ARCH 631 Applied Arch Structure | Case Study | Professor Anna Nichols | 12-04-2014

SHANGHAI TOWER

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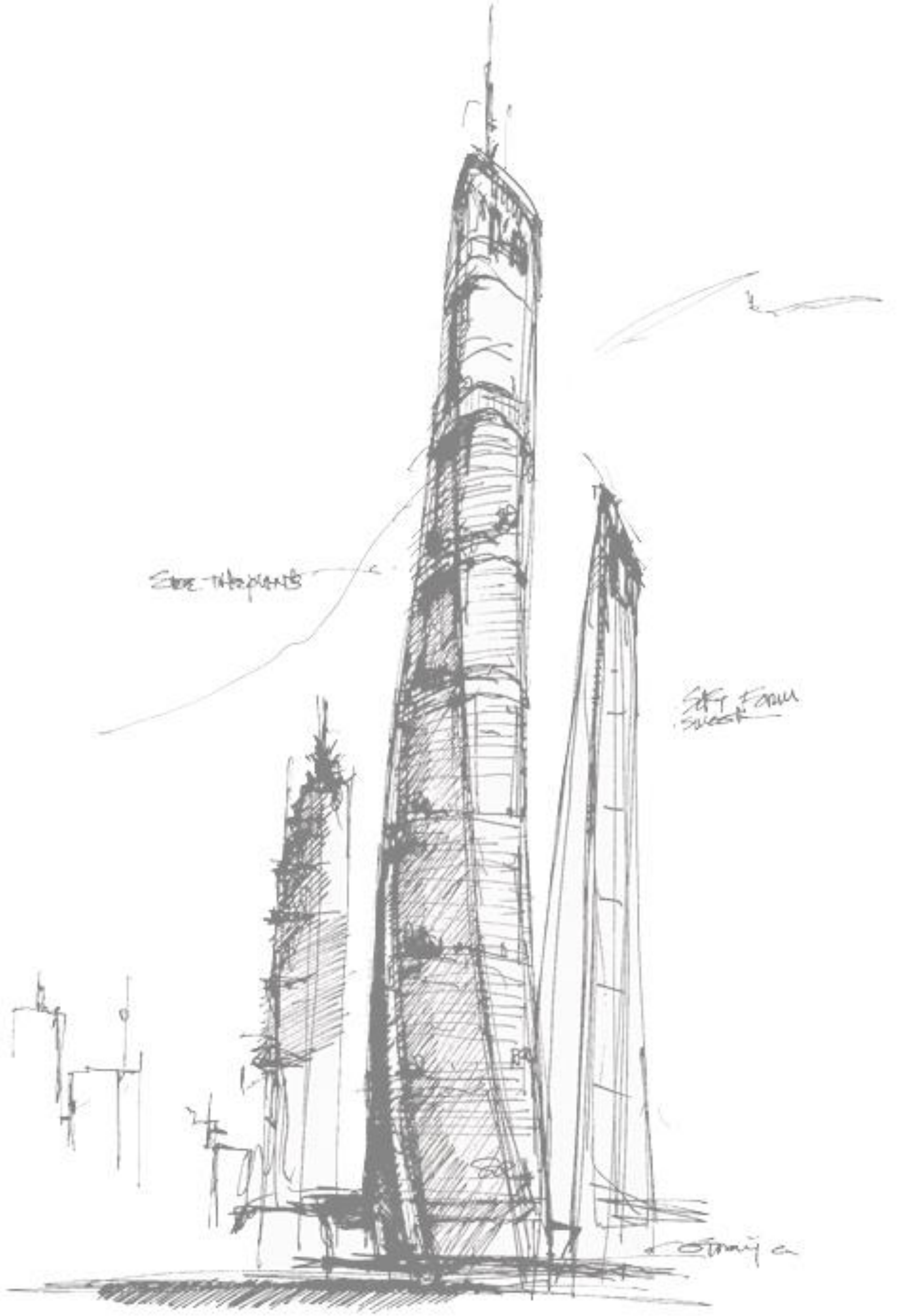
- INTRODUCTION
- STRUCTURE FEATURES
- FOUNDATION SYSTEM
- LOADING ANALYSIS
- LATERAL LOAD BEHAVIOR



PART 1 INTRODUCTION

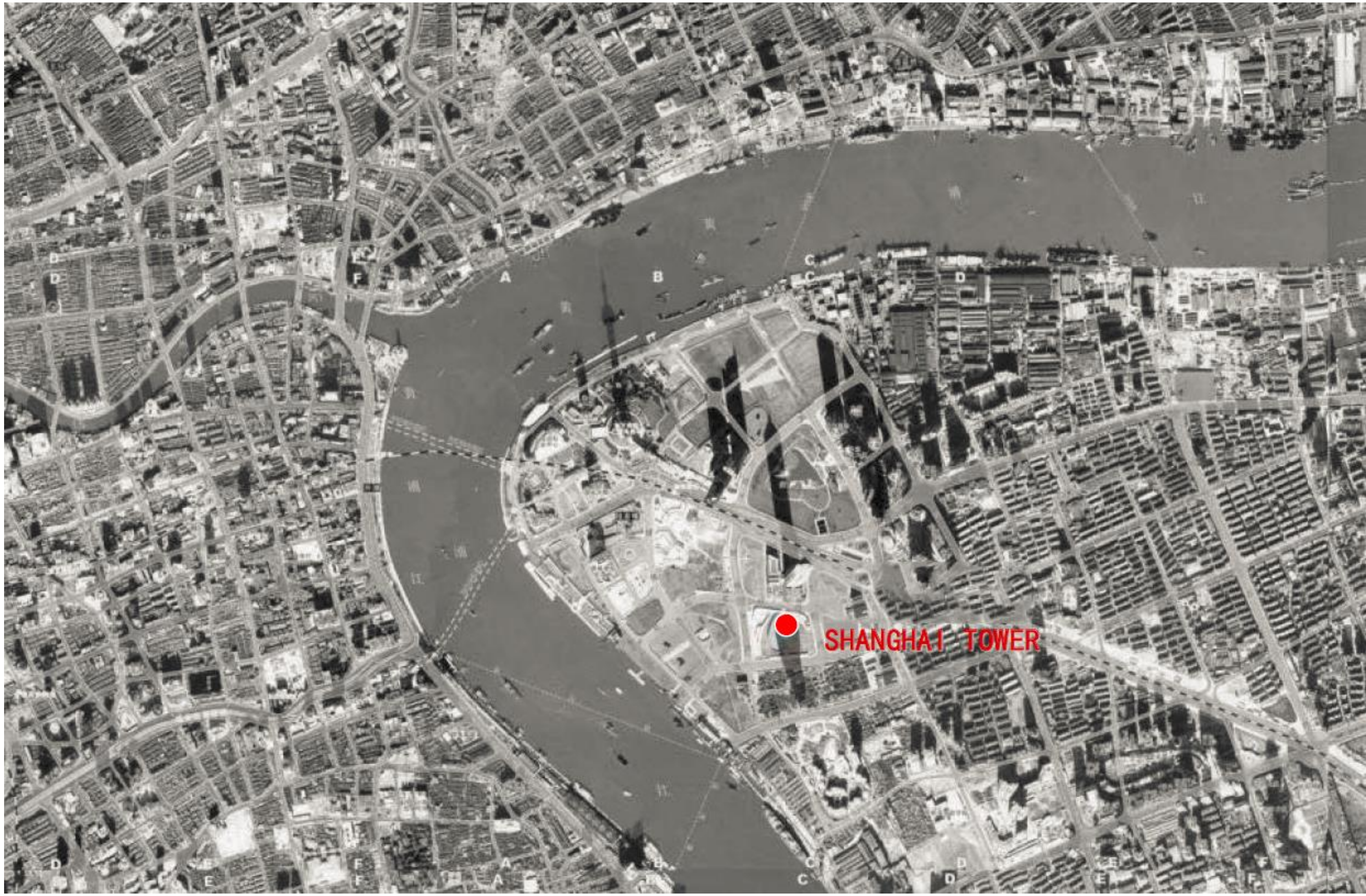
- **General Information**
- **Design Concept**
- **Building Layout**

General information

Status: Topped-out
Location: Lujiazui, Pudong, Shanghai

Architectural: 632 m (2,073 ft)
Floor count: 121
Floor area: 380,000 m^2 (4,090,300 sf) above
170 m^2 (1,800 sf) below

Architect: Gensler
Engineer: Thornton Tomasetti

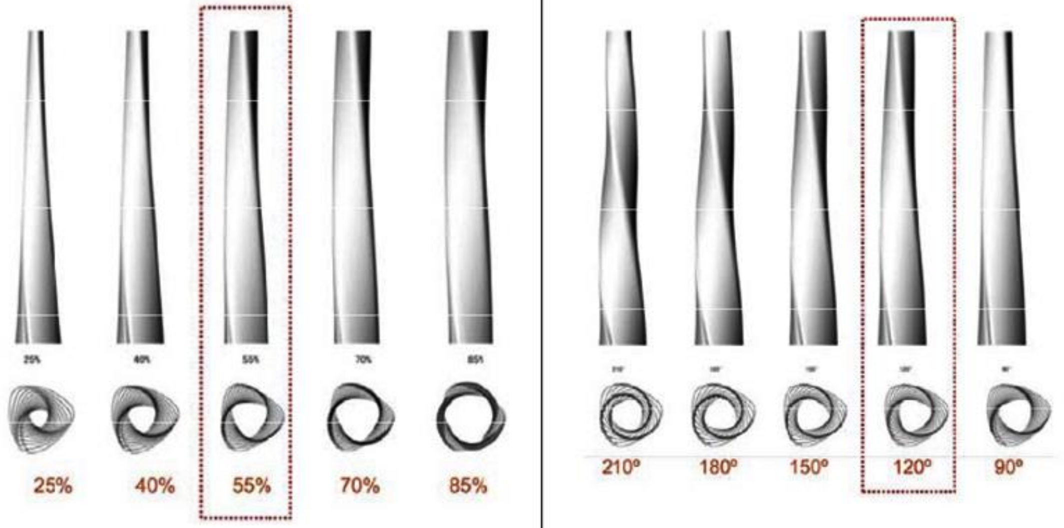



2008
Groundbreaking
2010
Foundation Poured
2011–2012
Core and Shell Rise
2013
Topping Out

Design Concept

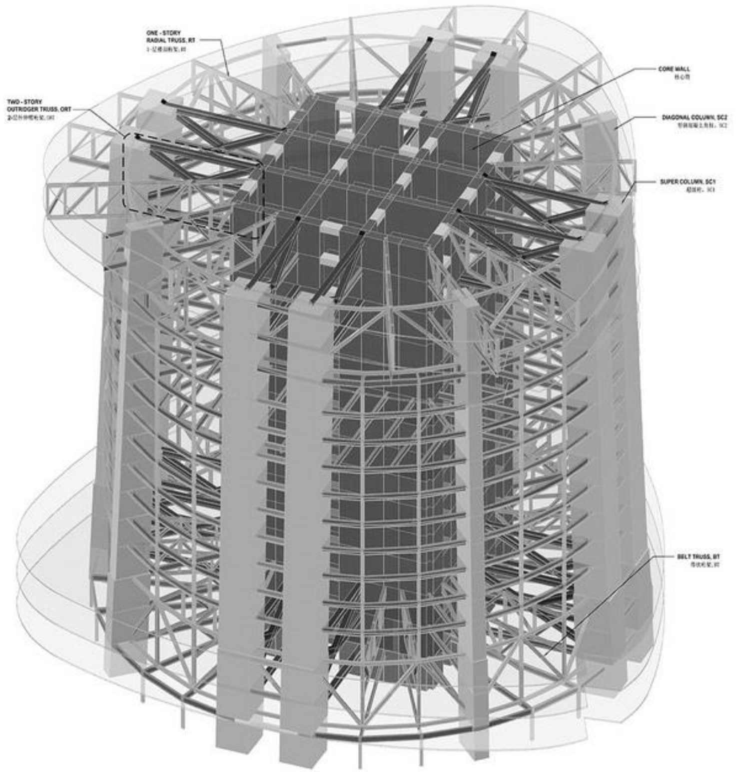
Sculpted for Efficiency

The wind tunnel test is used to find the most beneficial scaling factor of about 55% and rotation at 120°, which is account for the 24% savings of the wind load working on the structure.



Technical Innovation

The concrete core acts with outriggers and supercolumns are the advances science of super-high rises.



Vertical Community

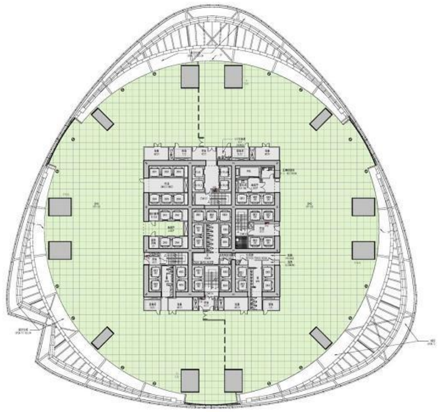
Shanghai tower embodies a new concept of super-tall building by emphasizing public spaces at the atrium levels.

Sustainable Achievements

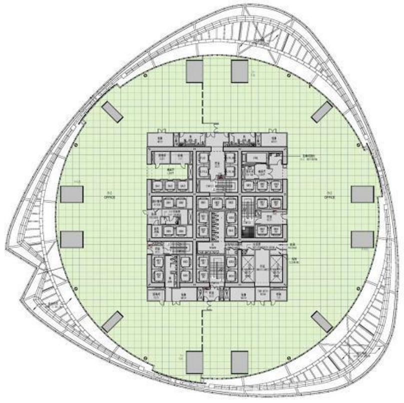
There are two lays of skin wrapping the entire building. The atriums created by the skins features as an insulation which keep the temperature stable.

Building Layout

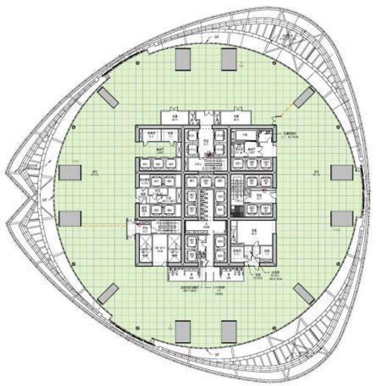
Shanghai tower's program is organized into 9 vertical zones.



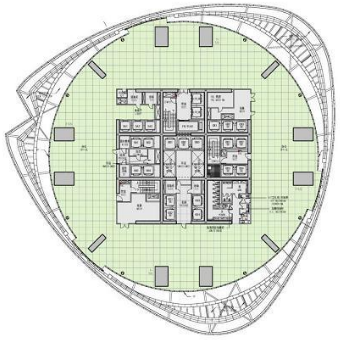
Lv8 6440m2
Lv9-19 4640m2



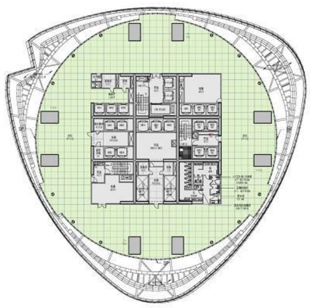
Lv22 5575m2
Lv23-34 3954m2



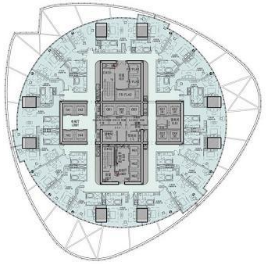
Lv37 4780m2
Lv38-49 3380m2



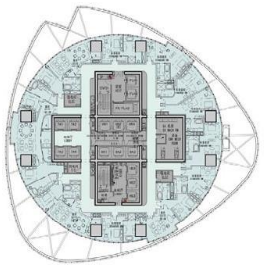
Lv52 4098m2
Lv53-65 2865m2



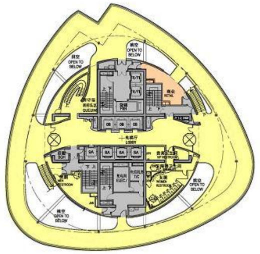
Lv68 3479m2
Lv69-81 2424m2



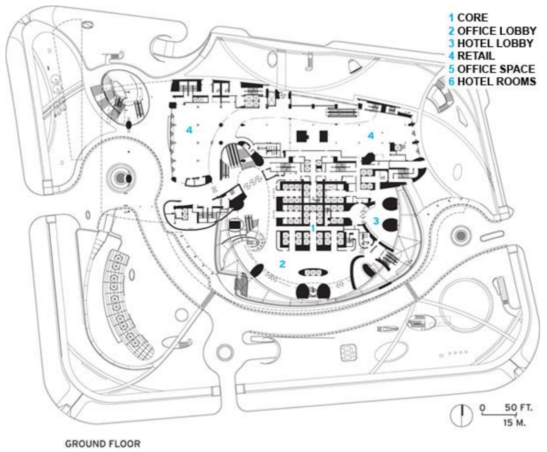
Lv84 2955m2
Lv86-98 2047m2

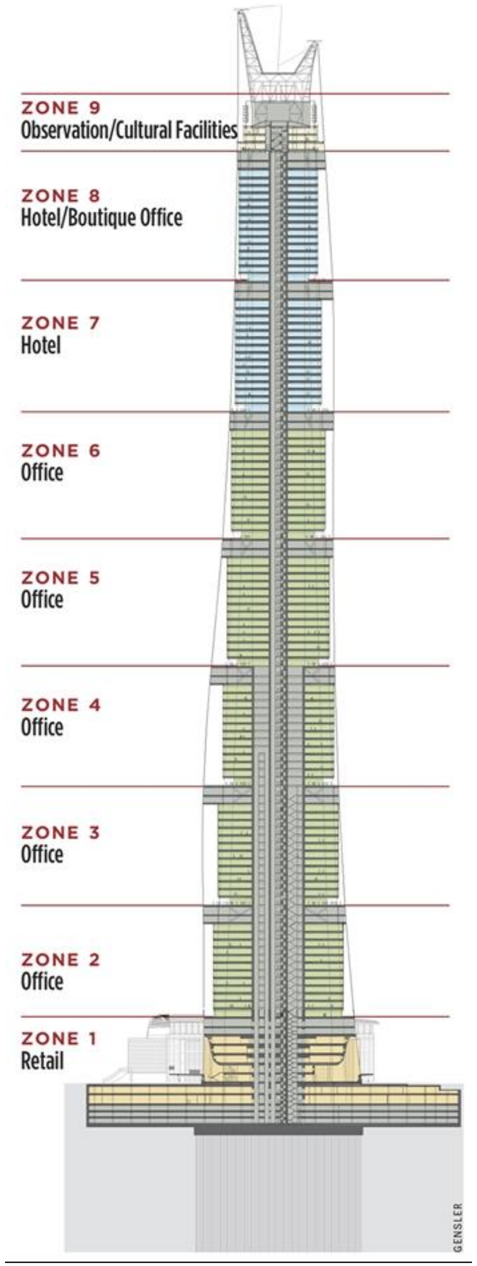


Lv 101 2497m2
Lv 106-110 1755m2



Lv 119 2080m2



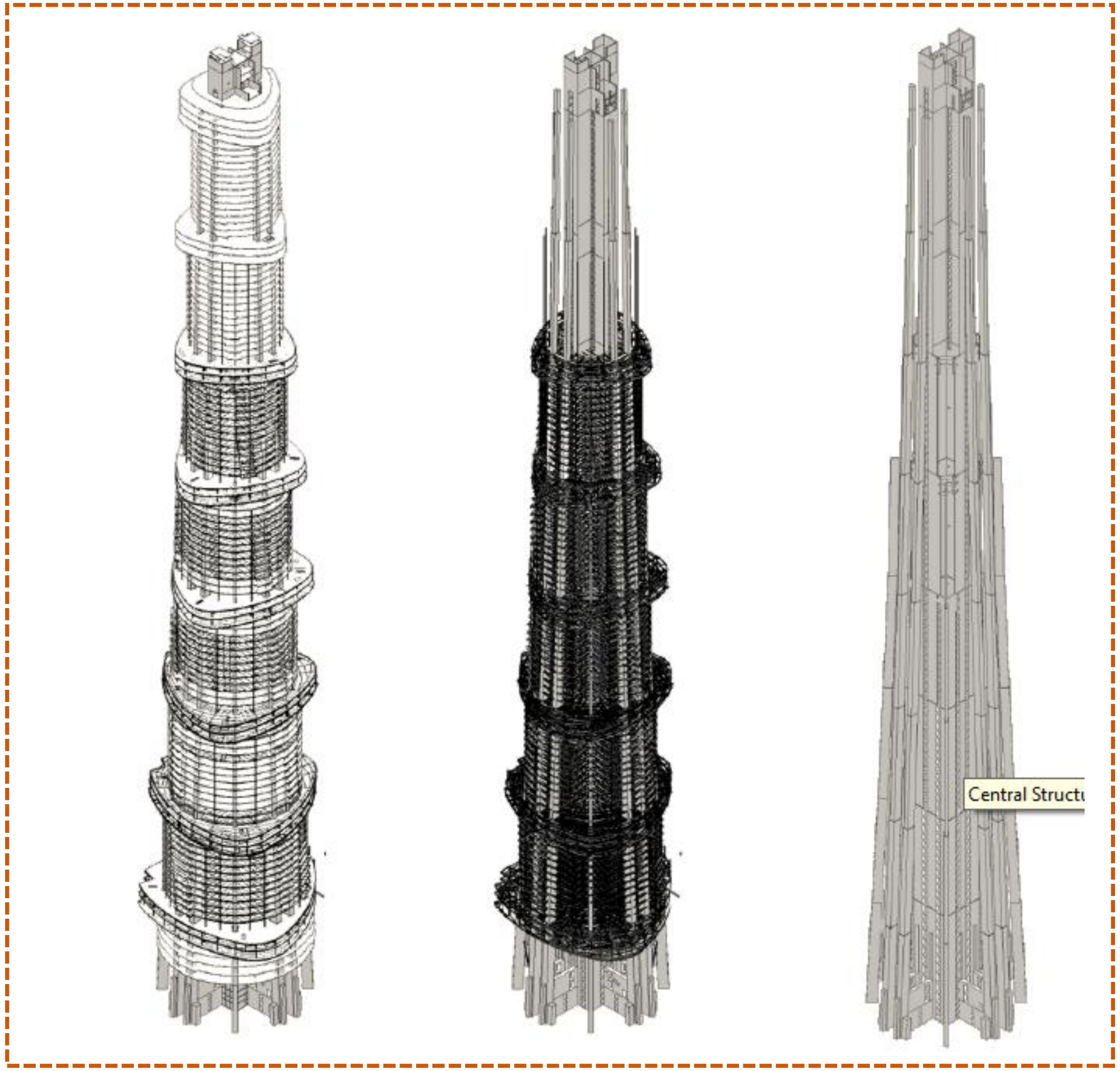


PART 2 STRUCTURE FEATURES

- Structure System
- Connection Description

Structure Component

- Curtain Wall System
- Main Structure System



Tower Top

Vertical fin-like truss
Two-way truss
Octagonal steel frame bracing system

Curtain Wall System

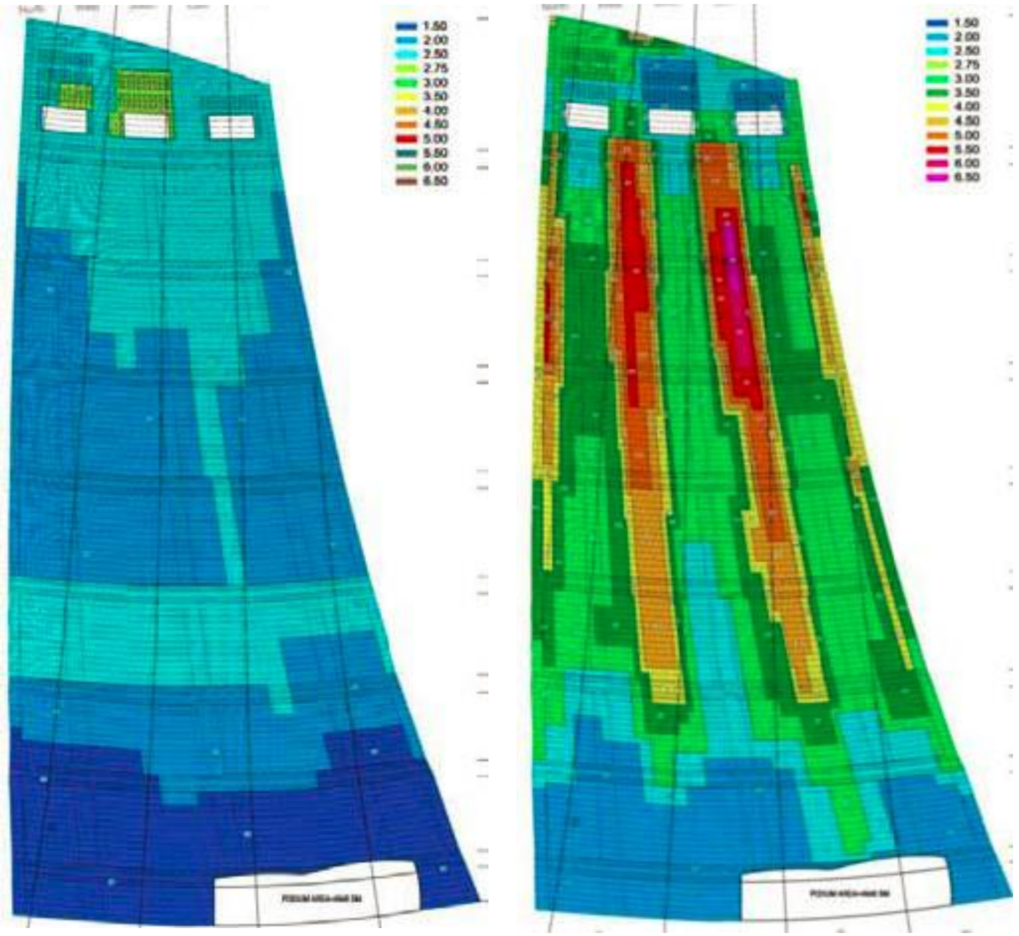
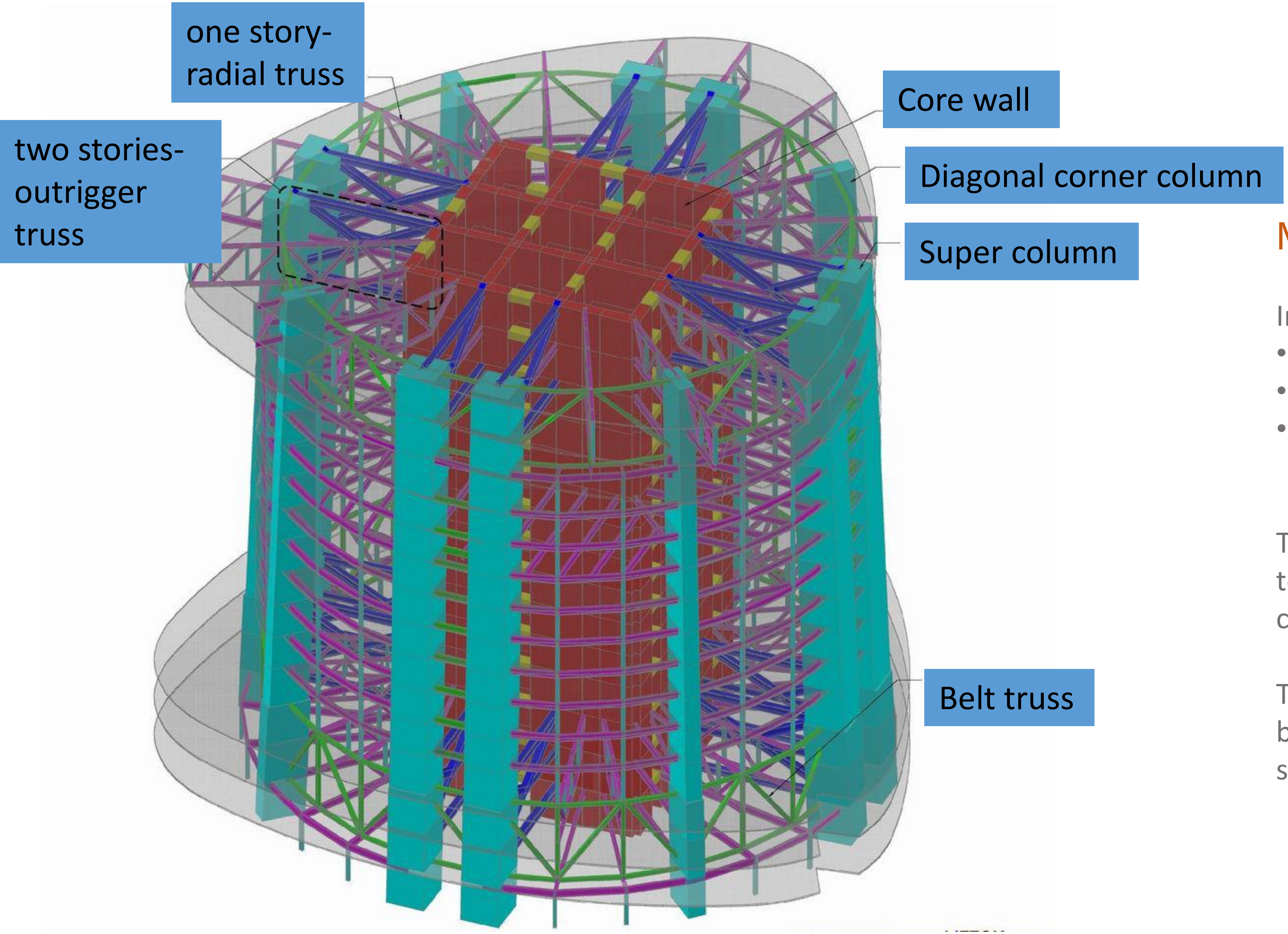


Diagram of positive and negative wind cladding loads (RWDI)



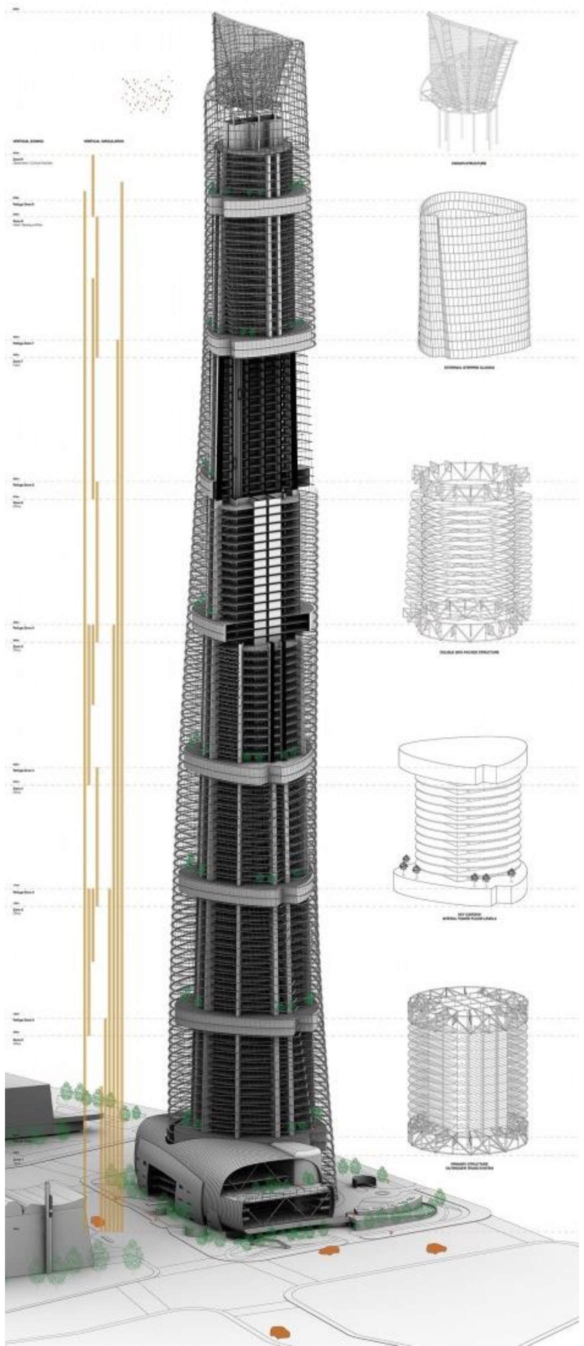
Main Structure

Inner Cylindrical Tower

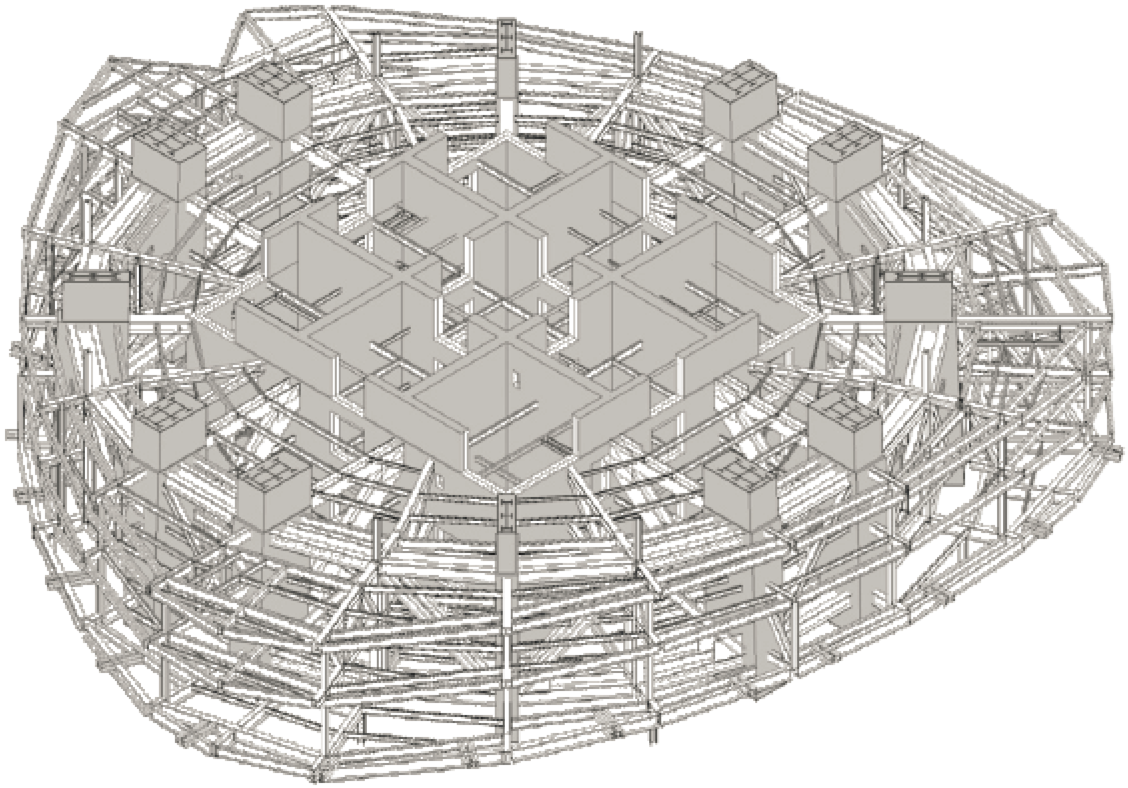
- Core
- Outrigger
- Mega Frame: Super column system and belt trusses

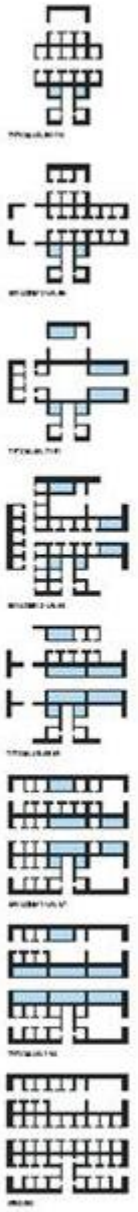
The lateral and vertical resistance of the tower will be provided by the inner cylindrical tower.

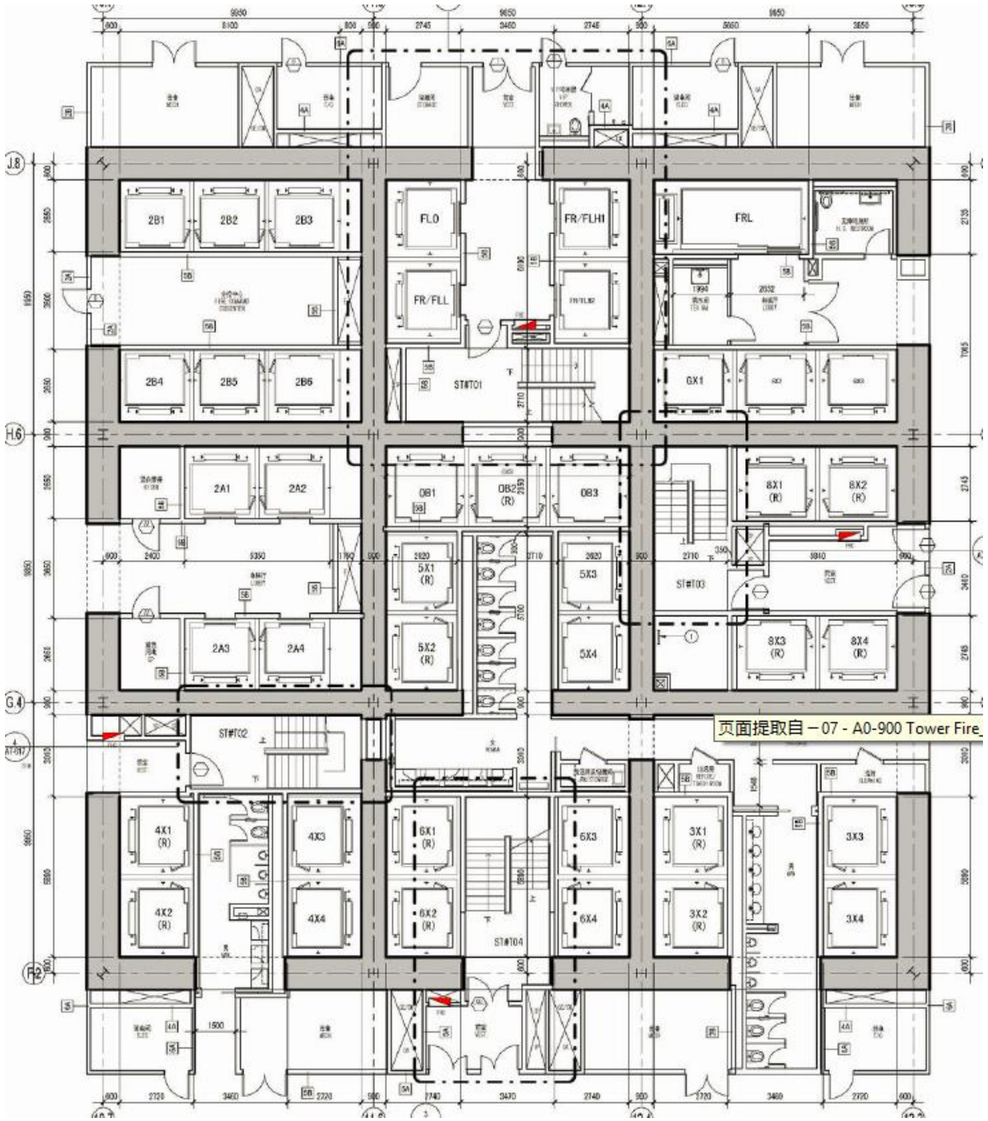
The primary lateral resistance is provided by the core, outrigger, and supercolumn system.



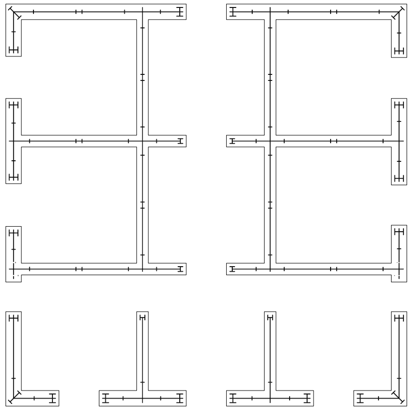
Inner Cylindrical Tower





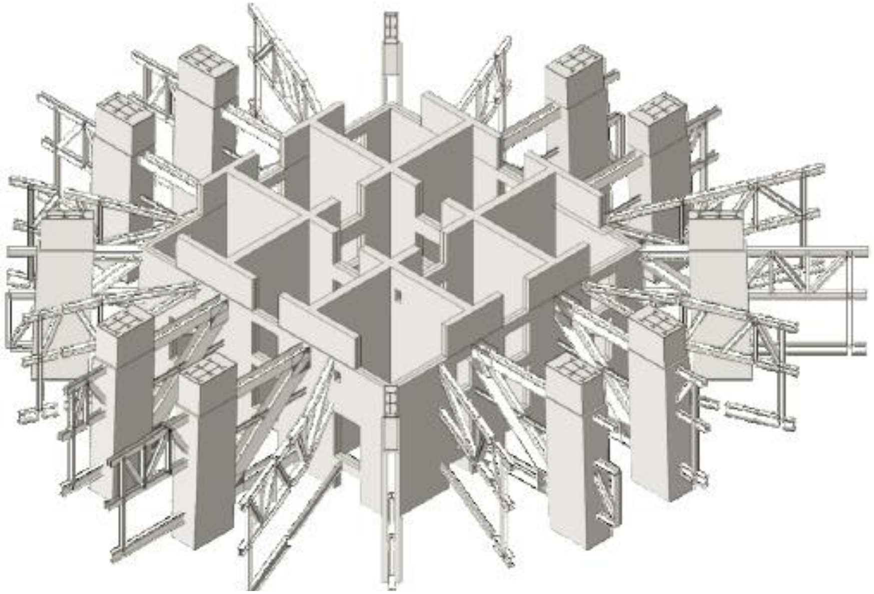


Core



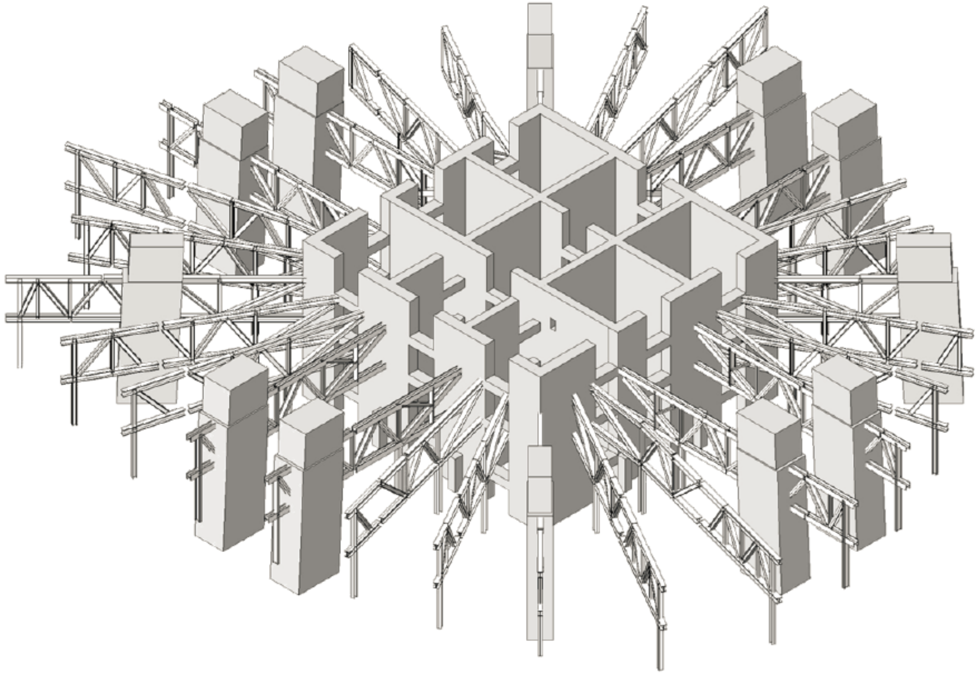
Core of the zone 1 and basement

shear wall: steel plate and concrete combination



Outrigger

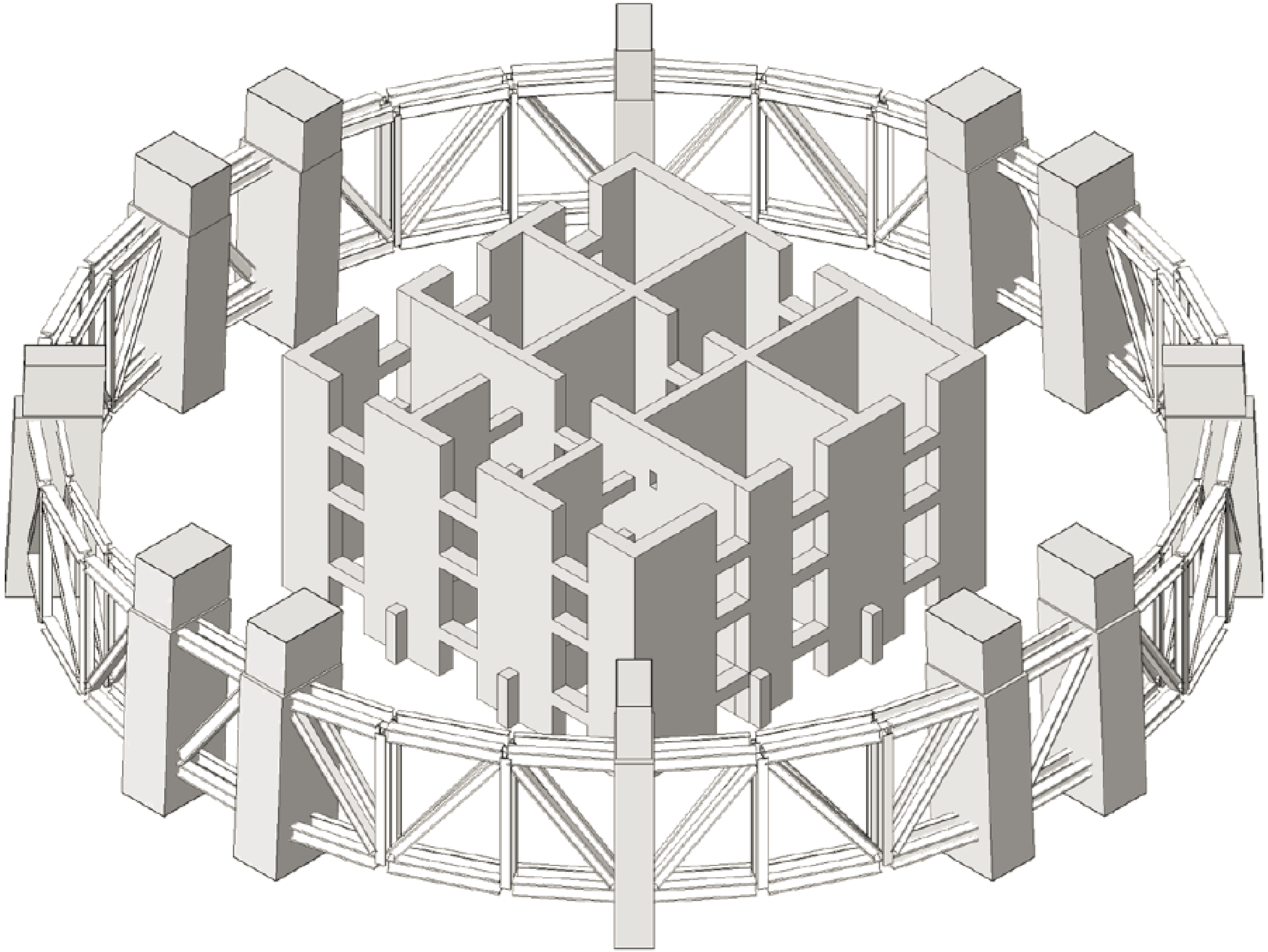
Double stories
In the steel section of the super columns, there are perpendicular cross ribs that align with belt trusses.



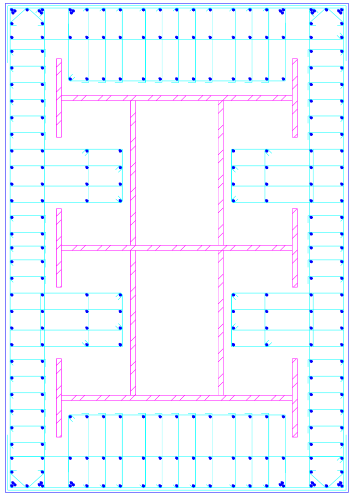
Radical Outrigger

One story

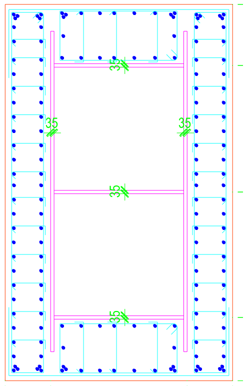
Mega Frame



Section of Super-column



1-6 zone

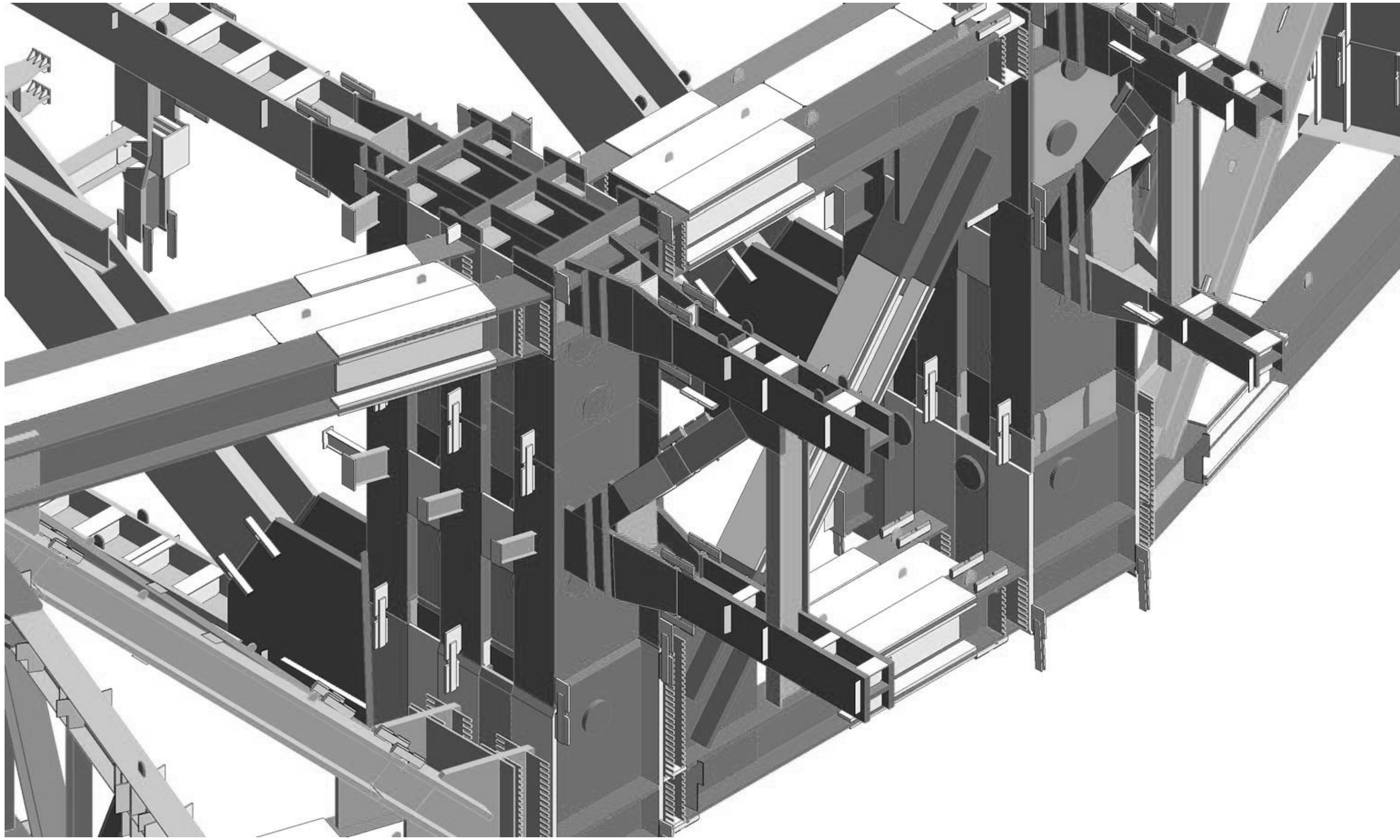


7-8 zone

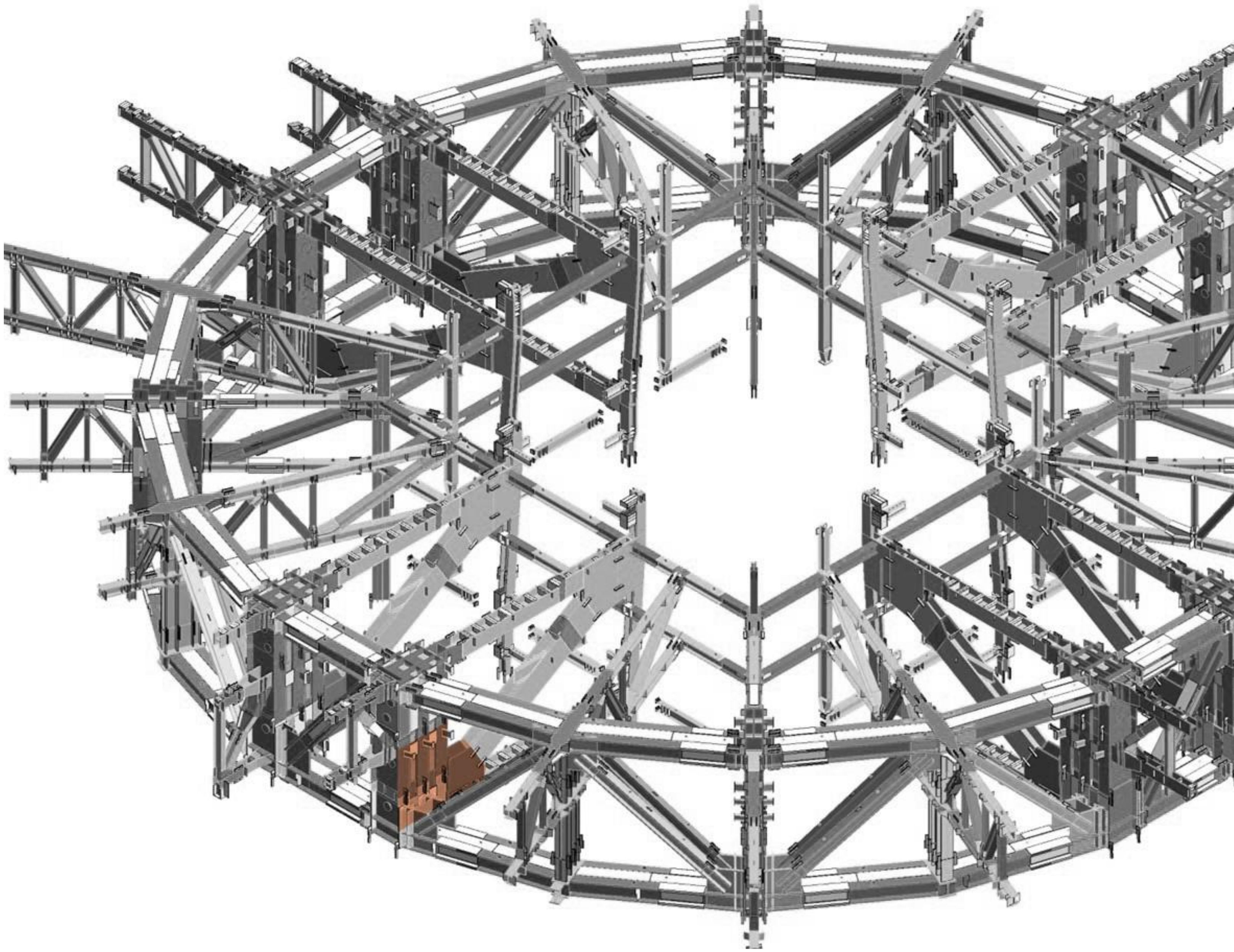
Supercolumn System: two at each end of each orthonormal axis
four diagonal supercolumns along each 45-degree axis

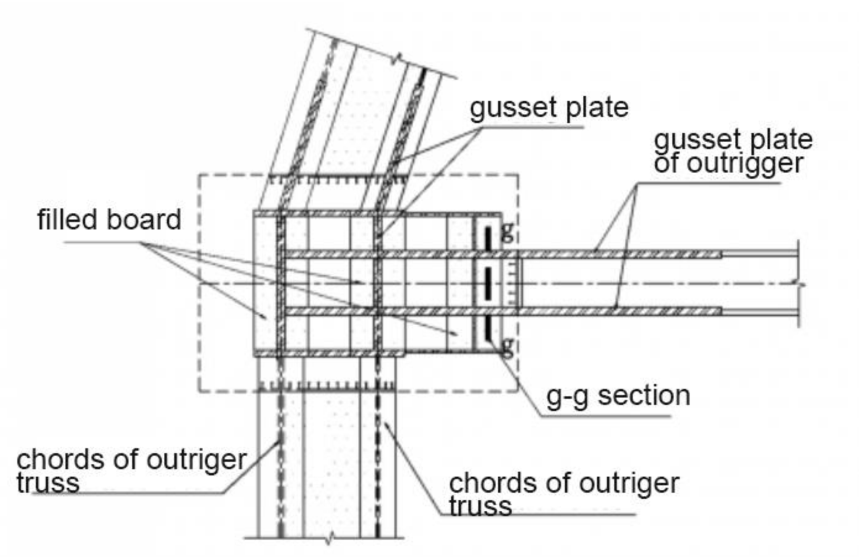
Connection Description

- Complexity of stress state.
- Connections should be broken after the destructiveness of members
- Different connections have different design criteria, according to the variation of structure members.



Type A: The Joint of Outrigger to Super-column

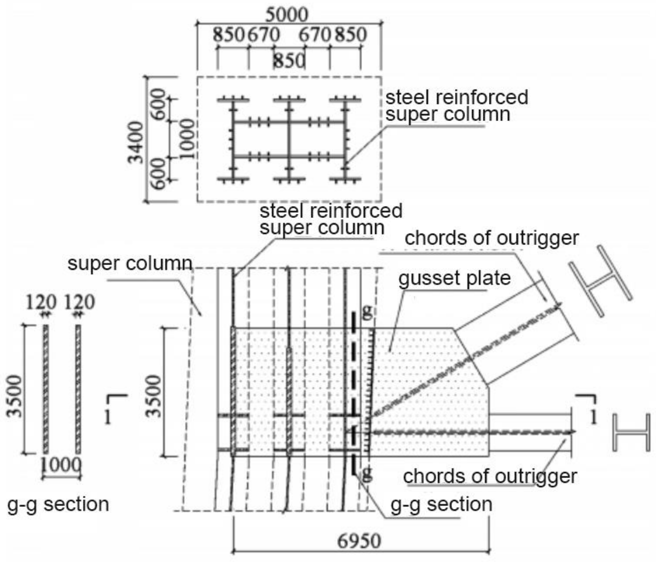




(b) PLAN (FOR 1-1 SECTION)

Technical Features

- The chords of outrigger truss
- Gusset plates, 120mm thickness, Q390GJC steel
- The steel reinforced dual web of the super-column
- The belts trusses



(a) ELEVATION

Design Principle

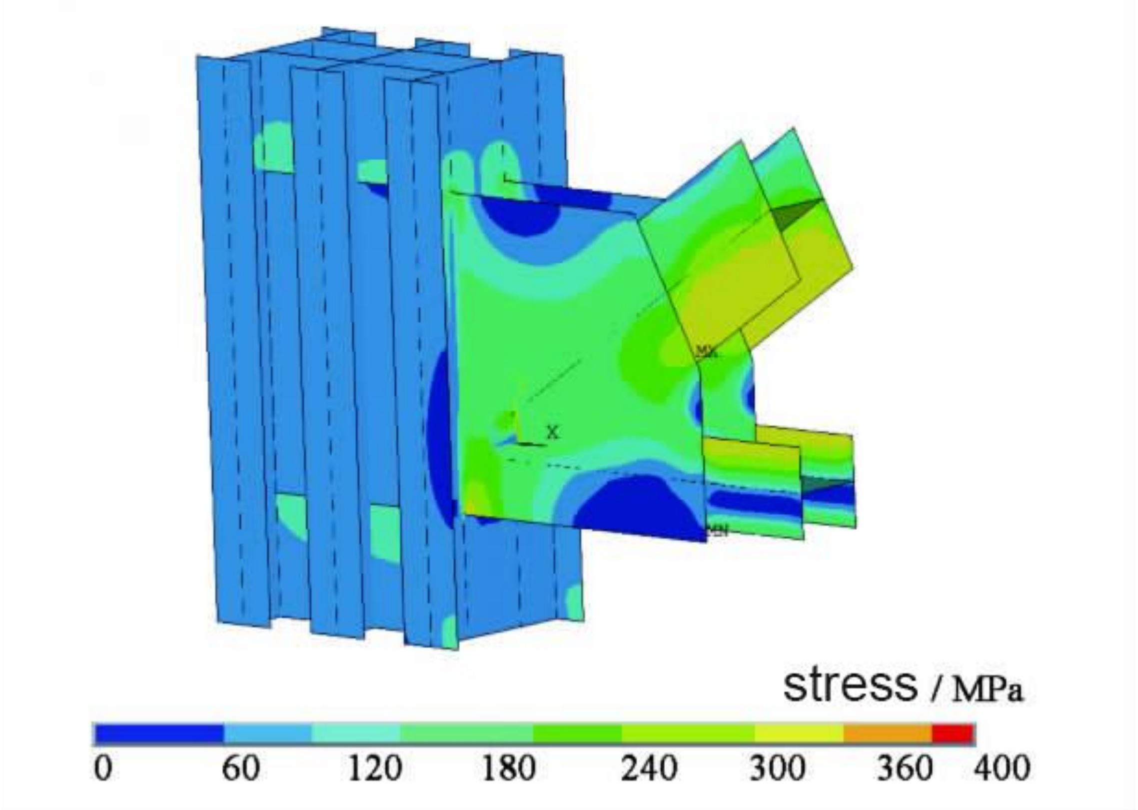
- Gusset plate design should ensure that every rods of outrigger truss would be anchored strongly in the gusset plate.
- Gusset plate design should ensure that the joint action of webs and chords of outrigger have enough strength.

Stress State

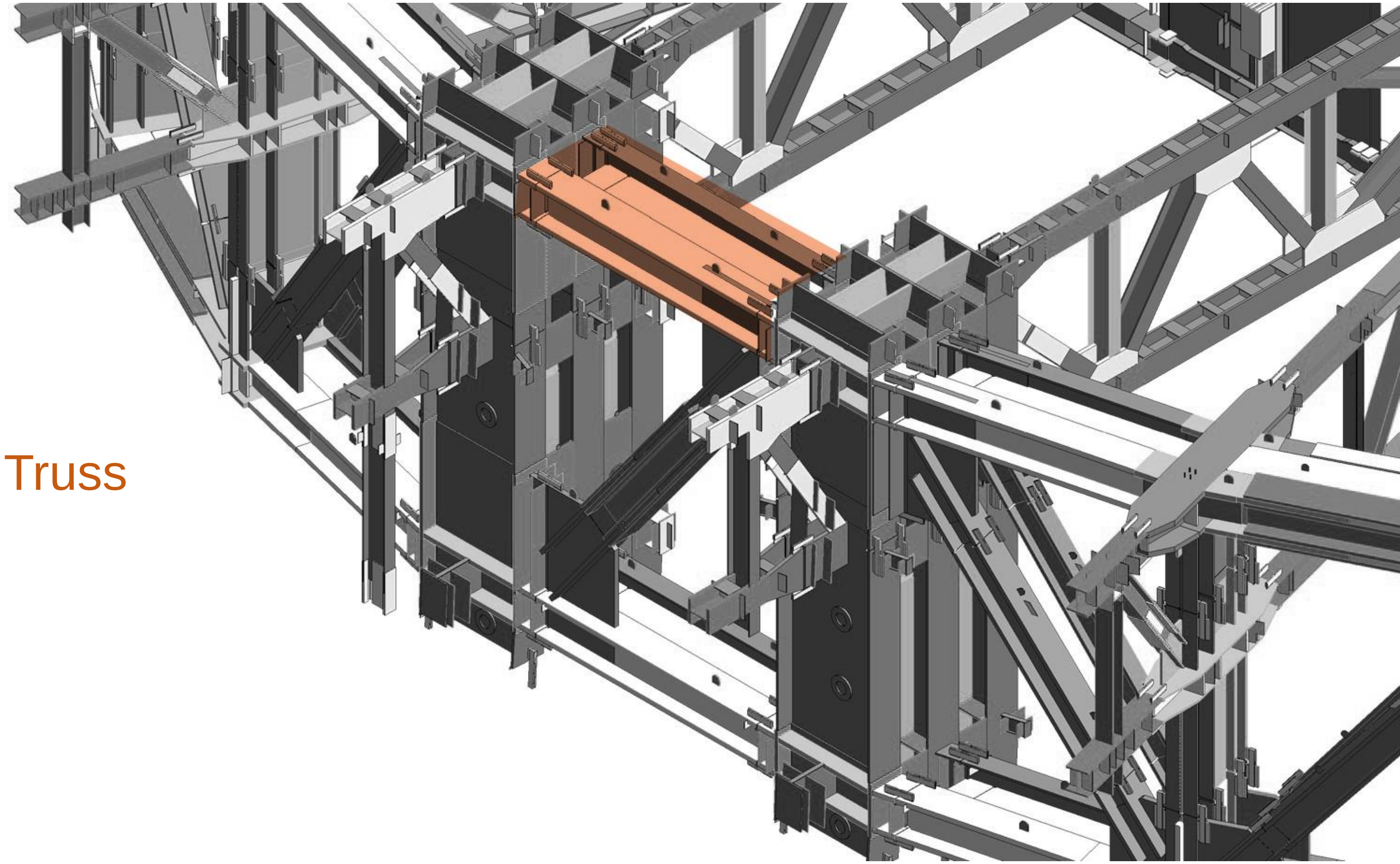
- The members of outrigger bear compress and tension bending.

Safety Estimation

- The final undermine performance are the local instability and over-large plastic deformation in each plates of diagonal web members of outrigger truss, while there is no damage in node area.

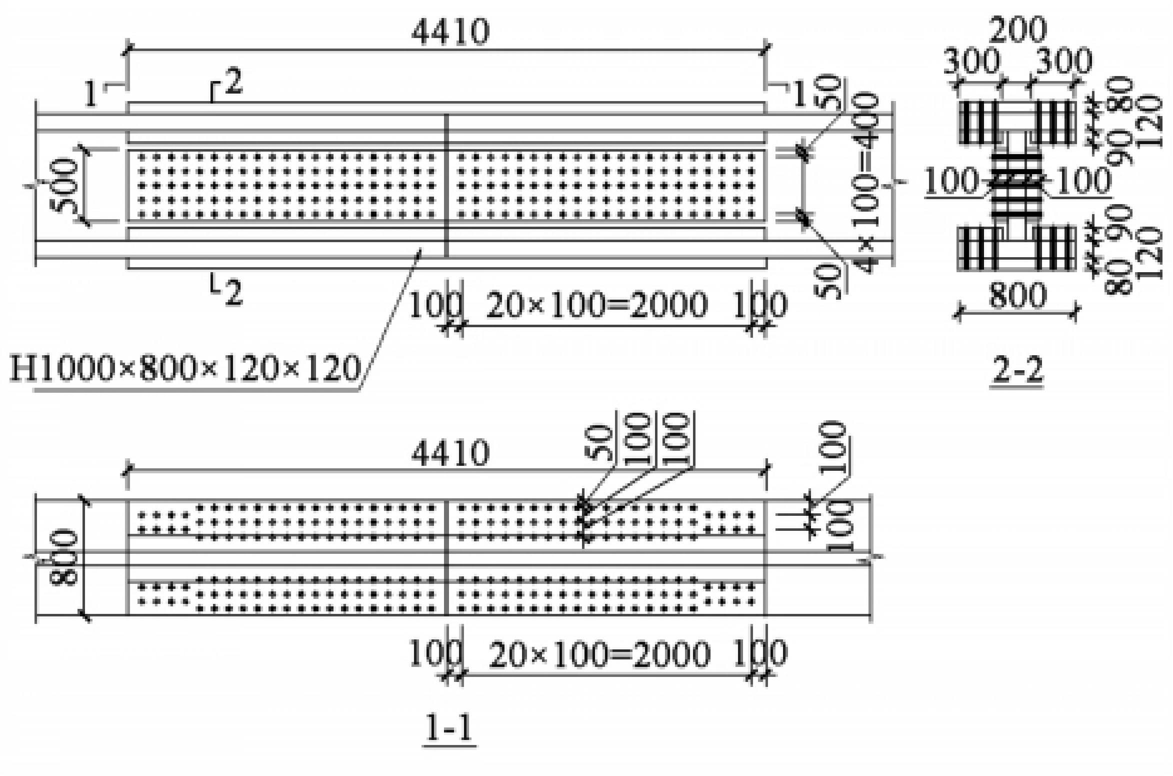


Type B: The Long Bolt Joint of the Belt Truss



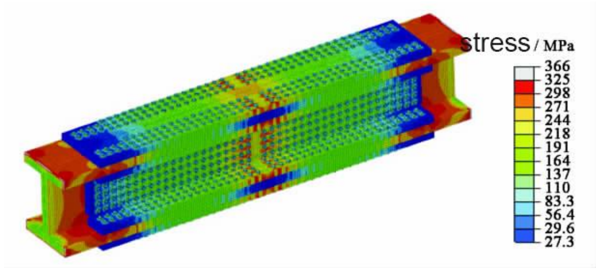
Technical Features

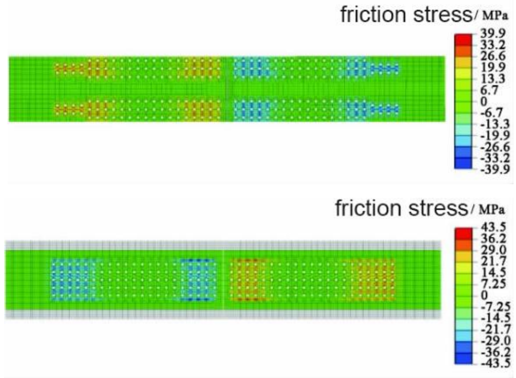
- Since there exist large member force of the chords in the belt trusses, there are large quantity of the bolts, and super length of the bolts set.



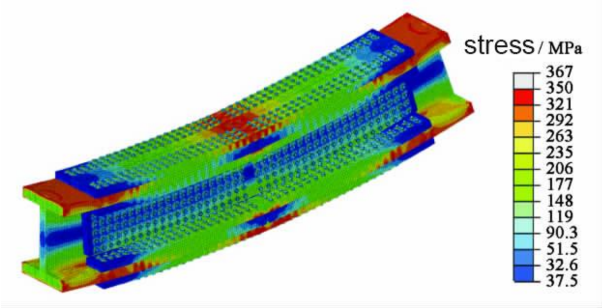
Stress State

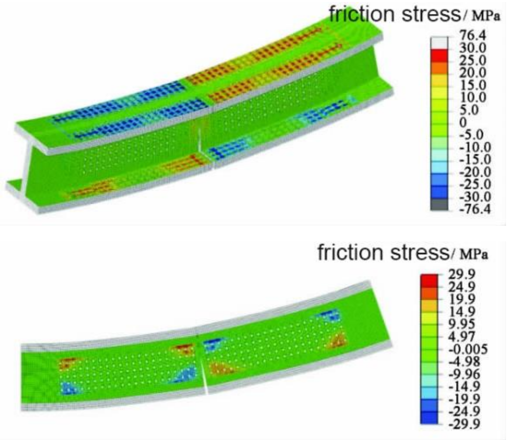
- Internal Force Analysis under axial force
- Internal Force Analysis under bending moment
- Internal Force Analysis under real loading



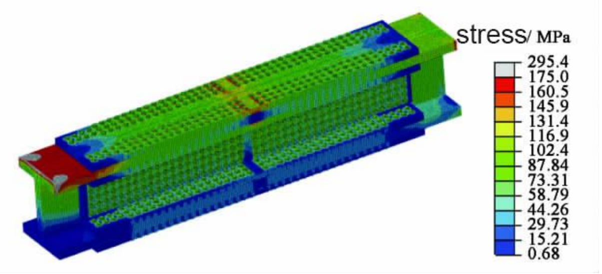


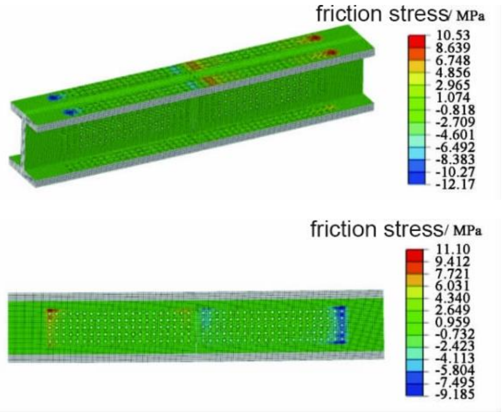
Axial Force





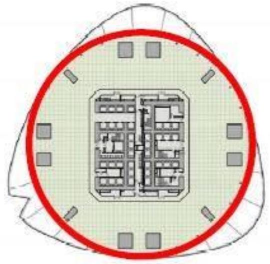
Bending Moment



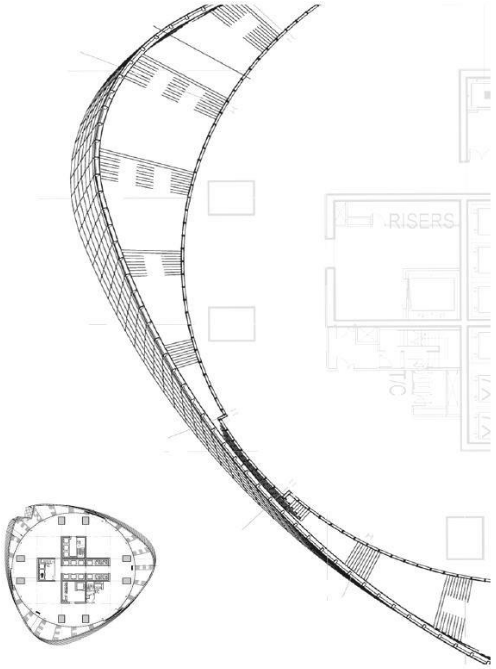


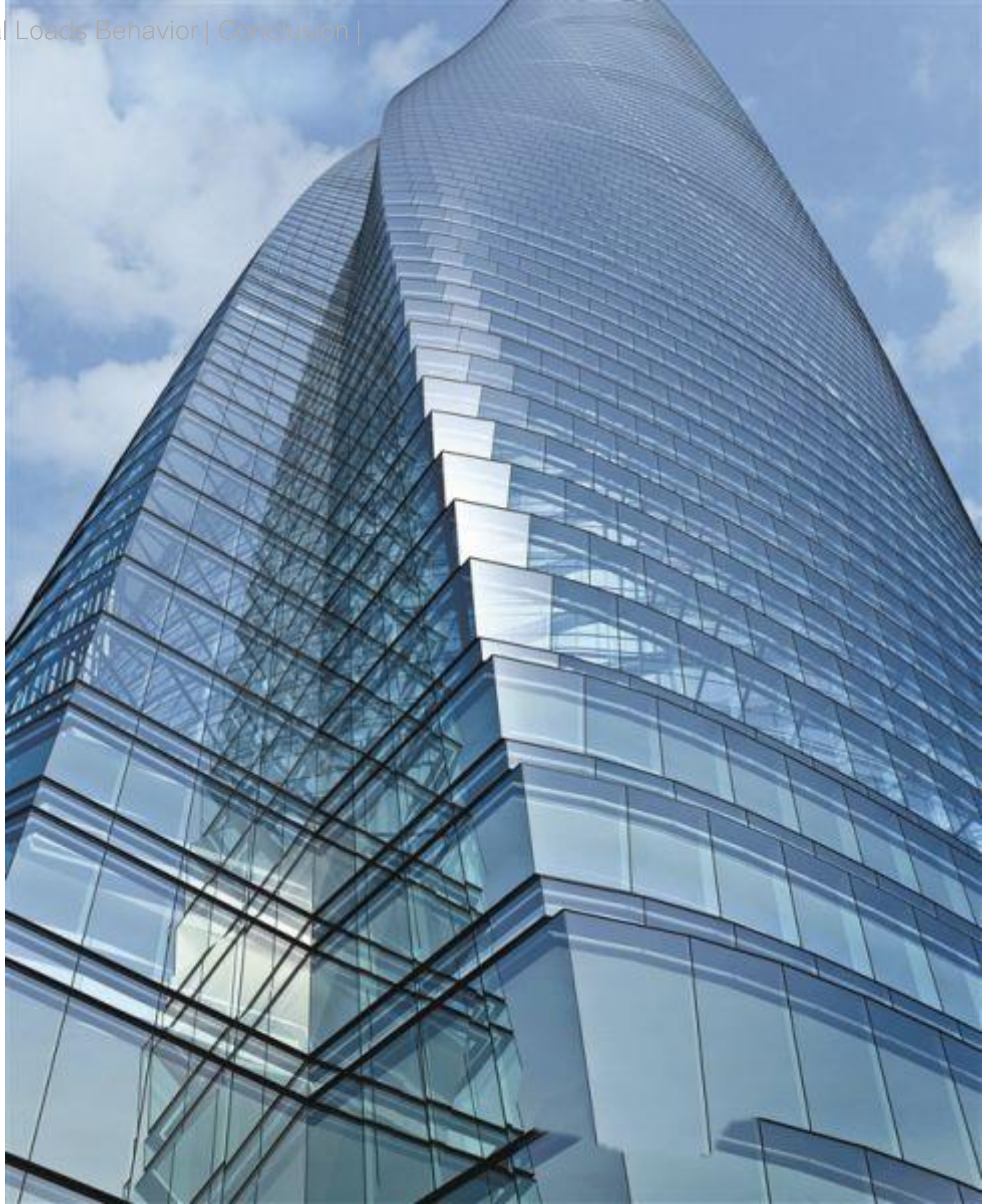
Real Loading

Type C: The Detail of Interior Curtain Wall



Type D: The Detail of Exterior Curtain Wall





PART 3 FOUNDATION

- **Soil Condition**
- **Foundation System**

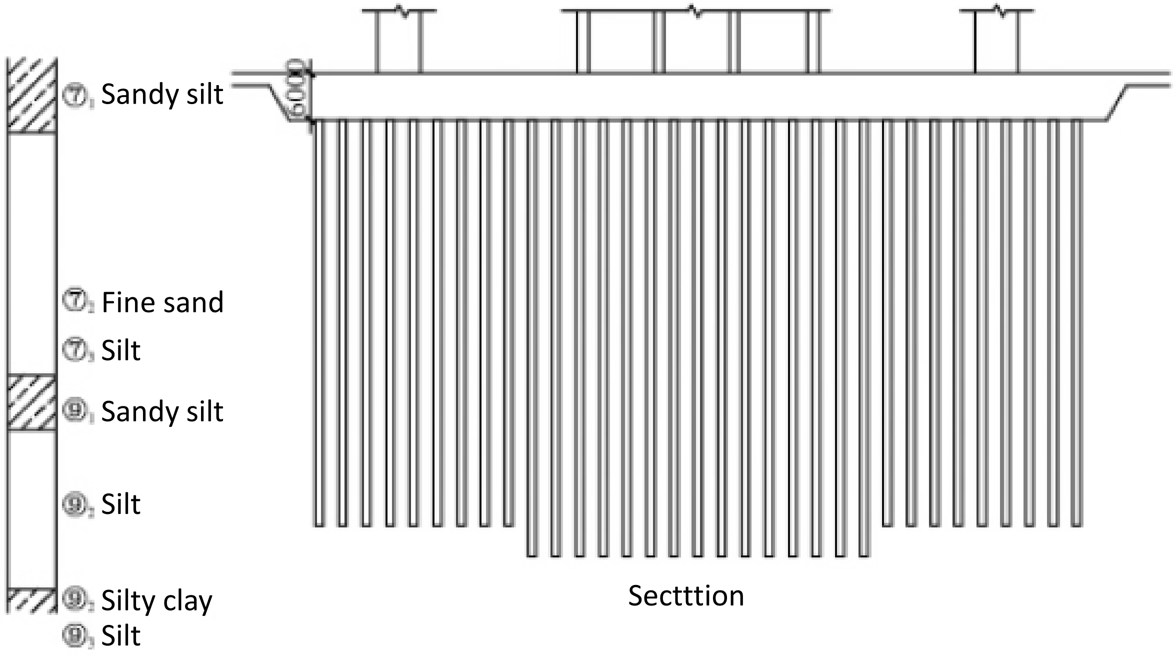
Soil condition and test pile

- Soft soil area
- Groundwater buoyancy 90%(practical design considerations 80% of water buoyancy)
- Select ⑨2 layer containing gravelly coarse sand layer, as pile bearing stratum

Section of soil layers and test pile

Foundation System

- Piled raft foundation
- Diameter 121 m, 6 m thick reinforced concrete circular platform
- Bored pile, pile length 56m in the core area, 52m in the extension area



Secttion

Load of Supercolumn and Core

巨柱编号	C218	C193	C169	C173	C209	C231	C207	C229	C171	C167	C220	C197	核心筒
DL/kN	403693	406632	195886	196516	386837	390033	403034	404702	196341	201084	409510	405155	2696986
LL/kN	403693	51980	29331	32124	45387	46761	54828	56425	32031	35069	53384	53576	381136

Excavation

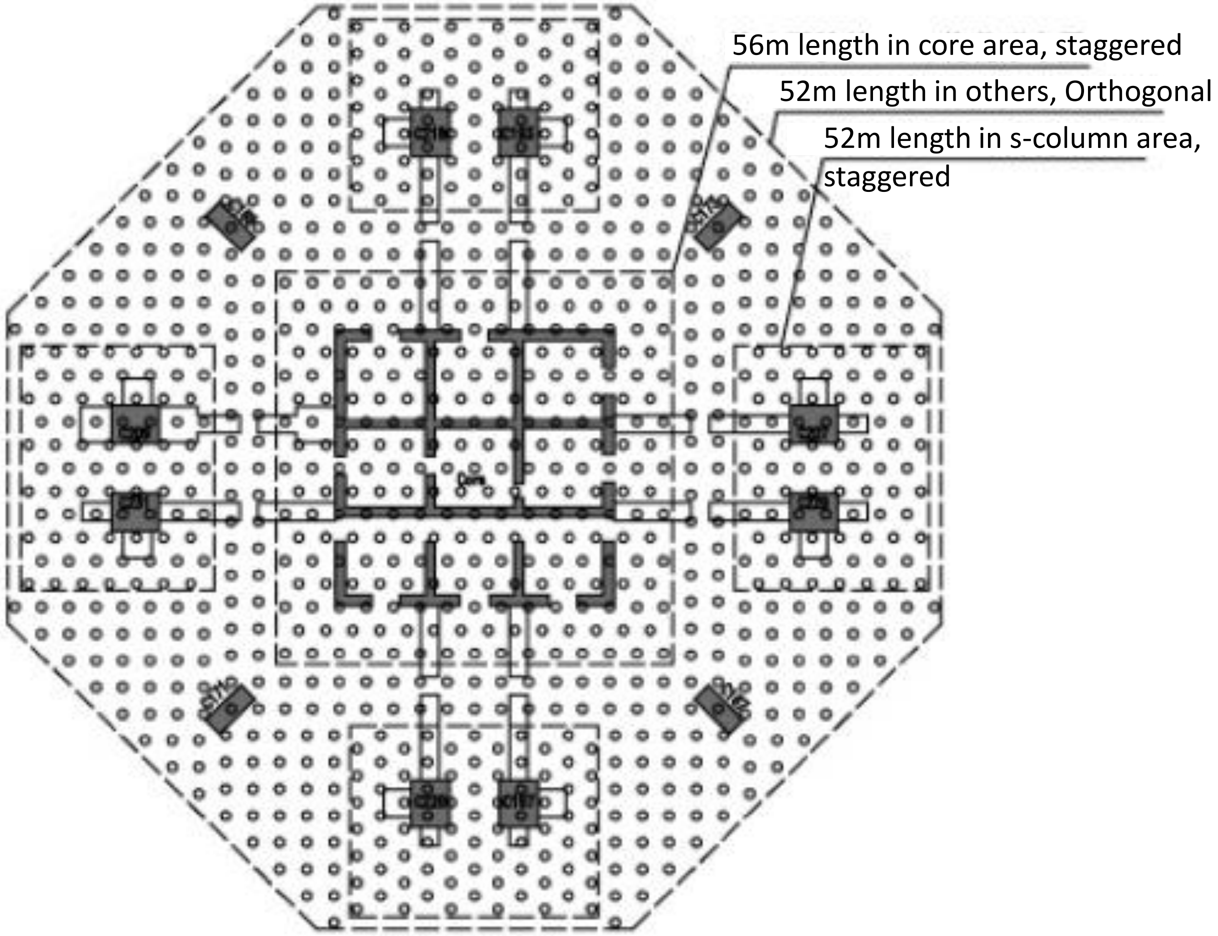
- Tower foundation pits area of 11,500 square meters and a depth of about 31 meters
- Non-beamed single building pit

Piles

- Staggered pile arrangement in load concentrated area
- Orthogonal shaped pile arrangement in other area

Table 3 Ratios of load by pile

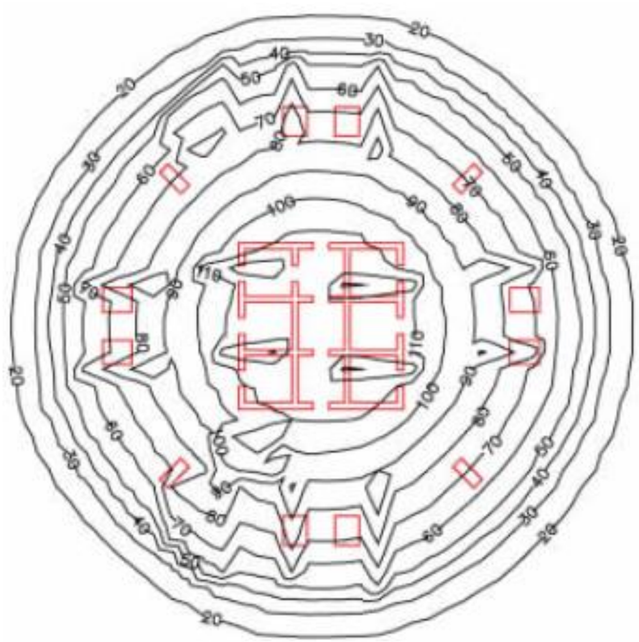
Method	Jin Mao Tower		SWFC		Shanghai Tower	
	Ratio of load	Ratio of buoyancy considered	Ratio of load	Ratio of buoyancy considered	Ratio of load	Ratio of buoyancy considered
1	70.9	100	68.0	100	62.1	100
1	90.0~95.0	0	77.6	60	68.1	80
2	70.7		68.0		62.4	



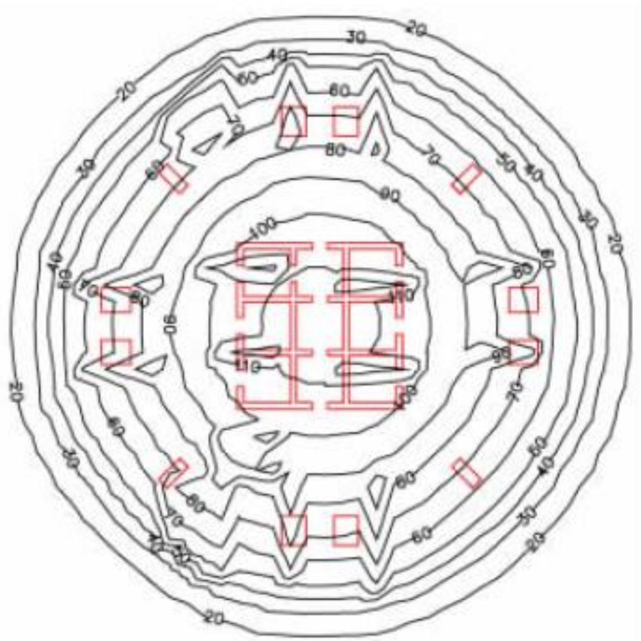
Piles Plan

Raft

- raft thickness is determined by the strength of anti-punching, and then check the flexural strength
- 6m thickness(3.7m of Dubai Khalīfa tower)
- Variable Stiffness Design to control Settlement
- Variable Stiffness iterative method to calculate the resulting of pile stiffness after the amended merger



Settlement of
Uniform stiffness design



Settlement of
Variable Stiffness Design

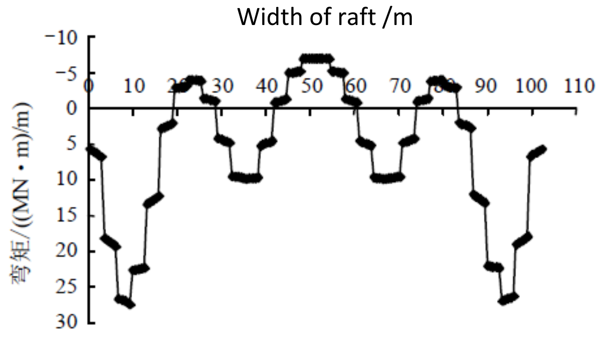


Fig.7 Distribution of bending moment of raft along center line

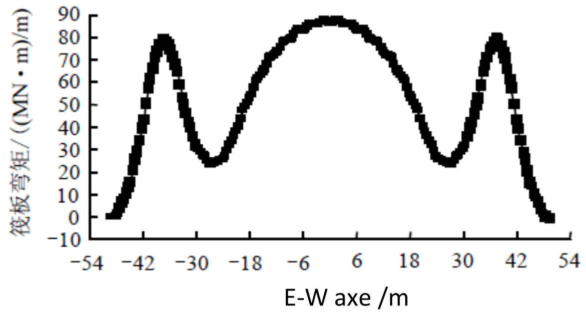


Fig.8 Distribution of bending moment of raft along east-west center line

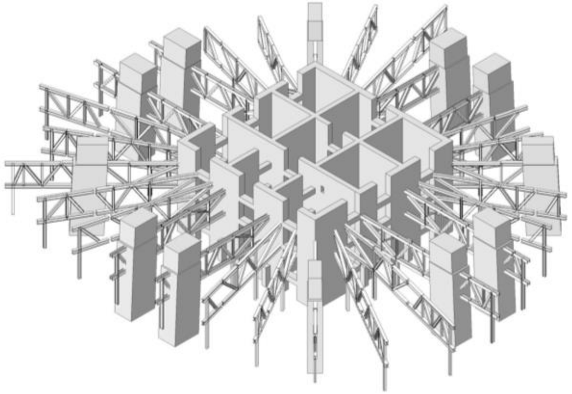
PART 4 LOADING ANALYSIS

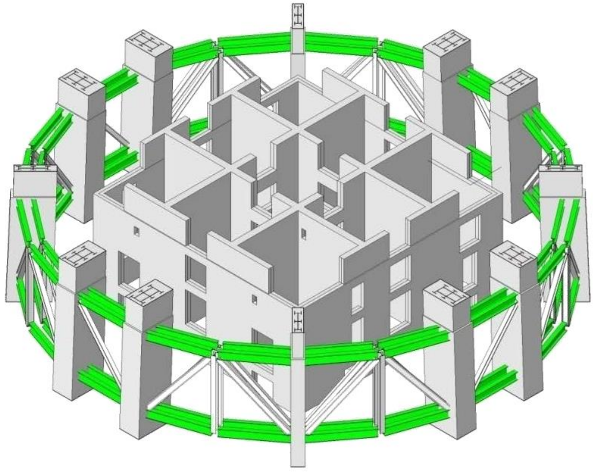
- Lateral Load Resisting System Description
- Gravity Loads Transfer Path
- Lateral Loads Transfer Path
- Multi-frame Analysis

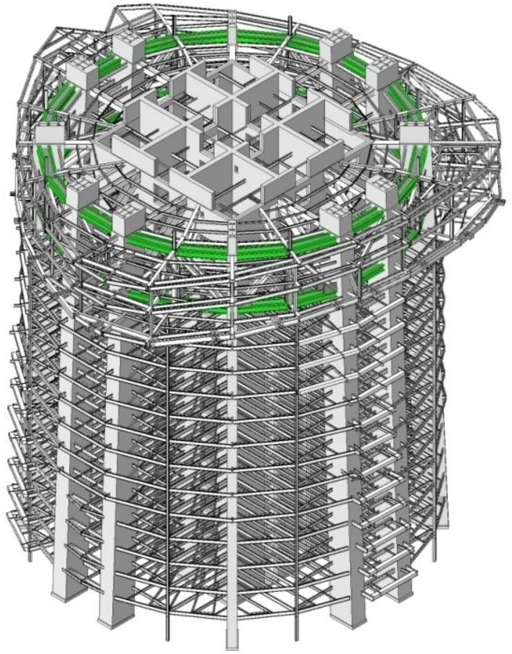
Lateral Load Resisting System

The lateral load resisting system is comprised of:

a) an interior reinforced concrete core
b) exterior composite super columns
c) steel outrigger and belt trusses





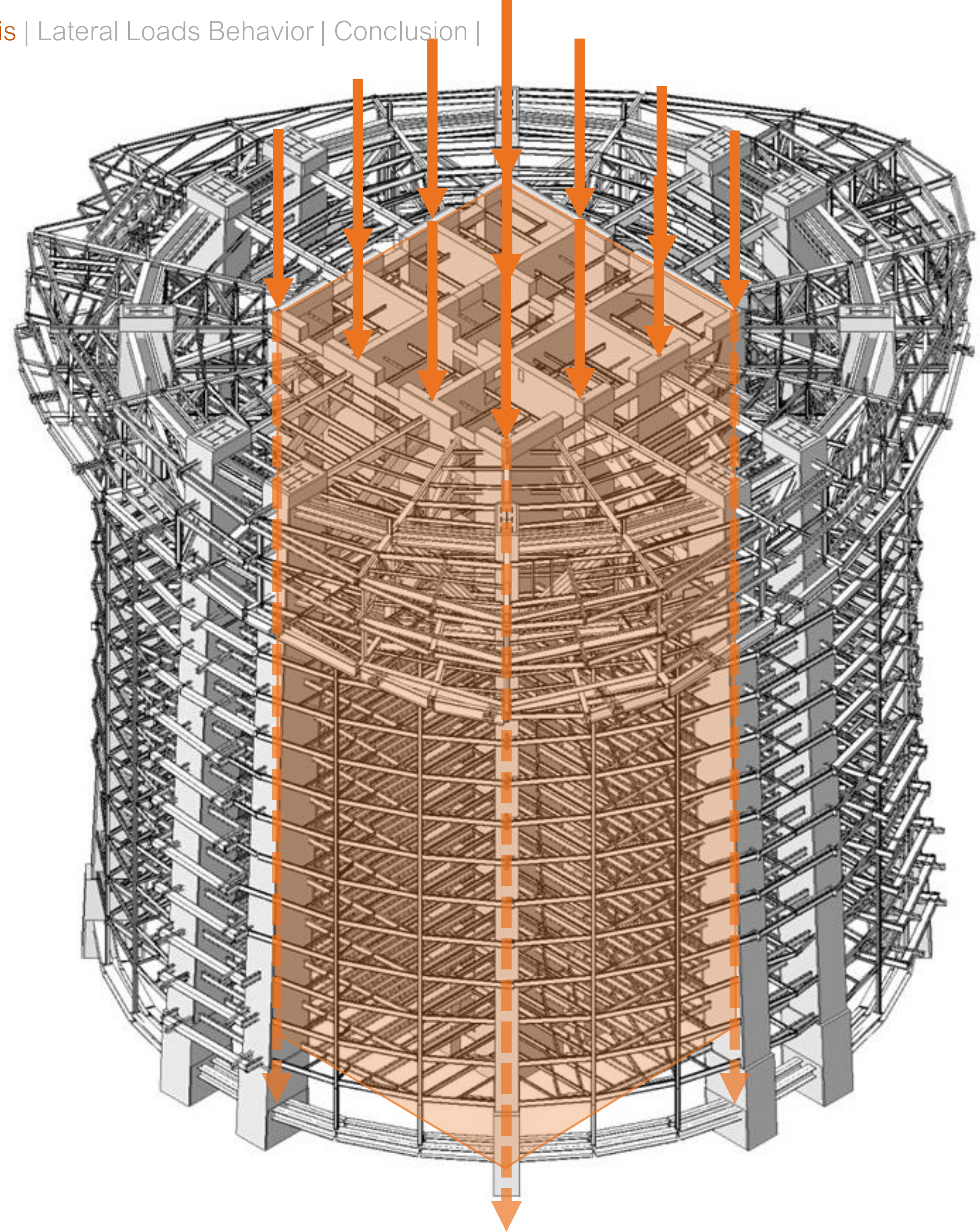


The proportion of loads carried by the mega-frame and tube of core

Structure components	Gravity loads	Shear force	Overturning moment
The Mega-Frame	50%	47%	76%
The tube of Core	50%	53%	24%

Gravity Loads Transfer Path

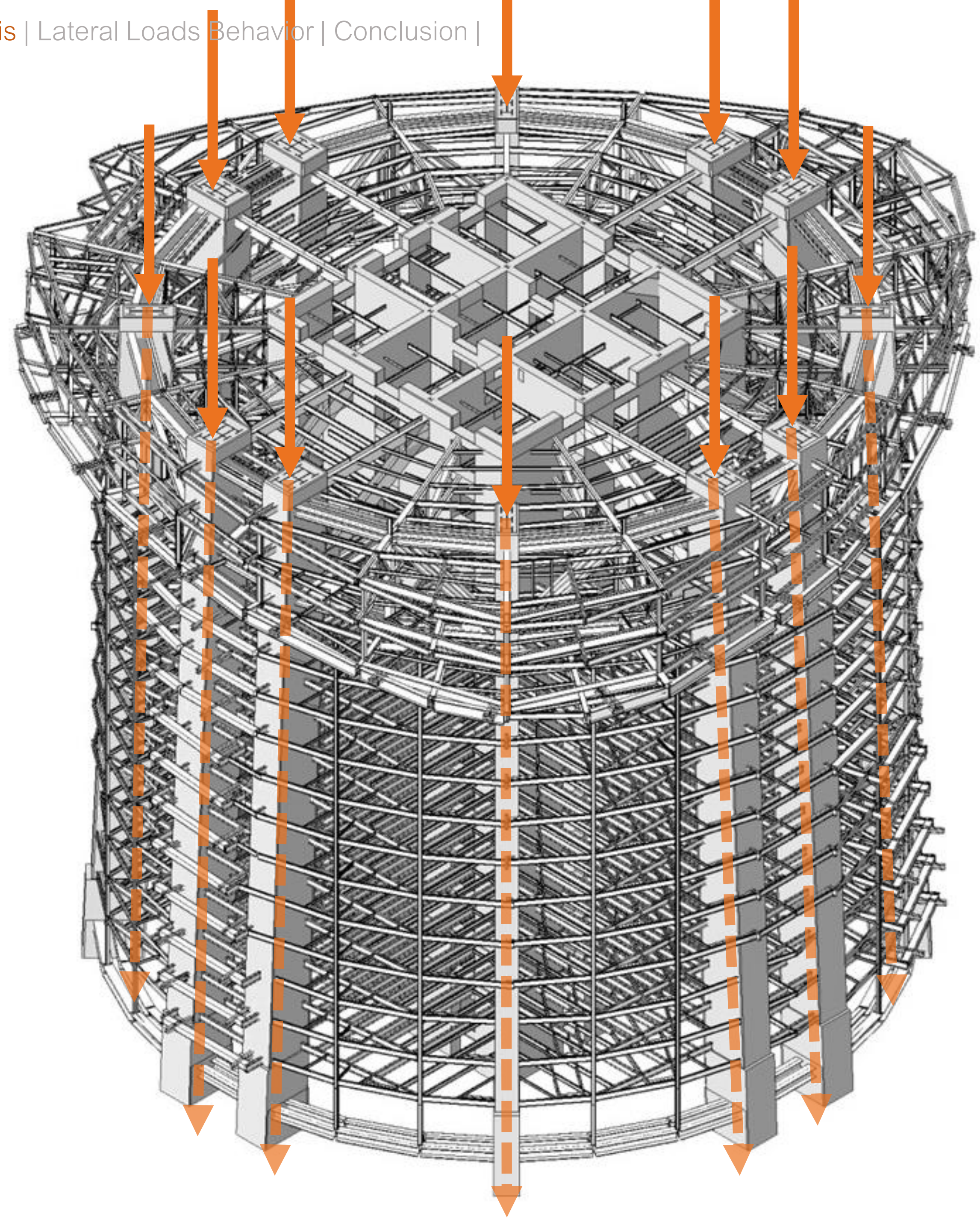
Structure components	Gravity loads
The Mega-Frame	50%
The tube of Core	50%

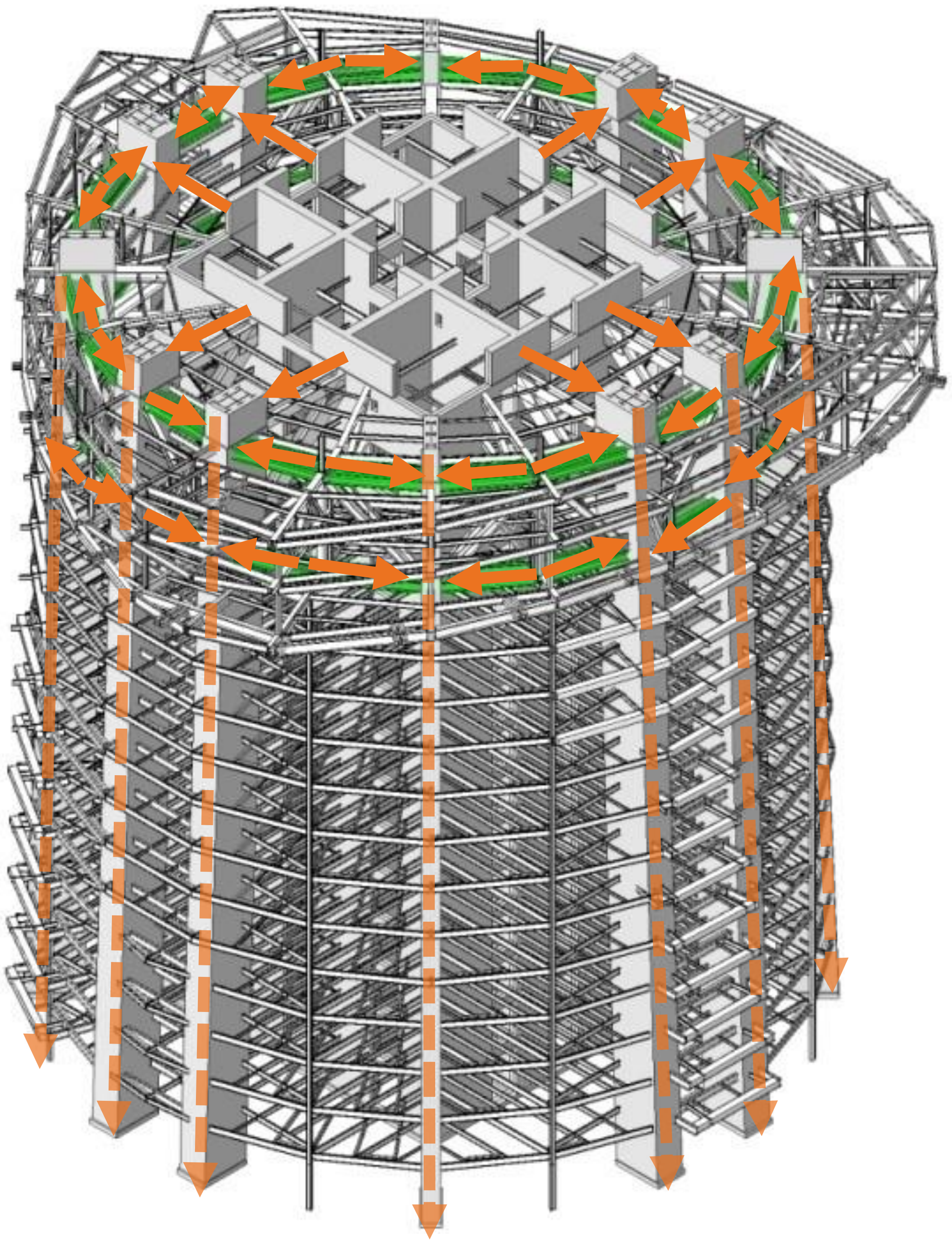


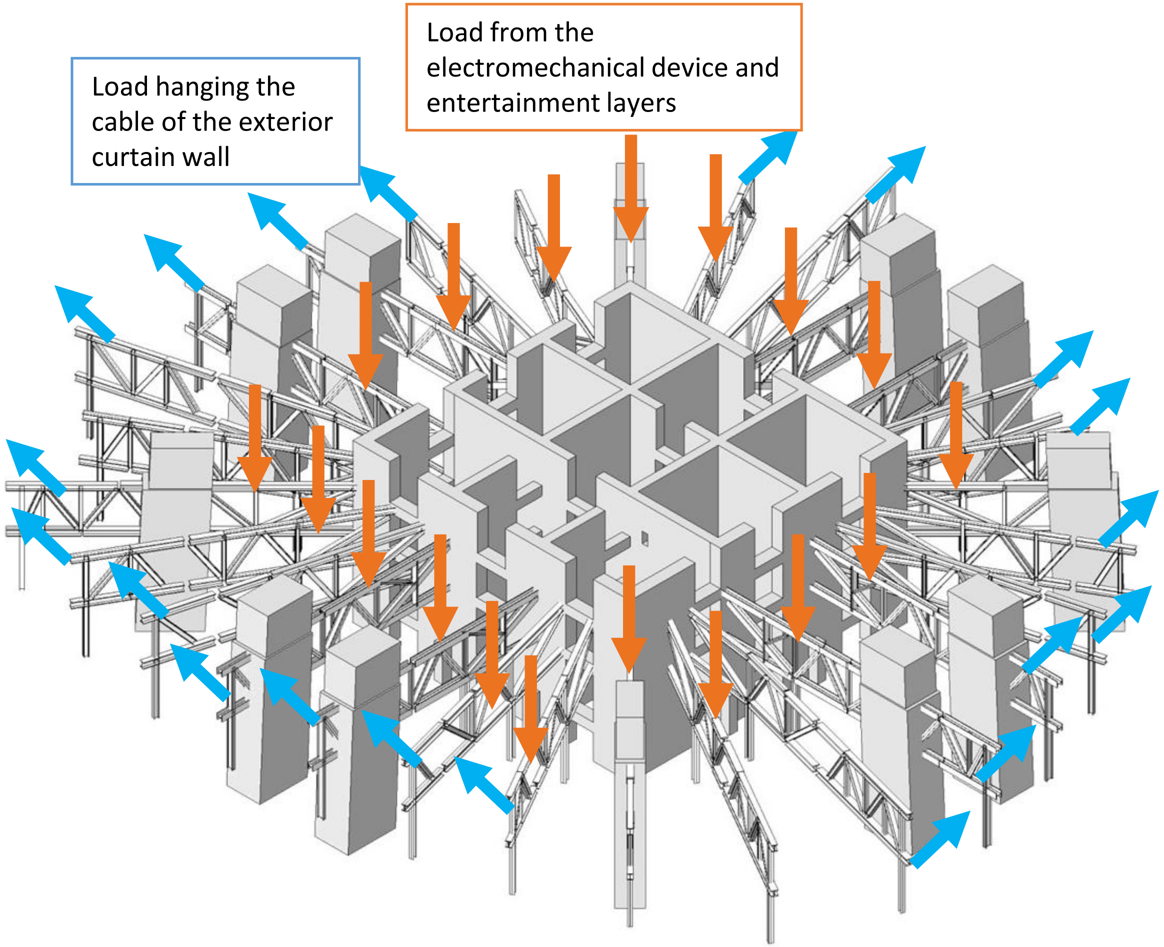
Gravity Loads Transfer Path

Structure components	Gravity loads
The Mega-Frame	50%
The tube of Core	50%

the belt truss of each reinforcement layer transfer the gravity load to the super-columns and corner columns.
In addition, in the device layer above the reinforcement layers, multi-channel **radial truss** are arranged to bear the vertical loads produced by electromechanical device and entertainment layers.
In the cantilevered end of the radial truss, there are cables hanging the exterior curtain wall of each zone below.



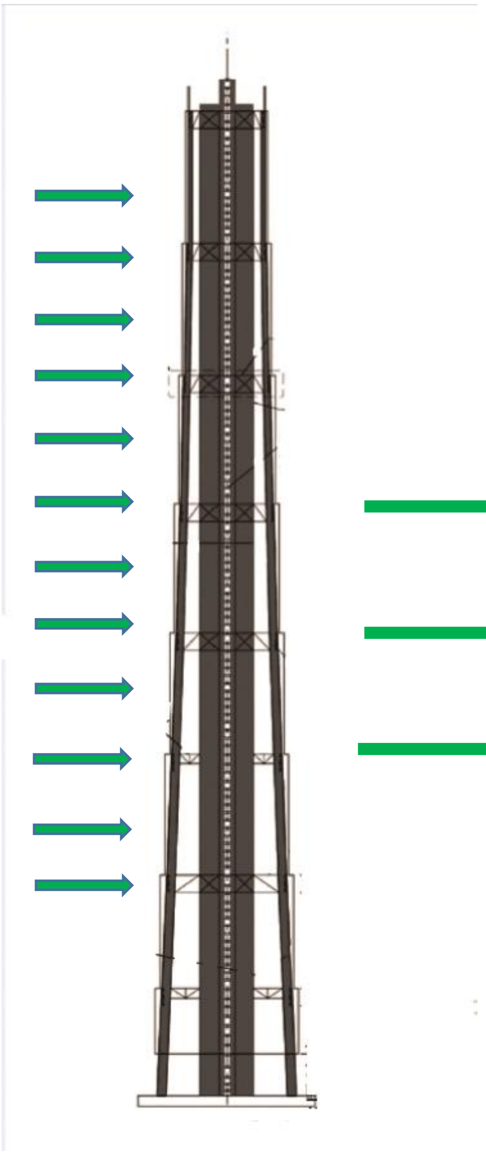


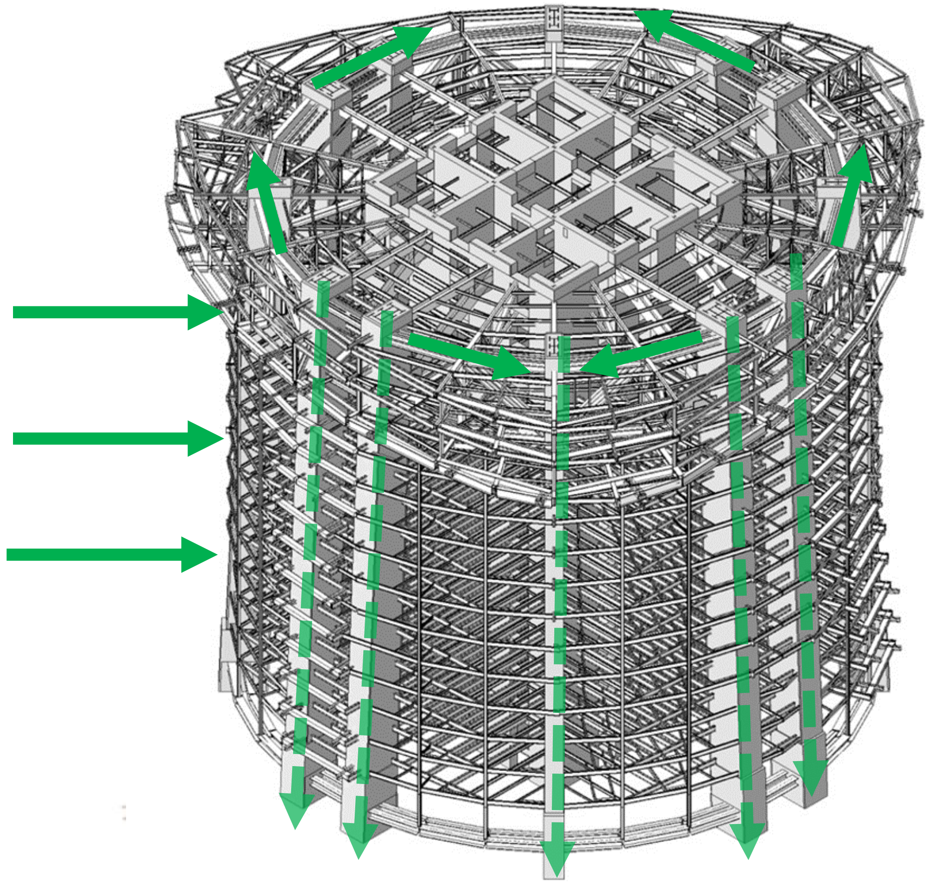

Load hanging the cable of the exterior curtain wall
Load from the electromechanical device and entertainment layers

Lateral Loads Transfer Path

Structure components	Shear force	Overturning moment
The Mega-Frame	47%	76%
The tube of Core	53%	24%

Wind loads reach to the surface of the building, and are transferred to the super-columns, thus the mega-frame could carry larger part of the lateral forces.

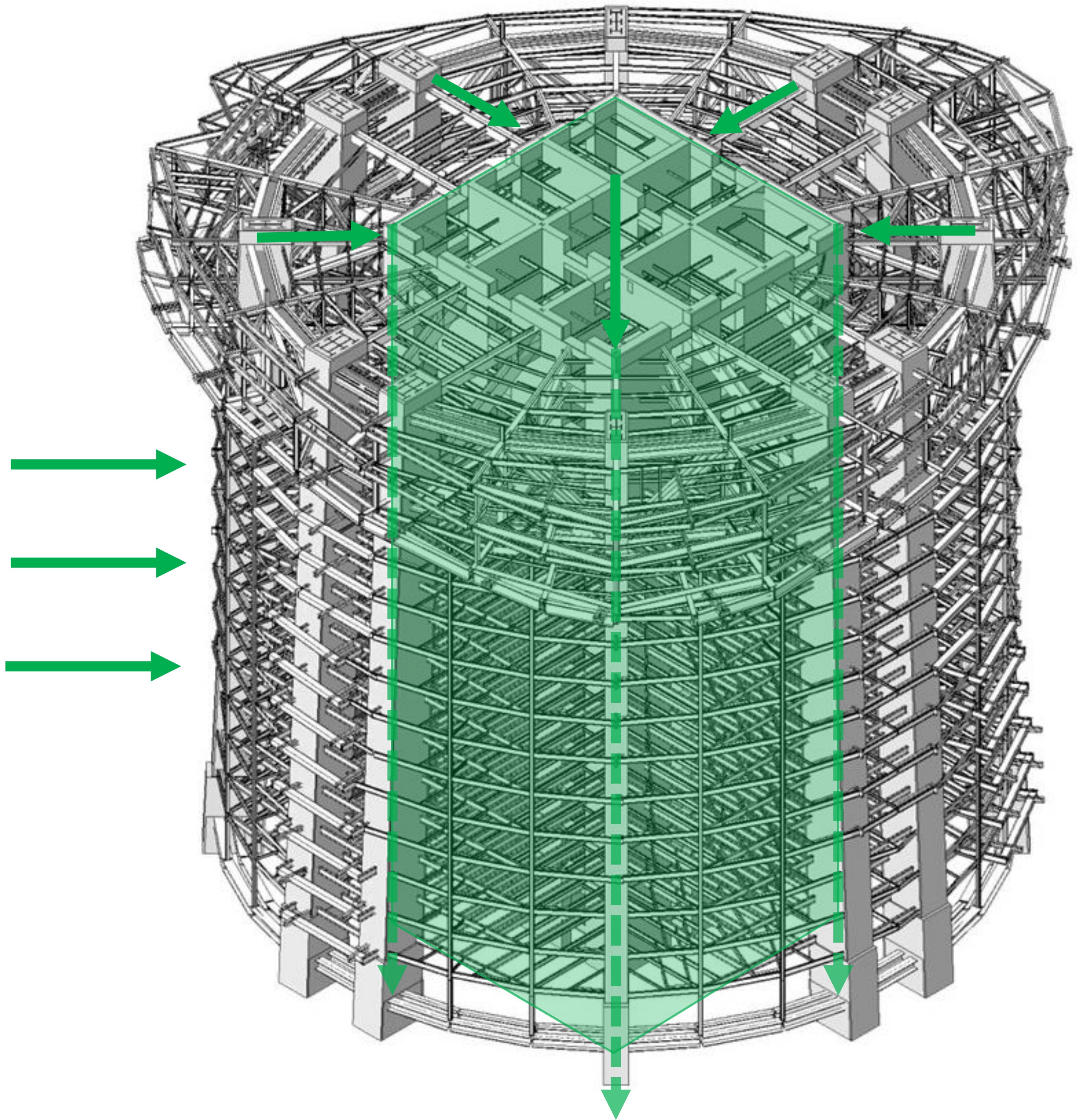




Lateral Loads Transfer Path

Structure components	Shear force	**Overturning moment**
The Mega-Frame	47%	76%
The tube of Core	53%	24%

In the reinforcement level, part of the wind load will be horizontally transferred through the outriggers to the concrete core, and then transferred to the foundation vertically.



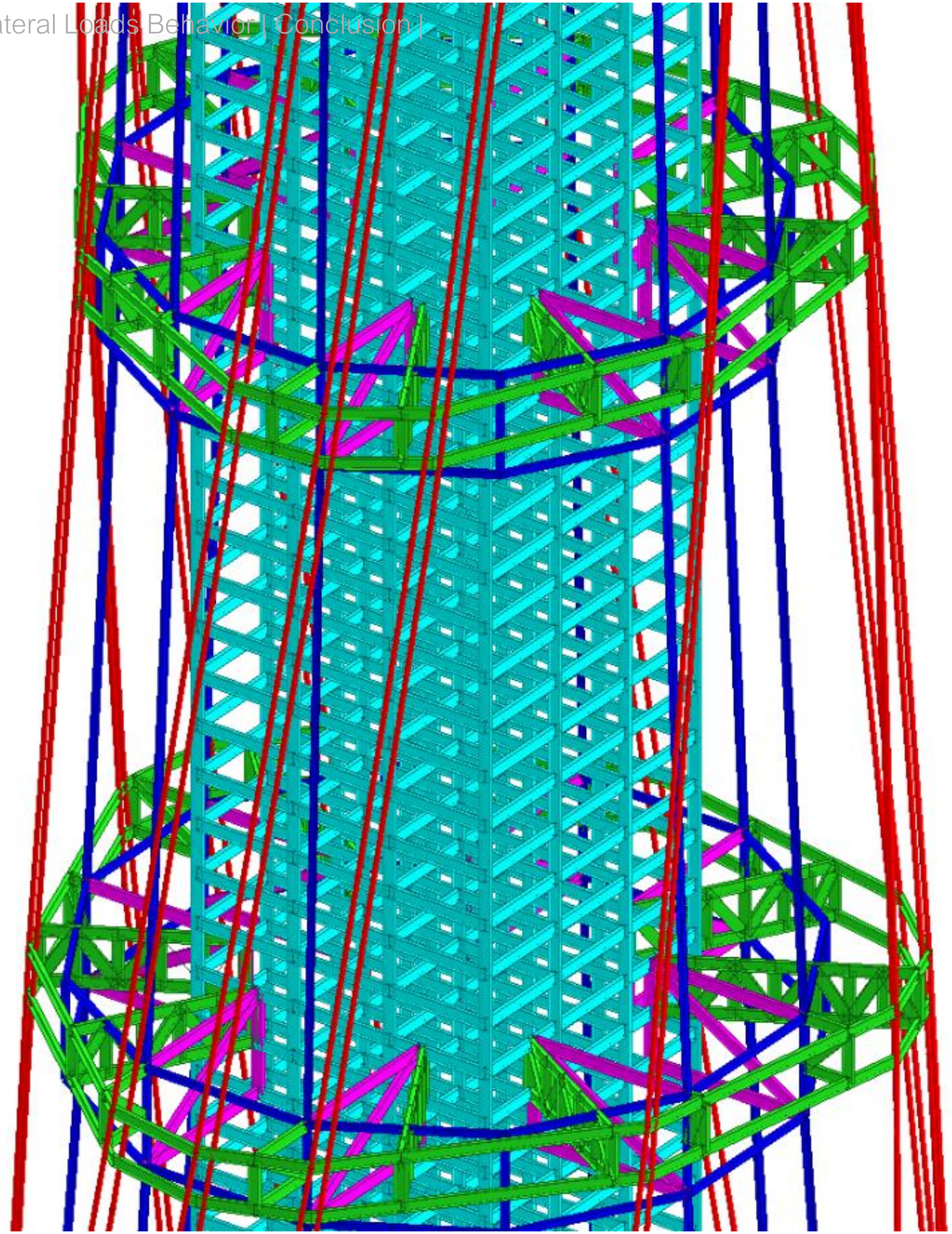
Multi-frame Analysis

Building resist to Lateral loads through 3 layers of structure, they transfer wind and seismic load one by one, from inside to outside.

The Supper core is the first layer of Resistance.

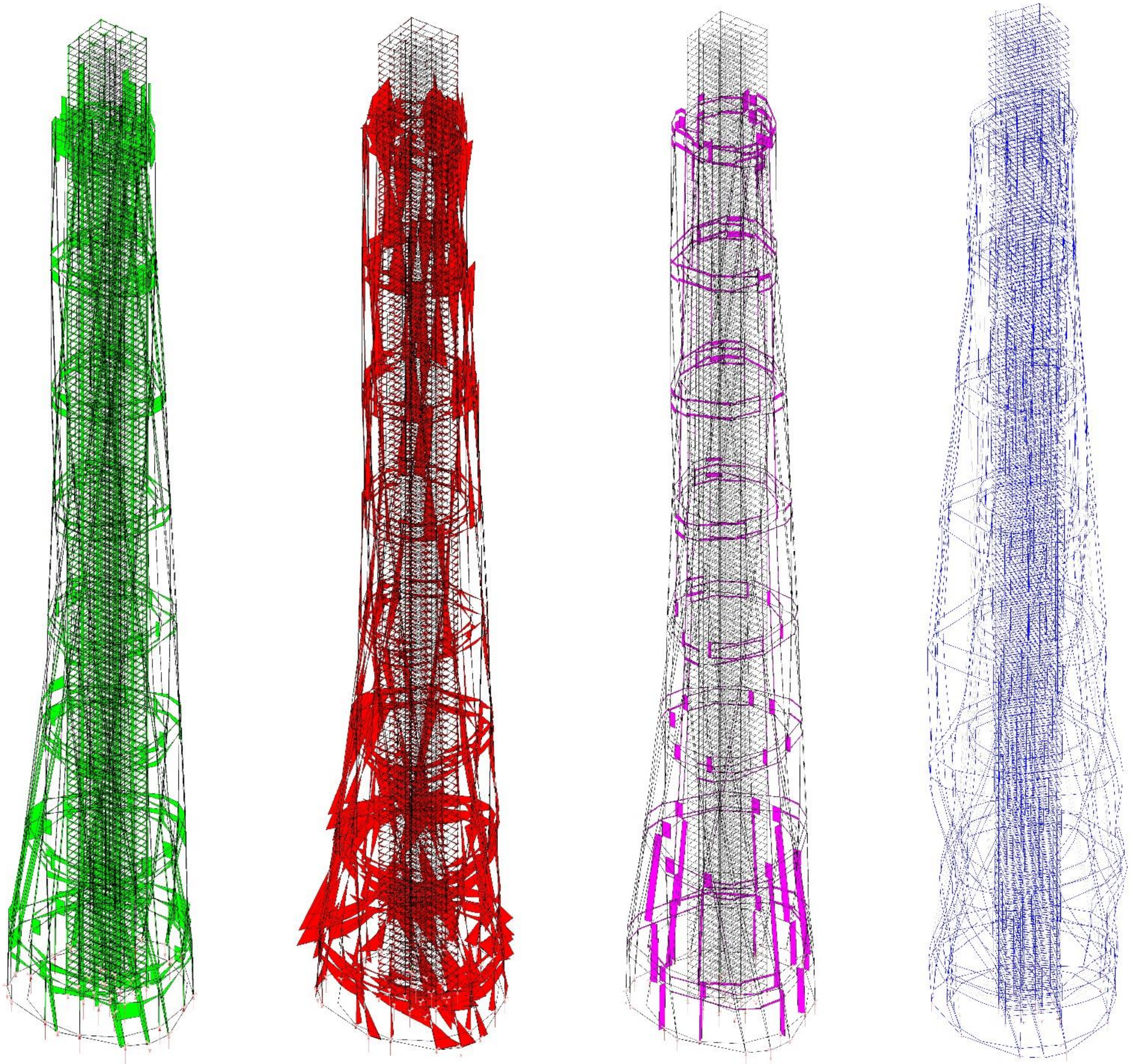
The double belt truss and super column are the second layer of Resistance.

The outriggers and radial trusses are the third layer.

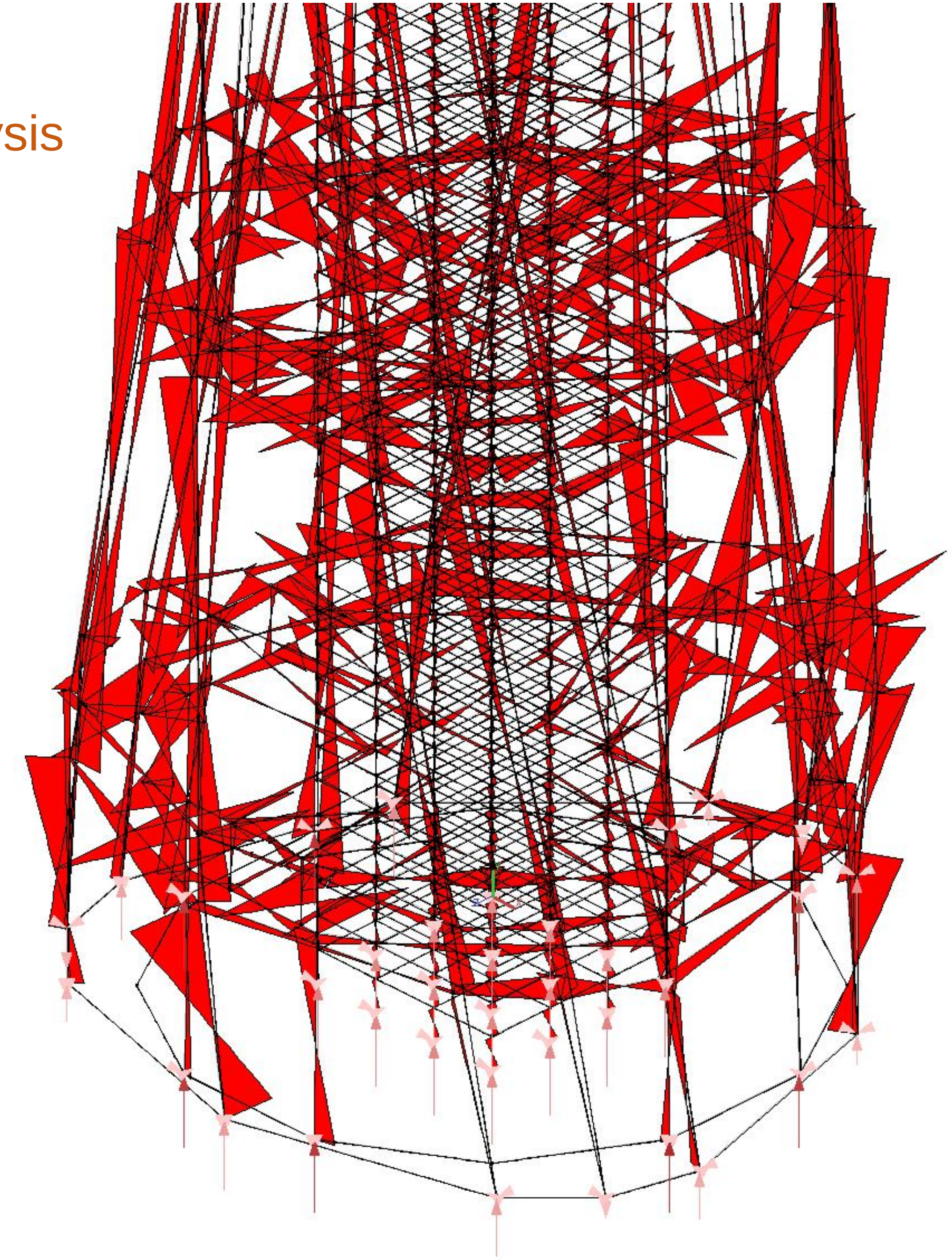


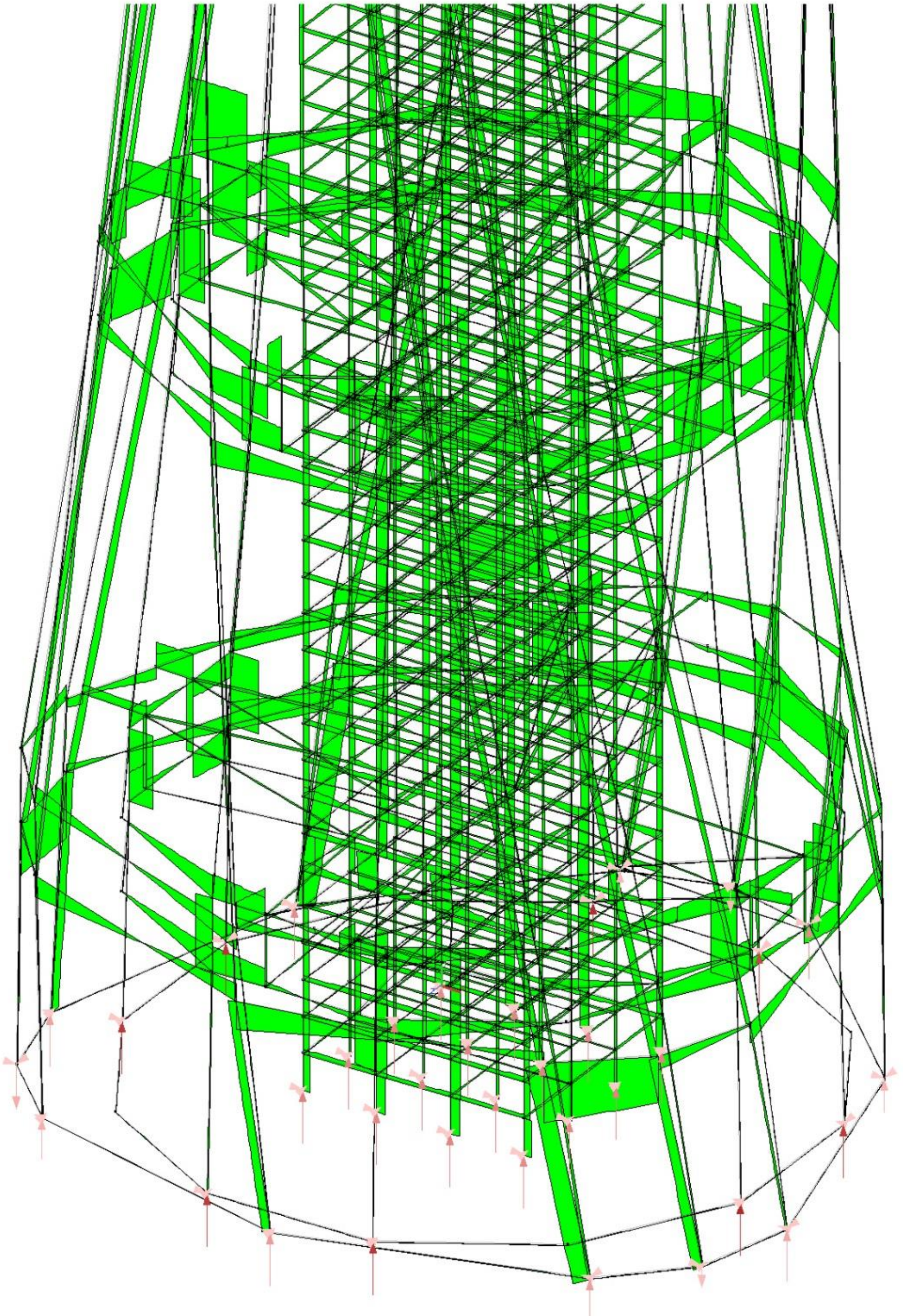
Multi-frame Analysis

- Shear
- Moment
- Tension
- Deflection



Multi-frame Analysis

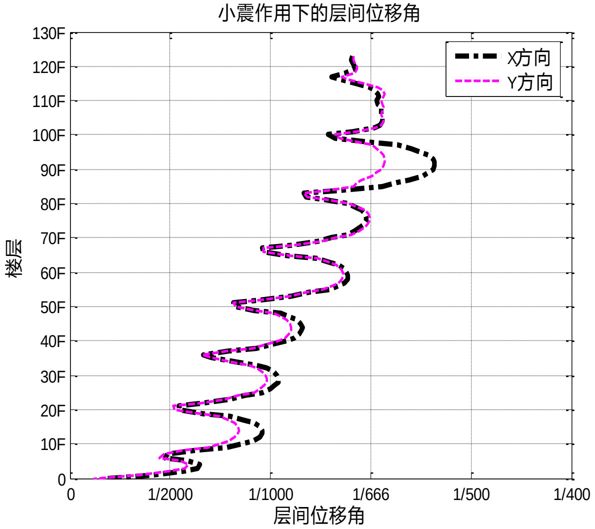


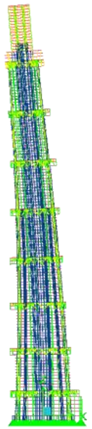


PART 5 LATERAL LOAD BEHAVIOR

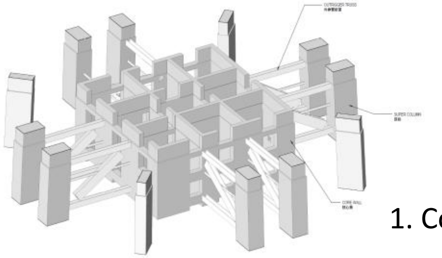
- **Wind Load Behavior**
- **Seismic Load Behavior**

Seismic Analysis

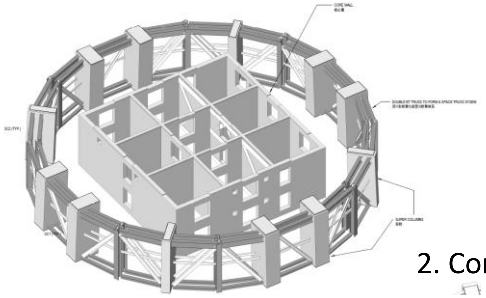




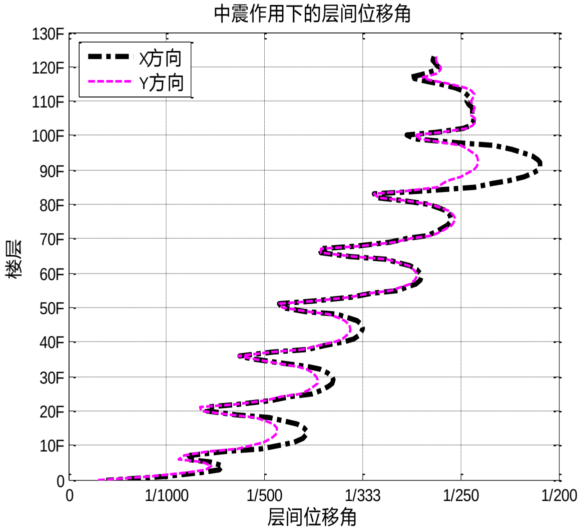
Building reposed to Minor Richer scale

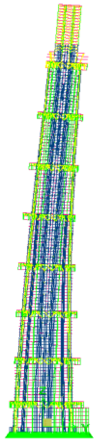


1. Core + Super Column

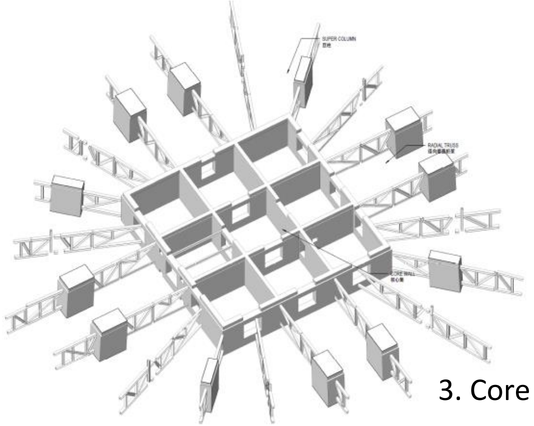


2. Core + Double Belt Truss





Building reposed to Strong Richer scale



3. Core + Radial Truss

Seismic Analysis

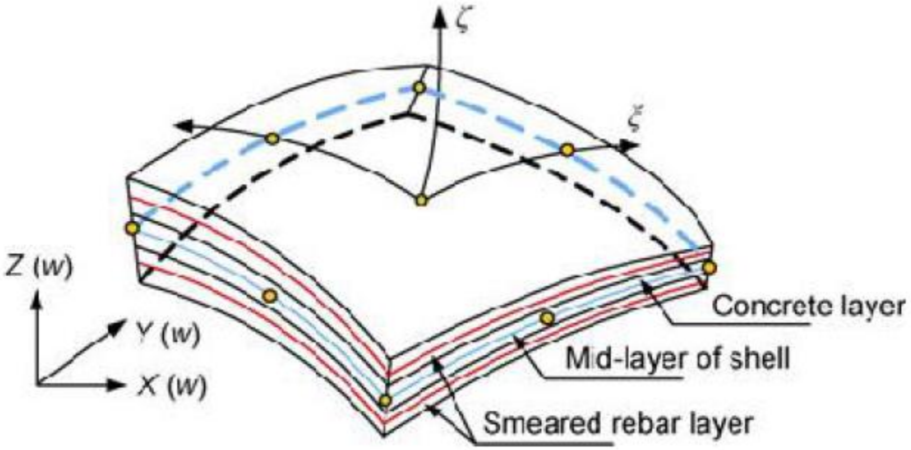
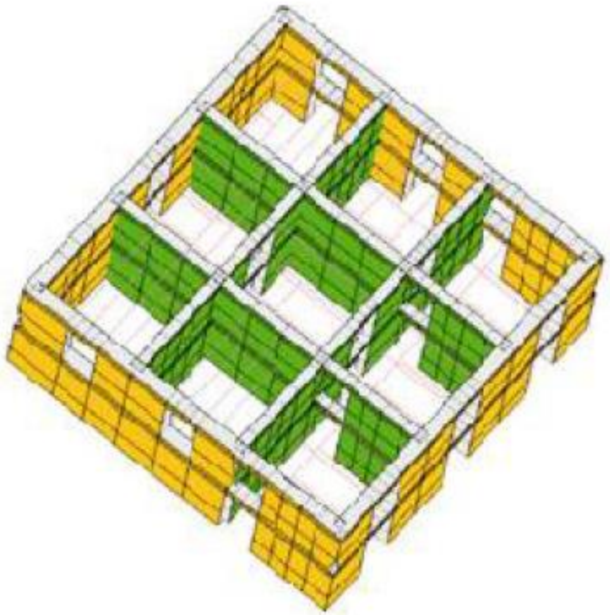
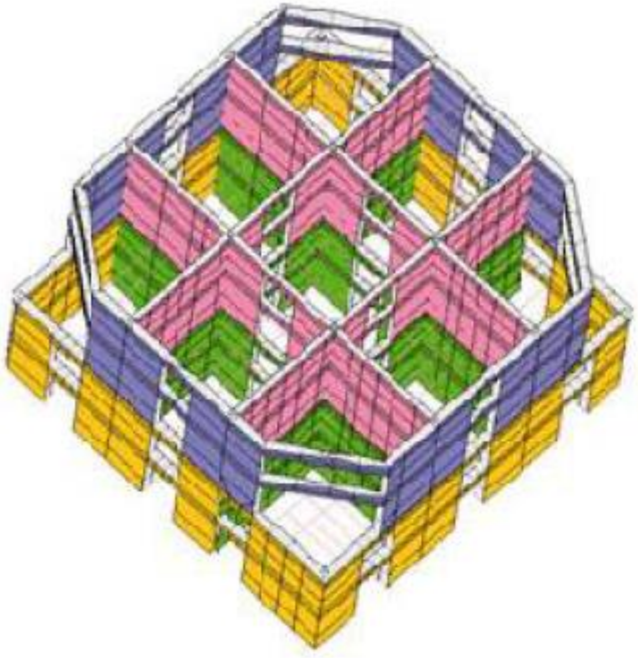
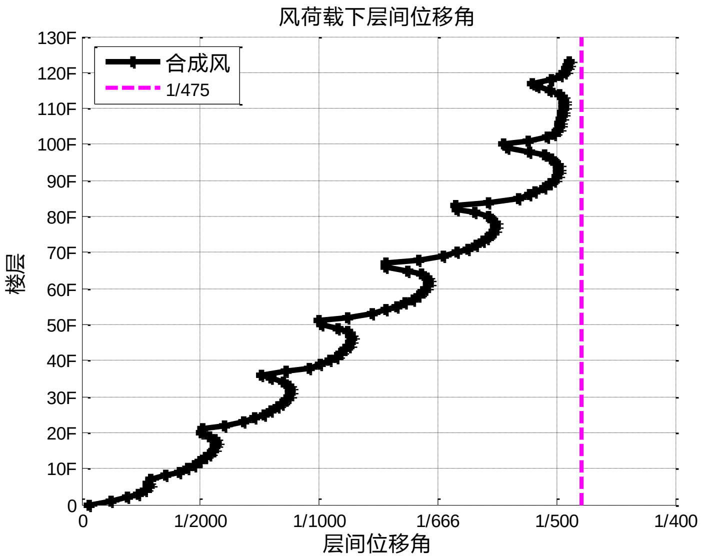


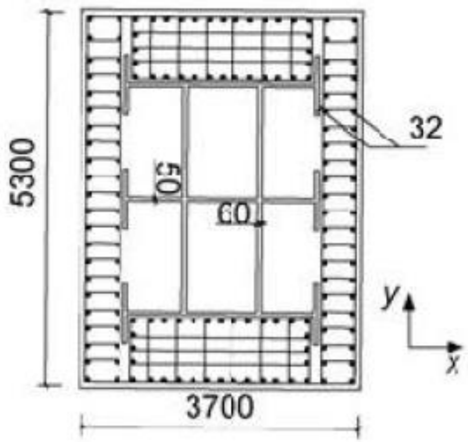
Figure 5 Multi-layer shell element.

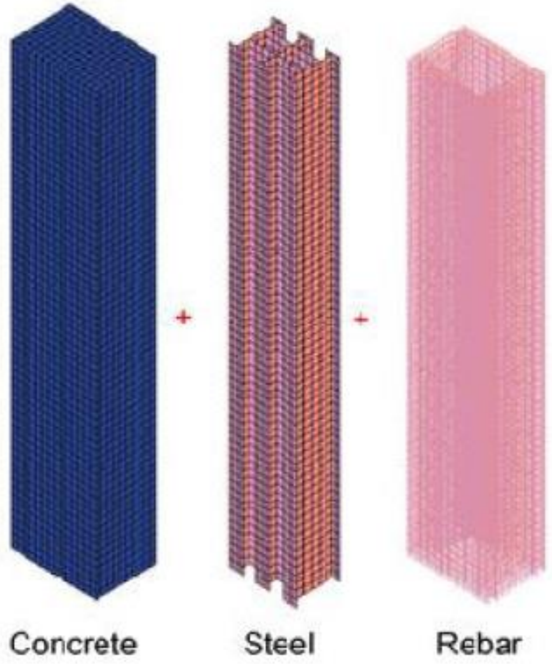




Wind Analysis







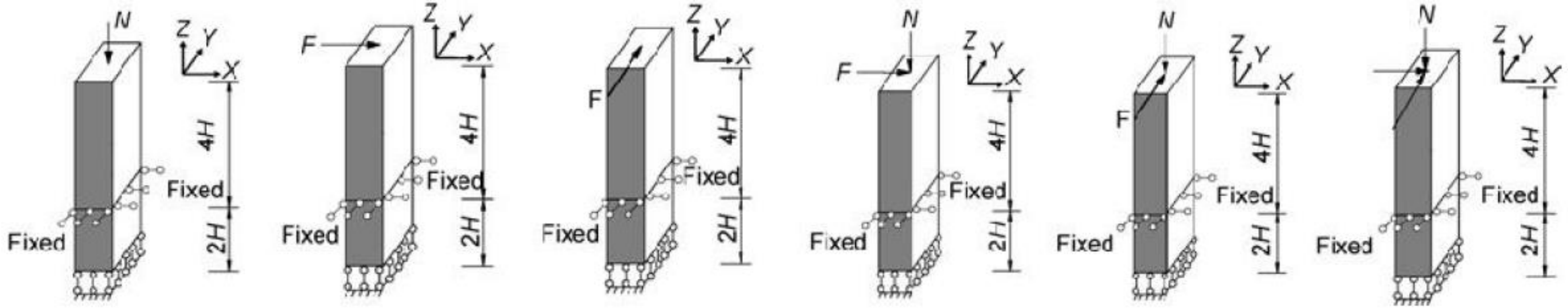


Figure 8 Typical load cases of mega-columns. (a) Axial compression; (b) bending in *X* direction without compression; (c) bending in *Y* direction without compression; (d) bending in *X* direction with varied compression; (e) bending in *Y* direction with varied compression; (f) bending in *X* and *Y* directions with varied compression.

Wind Load Resisted Methods

The effective building shape modification methods

a) the twisting angle
b) building orientation
c) shrink ratio of building plan along the building height

Table 2 Base reaction comparison of schemes with different twisting angle and orientation

Building scheme	Base overturning moment	Percentage
Rectangular section	6.22E+10	100%
100° TA, 0° OA	5.18E+10	83%
110° TA, 0° OA	4.92E+10	79%
180° TA, 0° OA	4.18E+10	67%
120° TA, 0° OA	4.75E+10	76%
110° TA, 30° OA	4.48E+10	72%
120° TA, 40° OA	4.15E+10	67%

Note: 100 years return period, damping ratio 2.0%. TA: twisting angle. OA: orientation angle

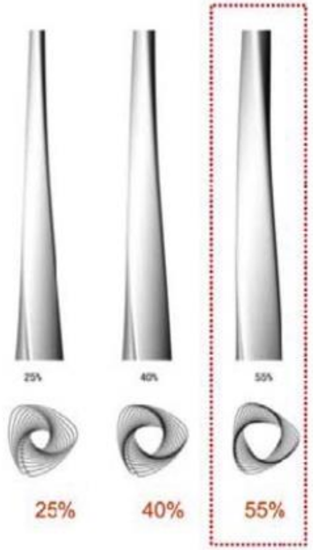


Figure 7: Wind tunnel study scaling models

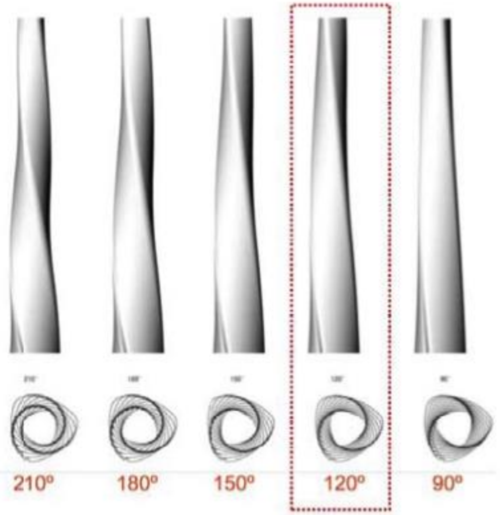
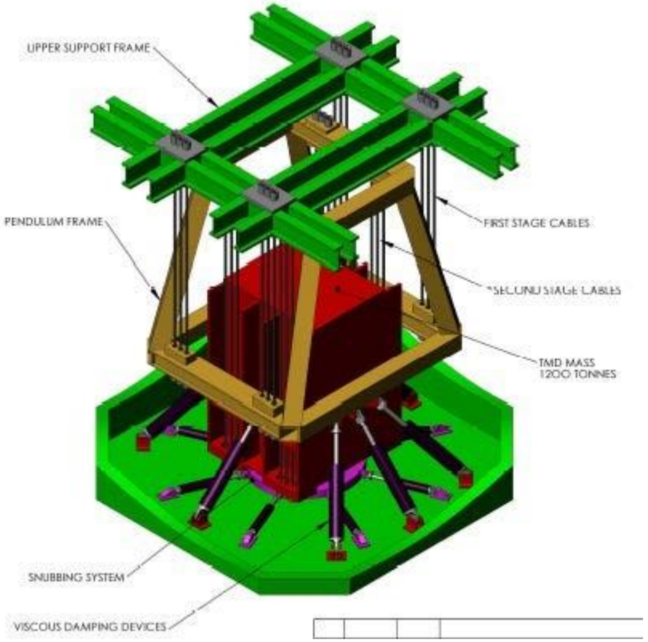
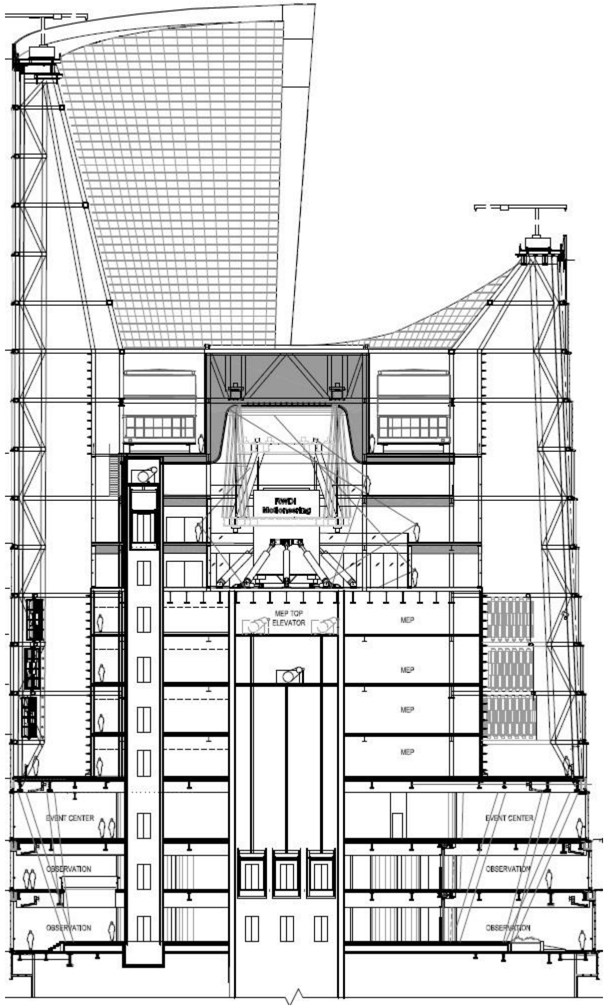


Figure 8: Wind tunnel study rotation models

Wind Load Resisted Methods

The tuned mass damper





THANKS!