Council on Tall Buildings and Urban Habitat Korea

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

*International Journal of High-Rise Buildings*
*June 2026, Vol 15, No 2, 73-83*
*https://doi.org/10.21022/IJHRB.2026.15.2.73*

# Force Characteristics and Design Ideas of Complex Multi-tower Connected High-rise Structures

**Yizhou Zhang, Yansheng Liu†, Zhengyu Li, and Jie Fu**

*Architectural Design and Research Institute of Tsinghua University, China*

**Abstract** In recent years, multi-tower connected high-rise structures led by architectural design have been increasingly applied, and rigid connection is an inevitable structural form under specific conditions. For complex multi-tower rigid connected high-rises, structural stiffness, including the stiffness of single towers, connecting components and the overall structure, serves as the fundamental basis for the selection of connection forms. In structural design, appropriate conjoined parts, connection types and construction modes should be determined rationally based on stiffness requirements, rather than pursuing excessive stiffness blindly. This paper analyzes the mechanical performance of connected high-rise structures, discusses key design issues and conceptual principles. Taking a practical four-tower conjoined high-rise project as the engineering background, it systematically summarizes technical difficulties and corresponding design countermeasures from the aspects of overall layout, connection structure design, complex joint detailing, seismic performance design and whole-life cycle analysis.

**Keywords:** multi-tower conjoined structurerigid connection, conjoined truss, stiffness requirement, steel joint

†Corresponding author:
Yansheng Liu
E-mail: 22373836@qq.com

## 1. Introduction

A connected structure is defined as a structure in which two or more towers are interconnected via a connector. From the viewpoint of architectural experts, on one hand, the connector serves to link different buildings, thereby facilitating their interconnection; on the other hand, the distinctive form of the connected structure generates a powerful visual impact, endowing the building with greater distinctiveness (Xu, 2005). Twin - tower connected structures are relatively prevalent; however, in recent years, there has been a tendency towards multi - tower connected structures, such as Chongqing Raffles City (Zhu and Tu, 2017), Nanjing Golden Eagle Tiandi Plaza (Liu and Jiang, 2019), and Zhuhai Hengqin CRCC Plaza (Sun and Zhao, 2020).

Connected structures can be classified into rigid - connected structures and flexible - connected structures. When the stiffness of the connector or the connection mode is relatively low, and it fails to coordinate the joint operation of the main structures on both sides of the connector, it is regarded as a flexible - connected structure. Flexible - connected structures are applicable to scenarios where each individual tower can stand independently, the connector has low stiffness, and it is unable to coordinate or can only weakly coordinate the internal forces and deformations among multiple towers.

When the stiffness of the connector and the connection mode is sufficient to integrate individual structures into a unified whole, coordinate load - bearing, and achieve collaborative deformation, it is a rigid - connected structure. Rigid - connected structures are suitable for the following situations: 1) Structures in which each individual tower cannot stand independently and needs to be coordinated through the connector to form an integrated structure; 2) Structures in which each individual tower can stand independently, but the overall performance is enhanced after coordination via the connector; 3) Structures with complex architectural layouts that do not meet the requirements for flexible connections. This paper will concentrate on the analysis of rigid - connected structures.

## 2. Force-Bearing Characteristics of Connected Structures

### 2.1. Dynamic Performance Analysis of Individual Tower Structures

Each individual tower ought to possess comparable structural dynamic performance. The connector serves to link two or more lateral force - resistant structures, enabling them to operate collaboratively and jointly bear horizontal loads. When the dynamic characteristics of individual towers exhibit significant disparities, the connector structure compels the coordinated deformation of the towers. On one hand, this gives rise to substantial stress and strain within the connector structure; on the other hand, it

results in large internal forces at the connection parts of the main structures and the connection joints, leading to a marked decline in the rationality and economy of the connected structure. The code stipulates that "Each independent part of the connected structure should have identical or similar shape, planar layout, and stiffness" (JGJ 3 - 2010), which is considered from this perspective. When the shape and period of the towers are relatively alike, the internal force that the rigid connector needs to transmit is minimized (Xu and Peng, 2020).

### 2.2. Selection of Connector Types

The structural form of the connector shall be determined in accordance with the stiffness required by the structure. Under horizontal loads, for a connector with high stiffness, the overall bending moment at its end is relatively large (in the case of trusses, this is manifested as large axial forces in the upper and lower chords and web members). This exerts strong rotational constraints on the individual tower structures, leading to overall deformation of each individual tower structure. The members within the individual tower structures generate axial forces, and the load - bearing mode of the overall structure is similar to that of a frame, primarily undergoing shear deformation under horizontal forces.

A connector with low stiffness has a small bending moment at its ends and weak rotational constraints on each individual tower structure. The load - bearing mode of the overall structure is similar to that of coupled shear walls, mainly undergoing bending deformation under horizontal forces. When the stiffness of the connector is moderate, the load - bearing mode of the structure is similar to that of a frame - shear wall structure, mainly undergoing bending - shear deformation under horizontal forces, as depicted in Figure 1.

When a rigid connection method is employed for the connector, the lateral stiffness of the connected structure is positively correlated with the rotational constraints exerted by the connector on the individual tower structures. If the connector is considered as a mega - beam, as the stiffness of the mega - beam increases, the lateral stiffness of the structure will gradually increase; simultaneously, the internal force of the connector will also gradually increase. Figure 1 Structural Deformation Modes

The connectors of rigid-connected structures can be steel trusses, vierendeel trusses, steel beams, steel-reinforced concrete beams, etc. These connectors have different stiffnesses and thus exert different rotational constraints on the connected vertical members. Generally, steel trusses have the highest stiffness, followed by vierendeel trusses, and steel beams and steel-reinforced concrete beams have the lowest stiffness.

When an individual tower structure cannot stand independently and requires the connected structure to assist in controlling structural deformation; or when the span of the connector is large, and the connector must have sufficient stiffness under vertical loads to meet the conditions of the ultimate limit state of bearing capacity and the serviceability limit state, a connector with high stiffness should be selected, usually a steel truss.

When an individual tower structure can stand independently, a connector with lower stiffness can be selected as much as possible based on the span of the connector and the architectural plane or elevation conditions. Options include vierendeel trusses, steel/steel-reinforced concrete beams, etc., to reduce the impact of the connector's stiffness on the force-bearing performance of the individual tower structures and minimize the internal force of the connector.

### 2.3. Selection of Connection Methods

The connection method of the connector has a significant impact on the stiffness and internal force of the overall structure.

When the individual tower structures are considered as mega columns and the connector as a mega beam, as the connection mode of the connector shifts from a “hinge - like” state to a “rigid - like” state, the load - bearing mode of the overall structure changes from the “bent frame mode” to the “frame mode.” The lateral stiffness of a frame structure with rigid beam - column connections is significantly higher than that of a bent frame structure with hinged beam - column connections.

Taking the bent frame and frame in Figure 2 as an illustration, assuming the stiffness of the frame beam is

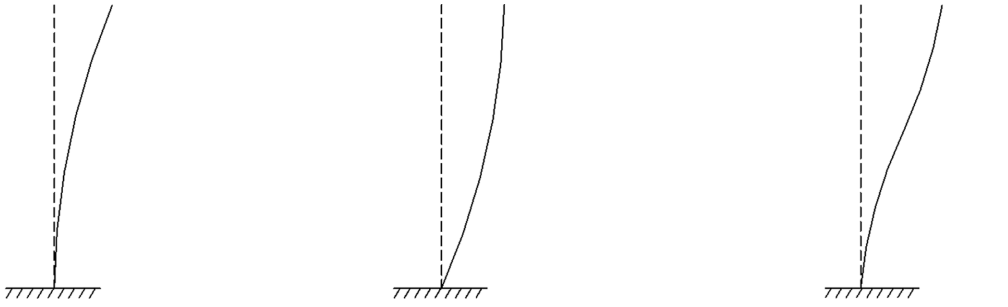
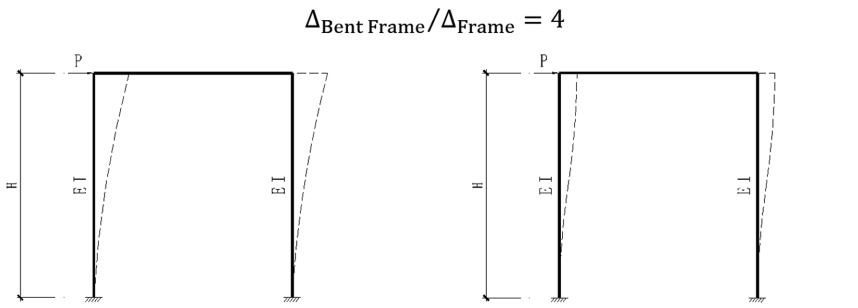



**Figure 1.** Structural Deformation Modes.




**(a)Hinged Beam-Column Connection, with Small Rotational Restraint on Vertical Members**

**(b)Rigid Beam-Column Connection, with High Rotational Restraint on Vertical Members**

**Figure 2.** "Bent Frame Mode" and "Frame Mode".

infinite, the stiffness of both the bent frame column and the frame column is EI, and the height is H. Under the action of a horizontal force P, the horizontal lateral displacement of the bent frame (Δ_bent frame) is $PH^3$/6EI, and that of the rigid frame (Δ_frame) is $PH^3$/24EI. The constraint exerted by the frame beam on the column enhances the structural integrity, and the lateral stiffness of the frame is greater than that of the bent frame (Liu and Zhang, 2019).

Consequently, the stronger the connection between the connector and the individual tower structures, the greater the stiffness of the overall structure. Figure 2 "Bent Frame Mode" and "Frame Mode".

Simultaneously, the connection mode between the connector and the individual tower structures also determines the internal force dissipation path and dissipation gradient of the individual tower structures connected to the connector. When the connector truss extends into the individual tower structure, it creates favorable conditions for the internal force dissipation of the connected frame columns and beams, facilitating the transfer and dispersion of their substantial internal forces to the surrounding frame columns or shear walls. As the number of spans of the connector truss extending into the individual tower structure increases, the internal force dissipates successively with a gentle variation, and the internal forces of the connected frame columns and beams are notably reduced, leading to superior structural performance. Nevertheless, a balance needs to be achieved between the rationality of structural force - bearing and the constraints of architectural requirements.

### 1.4. Selection of Connection Positions

The position of the connector has a significant impact on the force bearing and deformation of the structure. In practical engineering, the position of the connector is mainly determined by architects based on the building shape and architectural functions, and is generally located in the middle or upper part of the towers.

When the connector is located at a high position, its collaborative effect on each individual tower is significant, and its force transmission efficiency between the individual towers is higher than that when it is located in the middle. However, in this case, the connector needs to coordinate a large amount of deformation, which requires high stiffness of the connector, and the internal force of the connector members is large.

When the connector is located in the middle part, the structure is divided into two parts: the part below the connector works collaboratively; each individual tower above the connector resists horizontal forces independently, and the collaborative effect of the connector on each individual tower is weak. At the same time, the greater the difference in stiffness between the upper and lower parts of the structure, the more obvious the whipping effect of each individual tower above the connector under earthquake action.

Considering various situations comprehensively, it is recommended that the connector be located in the upper-middle part of the building for general constructions, which is more reasonable.

### 1.5. Key Issues in the Design of Connected Structures

(1) Overall torsion problem of connected structures. Rigid-connected structures use rigid connectors to integrate individual tower structures for collaborative work. Due to differences in the dynamic characteristics of each individual tower and asymmetry in the plane layout, the center of mass and the center of stiffness of the overall structure will inevitably not coincide, resulting in a planar-torsional coupling effect of the structure, and the connected structure is prone to overall torsion. How to control the overall torsion of the structure will be a key issue in structural design.

(2) Stiffness degradation problem of the connector. Under normal service conditions, the connector coordinates the joint work of each individual tower, and horizontal forces are mainly transmitted through the floor slabs. The floor slabs are no longer secondary members that only bear vertical loads, but become key members that directly determine the overall working performance of the structure. At the same time, it should be noted that under special conditions such as moderate and strong earthquakes, the

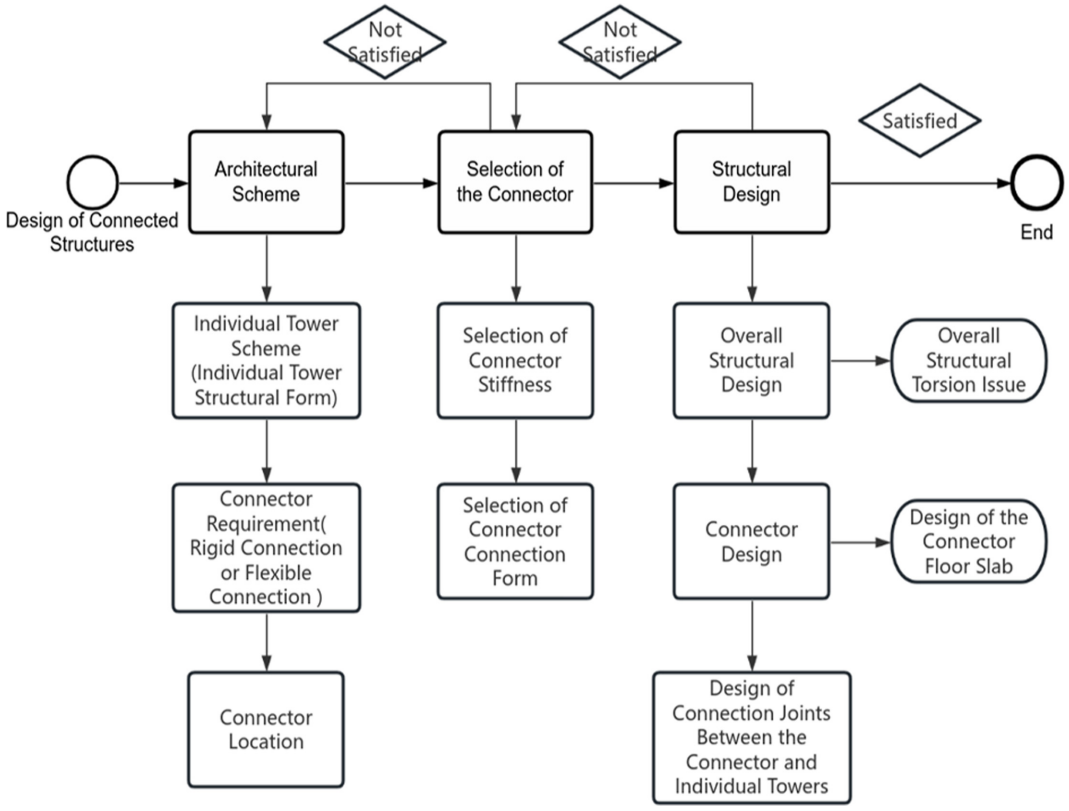



**Figure 3.** Design Idea of Rigid-Connected Structures.

floor slabs may be damaged and fail to function. At this time, the plane of the connector becomes a parallel chord truss, and the horizontal forces will be transferred to the upper and lower chords of the steel truss of the connector. The stiffness of the connector is greatly reduced, which in turn reduces the stiffness of the overall structure, causes re-distribution of internal forces of members, and may even affect the integrity of the connected structure as a whole.

(3) Force transmission problem between the connector and the main structure. For rigid-connected structures, the connection part between the steel truss of the connector and the main structure has stress concentration and complex force-bearing conditions. The connection joint must realize a reasonable internal force transmission path and dissipation gradient to ensure the effective transmission of internal forces between the connector and the main structure, and should be the part with the highest reliability in the entire structure. Usually, there are many intersecting members at this joint, leading to high construction difficulty, which contradicts the requirement for extremely high reliability. Therefore, special research on such complex joints is required.

### 1.6. Design Idea of Connected Structures

Based on the above analysis of the force-bearing characteristics of multi-tower connected high-rise structures, the design idea of connected structures can be derived, as shown in Figure 3.

## 3. Project Overview

Multi-tower connected high-rise structures have various forms, and each faces different technical difficulties. This paper relies on an actual project to sort out the technical difficulties and design countermeasures in the design of complex multi-tower connected high-rise structures.

The Jiangmen Archives Center Project is located in Jiangmen City, Guangdong Province, and is a complex high-rise structure with four towers (four-tower) connected at a high position. The total construction area is 104,475 $m^2$, including 80,676 $m^2$ for the above-ground part (15-18 floors) and 23,799 $m^2$ for the underground part (2 floors). It is 128.6 m long from east to west, 100 m wide from north to south, and the roof structure height is 84.6 m. The connector is located on the 14th-15th floors, with a top elevation of 72.6 m, a height of 9 m, and a span ranging from 25.2 m to 42 m. The architectural effect is shown in Figure 4.

The four individual structures consist of 3 towers and 1 elevator transportation and observation tower, with the plane layout and zoning diagram shown in Figure 5. The elevator transportation and observation tower (Area A) adopts a shear wall structure, and the 3 towers (Areas B, C, and D) adopt a frame-shear wall structure. The four individual structures are connected by a connector composed of 2-story tall steel trusses on the 14th-15th floors. The structural plane layout of the connected floor is shown in



**Figure 4.** Architectural Rendering.

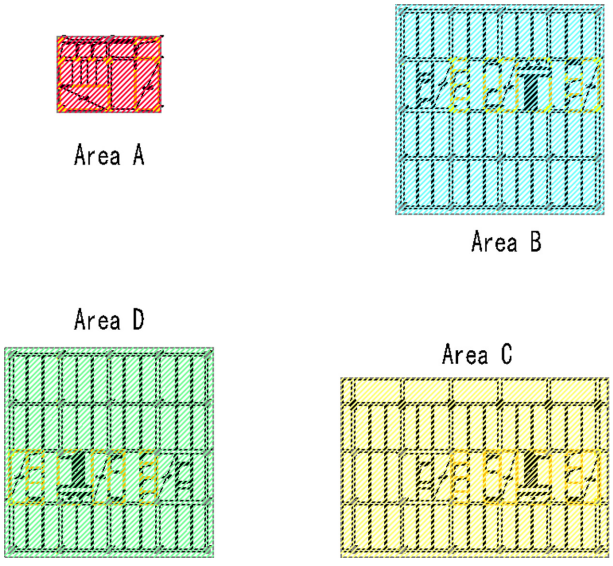



**Figure 5.** Structural Plane Layout and Zoning Diagram of Floors 4-13.

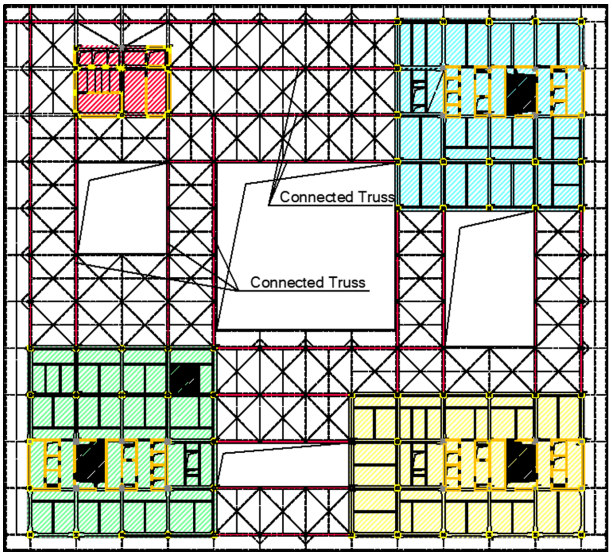



**Figure 6.** Structural Plane Layout of the Connected Floor.

Figure 6. The diagonal web members of the connector truss are arranged in combination with the layout of the building rooms to minimize their impact on the building's service functions.

Shear wall thickness: 500 mm and 400 mm for the outer ring of the core tube, 250 mm and 200 mm for the inner part; cross-section of ordinary reinforced concrete frame columns: 900 × 1,400 mm, 900 × 1,200 mm, 800 × 1,000 mm; cross-section of steel-reinforced concrete frame columns connected to the connector: 900 × 1,200 mm (with steel skeleton H700 × 500 × 40 × 40), 1,000 × 1,000 mm (with steel skeleton H600 × 600 × 40 × 40); cross-section of ordinary frame beams: 400 × 800 mm, 400 × 900 mm, 600 × 900 mm; cross-section of steel-reinforced beams on the connected floor: 900 × 1,100 mm (with steel skeleton H800 × 450 × 20 × 40), 700 × 900 mm (with steel skeleton

**Table 1.** Outline Dimension Information of Each Area

| Individual Unit Name | Above-Ground Floors / Height(m) | Length×Width(m) | Aspect Ratio | Height to Width Ratio |
|---|---|---|---|---|
| Area A | 15F/72.6 | 16.8×12.0 | 1.40 | 6.05 |
| Area B | 15F/72.6 | 33.6×33.6 | 1.00 | 2.16 |
| Area C | 18F/84.6 | 42.0×25.2 | 1.66 | 3.35 |
| Area D | 15F/72.6 | 33.6×33.6 | 1.00 | 2.16 |

H500 × 250 × 20 × 30); chord members of the connector: □800 × 500 × 20 × 30 mm, □1,000 × 500 × 20 × 30 mm, □1,000 × 500 × 30 × 60 mm; diagonal web members of the connector: □500 × 500 × 25 × 25 mm, □400 × 400 × 25 × 25 mm; vertical web members of the connector: □600 × 500 × 30 × 30 mm, □500 × 500 × 30 × 30 mm.

The height and outer contour dimensions of the individual structures in each area are detailed in Table 1. There is a significant difference in scale between Area A and the other three areas. Due to the small scale of Area A itself and the complex connection relationship with Areas B and D, the arrangement of the connector structure is restricted, and the conditions for flexible connection between the connector and the individual structures are not met. Therefore, a rigid-connected structure scheme is adopted for this project.

The structural safety grade of the project is Grade II; the design service life of the main structure is 50 years; the seismic fortification intensity is 7 degrees, the basic design acceleration is 0.10g, the design earthquake group is the first group, the site category is Class III, and the seismic fortification category is Class C.

The basic wind pressure is 0.6 kN/m$^2$ (once in 50 years), and the ground roughness category is Class B. Since this project is a high-rise building sensitive to wind loads, the ultimate limit state design is carried out according to 1.1 times the equivalent floor wind load provided in the wind tunnel test report, and the serviceability limit state design of the structure is carried out according to the equivalent floor wind load (GB 50009-2012).

The high-position connector is located on the roof of the main structure with a large span and is sensitive to temperature effects. The structure closure temperature is considered as 20°C, the maximum temperature rise is 25°C, and the maximum temperature drop is –25°C.

## 4. Structural Technical Difficulties

(1) Due to the constraints of architectural conditions, the connector and the individual towers must adopt rigid connections. At the same time, due to the large span of the connector itself, under vertical loads, the cross-section and self-stiffness of the structural members are large, leaving no room for adjustment. This results in obvious constraint effects of the connector on each individual tower, and the design must be carried out with the four towers connected rigidly as an integrated structure.

(2) The rigid connection integrates the four towers to work collaboratively as a whole. The center of mass and the center of stiffness of the overall structure do not coincide, resulting in a planar-torsional coupling effect of the structure, and the structure is prone to overall torsion.

(3) The four individual structures have different forms and significant differences in dynamic characteristics. The connector forces the coordinated deformation of each individual tower and changes the original dynamic characteristics of each individual tower, resulting in large internal forces and complex force-bearing states in the connector structure, the connection parts between the individual towers and the connector, and the connection joints. In addition, the connector is located on the top floor, so it needs to coordinate a large absolute deformation. At the same time, the connector has high stiffness, leading to even larger and more unfavorable internal forces.

## 5. Structural Design Countermeasures

### 5.1. Structural Layout

(1) Determine the structural form of the connector based on its span and service function. Since the maximum span of the connector reaches 42 m, the connector members must have a large cross-section and sufficient stiffness under vertical loads to meet the requirements of the ultimate limit state of bearing capacity and the serviceability limit state (Yang and Jiang, 2018). A two-story full-height steel truss is adopted for the connector, with the steel grade of Q390B. The chord members of the truss use box sections of □1000 × 500 × 30 × 30 and □1000 × 500 × 50 × 50, while the web members of the truss adopt box sections of □500 × 600 × 40 × 40 and □500 × 500 × 25 × 25.

(2) Optimize and adjust the structural plane layout on the basis of meeting the requirements and constraints of architectural functions. A reasonable structural layout for each of the four individual towers does not necessarily equate to the most optimal layout for the integrated structure of the four connected towers. In the overall structure, the longitudinal and transverse lateral force-resistant units work together to resist torsion; the farther a lateral force-resistant unit is from the stiffness center, the greater its contribution to the torsional stiffness. For each individual tower structure, appropriately offsetting the main lateral force-resistant units to the outside can

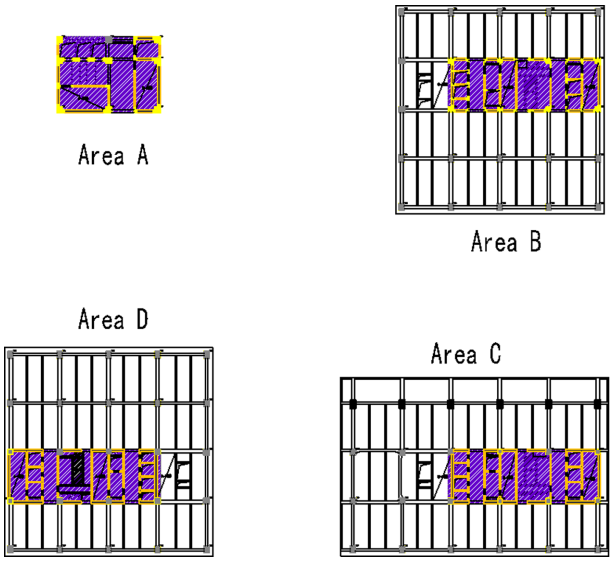



**Figure 7.** Adjustment of Shear Walls in Each Individual Tower.

enhance the torsional stiffness of the overall structure, as shown in Figure 7. Considering the reliability issue, the design of individual tower structures should also be taken into account to ensure their safety under extreme working conditions.

Since the connector significantly alters the dynamic characteristics of each individual tower, from the perspective of design guarantee rate, the connector and its related parts should be the last to fail in the structure. Meanwhile, the special stress conditions when individual tower structures work independently should also be considered.

(3) Optimize the layout of individual tower structures to minimize the internal force of the connector. Area A adopts a shear wall structure, which exhibits flexural deformation under horizontal actions; Areas B, C, and D use frame-shear wall structures, showing flexure-shear deformation under horizontal actions. After the individual towers are forced to coordinate their deformation through the rigid connector, the overall structure mainly undergoes flexure-shear deformation under horizontal actions. Therefore, it is necessary to appropriately reduce the thickness of the shear walls in the upper part of Area A to decrease its stiffness, thereby minimizing the internal force caused by the connector's forced change of its lateral force-resistant performance.

(4) Determine the connection degree and connection method between the connector and the individual tower structures. Taking the connector linking Area A and Area B as an example, a comparison is made between the scheme where the connector truss extends into the main structure (Scheme 1, Figure 8(a)) and the scheme where only the upper and lower chords of the connector extend into the main structure (Scheme 2, Figure 8(b)). Table 2 presents the internal forces of the connected frame columns and beams, as well as the ratio of the results between Scheme 1 and Scheme 2. It can be seen that when the connector truss extends into the main structure, the internal forces of the connected frame columns and beams are significantly reduced, resulting in better structural performance.

However, considering the constraints of structural stress performance and architectural service functions, in this project, the connector truss is directly connected to the shear walls in Area A and linked to the outermost frame columns in Areas B, C, and D. The upper and lower chords extend into the individual tower structures and connect to the shear walls, as shown in Figure 8(b).

### 5.2. Connector Design

(1) Classified design of connector trusses. According to

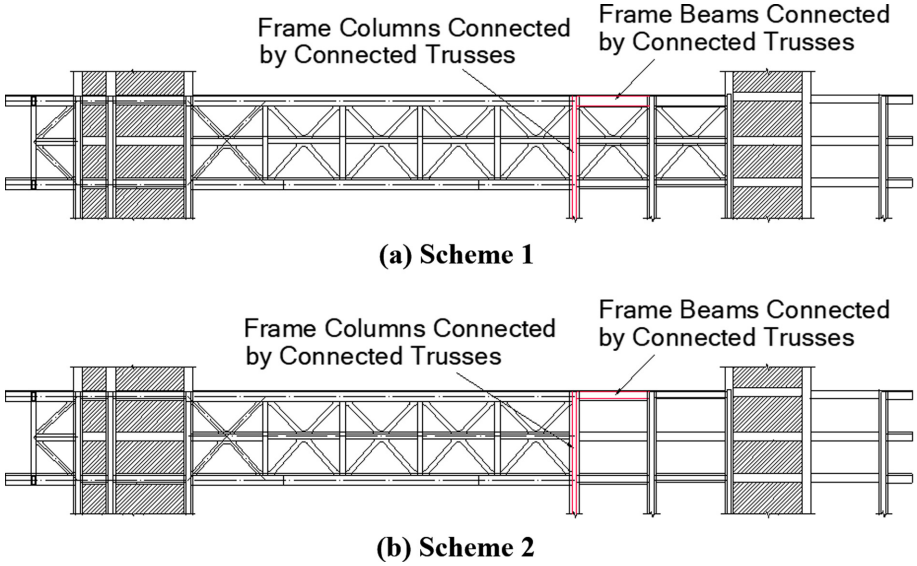



**Figure 8.** Connection Schemes Between the Connector and Individual Tower Structures.

**Table 2.** Comparison of Internal Forces of Relevant Members Under Different Connector Connection Methods

| | Axial Force of Connected Frame Columns(kN) | Shear Force of Connected Frame Columns(kN) | Shear Force of Connected Frame Beams(kN) |
|---|---|---|---|
| Scheme 1 | 443 | 329 | 257 |
| Scheme 2 | 1239 | 444 | 422 |
| Ratio | 0.36 | 0.74 | 0.61 |

the architectural conditions and the plane layout of the connected floor, the connector trusses are divided into two categories: The first category consists of connector trusses with both ends directly connected to the individual tower structures, resulting in large bending constraints at the truss ends and relatively large internal forces in the members. The second category includes connector trusses with one end connected to the individual tower structure and the other end linked to a connector truss or a cantilever truss; only one end has large bending constraints, and the internal forces are relatively smaller compared to the first category. During member design, distinctions are made based on different stress conditions.

(2) Refined design of connector trusses. The members of the connector steel truss are compression-bending or tension-bending members. Unlike general steel members that are mainly subjected to bending, these members bear a relatively large proportion of axial force. Box sections are used to reduce the cross-sectional size of the members. For members farther from the stiffness center, which bear greater internal forces, larger cross-sections are adopted.

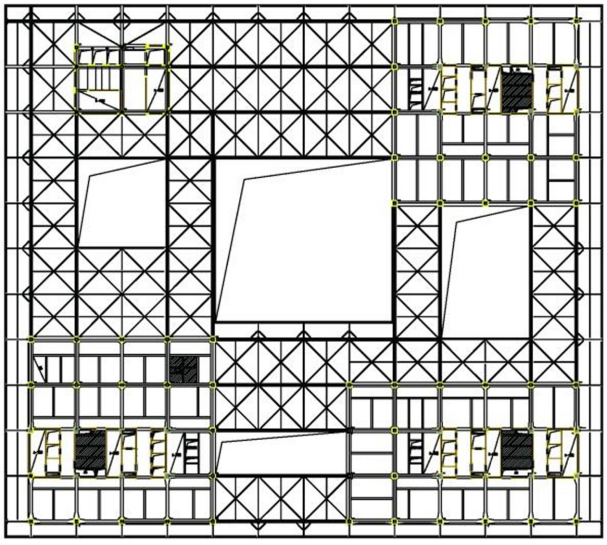


**Figure 9.** Layout of In-Plane Horizontal Braces in the Connector Floor Slab.

### 5.3. Structural Life-Cycle Analysis

(1) Consider the redistribution of internal forces caused by the damage of the connector floor slab under extreme conditions. The connector coordinates the joint work of each individual tower under horizontal forces, and the horizontal forces are mainly transmitted through the floor slab. Under special conditions such as moderate and strong earthquakes, the floor slab may be damaged and cease to function. At this point, the plane of the connector transforms

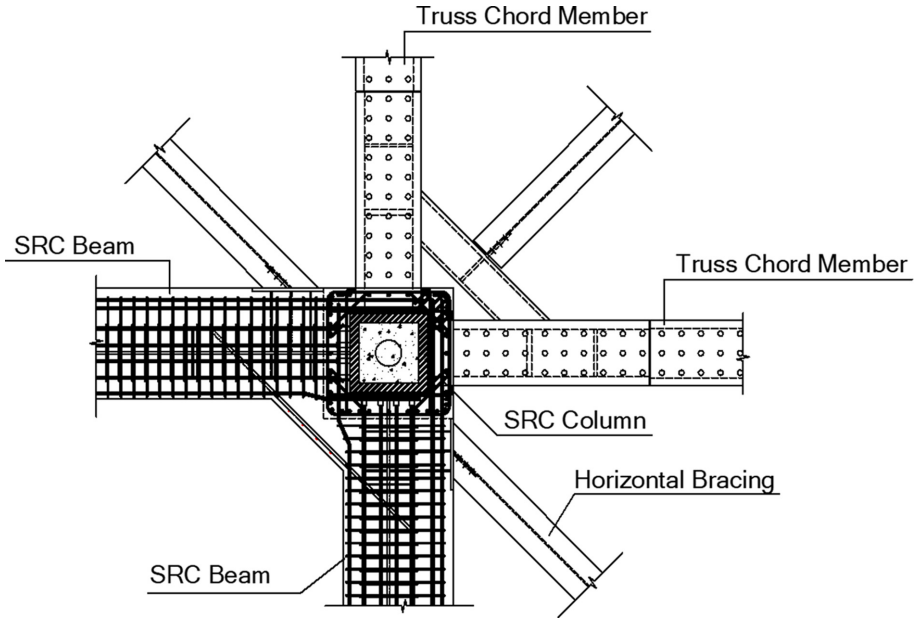



**Figure 10.** Connection Joints Between the Connector Steel Truss and Individual Tower Structures.

into a parallel-chord truss, and the horizontal forces are transferred to the upper and lower chords of the connector steel truss. This leads to a significant reduction in the stiffness of the connector, which in turn decreases the stiffness of the overall structure, causes the redistribution of internal forces among members, and may even affect the integrity of the four towers as a single integrated structure.

The countermeasures adopted are as follows: Firstly, adjust and strengthen the layout of the connector structure, and install in-plane horizontal braces in the floor slab (Figure 9) to ensure that after the floor slab fails, the plane of the connector can still form a truss and maintain a certain level of horizontal stiffness to coordinate the joint deformation of each individual tower. Secondly, as the stiffness of the connector decreases, the internal forces of some members (such as frame columns and connector chord members) increase significantly. To prevent these members from being damaged or failing under special conditions, it is necessary to design and analyze all possible working conditions throughout the structural life cycle. Therefore, recalculations are conducted using the zero-stiffness floor slab model to analyze the internal forces of members (especially those with increased internal forces) under the floor slab damage condition, and the design is carried out accordingly.

(2) Consider the redistribution of internal forces caused by the damage of shear wall coupling beams under extreme conditions. Areas B, C, and D are frame-shear wall structures. Under moderate and strong earthquakes, the coupling beams of the shear walls first enter the plastic state. When accurate calculation and analysis are difficult, based on conceptual design, the stiffness of the shear walls decreases, leading to the redistribution of floor shear force between the shear walls and frame columns, and an increase in the internal forces of the frame. Based on the repeated load tests of a 1:3 scaled spatial frame-shear wall structure model and the elastoplastic analysis results of this test model, the Code for Seismic Design of Buildings (GB 50011—2010) provides a method for adjusting the internal forces of the frame in frame-shear wall structures. During the design process, the elastic calculation results of the frame are adjusted to increase the seismic shear force borne by the frame, and the reliability of the design is verified through the elastoplastic time-history analysis under strong earthquakes.

### 5.4. Complex Joint Design

The joints at the connection between the connector steel truss and the individual tower structures have a large number of intersecting members, including truss chord members, diagonal web members, frame columns and beams of the individual towers, and horizontal braces of the connector. Except for the horizontal braces, the other members are large in size, which not only makes joint connection difficult but also leads to extremely high construction difficulty. In particular, for the joint where the bidirectional connector truss connects to the corner column of the same individual tower, the arrangement of longitudinal reinforcement in the steel-reinforced concrete column and beam is complex. Finally, the connection joint is realized by means of horizontal haunches on the steel-reinforced concrete beam and the installation of steel corbels, as shown in Figure 10.

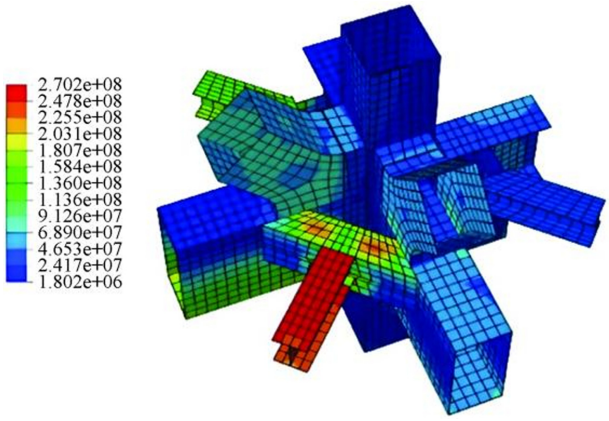



**Figure 11.** Stress Cloud Diagram of the Steel Skeleton in the Finite Element Joint (ABAQUS) /(N/m$^2$).

Since the joint members cannot be simplified, and the connection joints between the connector and the individual tower structures should be the parts with the highest reliability in the entire structure, special research is conducted on these complex joints. A three-dimensional finite element model is established using the general finite element software ABAQUS to numerically simulate and analyze the stress state of the joint under rare earthquakes, and to examine its stress condition and the rationality of its structure, as shown in Figure 11. The analysis and calculation results indicate that under the action of rare earthquakes, the concrete in the joint area suffers relatively serious tensile damage, while the steel skeleton and steel reinforcement in the joint area basically remain in the elastic state.

### 5.5. Seismic Performance-Based Design

This project is an out-of-code high-rise structure. In addition to conducting structural design in accordance with the above countermeasures, performance-based design is also carried out based on the set seismic performance objectives. The structural seismic performance objective is set to Level C, and the corresponding perfor-mance levels under frequent earthquakes, design-basis earthquakes, and anticipated rare earthquakes are Levels 1, 3, and 4 respectively. Under earthquake actions, the connector steel truss and the top and bottom parts of the four individual tower structures are the parts with the most complex stress conditions and the highest reliability requirements. Their seismic grade is increased by one level, and they are designated as key members in the performance-based design. Through the elastoplastic analysis under strong earthquakes, the potential weak parts and members of the structure are analyzed, the structural damage status is

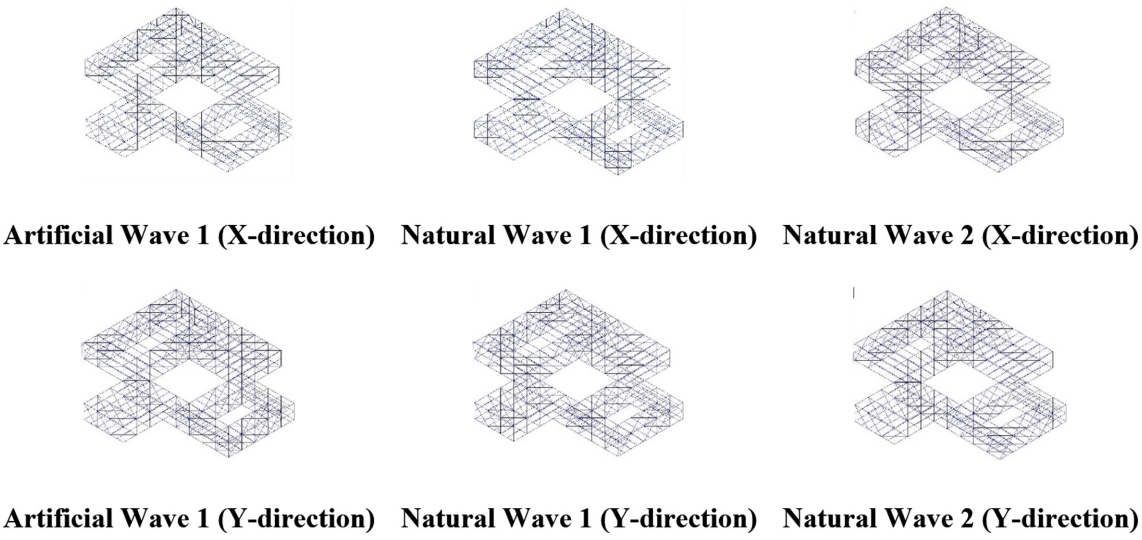



**Figure 12.** Schematic Diagram of Cumulative Plastic Strain of the Connector Steel Truss.

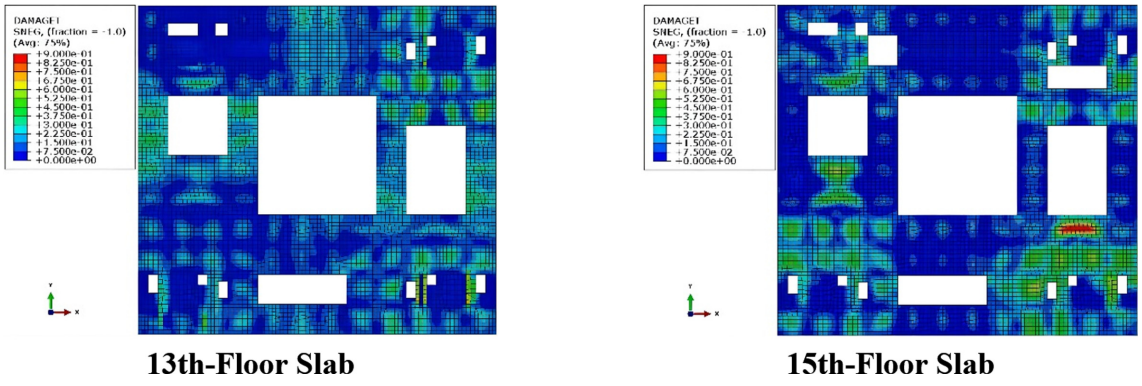



**Figure 13.** Tensile Damage Cloud Diagram of the Floor Slab When Natural Wave 1 is Input.

determined, and the reliability and safety of the structure are further verified.

Figure 12 is a diagram showing the cumulative plastic strain of the connector steel truss. It can be seen that the connector steel truss does not yield under rare earthquakes and remains in the elastic stage.

Figure 13 is the damage cloud diagram of the concrete in the floor slabs of the 13th and 15th floors of the connector when Natural Wave 1 is input. As can be seen from Figure 13: 1) The concrete damage is mainly distributed around the core tube, near some openings, and in the connection structure part; 2) The damage factor of the floor slab concrete mostly ranges from 0.3 to 0.5, corresponding to a tensile stress of approximately 1.2 MPa and a compressive strain of 1155με.

## 6. Conclusions

(1) For rigid-connected structures, stiffness is the fundamental basis for selecting the form of the connected structure. In structural design, the stiffness of the individual tower structures, the stiffness of the connector structure, and the stiffness of the overall structure should be comprehensively considered. Appropriate connection positions, connector structure types, and connection methods should be selected according to the stiffness requirements.

(2) There is a trade-off relationship between the stiffness of the connected structure and the internal forces of the structure. Blindly pursuing an increase in stiffness should be avoided in the design process.

(3) In structural design, priorities should be clarified. Based on the stress characteristics of the connected structure, key parts should be emphasized in the design.

(4) Architectural constraints have a significant impact on the selection of structural schemes. Under the premise of meeting architectural requirements and constraints, efforts should be made to achieve a reasonable and optimized structure as much as possible.

## REFERENCES

Xu, P. F.(2005). Design of Complex High-Rise Building Structures. China Architecture & Building Press.

Zhu, L. G., & Tu, W. L.(2017). Brief introduction to structural

design of Chongqing Raffles City Project. Chongqing Architecture, 16: 18-21.

Liu, M. G., Jiang, W. W., and Yu, Q.(2019). Analysis and design of super high-rise three-tower connected structure of Nanjing Golden Eagle Tiandi Plaza. Building Structure, 49: 15-21.

Sun, L., Zhao, N., Fan, B., et al.(2020). Structural design of high-position connected structure with four towers of Zhuhai Hengqin CRCC Plaza Project. Building Structure, 50: 50-57.

Technical Specification for Concrete Structures of Tall Buildings: JGJ 3-2010. China Architecture & Building Press.

Xu, L., Peng, L. H., Yi, Y. F., et al.(2020). Analysis on mechanical characteristics and difficulties of a super high-rise complex connected structure [J]. Building Structure, 50: 106-111, 48.

Liu, K., Zhang, C. H., Liu, Y. S., et al.(2019). Application issues of waist trusses and outrigger trusses in super high-rise building structures. Building Structure, 49: 12-16.

Code for Loads on Building Structures: GB 50009-2012. China Architecture & Building Press.

Yang, X., Jiang, B. L., Wang, L., et al.(2018). Design of a super long-span connected structure. Building Structure, 48: 47-52.

Code for Seismic Design of Buildings: GB 50011-2010. Beijing: China Architecture & Building Press.