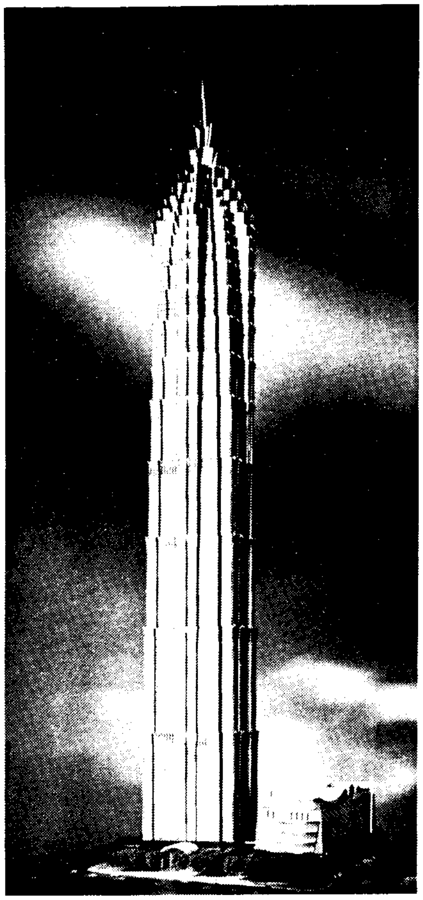

Figure 1 Building Elevation

The composite mega-columns (composed of reinforced concrete and structural steel) are linked to the core by eight (8) structural steel outrigger trusses in two-story high spaces

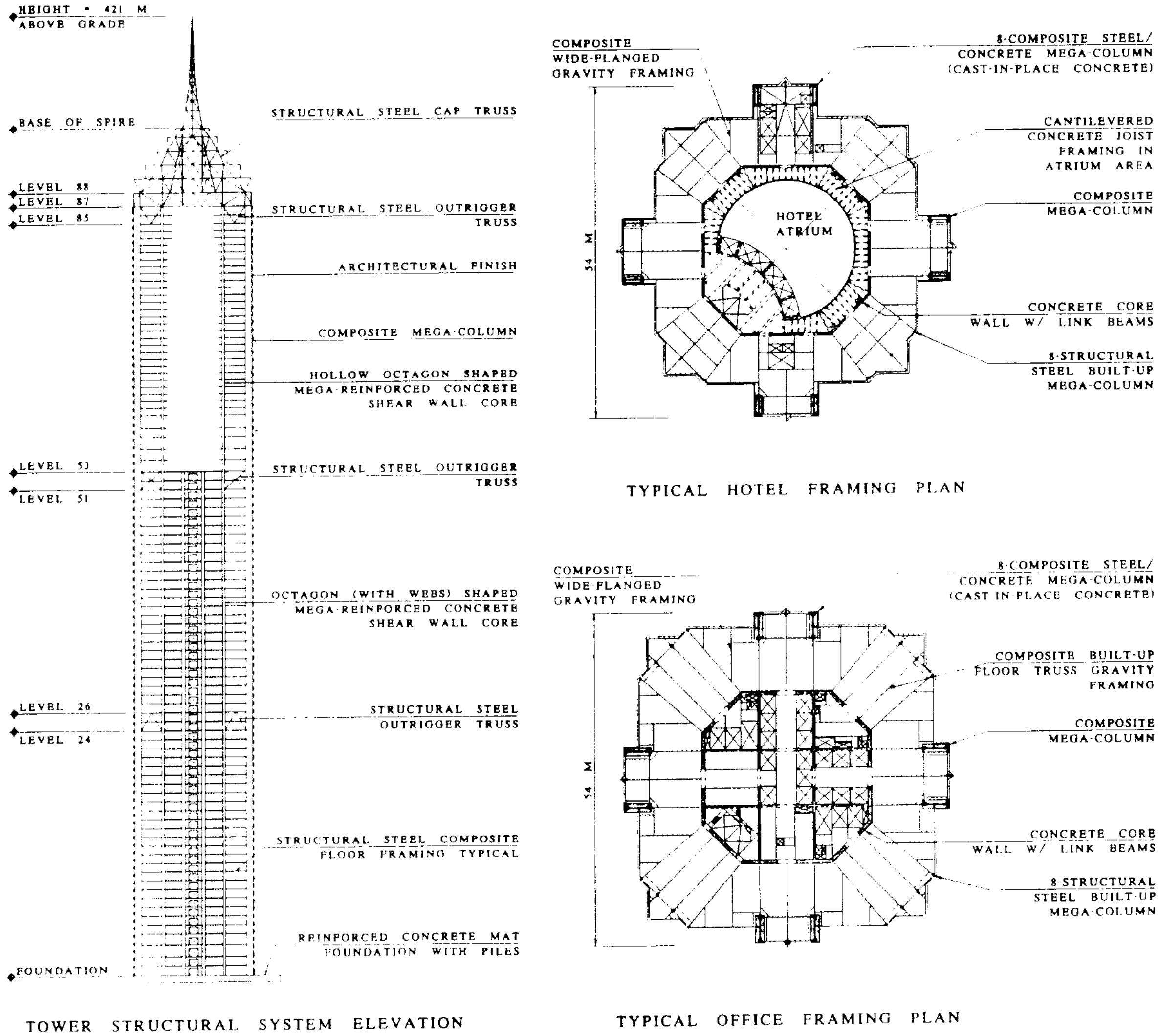

Figure 2 Structural System Elevation and Framing Plans

within the mid-height of the building and one multiple-story high space at the top of the building. The floor framing for the office zone consists of 44 (1/2 the number of stories) interior primary floor framing members and 16 (2 times 8) exterior floor framing members. The floor framing for the hotel floors consists of varying numbers of interior framing members because of the partition layouts of the spaces; however, 16 exterior floor framing members exist at the perimeter.

The primary components of the lateral system were developed to provide maximum structural efficiency with minimal effects on occupied spaces. The lateral system for the Tower provides resistance to lateral seismic and wind loadings with an inter-linked, combined system of an interior reinforced concrete core and exterior composite mega-columns. The core and mega-columns are linked by structural steel outrigger trusses acting compositely with horizontal diaphragm slabs. The outrigger truss system maximizes the effective depth of the structure under bending deformations while acting as a vertical cantilever, inducing tension in the windward columns and compression in the leeward columns. The outrigger trusses are located between Levels 24 and 26, between Levels 51 and 53, and between Levels 85 and the roof. The outrigger truss system at the top reflects the pagoda form. The pagoda form of the truss system is an efficient form to transfer lateral loads between the core and the exterior composite columns by providing a continuum over the open core. It furnishes a solution to the local lateral system requirement at the top of the building which interfaces with the spire and also supplies gravity load support of heavy mechanical spaces located in the penthouse floors allowing loads to travel around the open atrium below.

Gravity loads are distributed to eliminate any uplift in the exterior composite mega-columns. Four (4) composite mega-columns are activated in each primary direction with lateral loads applied normal to the building face while all eight (8) composite mega-columns are activated to resist lateral loads in the diagonal direction. The composite mega-columns are subjected primarily to axial loads induced from the overall bending moment, and the majority of the shear is resisted by the shear wall core. The proportioning of the core wall element sizes and the composite mega-column sizes is based on an equal stress principle for both gravity and lateral loads.

The structural form compliments the exterior expression and the interior use of the building. A central core wall houses the primary building functions including elevators, mechanical fan rooms for HVAC services, and washrooms. Floor spaces are column free from the core to the exterior columns where these columns are spaced between 9 meters (29'-6") and 13 meters (42'-6") with large composite mega-columns anchoring the strong cruciform shape in plan. The octagon-shaped core, nominally 27 meters (90'-0") from centerline-to-centerline of perimeter flanges, exists from the foundation to Level 87 with four (4) interconnecting webs located within the core

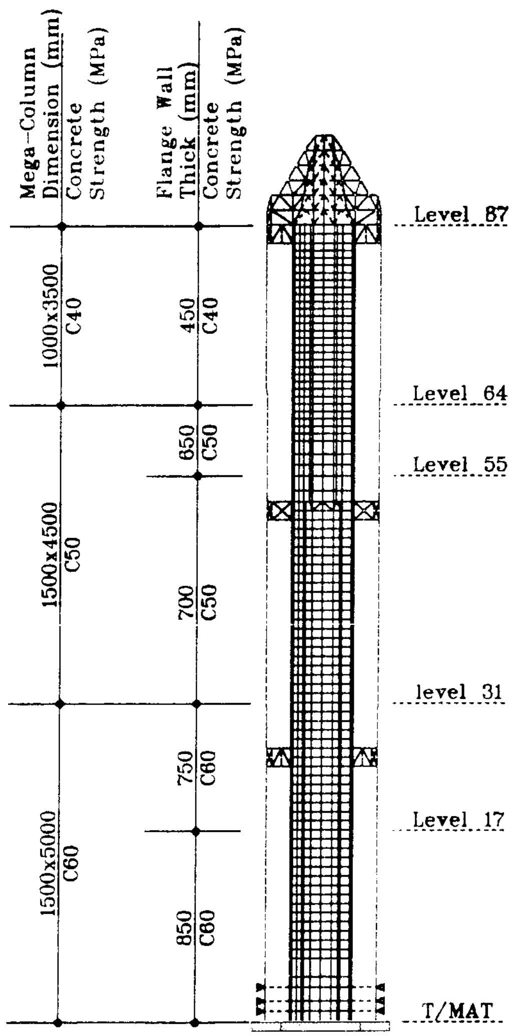

Figure 3 Concrete Strengths and Sizes of Composite Mega-Columns and Central Core

from the mat foundation through the office floors (Foundation to Level 53). The central area of the core is open without webs from Level 53 to Level 87 or typically through the hotel floors creating an atrium which leads into the spire (the spire is hollow to allow light to pass into the atrium below) with a total atrium height of approximately 206 meters (675 feet), most likely the tallest atrium space in the world. The core flanges vary from 850mm (33") thick at the foundation to 450mm (18") thick at Level 87, and the core webs typically are 450mm (18") thick. The core is linked to eight (8) composite mega-columns at the outermost portions of the structural floor plate. The composite mega-columns vary from a concrete cross-section of 1500mm x 5000mm (5'-0"x 16'-0") at the foundation, to 1000mm x 3500mm (3'-3" x 11'-6") at Level 87. Composite columns typically consist of 1% reinforcing steel and 1%-2% structural steel. The exterior face of the composite mega-columns remains vertical for the entire height of the building. The concrete strength for the core and mega-columns varies from C60 (7500 psi) at the foundation to C40 (5000 psi) at the top of the structure.

The structural elements which solely resist gravity loads include eight (8) structural steel built-up mega-columns and composite wide-flanged beams and built-up trusses used to frame the floors. The floor framing elements typically are 4.5 meters (14'-6") on-center with a composite metal deck slab, 75mm (3") deep metal deck with 80 mm (3 1/4") normal weight topping slab, framing between steel members.

Reinforced concrete was used extensively in the foundation system for the Tower. The foundation system for the Tower consists of deep, high capacity piles, a deep reinforced concrete mat, a continuous reinforced concrete slurry wall (diaphragm) along the perimeter of the site temporarily braced by a reinforced concrete cross-lot support system during excavation, a system of construction phase dewatering, and a permanent, hydrostatic pressure relief system.

The octagonal reinforced concrete mat measures approximately 62m x 62m (203'-0"x 203'-0") in plan. The mat is typically 4.0m (13'-0") thick is supported by 429 piles. The piles consist of 315 Mpa (46 ksi) steel tubes, 914mm (3'-0") in diameter with 20mm (¾") thick walls. The high capacity piles have an individual capacity of 750 tonnes (1650 kips) are typically spaced at 2.7m (8'-10") on center with 3.0m (9'-10") spacing used in areas away from the central core. Piles, driven from the existing grade surface with 15m (49'-0") followers, are typically 65m (213'-0") long and are driven into a deep, stiff sand layer, locally described as the 9-2 stratum. The pile tip elevation is at -78.5m Mean Sea Level which is 85m (275 feet) from existing grade. The bottom elevation of the piles is the deepest ever attempted in China. The total service design load for the mat foundation is 305,400 tonnes (671,880 kips). Based on the Tower load, pile length, and soil conditions, the expected settlement for the Tower is 50mm (2").

C50 (Cube strength - 50 Mpa with a cylinder strength of 6300 psi) concrete and 315 Mpa (46 ksi) reinforcing steel are used for the construction of the mat. The main reinforcement consists of bundled d35 bars, two bars per bundle. Seven groups bundled reinforcement are spaced at 300 mm (12") with the eighth bundle spaced at 600mm (24") to provide a less congested area for the placement of concrete. At the bottom of the mat, a minimum of two layers of bundled bars are used for temperature and shrinkage reinforcement in each direction, and a maximum of 10 layers are used in the region of highest bending moments. At the top of the mat, a minimum of two layers of bundled bars are used for temperature and shrinkage reinforcement topped with small, tightly spaced bars (d8 at 100m) used for crack control.

Since the ground water table at the site is basically within one (1) meter (3'-0") of grade, a slurry wall is used for a temporary retaining wall, for a permanent basement wall, and for a permanent ground water cut off. The wall extends approximately 3/4 kilometer (1/2 mile) around the perimeter of the site and approximately 36 meters (120 feet) below grade. The slurry wall is the deepest ever attempted in China. The flat-panel slurry wall system is sealed into a soil stratum having very low permeability at that elevation. The cut-off of the ground water table allows the hydrostatic relief system to perform reasonably with a maximum design flow rate of 30 liter/sec (8 gallons/second). The slurry wall flat-panel system is 1 meter (3'-3") thick and has panel widths ranging from 4m (13'-0") to 6m (19'-6") wide. The slurry wall is also used as a permanent foundation wall for the three (3) levels below grade (approximately 18 meters (60'-0") below existing grade at the deepest areas) and is waterproofed naturally by the sodium bentonite/soil "cake" interface formed at the exterior face of the wall.

The Use of a "Mixed" in the Structural System and Its Influence on Behavior

The environment at the site in Shanghai was not naturally conducive to an ultra-tall Tower. It was necessary to develop a structural system which responded to very poor soil conditions and potential typhoons and earthquakes. The soil conditions are so poor, that many of the existing structures in the Shanghai Area founded on shallow foundations have settled 250mm (10 inches). Wind speeds can average 55m/s (125 mph) as defined by Code, at the top of the building, over a 10-minute time period during a typhoon event and earthquakes can generate ground accelerations comparable to UBC Zone 2A.

Because of the difficult site conditions, the structural system for the superstructure and foundations relies heavily on the excellent behavioral characteristics of a mixed structural system.

The concept for the structural system of the Jin Mao Tower is based on:

1. Using strategically placed reinforced concrete combined with structural steel to resist extreme lateral loads in addition to gravity loads with maximum structural efficiency and without significant structural material premiums.
2. Using basic physics through the behavior of levers to maximize the effective building moment of inertia.
3. Reducing the redundancy of structural elements, forcing the system to approach global static determinacy, significantly increasing economy.

The lateral load resisting system for the Jin Mao Tower essentially relies on the bending and shear resistance of the central core, the axial stiffness of the exterior composite mega-columns, and the bending and shear stiffness of the outrigger trusses. The system's efficiency centers around the direct load transfer from the central reinforced concrete core to the exterior mega-columns without the need for a perimeter frame or "belt." The structure's torsional resistance is achieved with the closed-shaped central core. The purity of the structural system is compromised somewhat by the architectural requirements for the use of interior spaces, however is respected in an overall successful building design. The compromises include penetrations through the central core wall, limitations of depth and thickness of the core walls, limitations of the size and locations of mega-columns, and the location and depth of the outrigger truss systems.

The efficiency of the lateral load resisting system, when considering building drift, is related to the axial and shear deformation of the core, the axial shortening of the mega-columns, and the axial deformation of the outrigger trusses.

In evaluating the system's structural efficiency, based on the section properties used for final design, one can consider that a 100% structurally efficient system would yield an overall building drift, acting as a pure cantilever, of H/850 based on the Chinese Code wind. Also, with a 100% efficient system one can consider a 100% effective interconnection of vertical core elements, not considering shear deformations of the core and bending and shear deformations of the link beams, and 100% engagement of the exterior mega-columns.

However, due to the slight inefficiencies of the system, primarily related to the effectiveness of fully developing the axial area of the mega-columns by the interconnection of the outrigger trusses, the drift is H/575 based on the Chinese Code. This comparison yields a structural system of 70% structural efficiency, which is comparable to structural tube systems. **Figure 4** shows the behavior and the effectiveness of the outrigger truss system.

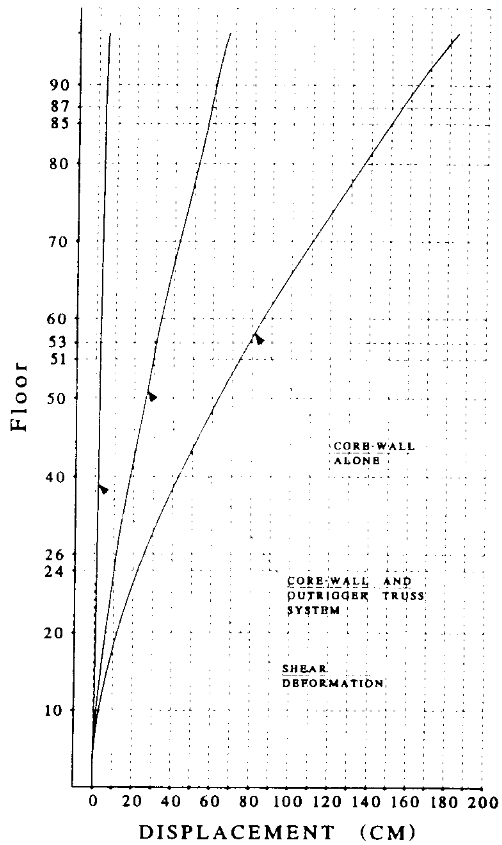

Figure 4 Structural System Displacements Under Wind Loads

Cost as a Measure of Structural Efficiency

The "mixed" structural system contributed significantly not only in controlling building behavior but also controlling building costs. Structural efficiency is directly related to the cost of the structure. Comparisons can be made to an alternate "all-steel" structural system considering the same base building architectural design requirements or, more importantly, to other ultra-tall structures considered the most efficient in the world.

Based on the given architectural design, analysis was given to an alternate "all-steel" structural system. It was found to be cost prohibitive since 34,000 tonnes (34.0 psf) of steel would be required yielding a cost premium of over 50% when compared to the as-designed "mixed" reinforced concrete and structural steel system. The Jin Mao Tower's structural system efficiency is compared to other ultra-tall structures as follows. The comparison is based on only the primary superstructure elements:

Table 1 Cost Comparison of Structural Efficiency Based on Unit Cost

		Structural Steel		Concrete				Total Costs	
Building	**Height**	**Quantity (PSF)**	**Unit Cost ($/SF)**	**Rebar Quantity (PSF)**	**Unit Cost ($/SF)**	**Concrete Quantity (CF/SF)**	**Unit Cost ($/SF)**	**Total Unit Cost ($/SF)**	**Unit Cost Compar -ison**
Sears Tower	445m	33.0	$36.30	-		-	-	$36.30	1.67
Jin Mao Tower	**421m**	**15.0**	**$16.50**	**5.3**	**$2.40**	**0.83**	**$2.90**	**$21.80**	**1.00**
World Trade Center	417m	37.0	$40.70	-	-	-	-	$40.70	1.87
Amoco Building	346m	31.5	$34.70	-	-	-	-	$34.70	1.59
John Hancock Center	344m	29.8	$32.80	-	-	-	-	$32.80	1.51

Unit Costs: Structural Steel - $2200 / ton = $1.10 / lb
Rebar - $900 / ton = $0.45 / lb
Concrete & Formwork - $95 / yd^3 = $3.52/ cf

The quantity of structural steel for the Jin Mao Building includes 2 psf for connections. Concrete and reinforcing for metal deck slabs are not considered in the comparison and the reinforcing and concrete for the Jin Mao Building is based on the central core, the mega-columns, and local reinforced concrete areas within the hotel atrium.

Wind Engineering

Two approaches were used to evaluate wind loadings for the Jin Mao Building including considerations for both Chinese Code-defined wind criteria and the actual, local "rational" Shanghai wind climate established for historical climatological data gathered at a site in close proximity to the proposed building location. The wind tunnel studies, conducted at the University of Western Ontario under the direction of Dr. Nicholas Isyumov in conjunction with the Shanghai Climate Center, modeled the effects of extratropical winds and typhoon winds. The wind tunnel investigation included a local climate study, construction of proximity models, a force balance model, an exterior pressure model of the Tower and Podium Buildings, a study of pedestrian level winds, and a structural aeroelastic model.

All lateral load resisting structural systems, including all individual members, are designed for strength to satisfy the People's Republic of China Building Structural Design Code wind loads. Strength design of the structure is based on a code specified 100-year return wind with a basic wind speed of 32.5 m/sec for a 10-minute average time for the Tower. The basic wind speed corresponds to a design wind pressure for the Tower of approximately 0.7 kN/m^2 (14 psf) at the bottom of the building and 3.6 kN/m^2 (74 psf) at the top of the spire.

The wind tunnel studies, used for serviceability performance, model the Tower in both "existing condition" and "developed Pudong" situations. The "existing condition" of the site corresponds to placing the Tower into the locally built environment which exists presently and typically consists of structures in the one to two-story range with some buildings as tall as ten (10) stories. The "developed Pudong" corresponds to the condition of the Tower within the proposed Pudong Masterplan environment. This developed environment will consist of several buildings of approximately 30 to 40 stories in height with two very tall towers proposed to be located directly adjacent to the south and southeast of the Jin Mao Building. "Rational" winds for 30-year, 50-year, and 100-year return periods were studied. The overall building drifts considering the "existing condition" and "developed Pudong" are shown in **Table 2.**

Table 2 Summary of Building Drift Ratios

	Existing Condition	Developed Pudong
30-Year Return with 1.5% Damping	H/1210	H/908
50-Year Return with 2.5% Damping	H/1142	H/857
100-Year Return with 3.5% Damping	H/1008	H/757

The two tall structures proposed, to be located within a few building widths of the Jin Mao Building, have little effect on the static wind pressures for the Tower but may have a significant effect on the dynamic behavior, therefore increasing the effective design pressures. In addition, the Jin Mao Tower was evaluated for drift based on specific Chinese Code defined winds. The wind tunnel studies determined that the Chinese Code-defined winds were equivalent to a 3000-year "rational" wind. The overall building drift is H/575 based on this conservative wind loading.

The following is a summary of building accelerations and torsional velocities based on characteristics of the structural system and the expected wind loads based on the Wind Tunnel Study.

Table 3 Summary of Building Accelerations and Torsional Velocities

	Existing Condition		Developed Pudong	
	1-Year Return	10-Year Return	1-Year Return	10-Year Return
Acceleration at 322m (milli-g)	3.4-3.9	9.6-10.9	4.5-5.1	15.7-17.9
Accepted Acceleration for Hotel (milli-g)	7-10	15-20	7-10	15-20
Torsional Velocity at 322m (milli-rad/sec)		0.26		0.35
Accepted Torsional Velocity for Hotel (milli-rad/sec)		3.0		3.0

Seismic Design

The Jin Mao Building is located in Chinese Seismic Zone with a degree 7 intensity, which is slightly less intense than Zone 2A per The Uniform Building Code (UBC). Considering the dynamic characteristic of the building, the geology of the site, the requirements of Shanghai Aseismic Design Code for Buildings, DBJ-08-92, and the National Standards for the People's Republic of China, Building Design Code GBJ-11-89, Volume 5, the following seismic analyses, design, and detailing are incorporated in the design. An equivalent static force method was used to obtain the base shear in accordance with the design codes outlined above. The base shear calculated with this method was distributed vertically along the height of the building taking into account building mass distribution. The additional force applied at the top of the building was limited to 25% of the base shear as per UBC rather than the 44% as per Shanghai Aseismic Design Code and the National Standards Code. Dynamic response spectrum and time history analyses show that the 44% and even the 25% requirement was excessive. The vertical load distribution of seismic force along the height of the Jin Mao Tower is better represented by dynamic analyses. Hence, response spectrum and time history analyses were considered and used for final analysis and design considerations.

The Jin Mao Building was considered for two (2) types or phases of earthquakes. The first phase represents a frequent earthquake with 63% probability of occurrence in 50 years. The second phase earthquake represents the maximum credible earthquake with 10% probability of occurrence in 50 years; however, due to the importance of major structural members including the outrigger trusses and composite mega-columns, a more severe earthquake with 10% probability of occurrence in 100 years is considered for the design. Considering this extreme earthquake, the outrigger trusses and mega-columns are designed to remain elastic.

Primary results from seismic considerations are presented in **Tables 4** and **5**.

Table 4 Phase I, Frequent Earthquake, Analysis Summary

Design Criteria Method of Analysis	**Base Shear (kn)**	**Overall Drift Ratio**	**Inter-story Drift Ratio**
Equivalent Static* Analysis Method	28460	H/845	h/750
Dynamic Response Spectrum Analysis using Shanghai Aseismic Design Code	23940	H/1928	h/1928
Dynamic Time History Analysis using Shanghai Aseismic Design Code	25403	H/1476	h/1476
Dynamic Response Spectrum Analysis (63% probability of occurrence in 50 years) provided by Shanghai Seismological Bureau (SSB)	15000	H/4170	h/4166

* For final seismic considerations, the equivalent Static Analysis is not considered appropriate for the Jin Mao Tower since the seismic force distribution along the height of the building is not representative of the actual behavior of the system.

Table 5 Phase II - Maximum Credible Earthquake Analysis Summary

Design Criteria Method of Analysis	**Base Shear (kn)**	**Overall Drift Ratio**	**Inter-story Drift Ratio**
Response Spectrum Analysis using response spectrum curves provided by Shanghai Seismological Bureau (SSB) 10% probability of occurrence in 50 years	49043	H/1360	h/1360
Response Spectrum Analysis using response spectrum curves provided by Shanghai Seismological Bureau (SSB) 10% probability of occurrence in 100 years.	67054	H/1190	h/1190
Time History Analysis Ground Accelerator Record is provided by SSB with 10% probability of occurrence in 100 years	68343	H/1160	h/1160

Creep, Shrinkage, and Elastic Shortening

The Tower presents three (3) difficult problems related to overall and relative movement of primary vertical structural elements. The first is that reinforced concrete, composite, and structural steel vertical members exist on all floors an are spaced as close as 5 meters (16 feet) apart. Reinforced concrete is extensively used because of its excellent mass, stiffness and damping characteristics. Structural steel members are used for both steel erection and axial stiffness in composite columns. Structural steel is used in the remaining columns to accomplish off-set transfers for columns which set back along the height of the Tower and to maximize usable floor area and maximize views of surrounding areas. The second is that the building is extremely tall, increasing the potential for large overall displacements and relative movements. The third and probably the most important, the central core and the composite mega-columns are interconnected by structural steel outrigger trusses at three (3) two-story positions within the Tower to form the lateral load resisting system. Relative movement between the central core and the composite columns has a significant effect on the design of the trusses.

A unique approach was used to control the structural behavior between the central core and composite columns. Steel pins were introduced within the outrigger trusses to enable the trusses to behave as mechanisms, allowing free motion and developing no internal forces for a long period during construction. The "pin concept" allows the very large outrigger truss members to be erected during the normal construction process and allows the central core and composite columns to move freely relative to one another for a defined period of time during construction.

The effect of creep, shrinkage, and elastic shortening dictated a specific need to control building behavior related to shortening due to short-term and long-term sustained loads. The superstructure will be built to as-designed building elevations adjusting for building movements during construction and establishing design benchmarks where additional corrections can be made. A rigorous monitoring program is designed into the Tower's construction program to force an intimate relationship between analysis, design, and construction. Advanced laser surveying and computer monitoring techniques will be used from off-site locations to avoid floor-by-floor measured length techniques for constructing each lift of concrete or tier of steel. Building floors to the as-designed elevation creates a discipline in controlling the behavior of the mixed structural system consisting of both reinforced concrete and steel.

The creep, shrinkage, and elastic shortening analysis is based on construction sequence of two (2) floors per week or a 3-1/2-day construction cycle. The construction sequence is complex since it is anticipated that the central core will be constructed first, the structural steel for the floor framing, steel mega-columns, and steel to be encased in the composite mega-columns second, and the concrete encasement for the composite mega-columns last. The construction sequence is as follows:

Calendar Day	Tower Construction Activities
Day 1	- Start of central core wall construction from top of foundation mat
Day 42	- Start of steel erection from top of foundation mat
Day 56	- Start of metal deck placement
Day 70	- Start of concrete on metal deck
Day 84	- Start of concrete encasement of composite mega-columns
Day 150	- Start of exterior wall
Day 180	- Start of superimposed dead load placement
Day 1000	- Start of superimposed live load placement

Applied Loads:

Overall shortening of elements in the Tower is important as it relates to building systems such as elevatoring and continuously connected pipes for mechanical systems, however it is the relative shortening between structural elements which directly effects the strength and serviceability of the Tower. The structural system was designed to control the state of stress within elements. The specific loads considered for analysis are as follows:

Loading Type kN	Structural Element					
	Central Concrete Core Wall *		Composite Mega-Column		Steel Mega-Column	
Dead Load	1,033,221	(85.6%)	76,457	(82.1%)	3,611	(58.2%)
Superimposed Dead	97,660	(8.0%)	5,373	(5.8%)	6,849	(16.9%)
Exterior Wall Dead Load	0	(0%)	6,138	(6.6%)	5,473	(13.5%)
Total Dead Load	1,130,881	(93.6%)	87,968	(94.5%)	35,933	(88.6%)
Total Live Load	75,674	(6.3%)	5,089	(5.5%)	4,601	(11.4%)
Total Load	1,206,555	(100%)	93,057	(100%)	40,534	(100%)

* Representative Section Only

The state of stress was equalized between the central core and the composite mega-column. This control forced these elements to behave in a similar manner, maintaining similar shortening characteristics, minimizing the strength effects on the outrigger trusses used to interconnect them and minimize relative movements of floor framing; eliminating floor levelness problems. The state of stress in the concrete due to sustained loads shown as a function of percent of concrete strength for the central core and composite mega-columns is illustrated in **Figure 5**. The state of stress due to sustained loads in the steel mega-column was maintained, on the average, as 50% of yield. However, the stress near the base of the building was 60% of yield and at the top of the building was 40% of yield.

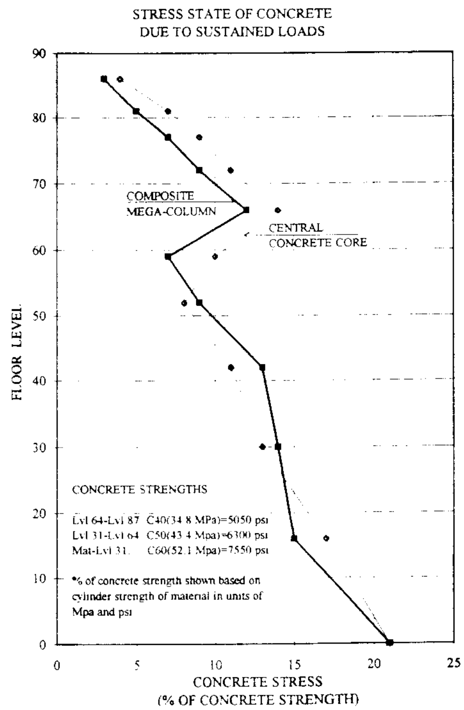

Figure 5 - State of Stress in Concrete

Outrigger Truss Pin Concept:

The clue to controlling building behavior resided with the outrigger trusses using "pinned" joints. The trusses could be erected during the normal construction process allowing the members to act as mechanisms for a specified period of time and then allowing full bolting to occur for permanent service. Allowing the trusses to act as mechanisms for an extended period of time during construction greatly reduces the imposed loads on very stiff outrigger truss members due to relative movements.

The outrigger truss pin concept was conceived considering a basic model using popsicle sticks and wood dowels. Based on this working model it was discovered that the key to allowing the trusses to act as mechanisms resided to utilizing slots in the diagonal truss members so pins could slide in the joints. The working popsicle stick model is shown in **Figure 6** with the actual outrigger truss elevation and details shown in **Figure 7**. Only certain bolts are installed in members at the time of initial erection, allowing the pins to move freely. The pin concept forces a great deal more creep, shrinkage, and elastic shortening to occur between the central core and composite mega-columns before final connection, reducing the demand on structural members, and minimizing structural steel quantities. A summary of the outrigger truss pin connection concept is as follows:

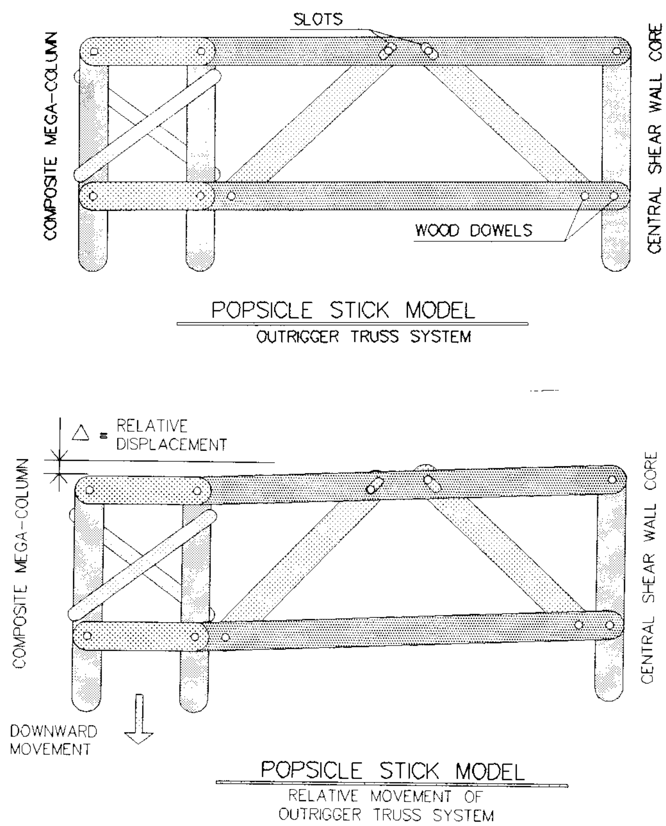

Figure 6 - Working Model of Outrigger Truss System

Outrigger Truss Level	Time Between Initial "Pinning and Final Connection	Fully Torqued, Final Connection Reference Time	Remarks
Levels 85-87	160 days	Exterior wall erected to base of spire	- Concrete encasement for mega-columns complete - Full dead load on structure
Levels 51-53	120 days	Initial "pin" erection of Level 85-87	- Concrete encased mega-columns to Level 75 - Central core topped out - Deck slabs to Level 79
Levels 24-26	95 days	Initial "pin" erection of Levels 51-53	- Concrete encased mega-columns to Level 41 - Central core to Level 65 - Deck slabs to Level 45

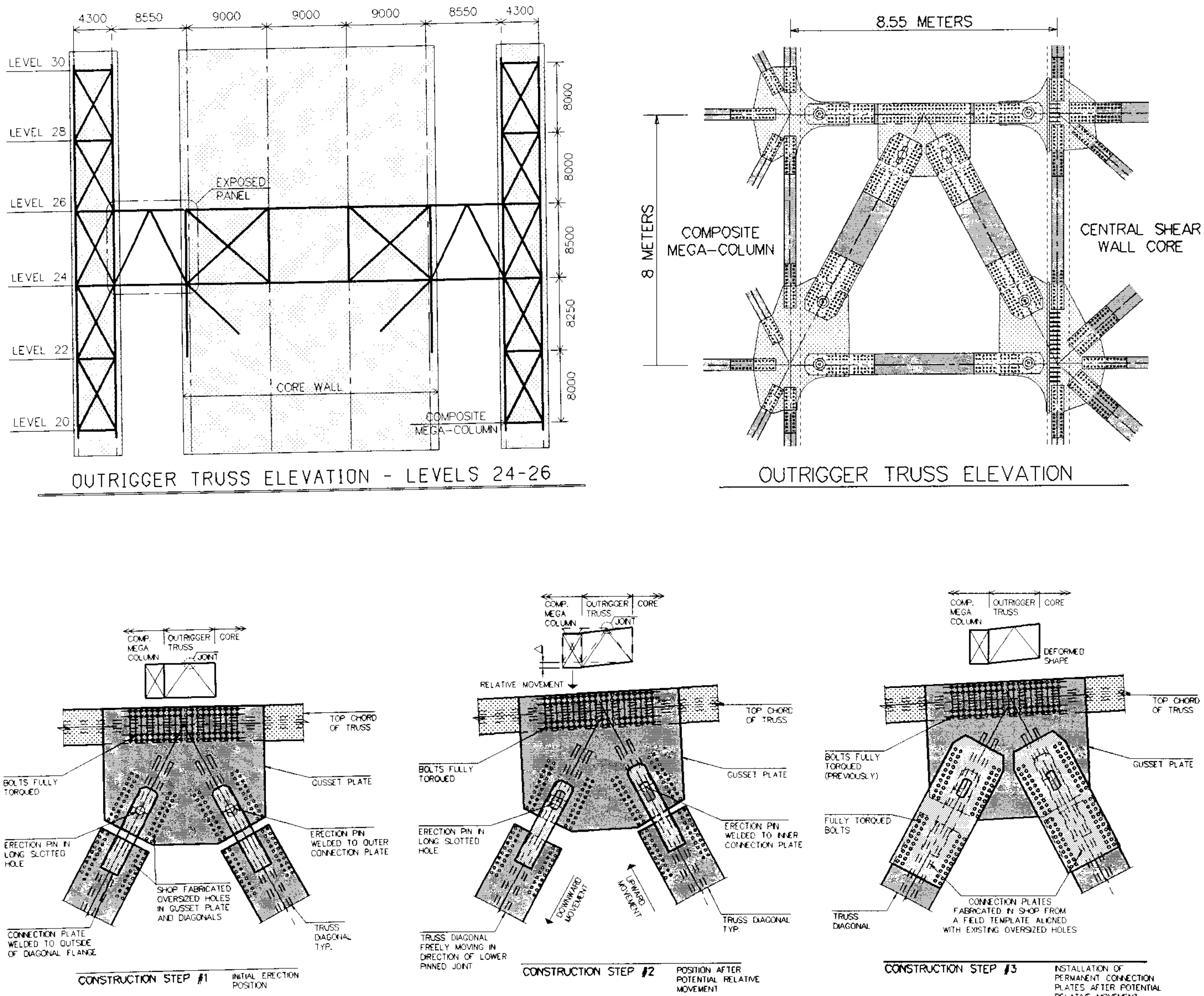

Figure 7 - Outrigger Truss Elevations and Details Describing Expected Movement at Joint for Diagonal Members

The following is a summary of the long-term relative movements at outrigger truss locations when considering the central core and composite mega-columns:

Relative Displacement (If trusses are fully connect at time of erection):

Outrigger Truss Level	Lower Bound (mm)	Upper Bound (mm)	% of C, S, & ES Core	M.C.
Levels 85-87	+32	+48	71%	49%
Levels 51-53	+26	+45	46%	23%
Levels 24-26	+13	+32	24%	9%

Relative Displacement "Pinned" Joints Used For Initial Erection:

Outrigger Truss Level	Lower Bound (mm)	Upper Bound (mm)	% of C, S, & ES Core	M.C.
Levels 85-87	+2	+11	80%	73%
Levels 51-53	+6	+16	73%	63%
Levels 24-26	-1	+7	54%	45%

The following are notes related to the relative movement at outrigger truss locations:

1. Lower bound corresponds to creep and shrinkage displacement restraint provided by the structural steel within the composite mega-columns.
2. (+) - composite mega-columns shorten more than central core.
3. Specific effects of outrigger truss load sharing are not considered in this comparison.
4. Percentage (%) of C, S, and ES - % of creep, shrinkage and elastic shortening having occurred at time of full connection.

Long-Term Effect of Sustained Loads and the Value of Erecting Steel to Design Elevations:

The concept of building the Tower to design elevation is a novel one, however the benefits that have a great effect on building behavior. The concept is as follows:

1. Construct central core to design elevation.
2. Construct steel columns within composite mega-columns and steel mega-columns to design elevation.
3. Construct steel floor framing flat, at design elevation,recognizing that embedded plates within the central core which were originally constructed to design elevation have moved downward due to the creep, shrinkage, and elastic shortening of the core between initial pouring and time of steel erection. The placement of shear tabs typically used to connect steel framing members at the core are field installed on embedded plates, which were slightly over-lengthened allowing for this movement.
4. Construct concrete encasement of composite mega-column to a referenced top of slab elevation which will be lower than design elevation due to elastic shortening of the steel columns before encasement and the creep, shrinkage, and elastic shortening which has occurred in the composite mega-column below between the time of steel erection and encasement.

The effects of erecting the structural steel to design elevation are significant. **Figure 8** is a collection of data which compares long-term movements relative to the central core when elements are constructed to measured floor-by-floor lengths and when steel is erected to design

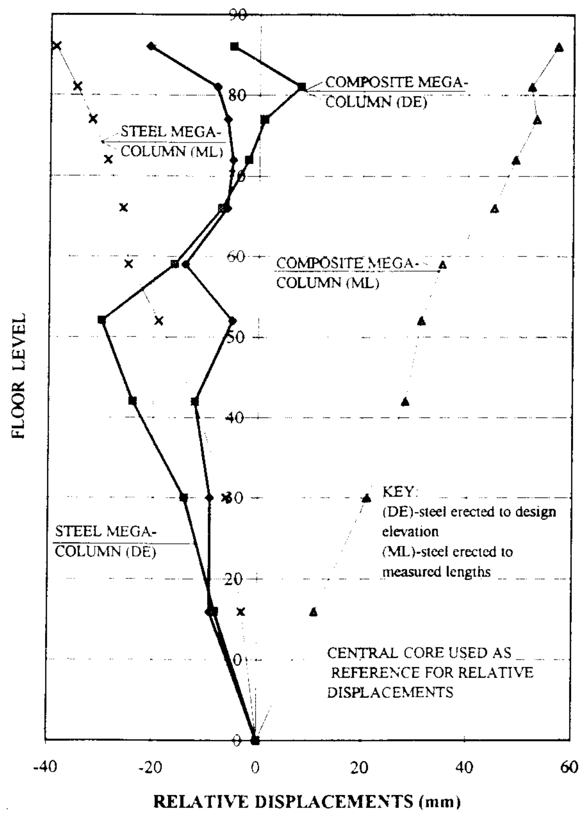

Figure 8 - Long Term Relative Movements

elevation. The relative displacements between elements are significantly more controlled when the steel is erected to design elevation, potentially requiring corrections to elevations of members to obtain level floors near the mid-height of the building only where the greatest relative movement occurs between the central core and the steel mega-column with a magnitude of 30mm. Without the program of erecting floors to design elevation, the relative difference between the steel mega-column and the composite column is as high 96mm at the top of the building where column spacing is merely 6 meters (20 feet).