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Analysis and Design of Vertical Load Transfer and Transfer Structure in Complex High-rise Buildings

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Abstract With the pursuit of more expressive shapes and diverse functions in modern architecture, the discontinuity of vertical components is increasing, leading to complex vertical load transmission paths. Therefore, by summarizing the types and characteristics of vertical loads, the transmission paths of vertical loads were classified. The transmission path is closely related to the architectural form and function. This article analyzes the transmission mode of vertical loads in complex high-rise building structures based on typical engineering cases. The main focus was on the load transmission paths, stress characteristics, and design methods under different structural forms. Research has shown that rational design of conversion structures and suspension systems can effectively solve the problem of vertical load transmission in complex high-rise buildings and achieve harmonious unity between buildings and structures.

Keywords: Complex architecture, vertical load, transfer path, transfer structure, suspended structure

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1. Introduction

Traditional high-rise building structures typically transmit vertical loads directly to the foundation through vertically connected components. However, with the development of the social economy, the pursuit of aesthetic and functional diversity in modern architecture has led to the increasing prevalence of designs such as building facades, corridors, large spaces at the bottom, and large overhangs. This has resulted in discontinuous vertical structural components, and traditional direct downward transmission paths often cannot be achieved. Therefore, how to safely and effectively transfer vertical loads to the foundation through structural transformation or suspension systems has become a key issue in the design of complex high-rise building structures.

To explore the transmission path of vertical loads in complex structures, this article selects four representative over limit high-rise building projects, including the typical suspension structure Taohuayuan Phase II expansion project, the typical giant frame core tube structure Qianhai Financial Headquarters Building, the typical complex connected and conversion structure Pujiang Laboratory, and the large-span conversion structure China UnionPay Operation Center. The different vertical load transmission mechanisms are comprehensively sorted out to provide reference for the design of similar complex projects.

2. Classification and Design Focus of Vertical Load Transfer

2.1. Types of Vertical Load Transmissions

The vertical loads of complex building structures are mainly divided into dead loads and live loads. Among them, the dead load includes the self-weight of columns, walls, floors, and additional dead loads, while the live load includes floor live load and roof live load. The vertical load transmission path of complex high-rise buildings can be mainly divided into three categories as in Figure 1: Vertical load transfer type:

a) The first type is direct vertical downward transmission.

b) The second type is horizontal transmission first and then vertical transmission downward. In the structure, the transfer is realized through transfer beams, trusses, slant support, etc.

c) The third type is the suspension structure, where vertical loads are first transmitted upwards, then horizontally, and finally vertically downwards. This is achieved through the installation of suspension rods and horizontal conversion components in the structure.

For complex structures, it is usually necessary to use the second and third types of load transfer paths to meet the unique architectural design or complex distribution of building functions.

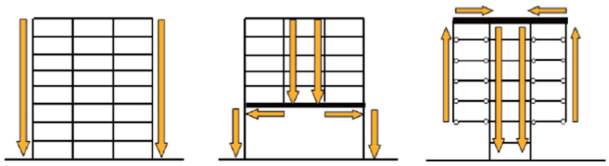


Figure 1. Vertical load transfer type.

2.2. Key of structural design

2.2.1. Clear load transmission path

In design, the transmission path of vertical force should be clearly defined, and the proportional distribution of vertical force should be calculated. By using design methods, the proportion of force transmitted directly downwards can be increased, reducing the vertical load in the conversion and suspension areas, and improving structural safety. Try to shorten the transmission path as much as possible, transmit force directly, and avoid multiple conversions.

2.2.2. Complex stress distribution of conversion components

The components in the vertical load transmission path of the transformation structure and suspension system are key components with complex stress. When designing, it is necessary to improve its seismic performance goals, ensure that it will not collapse during a major earthquake, and enhance safety reserves.

2.2.3. The construction sequence has a significant impact on the structural performance

For structures with complex vertical load transmission, construction simulation analysis needs to be carried out according to the actual sequence, and the calculation results often differ significantly from "one-time loading", especially for suspended structures and large-span structures. Due to deformation differences during the construction process, internal forces in the components may be redistributed, which needs to be considered and corresponding measures taken in the design to eliminate adverse effects.

3. Typical cases

To explore the transmission paths of vertical loads in complex structures, four representative super tall building projects were selected, including complex connected and conversion structures, giant frame core tube structures, conversion beams & conversion cable structures, and suspension structures. A comprehensive review was conducted on their different vertical load transmission mechanisms, providing reference for the design of similar complex projects

3.1. Complex Conjoining and Transformation Structures

3.1.1. Characteristics of vertical load transmission

The permanent building project of Pujiang Laboratory is a 17 story research and office building with characteristics such as large space, complex functions, and large span, as shown in Figure 2: The permanent building project of Pujiang Laboratory. The building has a height of 99.85m and a structural height of 96.65m. It consists of four vertical traffic tubes and a large-span connected structure, with only the traffic tubes and one span column around them maintaining a vertical connection; There are 10 large-span connected areas between the four vertical traffic tubes, ranging in size from 36 to 63m. Some of the connected areas contain large space laboratories with a width of 18 to 30m. Some large-span trusses cannot be directly placed on the vertically connected frame columns and need to be converted into trusses.

3.1.2. Key of structural design

3.1.2.1. Vertical force transmission analysis

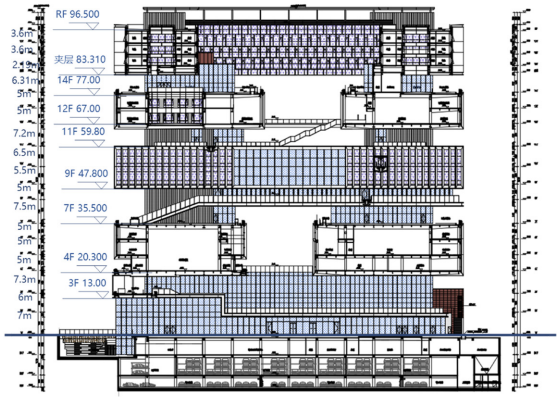
The basic structural components of this project are: a vertically continuous traffic tube and a surrounding one span frame+surrounding cantilever beams+large-span trusses. The vertical force transmission path is as follows: a) The vertical load on the outermost side of the building is transmitted to the traffic tube frame column through the cantilever beams, and then transmitted downwards; b) The load on the first and second floors is directly transmitted to the underground through the frame columns; c) The large-span area structure on the 4th to 6th and 8th to 10th floors adopts a form of large-span truss and suspension. The 4th and 8th floors are transmitted upwards to the large-span truss on the upper level through suspension columns, then horizontally to the vertically continuous frame columns, and finally downwards to the foundation; d) The vertical load at the large-span truss of the 15th to 17th floors is transmitted horizontally to the vertically continuous frame columns on both sides through the single-layer truss and the open web truss, and then transmitted downwards to the foundation. The schematic diagram of the vertical force transmission system of the structure is shown in Figure 2.

The distribution of vertical loads is shown in the table below. 94% of the load is transmitted through the traffic tube and the frame columns of one span outside the traffic tube, while the remaining 6% of the vertical load is transmitted vertically through the remaining frame columns on floors 1-2.

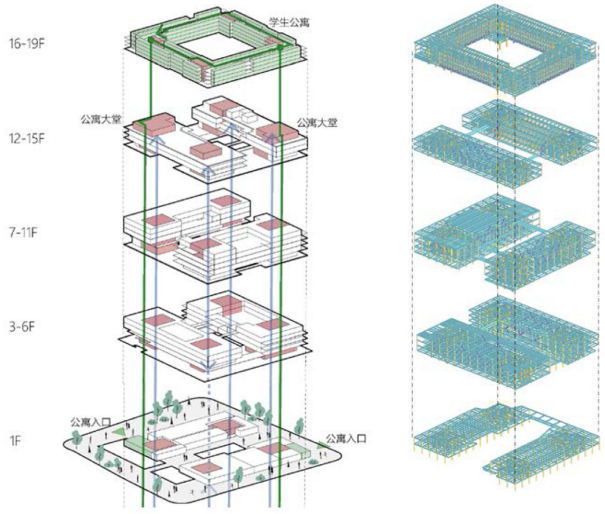
The main structure of this project consists of four support tubes and a large-span truss. In order to clarify the role of the four support tubes and the large-span truss in resisting horizontal loads, a model without diagonal web members of the large-span truss is used for comparative analysis with existing models. The comparison model is as follows: Model 1: The structural scheme adopted in this project retains diagonal web members for the large-span truss, as shown in Figure 3 (a); Model 2: Based on Model 1, remove the diagonal web members of the large-



(a)Architectural effect



(b) Architectural facade



(c)Schematic diagram of structural composition

Figure 2. The permanent building project of Pujiang Laboratory.

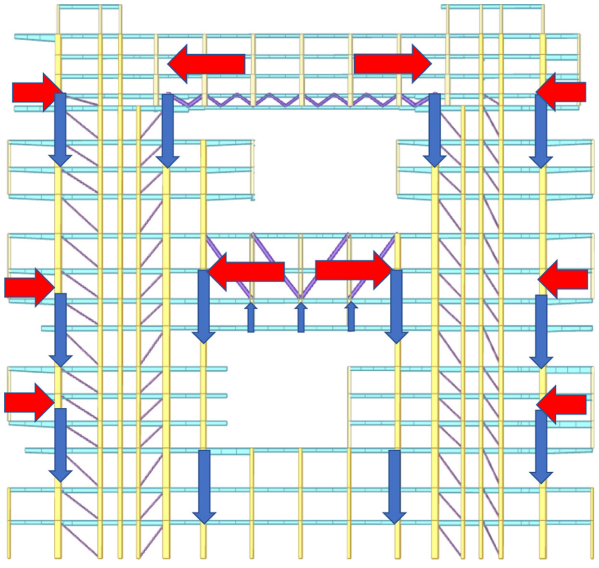


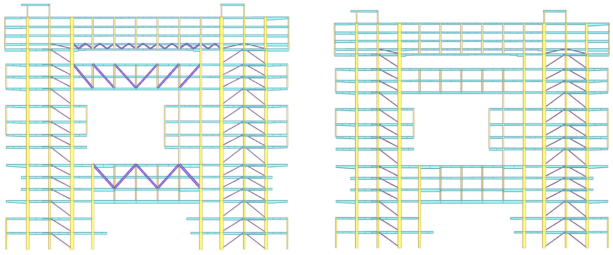
Figure 3. Schematic diagram of vertical force transmission system.

span truss and leave the chord members and vertical web members of the large-span truss, as shown in Figure 3 (b). From the above chart, it can be seen that after removing the diagonal web members of the large-span truss in Model 2, the self weight of the two models is consistent. The natural vibration period of Model 2 slightly increases, only by about 3% to 5%, indicating that the large-span truss contributes little to the overall lateral stiffness. The base shear force of Model 2 is about 88-93% of the base shear force of Model 1, indicating that the horizontal lateral resistance of the tower is mainly supported by four support tubes, which bear about 90% of the seismic action. The large-span truss only contributes about 10% to the overall lateral resistance. From the inter story displacement angle curve, it can be seen that the large-span truss only has a certain impact on the stiffness of the floor it is located on. The maximum inter story displacement angle of the two models is basically the same, with a difference of 2% to 4%.

In summary, the contribution of large-span trusses to

Table 1. Vertical load on the aboveground part

Total vertical loads (1.0D+1.0L)/kN		231615
Traffic tubes share vertical loads /kN	Traffic tube and surrounding one span pillar	Other frame columns on the 1st and 2nd floors are responsible for
	217719?94%?	13896?6%?



(a)Model 1 (b)Model 2

Figure 4. Comparison of computational modes.

the overall stiffness of the structure is minimal. The horizontal lateral resistance of the tower is mainly supported by four support tubes, while large-span trusses mainly bear vertical loads

3.2. Mega frame core tube structure

When the span of the conversion structure is large or there are many conversion floors, the section of the conversion beam will also increase accordingly, which is less economical. Therefore, conversion trusses can be considered. A typical conversion truss project is the Qianhai Financial Headquarters Building in Shenzhen.

3.2.1. Characteristics of vertical load transmission

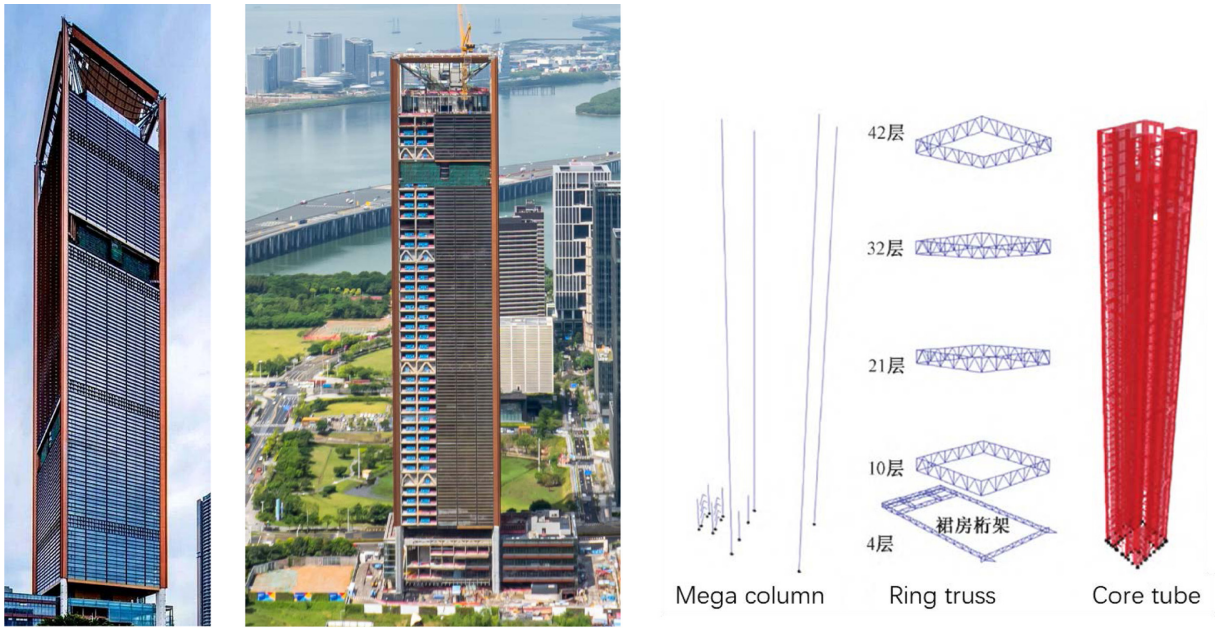
The total height of Qianhai Financial Headquarters Building is 245m. In order to meet the requirements of building effect and function, the gravity columns on some floors are discontinuous in the vertical direction. The outer frame column is mainly composed of four floor standing giant columns and a ring truss. The anti lateral force system is a giant frame core tube structure. The giant frame consists of four irregular multi cavity steel reinforced concrete columns and four ring trusses. The outer frame beam is hinged to the giant columns and gravity columns. Due to functional requirements, some floors have vertical discontinuous gravity columns, which



(a)3~4F (b)6~7F

(c)8~10F (d) 11~12F

Figure 5. Large-span corridor under construction.



(a) Completion effect (b)Under construction (c)Structural system

Figure 6. Qianhai Financial Headquarters Building Project.

are suspended in the form of hanging columns on the ring truss. The full height range of the gravity column section tower is 600 × 400 × 18 × 18 and 600 × 400 × 40 × 40. The outer beam has a cross-section of H650 × 250 × 10 × 16 and is hinged to both the giant column and the gravity column.

3.2.2. Key of structural design

32.2.1. Vertical force transmission analysis

The gravity columns on the exterior facade are hinged to the outer ring beams and floor steel beams, so the gravity columns do not bear seismic effects. The four exterior facades of the tower are equipped with building observation floors at different heights, resulting in vertical discontinuity of gravity columns on the facades. Therefore, gravity suspension columns are formed at different heights to support the floor structure. The structure of each facade is shown in Figure 7, where the red arrow line represents the downward transmission of gravity load to the truss, and the green arrow line represents the upward transmission of gravity load to the truss through the suspension columns. After calculation, the hanging load of the green arrow is about 4% of the total vertical load, which accounts for a relatively small proportion.

3.2.2.2. Design of Ring Trusses and Mega Columns

As a lateral force resisting system, the ring truss also bears the vertical load transmitted from the suspension column and transfers the vertical load to the giant column. The calculation results show that under the action of constant load and live load, the axial force of the giant column increases layer by layer, and the truss layer experiences a sudden increase of about 30%; The bending moment at the bottom of the columns in the main direction truss layer and the upper and lower layers of the truss is relatively large, and the bending moment at the bottom of the columns in the upper and lower layers of the truss rapidly decreases, about 10% of the maximum value. The shear force distribution law is the same as the bending moment. Under the action of earthquakes, the axial force of giant columns increases layer by layer, with

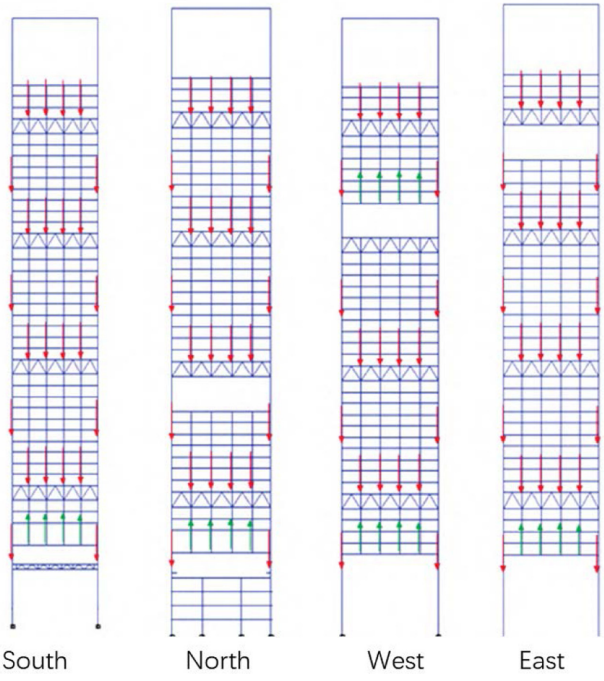


Figure 5. Large-span corridor under construction.

a sudden increase of about 30% to 50% in the truss layer. The bending moment at the bottom of the columns in the main direction of the truss layer and the upper and lower layers of the truss is relatively large. The internal forces generated by the giant column under the action of dead load and live load are much greater than those under earthquake action. Based on the above force characteristics, the section of the giant column in the truss layer and the upper and lower layers of the truss is increased in the design, and the thickness of the steel pipe wall is thickened. Due to the extremely high stiffness of the ring truss, the vertical load on its floor and upper and lower floors will suddenly increase by about 30%. Therefore, the design focuses on enlarging and thickening the sections of the giant columns on the ring truss layer and its upper and lower layers to cope with this concentrated axial force

3.2.2.3. Construction process simulation

Consider a reasonable construction sequence, analyze the deformation differences between giant columns and cylinders through construction simulation, and the adverse effects of internal force redistribution on the structure caused by this. The construction sequence has the following characteristics: 1) The ring truss is formed in one go without post installation; 2) Temporary supports shall be set up under the suspension column, and the suspension column and floor steel beams shall be constructed layer by layer. After the construction reaches the refuge level, the temporary supports shall be removed after the support ring truss of the suspension column is completed. The maximum number of support layers is 9; 3) After the temporary support is removed, pour concrete into the floor slab. The suspension column is a compression bending component during construction, and its bearing capacity and stability need to be verified during the construction process. The internal forces of the truss on the 10th floor of the tower are relatively large. Represented by the internal forces of some members of the truss on this floor and the maximum deformation at the mid span, the calculation results of the construction simulation model and the one-time loading model are compared. The internal forces of the members in the construction simulation model and the one-time loading model are basically the same, and the internal force level of the members in the construction simulation model is slightly higher than that in the one-time loading model.

3.3. Design of Conversion Beam and Conversion cable structure

As a common type of transfer structure, transfer beams are used when the structural span is not large and there are other vertical support components on both sides. Conversion beam is a simple, direct force transmission, and cost-effective conversion structure. The conversion cable, as an auxiliary conversion structure, can reduce the load borne by certain vertical components, represented by the China UnionPay Operations Center

3.3.1. Characteristics of vertical load transmission

The China UnionPay Operations Center is located in Shanghai, with a structural height of 150 meters, 36 floors above ground, and a building area of approximately 90000 square meters. The main building function is for office use. To achieve a lightweight and transparent effect, there are only 4 giant pillars at the bottom frame. The upper load needs to be transmitted to the bottom 4 giant columns through the conversion structure. According to the requirements of architectural design, the exterior facade should be clean and uniform, and diagonal web members are not allowed. Therefore, the problem of vertical load transmission path in the transition area is prominent. Through scheme comparison, umbrella shaped transfer beams (Figure 8: China UnionPay Centerc) are selected for vertical load conversion, which can make the vertical load borne by the outer frame columns more balanced and avoid the problem of stress concentration in individual frame columns caused by the use of cross shaped transfer beams. The umbrella shaped transition beam has a maximum span of 9.5m and a minimum span of 6.75m, and is a variable cross-section I-beam. The force form of the conversion structure is simple, the force transmission is uniform, and the size of the conversion beam and plate is small and easy to process.

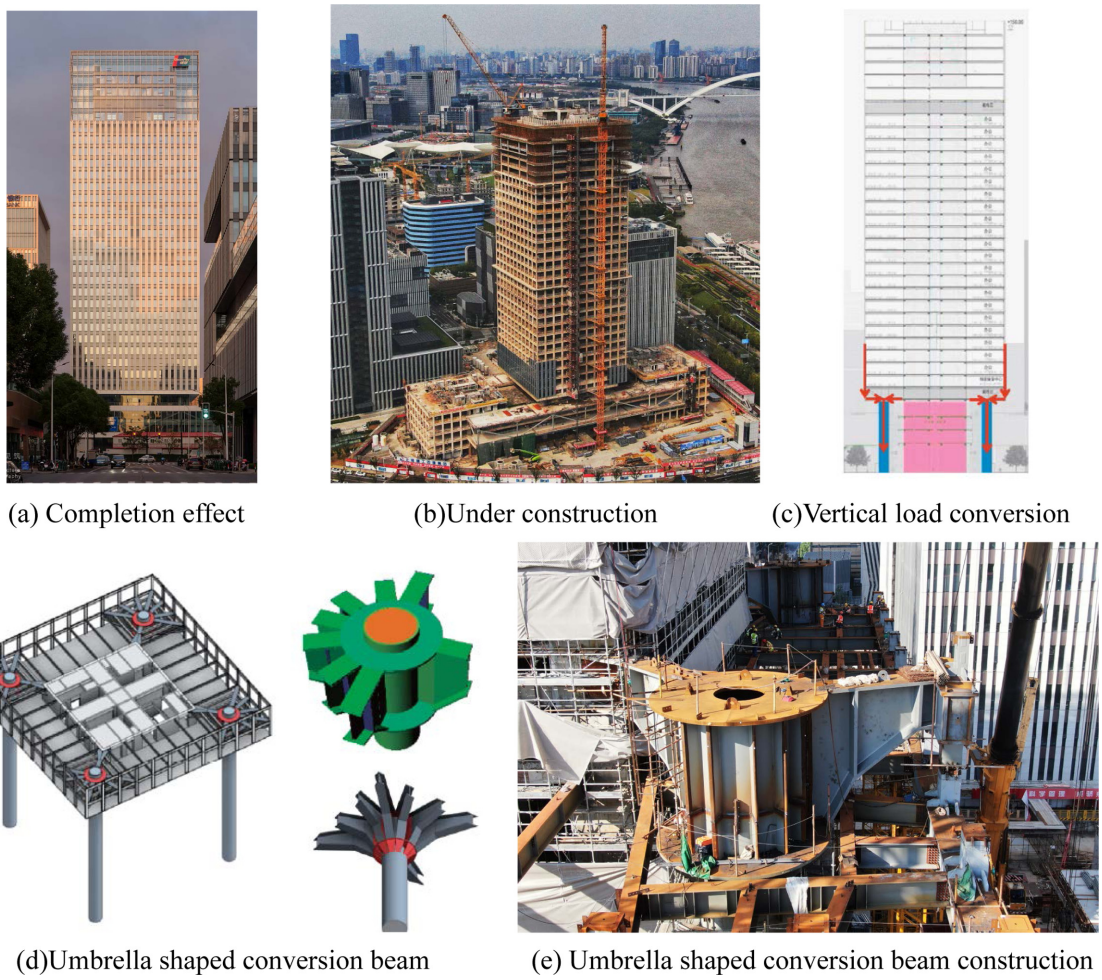
3.3.2. Key of structural design

3.3.2.1. Characteristics of vertical load transmission

Umbrella shaped transfer beams are used at the bottom (7th floor) of the China UnionPay operation center structure, and the structural design aims to minimize the axial force on the outer frame columns. Therefore, transfer cables are used in the upper high area of the structure to transmit some of the vertical loads borne by the outer frame columns. At the corners of the 17th and 28th refuge floors (Figure 9), a total of 8 cables are arranged, with 3 cables with a diameter of 120mm each. Each cable is prestressed with 2000kN, as shown in Figures 9b and 9c. By arranging cables on the 17th and 28th refuge floors, some of the outer frame loads are segmented and transmitted to the core tube, thereby reducing the vertical load borne by the outer frame. The axial force of the outer frame columns is further reduced by 15%, and the wall thickness of the outer frame columns and the flange thickness of the bottom (7th floor) transfer beam are also reduced.

3.3.2.2. Performance based design of key components

To ensure structural safety, key components and systems have been analyzed and performance strengthened in the design: a) The core tube is used as the main lateral force resisting component to improve its seismic performance, especially the bottom strengthening zone and adjacent layer shear walls of the transfer truss. It is required to



(a) Completion effect (b)Under construction (c)Vertical load conversion

(d)Umbrella shaped conversion beam (e) Umbrella shaped conversion beam construction

Figure 5. Large-span corridor under construction.

resist bending and shear elasticity under moderate earthquakes, and not yield under large earthquakes; b) The connection node between the conversion truss and the bottom deep beam is the key to ensuring that the vertical and horizontal loads of the upper hollow truss system are effectively transmitted to the lower giant column through the conversion system. To ensure the safety of the structure under earthquake action, ABAQUS software was used to verify its non-yielding target during large earthquakes

3.4. Suspension structure design

Roof suspension is the process of transferring vertical loads to the roof area through tension members such as suspension rods, and then transmitting them downwards through the vertical members. Its typical representative building is the Taohuayuan Phase II expansion project in Shenzhen

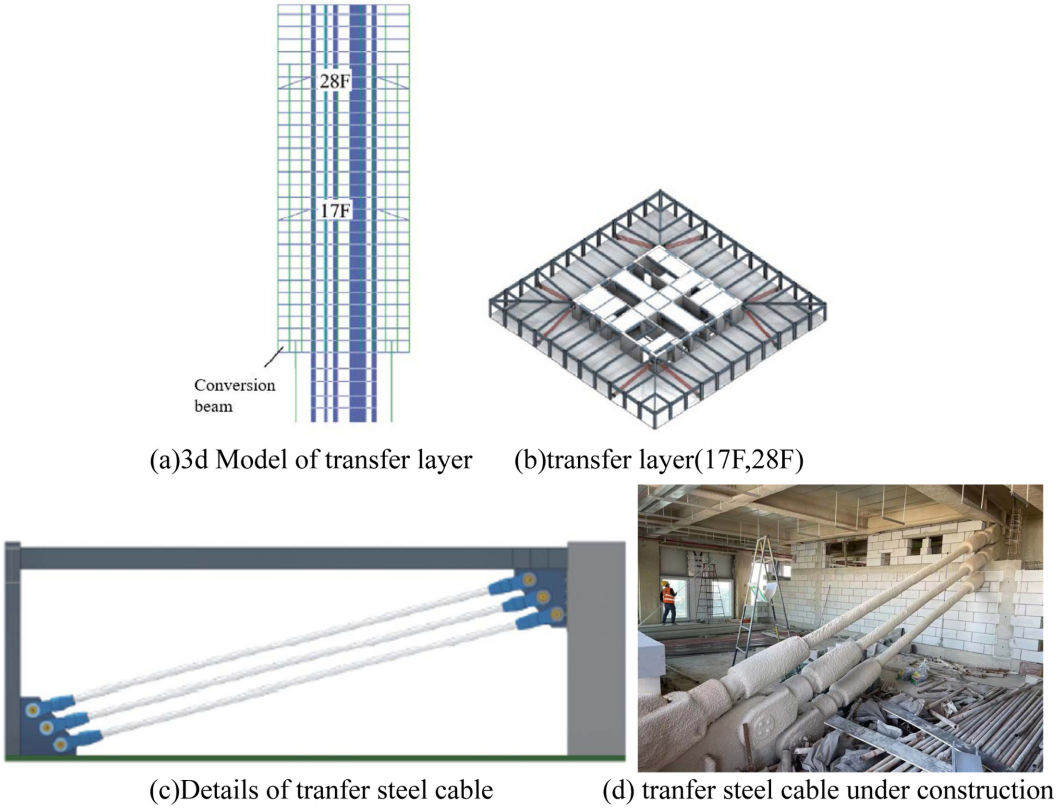
3.4.1. Characteristics of vertical load transmission

The Taohuayuan Phase II expansion project is located in Shenzhen and includes two towers. The south tower has 17 floors above ground with a building height of 79.5 meters, and the north tower has 13 floors above ground with a building height of 61.5 meters. The main building functions of the project are office, innovative industries, and service support. To create a visual effect of the tower's overall lightness and floating on the top of the slope, there are two discontinuous outer frame columns in the low area (5-6 floors) and middle area (9 floors) of the South Tower, and the outer frame columns of the North Tower are discontinuous in the low area (5 floors).

3.4.2. Key of structural design

3.4.2.1. Characteristics of vertical load transmission

The vertical load-bearing system of the tower consists of a floor system, a core tube, a cantilever truss, steel cables, and suspension columns. The transmission of vertical loads is divided into three areas: high, medium, and low. The transmission path is shown in the following Figure: 1) Part of the vertical load in the high area is transmitted from the floor beam to the core tube, and then transmitted downwards layer by layer from the core tube. The other part is transmitted upwards through the suspension



(a)3d Model of transfer layer (b)transfer layer(17F,28F)

(c)Details of tranfer steel cable (d) tranfer steel cable under construction

Figure 9. China UnionPay Application Center Vertical Transmission System.

column to the steel cable, and then transmitted to the top cap truss through the steel cable. The cap truss is then transmitted to the core tube and transmitted downwards; After calculation, the suspended load accounts for 33% of the total load in the high area (PA/P9) and 18% of the total load in the tower (PA/P1); 2) Part of the vertical load in the central area is transmitted to the core tube through the floor beams, and is transmitted downwards layer by layer from the core tube. Another part is transmitted to the core tube through the cantilever truss and transmitted downwards. The load transmitted downwards through the cantilever truss in the central area accounts for 9.6% of the total load of the tower (PB/P1). The vertical load transmitted upwards through steel cables and downwards through cantilever trusses is relatively low, indicating a high level of structural safety.

3.4.2.2. Performance based design of key structures

To ensure structural safety, key components are analyzed and performance strengthened in the design: a) The core



(a) Completion effect (b)Under construction

Figure 10. Taohuayuan Phase II expansion project.

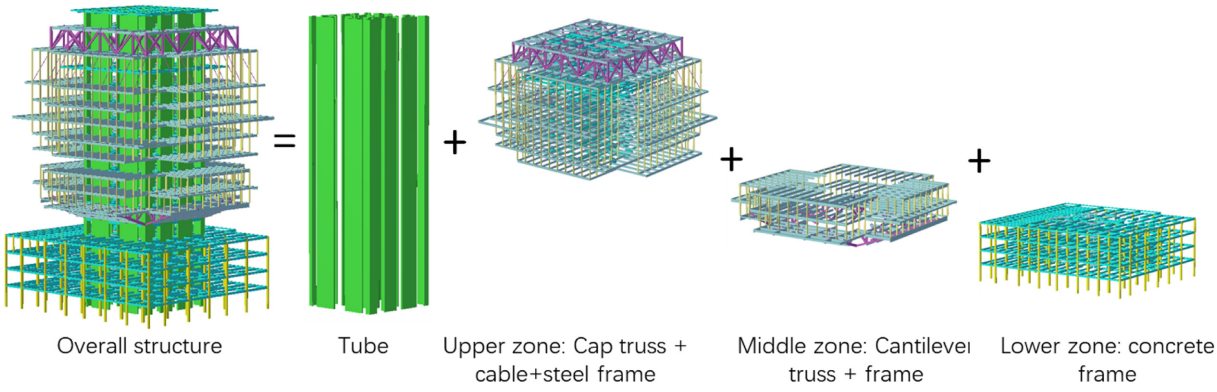


Figure 11. Compositon of structural system.

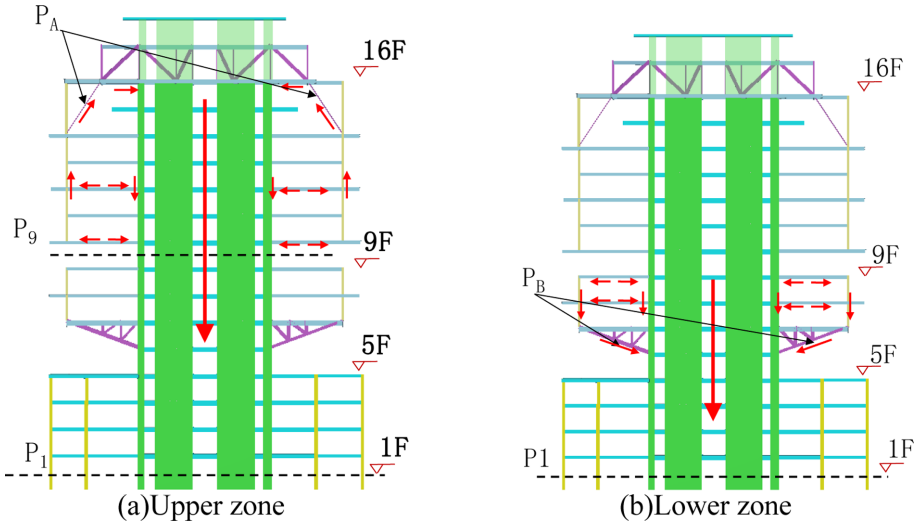


Figure 12. Vertical load transfer load path analysis.

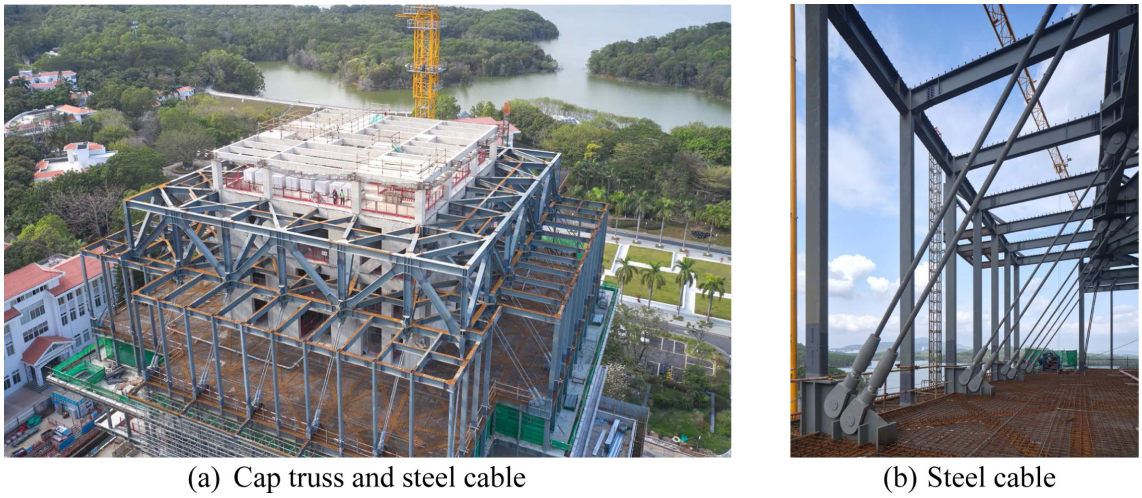


Figure 13. Taohuayuan Phase II expansion project under constructure.

tube serves as the main lateral force resisting component to improve its seismic performance, especially the bottom reinforcement zone, truss layer, and adjacent layer shear walls; b) Define the suspension conversion system as a key component, including the cap truss and steel cable, to improve its performance objectives. When designing, the

worst-case scenario of complete degradation of shear wall stiffness was considered for verification; c) High strength steel cables need to meet the requirements of large earthquake elasticity. Ensure that the safety factor is above 3 under the combination of non-yielding loads during major earthquakes, and improve the safety reserve.

3.4.2.3. Key technologies for forward construction of suspension structures

Based on the structural stress characteristics of the "upper support and lower suspension" in this project, and considering the impact of construction progress, the construction sequence of this project is as follows: a) Adopting the "sequential construction method", temporary supports are set up below the cantilever truss and cap truss, and construction is carried out layer by layer from bottom to top; b) After the installation of the cap truss is completed, the steel cables are tensioned. The cap truss is integrated with the hanging layer through the steel cables and the temporary support is removed for unloading; c) After unloading, pour the floor slab, and then complete the application of all dead and live loads.

4. Conclusions

1) In modern complex high-rise buildings that pursue diversity in form and function, it is usually necessary to use indirect transmission paths of the second and third types to solve the problem of vertical component discontinuity
2) Through a reasonable structural system and component design, complex load transfer can be efficiently and safely achieved. Different structural forms can be adopted for different building shapes and functional requirements, such as suspension systems combining steel trusses and steel cables, giant frame core tube systems, large-span transfer systems, and umbrella shaped transfer beam systems. These systems can effectively redistribute and transfer vertical loads to the foundation.
3) The design should follow a direct and concise force transmission path, with sufficient safety reserves, such as improving the seismic performance of key components

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