Structural Design Challenges of Shanghai Tower

Author: Yi Zhu

Affiliation: American Society of Social Engineers

Street Address: 398 Han Kou Road, Hang Sheng Building

City: Shanghai

State/County:

Zip/Postal Code: 200001

Country: People's Republic of China

Email Address: YZhu@ThorntonTomasetti.com

Fax: 1.917.661.7801

Telephone: 011.86.21.6057.0902

Website: http://www.thorntontomasetti.com

Author: Dennis Poon

Affiliation: Council on Tall Buildings and Urban Habitat

Street Address: 51 Madison Avenue

City: New York

State/County: NY

Zip/Postal Code: 10010

Country: United States of America

Email Address: DPoon@ThorntonTomasetti.com

Fax: 1.917.661.7801

Telephone: 1.917.661.7800

Website: http://www.thorntontomasetti.com

Author: Emmanuel E. Velivasakis

Affiliation: American Society of Civil Engineers

Street Address: 51 Madison Avenue

City: New York

State/County: NY

Zip/Postal Code: 10010

Country: Unites States of America

Email Address: EVelivasakis@ThorntonTomasetti.com

Fax: +1.917.661.7801

Telephone: +1.917.661.8072

Website: http://www.thorntontomasetti.com

Author: Steve Zuo

Affiliation: American Institute of Steel Construction; Structural Engineers Association of New York; American Society of Civil Engineers

Street Address: 51 Madison Avenue

City: New York

State/County: NY

Zip/Postal Code: 10010

Country: United States of America

Email Address: SZuo@ThorntonTomasetti.com

Fax: 1.917.661.7801

Telephone: 1.917.661.7800

Website: http://www.thorntontomasetti.com/

Author: Paul Fu

Affiliation:

Street Address: 51 Madison Avenue

City: New York

State/County: NY

Zip/Postal Code: 10010

Country: United States of America

Email Address: PFu@ThorntonTomasetti.com

Fax: 1.917.661.7801

Telephone: 1.917.661.7800

Website: http://www.thorntontomasetti.com/

Author Bios

Yi Zhu, Senior Principal of Thornton Tomasetti, has extensive experience internationally in the structural analysis, design and review of a variety of building types, including high-rise buildings and mixed-use complexes, in both steel and concrete. His notable projects include Taipei 101 in Taiwan, China; the Petronas Towers in Malaysia; Shanghai Tower and the 66-story Plaza 66 in Shanghai, China. He holds a bachelor's degree in structural engineering from Tongji University and a master's degree in structural engineering from the City College of New York.

Dennis Poon, Vice Chairman at Thornton Tomasetti, has 30 years of experience in the design of supertall structures and mixed-use buildings worldwide. High on the list of his accomplishments is the role he played in leading the structural design teams for three of the tallest buildings in China: Wuhan Greenland Center, Shanghai Tower, and Ping An International Finance Center, currently under construction. He was named one of the 25 Top Newsmakers of 2010 by *Engineering News-Record magazine* for the effort to modernize China's building codes for supertall structures.

Emmanuel Velivasakis' design experience with materials such as structural steel, cast-in-place concrete, carbon/glass fiber reinforced plastics, timber, precast and prestressed concrete and masonry, allows him to participate in the design of various building project types. He is responsible for managing major projects, such as high-rise buildings, hotels, long-span structures, industrial buildings, schools, airport terminals, stadia, pedestrian bridges, parking structures, special structures and failure investigations. His extensive investigation/forensic experience includes numerous types of cases, ranging from exterior walls, to structural collapses failures and colapses, including emergency response. He has provided expert witness testimonies for litigation cases involving a variety of issues in the Structural and Architectural Engineering arena. Mr. Velivasakis also has extensive experience in seismic design and analysis. He has worked on major projects in severe seismic zones including US/California, South America, Greece, Turkey, UAE, Guam, Puerto Rico and China and is familiar with a variety of seismic codes and criteria, as well as performance-based design.

Steve (Qing) Zuo, Vice President at Thornton Tomasetti, has experience in the structural design, investigation and review of a variety of building types, including high-rise buildings, commercial/residential, and mix-used complex. He is also well versed in conducting structural investigations of existing and proposed structures. Steve has been involved in the design of a number of high-profile projects in China over the past several years, including Shanghai Tower in Shanghai, Ping An International Financial Center in Shenzhen, and the Shangri-La Hotel in Shenzhen.

Paul Fu, Vice President at Thornton Tomasetti, has 20 years of experience in structural analysis, design, and review of super-tall buildings and mixed-use structures. He has been involved in major projects in Asia and the US, including Shanghai Tower, Ping An International Finance Center, Wuhan Greenland Center, and MGM City Center Block A in Las Vegas. Paul is a licensed professional engineer in New York. He holds a master's degree in civil engineering from the University of Toledo and a bachelor's degree in civil engineering from Southeast University, Nanjing, China.

Abstract

This paper discusses the structural challenges and solutions of the 632m tall Shanghai Tower. A unique "Core-Outrigger-Mega Frame" lateral system is used to meet China code requirements. The exterior perimeter Mega frame provides additional stiffness and strength. A foundation with a 6m thick mat and fin walls extending from a central core distributes loads to piles constructed with an end grouting technique to provide high bearing capacity and reduced settlement. The tower crown design incorporates features for construction efficiency while providing multiple load paths. Performance Based Design is used to verify tower performance under different seismic hazard levels through non-linear dynamic time-history analysis.

Keywords

Tall building; Performance-Based Design; Outrigger; Super column; Belt truss, Crown

PROJECT DESCRIPTION

Shanghai Tower in lot Z3-1 is adjacent to Jin Mao Tower, with its pagoda-like gesture to China's past, and Shanghai World Financial Center, representing China's present. Rising as a landmark on the city skyline to represent the future, the 128-story Shanghai Tower will house Class A office space, entertainment venues, retail stores, a conference center, a luxury hotel and cultural amenities. The 5-story deep basement serves retail, MEP and parking spaces (see Figure 1). Occupying a total site area of about 30,370 m2, the Shanghai Tower has a total gross floor area (GFA) of approximately 573,400 m2 (6.2 million ft2).

Figure 1

The tower structure takes the form of nine cylindrical buildings stacked one atop another, including a business zone at the bottom podium levels, five office zones, two hotel/apartment zones, and sightseeing or observation floors at the top. Each zone can be considered an independent city or village with communal space at an amenity level extending to the outer twisting façade (see Figure 2). The tower floor plate diameter varies by zone, from 82.2m at Zone 1 to 46.5m at Zone 8 (see Figure 3). The stacked-zone tower concept within an exterior façade tapering and twisting with height creates a spectacular architectural design.

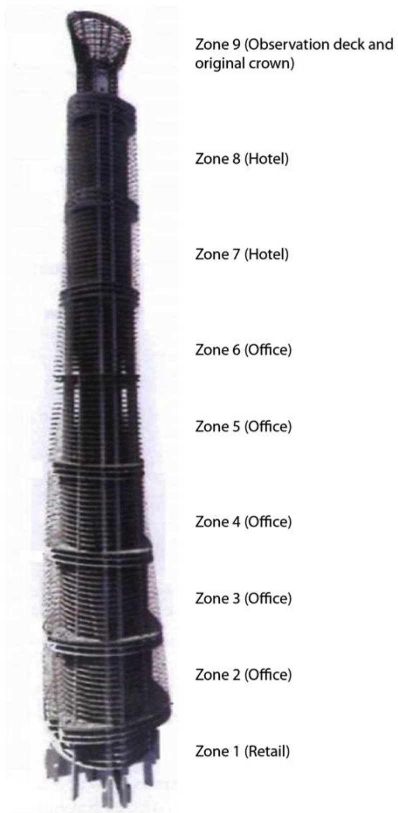
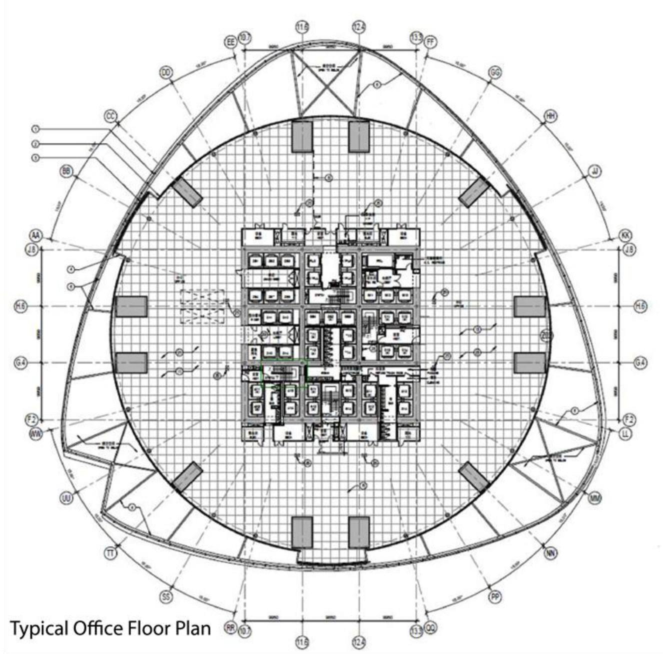
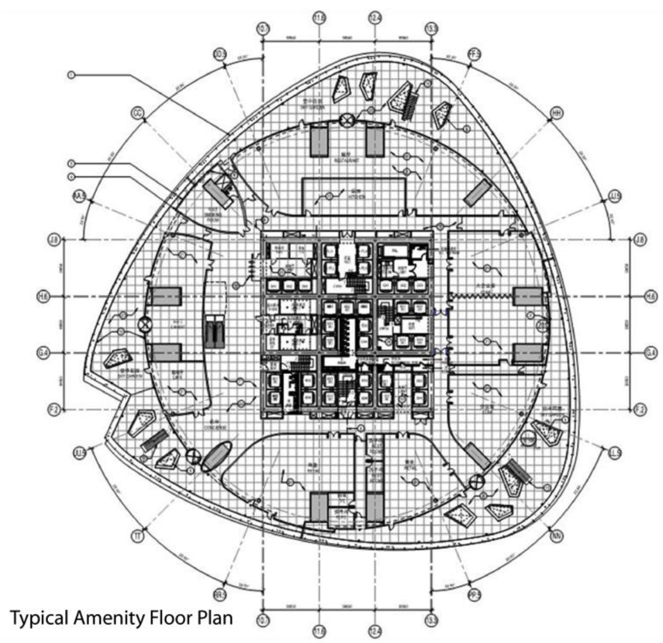


Figure 2



Typical Office Floor Plan



Typical Amenity Floor Plan

Figure 3

GEOTECHNICAL CONDITIONS AND TOWER FOUNDATION

Foundation design is always challenging for tall buildings due to large vertical forces from gravity and large overturning forces from wind and seismic loading. Site conditions at Shanghai Tower add to the challenge. Nine layers of sand and clay area alternating to at least 120m below grade. Bedrock is considered beyond reach for practical construction purposes. Because the top 15m is very soft silty clay the site for seismic design is considered as Type IV, the most unfavorabe class according to the China code and roughly comparable to Site Class ‘F’ under the International Building Code (IBC) (see Table 1).

Table 1- Soil Profile

Soil Stratum Succession	Soil Stratum Name	Average Soil Stratum Thickness (m)	Average Distance to the bottom of stratum (m)	Saturated undrained Shear Strength Cu (KPa)	Shear Wave velocity (m/s)
1	Fill	2.2	2.2	-	-
2	Silty clay	1.6	3.8	-	-
3	Very soft silty clay	5.2	9.0	30	125
4	Mucky clay	7.9	16.9	51	147
5_{1a}	Clay	3.7	20.6	70	178
5_{1b}	Silty clay	4.2	24.8	96	215
6	Silty clay	4.2	29.0	115	271
7_1	Sandy silt + silty sand	8.0	37.0	-	263
7_2	Silty sand	27.4	64.4	-	333
7_3	Silty sand	4.8	69.2	-	377
9_1	Sandy silt	9.0	78.2	-	399
$9_{2\text{-}1}$	Silty sand	11.2	89.4	-	421
$9_{2\text{-}2}$	Silty sand	9.6	99.0	-	457

Under the tower footprint a 6m thick mat foundation is supported by 947 piles with one meter in diameter. The cast-in-place (CIP) concrete piles have end grouting to increase their capacity and reduce settlement. Under the core and super columns load is concentrated so a staggered pattern pile layout is used to fit more piles than where using a simple grid arrangement. The 1000-metric ton capacity piles are effectively 52 to 56 m long and bear at layer 9-2-1, a thick silty sand layer.

Modest soil stiffness offers little ability to distribute gravity loads. Concentrating piles under the core and super columns is not sufficient by itself to provide reasonably uniform settlement; pile group effects also play a role. To distribute the tower load more uniformly and thus reduce the overall settlement and differential settlement, concrete fin walls five stories tall are provided at the basement levels to engage both core walls and super columns. To handle the large forces being redistributed the walls include embedded steel plates. These fin walls reduce the maximum predicted settlement by 20 - 30% and greatly reduce differential settlement. Figure 4 shows the settlement contours with and without fin walls. Tower peak settlement after 5 years is estimated to be 100 to 120mm.

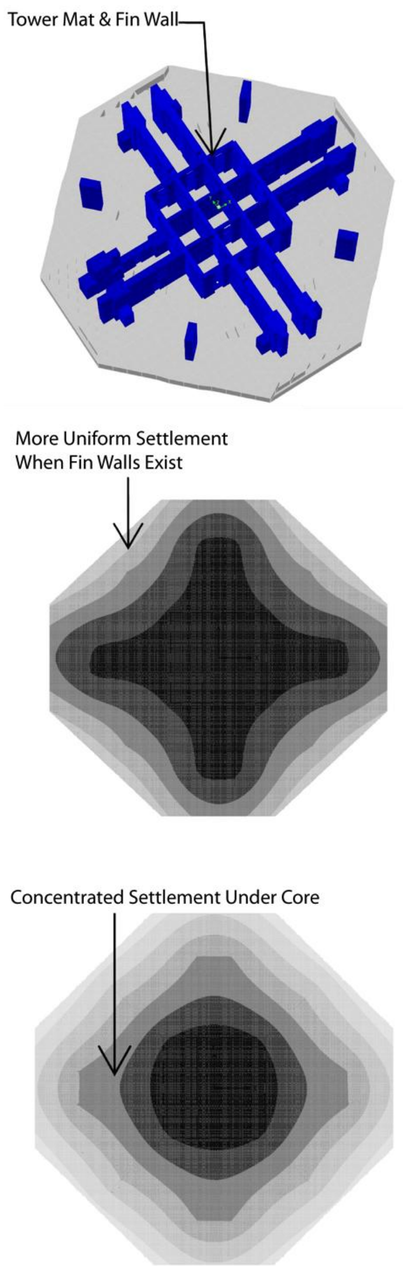


Figure 4

Differential behavior between the tower and surrounding podium also poses structural challenges. The water table is just 0.5m under grade, while the mat top elevation is at -25.4m. Under the tower footprint self-weight is sufficient to more than offset buoyancy, but the surrounding podium will have to resist net uplift forces due to high buoyancy forces. The difference in net foundation loads and the soft subgrade conditions will cause differential settlement between podium and tower. To reduce the effects of differential settlement, a delayed-pour strip is provided. The mat reinforcement design must consider loads and deformations occurring during different construction stages for independent and combined cases, and include additional reinforcement locally at the interface of tower and podium as needed.

TOWER LATERAL SYSTEM

The Shanghai Tower lateral system is a "Core-Outriggers-Mega Frame" and it consists of three parts: Concrete Composite Core, Exterior Mega Frame (Super Columns and Double Belt Trusses), and Outrigger Trusses (see Figure 5).

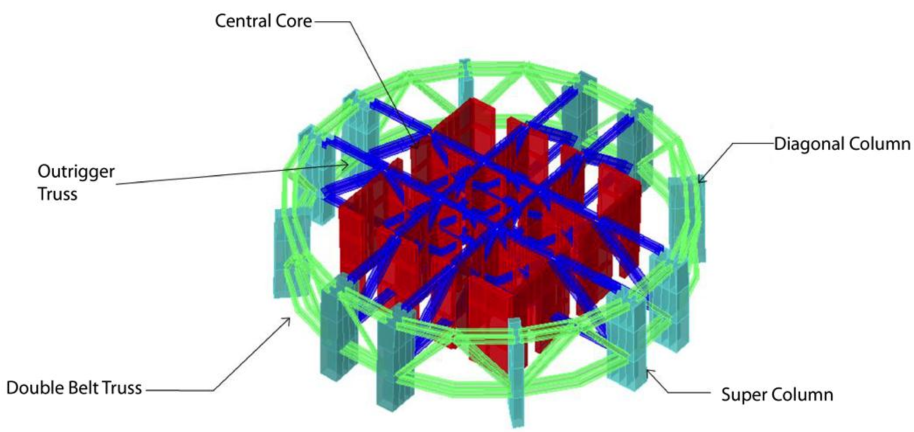


Figure 5

The core forms a nine-cell 30m square shape in plan from Zones 1 through 4. The four core corners are cut back at Zones 5 and 6, and the core becomes a cruciform plan at Zone 7 and 8. The flange (outermost) wall thickness varies in five steps from 1.2 m to 0.5 m. Interior web wall thickness varies from 0.9 m to 0.5 m. Embedded wide flange steel columns are provided at the boundary zones, or stressed core wall corners and ends to both strengthen the core and to provide a clear load path from outrigger forces into the core. Embedded steel plates are placed in the core walls at the bottom two zones to enhance wall ductility and permit a reduced wall thickness.

There are eight Super Columns up to Zone 8, and four Diagonal Columns up to Zone 5. Steel columns embedded in the super columns have areas from 4% to approximately 6% of Super Column plan areas. The Super Columns work together with eight sets of two-story-high double Belt Trusses to form the "Exterior Mega Frame" which serves as a second line of defense required by the China Code. Outer and inner belt trusses are laced together to form a boxed space truss for redundancy and torsional stiffness. Belts also serve to transfer secondary column gravity loads to the Super Columns.

Six sets of two-story high steel Outrigger Trusses are placed at the MEP floors as shown in Figure 6. The location and number of outrigger trusses was extensively studied and optimized. The outriggers at low zones are effective in reducing the building fundamental period, while upper outriggers contribute more to control of story drifts at upper zones.

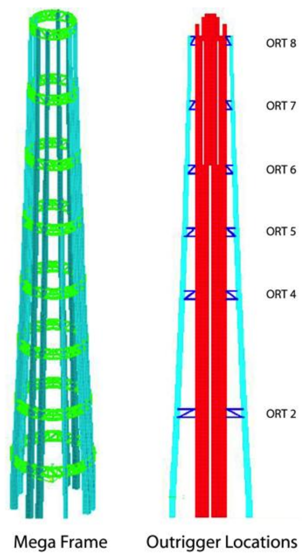


Figure 6

The fundamental period of the tower is shown in Table 2 with the first 3 modes representing X-direction Translation, Y-direction Translation and Torsion, respectively.

Table 2- Building fundamental Period

	ETABS
T1	9.05
T2	8.96
T3	5.59
T4	3.31
T5	3.20
T6	2.62

The Outrigger Trusses and Belt Trusses help the structural system to be stiff enough to meet the stringent story drift limit required by China Code. The story drift curves under the lateral load are shown in Figure 7. The max story drift is h/505 under resultant wind and h/623 under frequent seismic load.

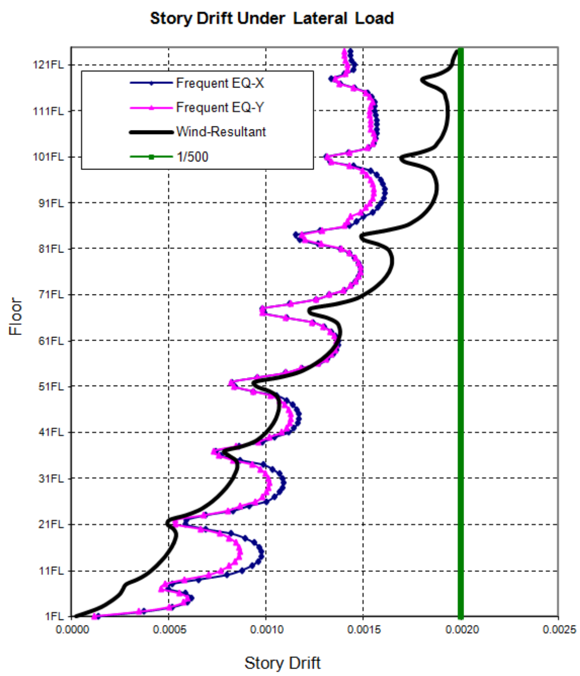


Figure 7

TOWER GRAVITY SYSTEM

Typical office floors use a 155 mm thick composite slab (80 mm concrete above a 75 mm deep profile metal deck) that provides a two-hour fire rating according to laboratory tests. Typical MEP levels and Amenity levels use 200 to 250 mm thick composite slabs (125 to 175mm above 75 mm metal deck). Steel perimeter gravity columns have their gravity loads transferred through the belt trusses into the super columns.

One-story-high radial trusses cantilever at the upper MEP level to support slab areas beyond the super columns. Those radial trusses also support the exterior facade system, as discussed below.

REDESIGN OF TOWER CROWN

The Shanghai Tower crown is an important part of the building façade system and serves multiple functions. It houses an 1,100-ton tuned mass damper on top of the central core at L125, a series wind turbines at the perimeter of L122~L124, cooling towers at L128 surrounding the TMD, and a window washing machine track along the crown top surface (see Figure 8).

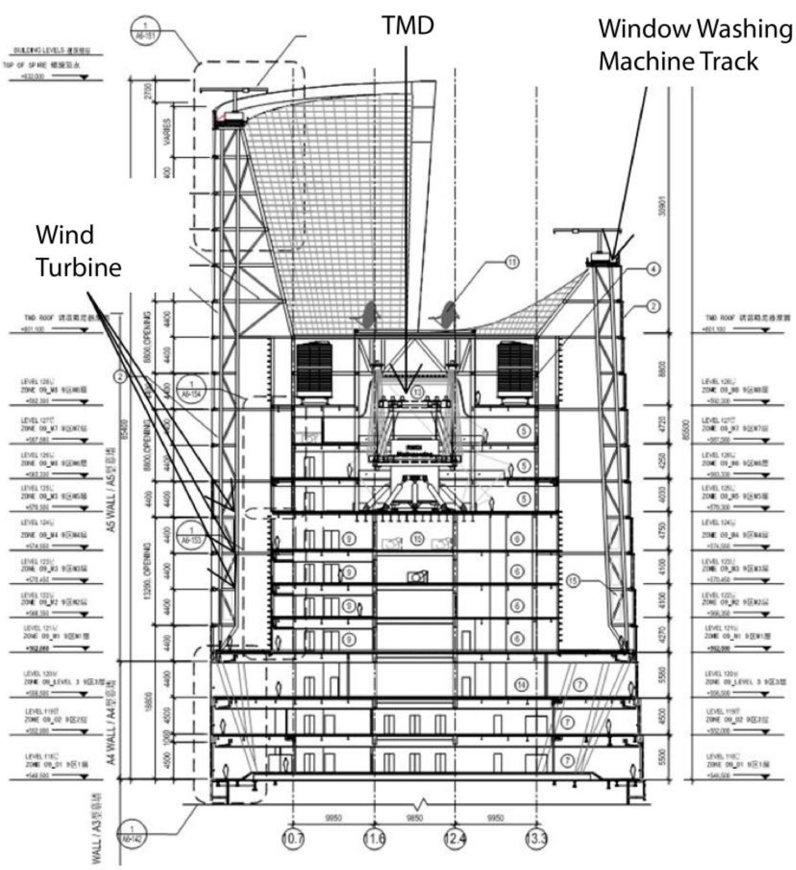
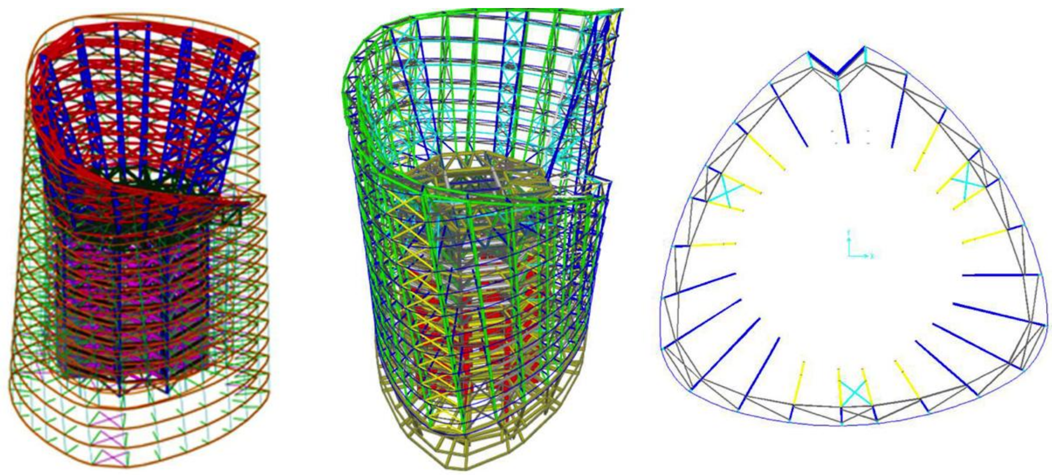


Figure 8

The original design was based on a pretensioned vertical cable net for the outer crown surface to satisfy architectural criteria. The crown inner surface was carried on radial, outward-sloping cantilevered 'fin' trusses that also supported the cable net upper end loads. The fin trusses stood on criss-crossed two-way trusses to transition to the core below.

Resisting lateral loads, particularly torsion, required circumferential horizontal trusses to tie the fin trusses to braced bays. While a perimeter building skin carried on tension rods hanging from the crown top would have minimal visual interface behind the glass, such a hung system would be costly and slow to build (see Figure 9 Original Tower Crown 3D view).



Original Tower Crown 3D View   Current Tower Crown 3D View   Current Struct Level Floor Plan

Figure 9

The current scheme follows a more conventional approach to cladding support and the structural system. Instead of suspended pretensioned rods, vertical trusses behind the crown outer face support the façade and deliver its gravity load directly to L118 below. Lateral loads from wind pressure are delivered directly to core framing through radial struts. Instead of cantilevered fin trusses, simpler kicker trusses support the crown inner face while laterally bracing the outer trusses above the tower roof level at L129. Simple vertically braced bays at three triangle corners work with a horizontal floor truss at every other floor to help the crown system resist the torsion. This system is more efficient by providing direct load paths and more conventional fabrication and erection, and more reliable by having multiple load paths. See Figure 9 Current Tower Crown 3D view and Current Strut Level Floor Plan.

PERFORMANCE BASED DESIGN

PBD explicitly considers the nonlinearity and ductility of structural members and can be used to evaluate structure overall behavior and member behaviors under different levels of seismic events. The PBD procedure of Shanghai Center Tower includes:

- Determining performance targets for the overall structure
- A PBD model incorporating the nonlinearity of structural components
- Determining appropriate ground motion time histories
- Performing a nonlinear dynamic time-history analysis
- Comparing member deformations and forces with the acceptance criteria

Performance goals for the overall structural system and structural components are summarized in Table 3.

<table>
<tr><td colspan="2">Seismic Hazard Level</td><td>Frequent Earthquake</td><td>Moderate Earthquake</td><td>Severe Earthquake</td></tr>
<tr><td colspan="2">Performance level description</td><td>No damage or negligible damage</td><td>Little Damage, Repairable</td><td>Serious Damage, No Collapse</td></tr>
<tr><td colspan="2">Structure Behavior Description</td><td>No damage, structure basically in elastic range</td><td>Allow minor damages , structure substantially retains original strength and stiffness</td><td>Allow serious damage, but no fracture of major connection joint; no shear fracture of super columns and core walls</td></tr>
<tr><td colspan="2">Story drift ratio limit</td><td>h/500; h/2000(bottom levels)</td><td>h/200</td><td>h/100</td></tr>
<tr><td rowspan="3">Member performance</td><td>Core wall</td><td rowspan="3">Elastic,

Strength design per code:
- factored seismic load
- material design strength</td><td>Code-based strength design
At outrigger floors:
- factored seismic load
- material design strength
At other floors:
- unfactored seismic load
- material ultimate strength</td><td>Plastic hinge rotation:
θ<IO at at bottom levels
θ<LS at other levels
Shear forces<= ultimate shear capacity</td></tr>
<tr><td>Link beam</td><td>Allow plastic hinge;
Code-based strength design</td><td>Plastic hinge rotation:
θ<LS and <=0.02 rad</td></tr>
<tr><td>Super column</td><td>Elastic,
Code-based strength design
- factored seismic load
- material design</td><td>Plastic hinge rotation:
θ<IO at bottom levels
θ<LS at other levels
Stress in reinf. f > fy but < fu</td></tr>
</table>

			strength	
	Belt truss		Elastic, -factored seismic load -material design strength	Elastic , steel stress f < fy
	Outrigger		Code-based strength design -unfactored seismic load -material ultimate strength	Plastic deformation: θ<LS and stress f < fu
	Critical Connections		Elastic, Strength design per code: factored seismic load, material design strength	Special FEM analyses are required and stress f<= fy

Table 3 Performance Target and Acceptance Criteria

Abaqus and Perform 3D computer programs, widely used for nonlinear analysis, were used to develop and analyze the mathematical models.

Seven sets of ground acceleration time histories were selected from among available worldwide records to match the soil profile and were scaled to reflect expected earthquake intensity at the Shanghai Center building site. Each set included two orthogonal horizontal components plus one vertical component acting simultaneously at a ratio of 1: 0.85: 0.65.

The nonlinear load-deformation characteristics of individual components were modeled according to the constitutive relation curves of concrete and steel provided in the China code.

A summary from extensive PBD analyses includes the following findings:

- For maximum story drift ratios, average values are 1/131(X) and 1/144(Y) (see Figure 10).
- Core compressive demand is below ultimate capacity except at a few local points.
- Most link beams exhibit plastic deformations within the “Life Safety” limit.
- Most outrigger trusses and belt trusses members are still in the elastic range.
- Embedded steel elements in super columns and core walls are in the elastic range.
- Overall, the tower achieves the requested “Life Safety” performance level.

CONCLUSION

The Shanghai Tower design brought structural engineers a series of challenges: supporting a heavy tower on soft soils, resisting huge lateral loads while controlling story drifts, supporting the curtain wall panels of a unique twisting exterior facade disengaged from the main building, and using advanced analysis methods to evaluate structural performance under different levels of seismic events. Creative structural solutions, such as an Exterior Mega Frame to enhance tower lateral stiffness and strength, and state-of-the-art analysis approaches from Performance Based Design were applied to result in an innovative and economical structural design.

ACKNOWLEDGEMENT

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PROJECT DESIGN TEAM CREDITS

Client: Shanghai Tower Construction & Development Co. LTD

Architect: Gensler

Structural Engineer: Thornton Tomasetti Inc.

MEP Engineer: Cosentini Associates

Local Design Institute: Architectural Design & Research Institute of Tonji University

Wind Engineering Consultant: Rowan Williams Davies and Irwin Inc. (RWDI)

Fire Safety Consultant: Rolf Jensen & Associates (RJA)

REFERENCE

IBC (2006), International building Code , International Code Council.

ASCE-41 (2006), Seismic Rehabilitation of Existing Buildings,

GB50011-2001 (2008 version), Code For Seismic Design of Buildings,

JGJ3 (2002), Technical Specification for Concrete Structures of Tall Buildings,

Shanghai Tower Detailed Reconnaissance Report (Final),   September 5, 2008, Shanghai Geotechnical Investigation & Design Institute Co., Ltd.

Image Captions

Include all figure reference captions in order of appearance in the main body text below using the following format:

Figure 1. Shanghai Tower 3D Rendering View (Source: Gensler)

Figure 2. Shanghai Tower Stacking (Source: Gensler);

Figure 3. Shanghai Tower Typical Floor Plans (Source: Gensler)

Figure 4. Settlement Contours With and Without Fin Walls (Source: Thornton Tomasetti)

Figure 5. Lateral System Components (Source: Thornton Tomasetti)