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Challenge in the Structural Design of Suzhou IFS

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Abstract

Core-outrigger-mega frame system is used in a 95-story, 450 meters-tall Suzhou IFS, which is beyond Chinese code limit. Besides simple introduction on design principle, presented in this study are structure system and analysis, key techniques including performance-based design criteria, frame shear ratio, capacity check of mega column, human comfort criteria under wind induced vibration and TSD design, all of which are presented in details for reference of similar super-tall building design.

Keywords: Super tall building, Core-outrigger-mega frame system, Mega Column, TSD

1. Introduction

Suzhou IFS is located at Cuiyuan road of Suzhou. The architectural design is by KPF and the structural design is taken charge of by ECADI.

The tower's form is reminiscent of a fish, a symbol of prosperity and a nod to the role that water has played in Suzhou's history and identity. Soaring upwards, the curved “tail” of the fish subtly transitions from the scale of the lake and surrounding buildings to the top of the tower.

Suzhou IFS won the Best Tall Building 400 meters and above 2021 Award of Excellence of 2021 CTBUH Awards.

The T1 tower has 95 floors above ground and 4 basements, with a building height of 450 m. The ground floor area is 310,208 m^2, the basement area is 83,000 m^2, and the total area is 393,208 m^2. The T1 tower functions as offices, hotels and serviced apartments, with a standard floor height of 4.35 m. Seismic joint has been set between the main tower T1 and the podium T2. Both of the lateral force resistance systems are independent.

2. Design Criteria

The design reference period of structural design is 50 years. The structural safety grade is level 1 for primary elements (such as core tube, mega column, outrigger truss, belt truss, etc.) and level 2 for secondary elements, such as floor beams and slabs.

2.1. Wind Load

The basic wind pressure of 50 and 100 years are 0.45 kN/m^2 and 0.50 kN/m^2 respectively, and the ground roughness is classified as class C. The return periods of 10 years (damping ratio 0.01), 50 years (damping ratio 0.02) and 100 years (damping ratio 0.02) have been adopted respectively to calculate the human comfort, story drift



Figure 1. Architectural scene.

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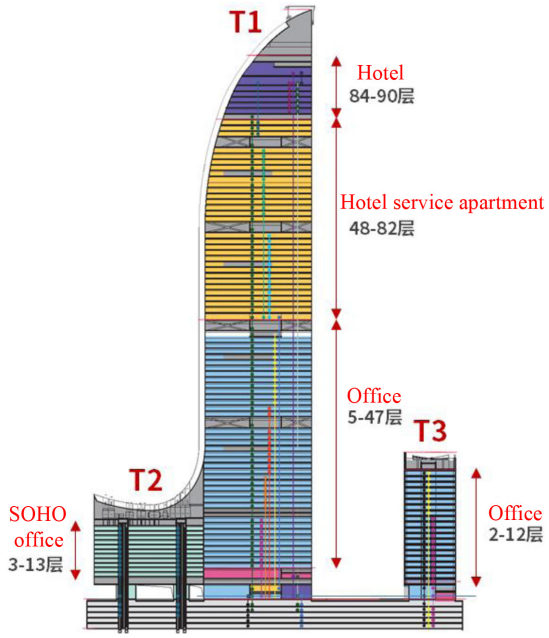


Figure 2. Typical building section.

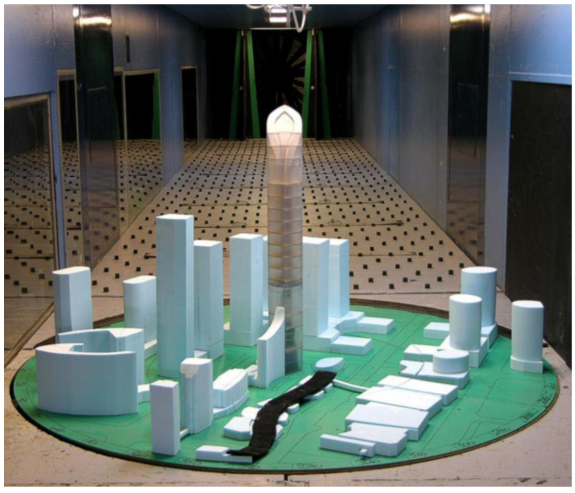


Figure 3. Wind tunnel test.

and element capacity check. Due to the special shape of the building, the owner commissioned RWDI to carry out wind tunnel test (Figure 3), and the results of wind tunnel test are used as the design basis (RWDI 2010).

2.2. Earthquake

The design seismic intensity is 6 degree and the seismic effect coefficient $\alpha_{Max} = 0.08$ (GB 50011-2010). The design characteristic period of ground motion $T_g = 0.45$s, the damping ratio $\zeta = 0.035$ (for elastic analysis) and 0.05 (for elastoplastic analysis), and the period reduction coefficient is 0.9. Building seismic fortification is classified as class B.

3. Lateral Force Resistance System

The project adopts a dual lateral force resistant structural

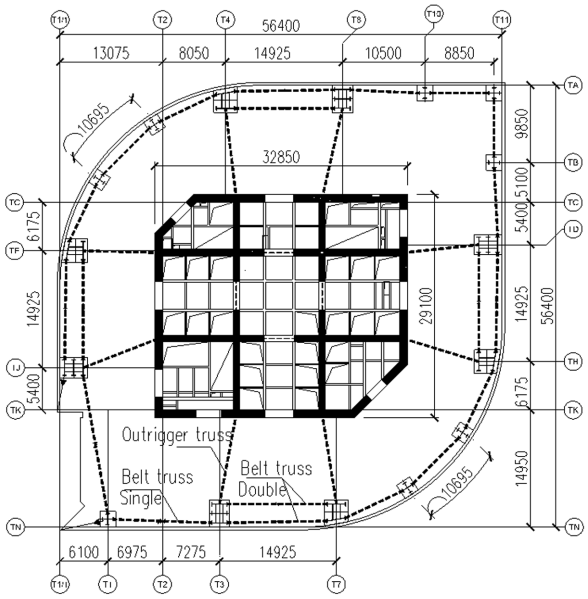


Figure 4. Strengthened floor structural plane.

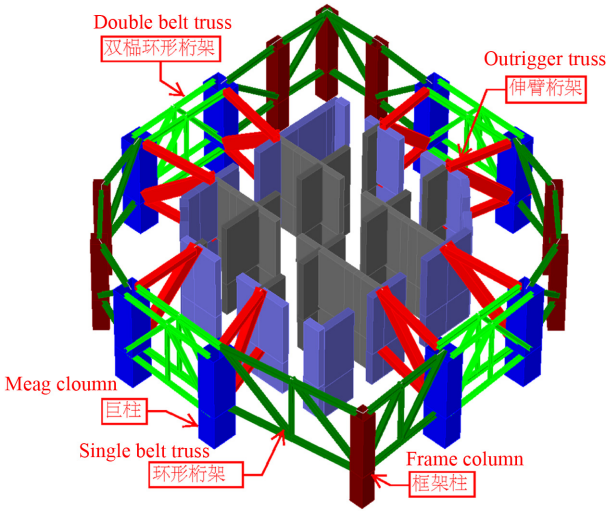


Figure 5. Strengthened floor layout diagram.

system: concrete core tube + outrigger truss + Mega frame to undertake the horizontal forces caused by wind and earthquake. In combination with the building equipment floor and refuge floor, the outrigger trusses and belt trusses have been evenly distributed along the building height (Figure. 4 and Figure. 5). The aspect ratio is 7.4 for building and 14.4 for core tube.

3.1. Concrete Core Tube

The concrete core plane is basically hexagonal (Figure. 4) with concrete grade of wall is C60~C40. The thickness of the outer wall is 1500~400 mm and the inner wall is 850~300 mm. Composite steel plate shear wall is set in the bottom strengthening zone with a steel ratio of 4%. Embedded steel columns have been set at the corner of

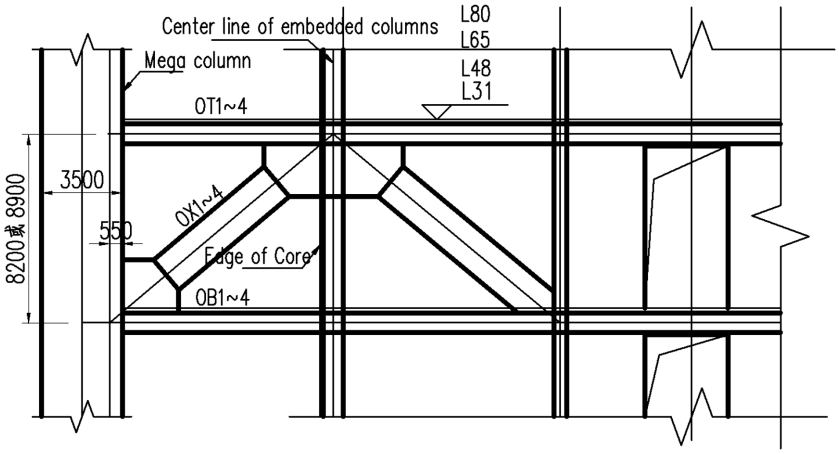


Figure 6. Elevation diagram of outrigger truss.

the core tube and the intersection of the wall, with a steel ratio of about 1%. The embedded steel columns and steel plates reduces the axial compression ratio and improves the flexural capacity of the wall to meet the requirements of seismic performance.

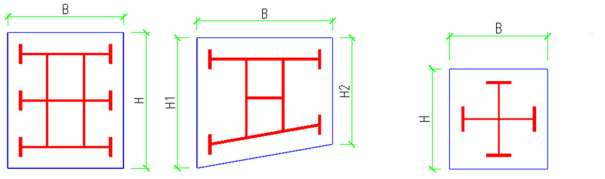
3.2. Outrigger Truss

Four outrigger trusses have been evenly distributed along building height (Figure 2). The height of the trusses is 8.9 m or 8.2 m which is about two stories. Embedded steel frames have been set through the concrete core (Figure 6) to ensure the continuity of force transmission of the outrigger truss. The section of outrigger truss is box section: 900 × (1700~900) × 100 × 45 with steel grade Q345GJC.The inner walls in the strengthened story and the upper and lower stories are thickened to 850mm for easy extension of the outrigger truss.

3.3. Mega Frame

The mega frame is mainly composed of 8 mega columns, 8 ~ 9 frame columns (9 in the low area), 6 belt trusses and frame beams.

Steel reinforced columns are used for both mega columns and frame columns. Typical sections are shown in Figure 7. A part of the mega columns are special-shaped sections to adapt to the curved plane of the building. The section sizes of the bottom mega column and frame column are 3 m × 3.5 m and 2.4 m × 2.4 m respectively, and the steel ratio is 6%-4%.



(a) Mega column section (b) Frame column section

Figure 7. Mega column and frame column sections.

Among the 6 belt trusses, except floor 15 (height of 6.4m) and floor 93 ((height of 6m), the floors and trusses heights of the other 4 belt trusses are consistent with the layout of the outrigger trusses. Double trusses are set between the mega columns to strengthen their torsional stiffness, while the other columns are all single trusses connected (Figure 4 and Figure 5).

The frame beams are H-shaped steel section. According to the requirements of building net height, the height of the frame beam is 950 mm.

The steel grade of the steel in mega columns, belt trusses and frame beams is Q345B or Q345GJB (plate thickness >35 mm).

4. Slab design

On the ground floors of the tower, the slabs on metal deck of 120 mm is used outside the core of the typical story. The concrete slab of 135 mm is used inside the core, and the concrete floor slab of 200 mm is used inside and outside the core of the strengthened stories.

According to the requirements of office zone net height of 3 m, the floor secondary beams outside the core are H-shaped steel beams with a height of 550 mm, which is designed based on composite beams. The typical beams are spaced at 3 m, and the maximum span-height ratio of composite beams is 19 considering the thickness of slab. In addition to meeting the strength and deformation requirements, the comfortability of floor vibration shall meet the requirements of the Floor Vibration due to human activity (AISC Steel Design Guide Series 11). The calculation results all satisfy the relevant code requirements.

5. Foundation Design

The foundation of main tower is consisting of 1000mm diameter and 66.3m long cast-in place piles with post grouting and reinforced concrete mat foundation. The bearing layer is ⑬ gray silt layer. The characteristic

capacity of pile is 12000 kN. The mat foundation thickness is 5.0 m typically.

6. Elastic Analysis Results

ETABS is used for elastic analysis. The elastic analysis results are shown in Table 1. Wind load is the controlled horizontal load. The adverse effect of P-Δ effect is considered.

7. Design Performance Target

In addition to satisfying the elastic design of frequent earthquake (JGJ3-2010) Table 2 presents the performance target for the critical members and joints of the structure under moderate and rare earthquakes.

8. Ratio of Seismic Shear Resisted by Exterior Frame

High-efficiency super high-rise structures should meet the following requirements: load-bearing members should be concentrated, far away from the center of gravity of the structure, and bear as much gravity load as possible, to improve the ability of resisting overturning moment (Taranath, Bungale S. 2011).

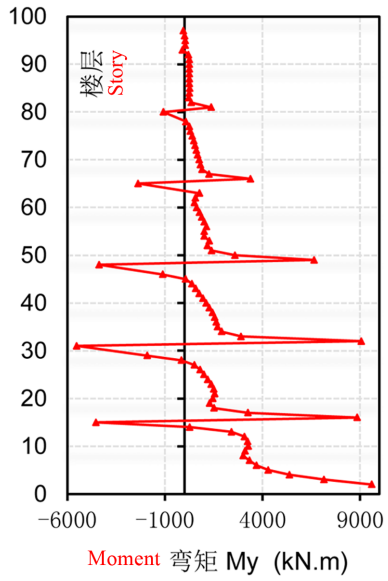


Figure 8. Bending moment mega column frame in plane.

Figure 8 shows the moment distribution of the mega columns in the frame plane under wind load. According to the figure, the restraint effect of the frame beam on the mega columns is quite limited due to the small linear stiffness ratio of the beam to column. The moment distribution of the mega columns is still quite different from that of the ordinary frame. There is nearly no inflection point between the strengthened floors.

Therefore, due to the existence of huge sections in super high-rise structures, simply strengthening the frame beam section and reducing the column distance are relatively limited to improve the lateral stiffness of the

Table 1. Elastic analysis results

Structure mass (10^4 t)	41.9
Period(T_1/T_2/T_3)/s	8.37(Y) / 7.49(X) / 5.42(Z)
Y story drift (Earthquake/wind) (Y direction is the control direction)	(1/1171) / (1/544)
Code Frequent Earthquake shear-gravity ratio (X/Y)	0.79 % / 0.71%
Stiffness-gravity ratio (X/Y)	1.63 / 1.48

Table 2. Seismic performance target

Seismic criteria		Moderate earthquake	Rare earthquake
Story drift		1/200	1/100(plastic drift 1/50)
Member performance	Core Wall	Elastic for walls of strengthened floors and one floor above and below the strengthened floors. Non-yielding for others.	Satisfy control conditions of shear limit, allow to enter plastic (plastic hinge θ < LS) Bottom strengthened zone is not allowed to enter plastic (θ < IO)
	Coupling beam	Allow to enter plastic and slight cracking	Allow to enter plastic(θ < LS), collapse not allowed, maximum plastic hinge < 1/50, failure allowed
	Mega column	Elastic	Allow to enter plastic(θ < LS) Bottom strengthened zone is not allowed to enter plastic (θ < IO), The reinforcement stress could exceed the yield strength, but not exceed ultimate strength
	Outrigger truss	Non-yielding	Allow to enter plastic(θ < LS), the reinforcement stress could exceed the yield strength, but not exceed ultimate strength
	Belt truss	Elastic	Non-yielding

Note: θ is the rotation of structure member, ε is strain; performance target IO means Immediate Occupancy, LS means Life Safety, CP means Collapse Prevention.

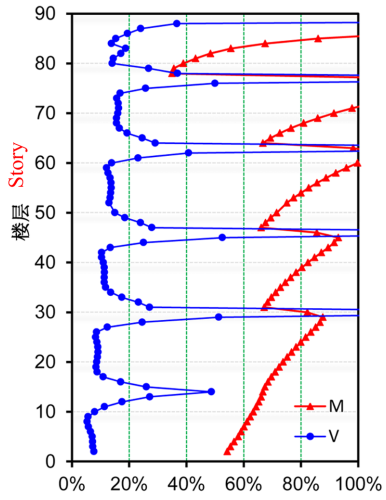


Figure 9. The ratio of shear V and overturning moment M resisted by frame under frequent earthquake.

frame, and the cost is high. Although the belt trusses can play the role of the mega frame beams, the calculated length of the mega column is the height between strengthened floors, the lateral stiffness of the mega frame still cannot be compared with that of ordinary frames [4].

Figure 9 shows that, due to the coordination of outrigger trusses, the ratio of overturning moment M resisted by mega-frames (mainly mega columns) is much higher than the ratio of shear force V resisted by mega frames. In the mega frame-outrigger truss-concrete core system, the mega frame (or mega column) is like the flange of the H-shaped section, which mainly bears the moment. while the core is equivalent to the web of the H-shaped section, which mainly bears the shear force and a part of the moment.

9. Mega Column Design

9.1. Form Selection of Mega Column

There are two common options for large composite sections: steel reinforced concrete (hereinafter referred to as "SRC") and concrete filled steel tube. The concrete filled steel tube column has two common forms: circular steel tube concrete column (hereinafter referred to as "CFT") and rectangular concrete filled steel tube column (hereinafter referred to as "CRFT").

Based on the following reasons, steel reinforced columns are used for mega columns and frame columns in Suzhou IFS.

(1) Under the premise that the axial compression stiffness and bearing capacity are basically the same, the cost of SRC column is the lowest and the economy is the best because the steel bone and steel bar can be reasonably matched.

(2) SRC column can reduce the difficulty of reinforcement construction through joint construction processing and ensure the reliability of joint force transmission.

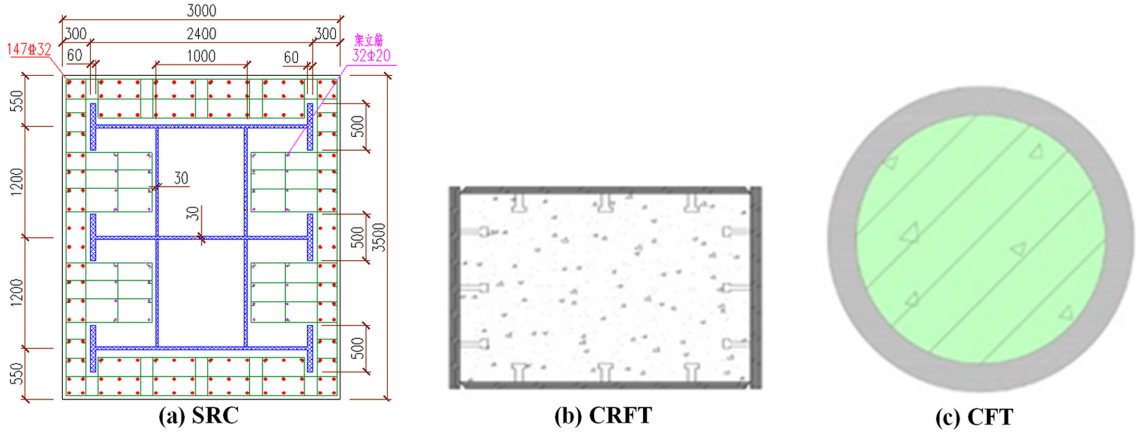
(3) The compactness of concrete in CFT columns, the structure of beam-column joints, the treatment of anti-corrosion and fire prevention and the later maintenance should be paid special attention and corresponding measures should be taken.

9.2. Mega Column Strength Capacity Check

According to the section 6.3.6 in Technical Specification of Steel-Reinforced Concrete Structures (YB 9082-2006), the bearing capacity of SRC columns under bidirectional compact-bending shall be checked by the following formula:

$$\frac{M_x}{M_{u(x,N)}}+\frac{M_y}{M_{uy,N}}\le 1$$

Where, M_x, M_y are respectively the design values of bending moments in two directions of SRC column under each load combination; $M_{ux,N}$, $M_{uy,N}$ are respectively the flexural strength capacity of SRC column in two directions when the design axial force is N, which can be obtained by simplifying the strength capacity *N-M* curve of the mega column with the method of piecewise Lines. The curve is calculated according to the finite element



(a) SRC (b) CRFT (c) CFT

Figure 10. Mega column sections.

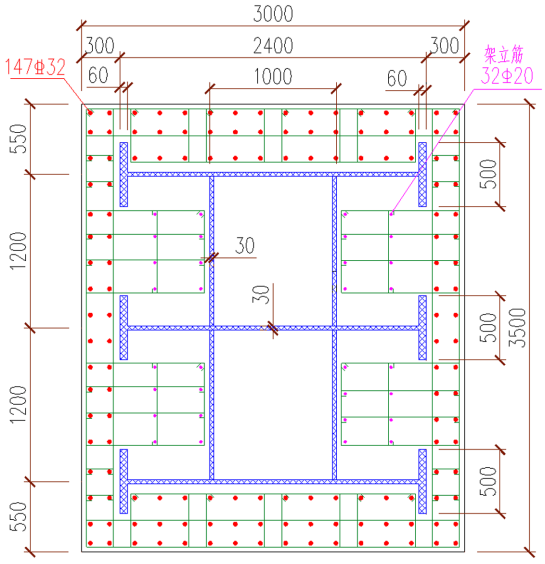


Figure 11. Detail of typical mega column section.

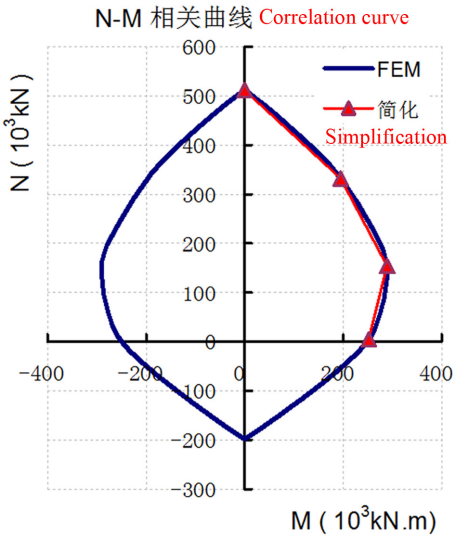


Figure 12. Typical mega column N-M strength capacity curve.

principle and the assumption of the plane section, see Figure 11,12. Point (N_b, M_{max}) is the limit compression strength capacity point of the section.

10. Design of Tuned Sloshing Damper

The effect of wind-induced vibration must be considered carefully for super high-rise building like Suzhou IFS. The research shows that the use of additional damping system can effectively reduce the wind-induced acceleration in the high zone of the building, improve the building quality and prolong the use of the curtain wall.

Tuned Sloshing Damper (TSD) is in fact a different form of the Tuned Mass Damper (TMD)(Figure 13). In the building, TSD is usually constructed as a rectangular water tank whose length, width and depth are designed to

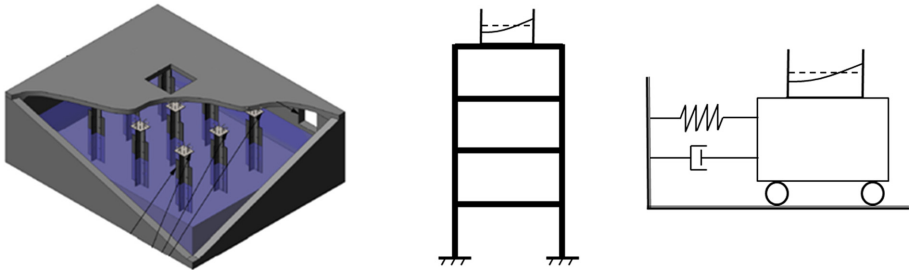


Figure 13. Concept of TSD.

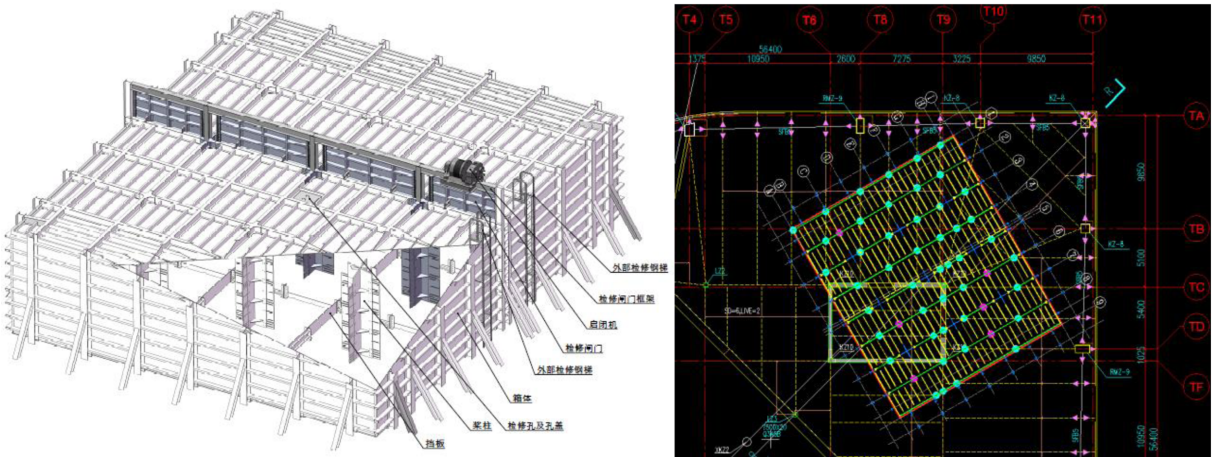


Figure 14. Layout of TSD.

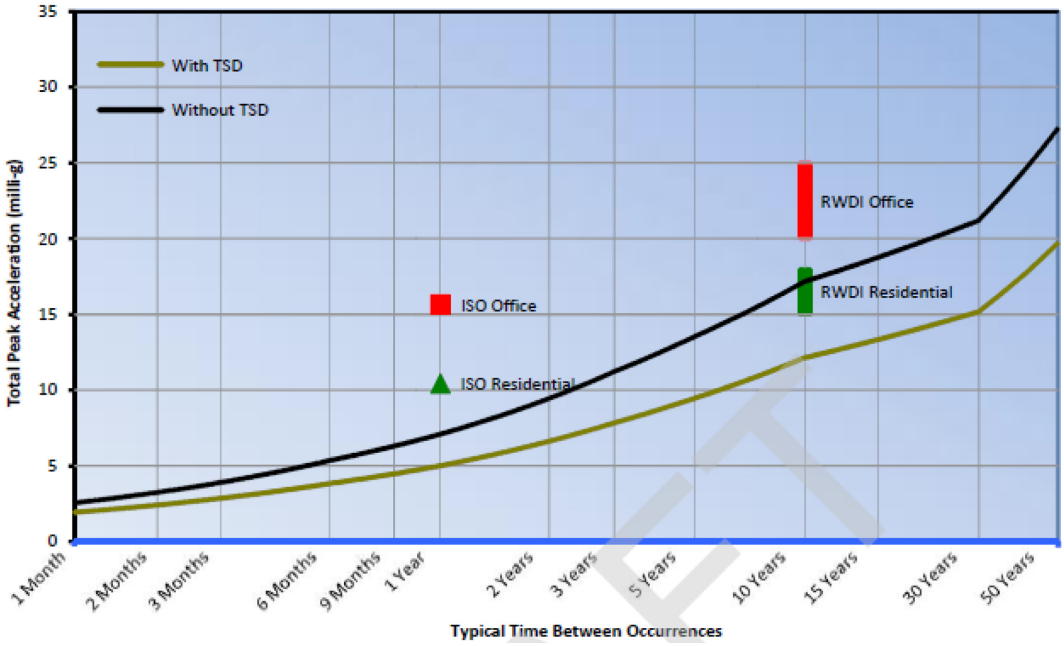


Figure 15. Wind-induced peak acceleration with and without TSD.

achieve the desired wave motion. The motion of the wave can be expressed as the motion mass equivalent to TMD. Energy dissipation is achieved through the use of damping system including louver panels, net, slurry column to generate turbulence.

The use of fire water tank designed as a tuned water tank damper, can achieve a better effect of reducing the wind acceleration, can reduce the acceleration by 30%, the hotel comfort to the residential standard requirements, while meeting the Japanese building code in H30 standard, greatly improving the quality of the building.

The net internal dimension of TSD is 19 m × 16.3 m × 4.2 m (L × W × H). The Angle between the short edge of TSD and the X-axis of the main structure is 30°(Figure 14), which makes it consistent with the direction of the translational vibration mode of the main structure. After a detailed performance analysis of the TSD and the tower's response to wind and earthquake, the design acceleration mitigation ratio for the TSD is 30%, and the wind-induced acceleration is expected to be reduced to 12 meli-g during the 10-year return period and 5.0 meli-g during the 1-year return period (AIJ Code H30 level) (Figure 15).

The use of TSD for reducing wind-induced acceleration in Suzhou IFS is the first one used in super high-rise buildings in China, which is extremely beneficial to the structural safety and the comfort of super high-rise hotels.

590-ton TSD damper has been designed on the floor level of 95.

Detailed measurement results are expected to verify the damping effect of TSD when the typhoon passes through Suzhou this summer.

11. Conclusion

(1) The system of concrete core tube+ outrigger truss + mega frame improves the capacity of the frame to resist the overturning moment and the aspect ratio of the structure. It has been widely used in super high-rise structures.

(2) The frame shear ratio restricts the application of the mega column system. This puts forward higher requirements to the section size of the frame column, the column distance, and the stiffness of the frame beam. In addition to affecting the building function, it also increases the steel quantity.

(3) The use of fire water tank designed as a tuned water tank damper can effectively improve the comfortability of wind vibration, reduce the wind load of the structure, relieve the fatigue of the structure, prolong the service life of the building, and improve the reliability of structure design.

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