Comparative Analysis of Mechanical Properties in the Core Tube of frame with Transfer Layer between the Solid-Wed Beam Transfer and New Type of Inclined Column Transfer with Shaped Steel

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Abstract. The inclined column transfer structure has been directly applied to the engineering practice due to its direct and clear transfer force, reasonable load transfer, simple structure and convenient construction. This paper firstly introduces the application of the inclined column transfer structure in engineering practice. Aiming at the practical construction of a frame structure with a transfer layer, the three types of transfer are then used respectively, and they are ordinary transfer inclined column transfer, the addition of shaped steel to the transfer girder between the inclined column and solid-web beams transfer. Finally, a comparative analysis is carried out from the aspects of cycle, displacement, stiffness ratio, section size of transfer girders, and shear-weight ratio. The results show that the inclined column transfer structure can effectively improve the lateral stiffness ratio of the transfer layer and the connected upper layer structure with its direct transfers force, thus avoiding the form of weak layers here.

1. Overview
The high-rise building constructed by connecting safe and reliable transfer members is called a high-rise building structure with a transfer floor as some vertical members of buildings with different functions cannot be directly connected to the ground [1-5]. The inclined column transfer structure, a new type of transfer in recent years, has been applied in many practical projects though neither with specific provisions in the current norms in our country, nor with few theoretical studies in this field. Professor Zhong Shusheng in Chongqing University made a series of theoretical analysis and experimental research on the application of inclined column transfer structure in framed short-leg shear wall structures [6-11]. Professor Shen Bo from Guizhou University proposed a new type of inclined column transfer structure based on Professor Zhong Shusheng's research and made a series of analysis and researches [12]. A holistic analysis of the inclined column transfer structure and a comparative analysis and experimental study on mechanical behavior between this structure and the solid-web beams transfer structure were all firstly made in Chongqing University [13-19]. The result shows that under the same conditions, the inclined column transfer structure with greater lateral stiffness than the solid-web beams transfer structure is easier to meet the requirements in the Technical Regulations for High-rise Building Concrete Structures (JGJ3-2010), which can effectively avoid the formation of the weak layer at the transfer story. With better seismic performance, the inclined column transfer structure can also greatly reduce the bending moment of the middle section of the transfer girder, so as to avoid the occurrence of plastic hinge and even its collapse at the bottom of the pillar of the structural frame. The inclined column transfer structure is a new type of transfer that is worthy of
promotion over the solid-web beams transfer structure.

2. Design points and Basic Requirements of Steel Reinforced Concrete Composite Structure

2.1 Structure Type
The steel reinforced concrete composite structure includes all structural members and some structural members using a steel reinforced concrete structure. The two types of structures are suitable for structural systems such as frame structures, frame-shear wall structures, frame-core tube structures, and tube-in-tube structures. The shaped steel in the steel reinforced concrete column should adopt H-shaped rolled steel with wide solid flange and welded steel with various cross-section types. For non-earthquake zones or high-rise buildings with design intensity of 6 degrees, lattice welded shaped steel with web members may be used, as shown in Figure 1. In this project, the inclined column adopts the first form of reinforcement—wide flange H-shaped steel.

![Fig.1 Steel section reinforcement of steel reinforced concrete column](image)

2.2 Design points and Basic Requirements
In the steel reinforced concrete composite structure, whether the shaped steel and the surrounding concrete can be deformed in a coordinated manner is a condition for the two to work together. For the frame column, when the shearing is large, it is easy to produce the shear bond failure. It is because the shaped steel and the surrounding concrete cannot work together well, resulting in a large range of concrete’s spalling, bearing capacity decline, affecting the deformability after destruction. According to the literature [20], in the case of a certain number of longitudinal bars and stirrups, the shaped steel and the surrounding concrete can work together better. Even if in the destruction phase, the surrounding concrete will not be severely peeled off. The plastic deformability of the shaped steel can get full display and the bearing capacity will not be significantly reduced. The literature [21] stipulates that in the steel reinforced concrete composite structure, the longitudinal reinforcement steel bar should not be less than 16mm in diameter, and the reinforcement ratio of all longitudinal reinforcement bars should not be less than 0.8%; The minimum volume-stirrup ratio is in the range of 1.00% to 1.25% for better deformability of the inclined column as larger stirrup ratio can increase the bond failure capacity. In order to ensure that both shaped steel and concrete can work well together to the yield of the shaped steel, it needs, for one thing, a sufficient bonding capacity between the shaped steel and the concrete; for another, the concrete protection layer will not be crushed or in instability before the shaped steel reaches the yield strength. Therefore, Zheng Shansuo and other scholars have conducted experimental analysis and theoretical calculations. It is recommended that the thickness of medium-sized steel concrete columns of the protective layer for engineering design should be no less than 100 mm [22]. This is not much different from the 120 mm specified in literature [23] while the thickness in this article is 100mm.

In the steel reinforced concrete structure, the steel sheet is restrained by the concrete, so that its bearing capacity of buckling or local buckling is improved. In general, the peak strain of concrete is greater than the yield strain of steel. Therefore, local buckling will not occur before the steel plate’s subjected to compression and yield. However, it is necessary to limit the width to thickness ratio of steel with the minimum thickness of steel less than 6m to promise the plastic deformability of the steel after taking into account the weakening of the constraining effect of the concrete on the steel during the destructive stage and the premature de-bonding of the concrete protective layer due to the
improper configuration of the stirrups, leading to a reduced restraining effect. Therefore, in the project, the inclined bar adopts the first type of reinforcement in Figure 1 - wide flange H-shaped steel. At the same time, the steel ratio of steel should not be less than 4%, and should not be greater than 10%.

3. Project Analysis

3.1 Project Profile
This project is located in a high-rise office building in a certain place in Guizhou. The structural design of this project has a service life of 50 years, a seismic fortification class of C, a seismic fortification intensity of 6 degrees. Design the earthquake grouping as the first group, and a basic earthquake acceleration of 0.05 g. The construction site category is II, basic wind pressure 0.3 kN/m2 and ground roughness category B. The reinforced concrete frame-core tube system is adopted. The outer frame has a plane size of 25.2m×33.6m. The central core cylinder has a plane size of 8.4m×16.8m. It has 22 floors with two-storied machine room excluded at a height of 86m. The first floor is used for column extraction for the large space requirements of the building transportation and the lobby. After analysis, it is decided to set up a conversion floor in the second floor. The height of the first floor and the conversion floor is 5m.

The thickness of transfer floor is designed into 180mm. The strength grades of the vertical component columns and shear walls are C40, while that of the horizontal component beams and slab concrete are C30. As the floors increase, the thickness of the shear walls gradually decreases. See Figure 2 for the plane of the solid-web transfer floor, and figure 3 shows the plane figure of the standard structure floor.
Fig. 2 Plane Figure of Transfer Floor
3.2 Plain Structure of Inclined Column in Transfer Story
The sectional height of the transfer girder of this project is 1800mm. The use of beam type conversion has a greater impact on the function of the building and at the transfer floor, a weak floor is formed here because of the sudden change of the stiffness of the upper and lower transfer girder. In order to avoid the formation of a weak layer at the transfer floor, a certain inclined columns are arranged around the structure without changing the original function of the building, which can avoid a sudden change of stiffness in the upper and lower transfer floor. After ensuring that the size of the section size of transfer girder is constant in each model, a total of seven models have been calculated for this project. Seven types of inclined columns with different sections are arranged. The sectional size shape of the inclined columns and the section size of the shaped steel are detailed in Table1 and Figure 4. The steel ratio, longitudinal reinforcement ratio and volume-stirrup ratio of the inclined columns are detailed in Table 2. The concrete strength grade of the inclined columns is consistent with that of the frame-supporting column of this story as C40. Both ends of the inclined columns are respectively connected with the transfer girder and the frame-supporting column. The plane figure and lateral view of inclined columns are shown in Figure 5 and Figure 6 respectively. The arrangement of the inclined columns needs to be as symmetrical as possible, and they must be arranged along the X and Y directions, so that the stiffness of the X and Y directions of the structure should not be too different.
from each other, and the rigidity of the structure and the center of mass should be as close as possible.

### Table 1 Section size of inclined columns

| Model | H(mm) | B(mm) | H(mm) | B(mm) | t1(mm) | t2(mm) | Ix(cm^4) | Iy(cm^4) | As(cm^2) |
|-------|-------|-------|-------|-------|--------|--------|----------|----------|----------|
| Model 1 | 650 | 650 | 350 | 350 | 12 | 20 | 41,140 | 14,296 | 177 |
| Model 2 | 600 | 600 | 350 | 350 | 12 | 20 | 41,140 | 14,296 | 177 |
| Model 3 | 550 | 550 | 350 | 350 | 12 | 20 | 41,140 | 14,296 | 177 |
| Model 4 | 550 | 550 | 350 | 350 | 8 | 14 | 29,901 | 10,005 | 123 |
| Model 5 | 550 | 550 | 300 | 300 | 12 | 20 | 25,317 | 9,004 | 151 |
| Model 6 | 500 | 500 | 300 | 300 | 8 | 14 | 18,532 | 6,301 | 105 |
| Model 7 | 450 | 450 | 250 | 250 | 8 | 14 | 10,487 | 3,646 | 87.7 |

Fig.4 Sectional View of inclined columns (The diagonal part of the figure is H shaped steel)

### Tab.2 Steel ratio, reinforcement ratio and volume-stirrup ratio of inclined column

| Model | Steel Rate(%) | Reinforcement Ratio(%) | Volume-Stirrup Ratio(%) |
|-------|---------------|------------------------|-------------------------|
| Model 1 | 4.20 | 0.964 | 1.03 |
| Model 2 | 4.92 | 0.89 | 1.12 |
| Model 3 | 5.85 | 0.814 | 1.23 |
| Model 4 | 4.07 | 0.814 | 1.23 |
| Model 5 | 5.00 | 0.814 | 1.23 |
| Model 6 | 4.20 | 0.986 | 1.00 |
| Model 7 | 4.3 | 0.97 | 1.13 |
3.3 Comparative Analysis of Transfer Structure of Inclined Column and the Solid-Web Beams

The calculation of this project adopts the SATWE module in the structural design software PKPM, and then uses the PMSAP to review the calculation results. When calculating the two modules, the
selection of the calculation model and the calculation parameters remain the same. The results show that: the cycle, the displacement and other results calculated by SATWE are the same with that of the PMSAP, as shown below for the SATWE calculation results.

### 3.3.1 Structural natural vibration period

| Tab.3 Structural Natural Vibration Period (Unit: s) |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Mode of Vibration One | Mode of Vibration Two | Mode of Vibration Three | Period Ratio |
| Inclined Transfer One       | 2.4063           | 2.2365           | 1.9938           | 0.8286          |
| Inclined Transfer Two       | 2.4109           | 2.2407           | 1.9960           | 0.8280          |
| Inclined Transfer Three     | 2.4159           | 2.2451           | 1.9985           | 0.8272          |
| Inclined Transfer Four      | 2.4188           | 2.2476           | 1.9999           | 0.8268          |
| Inclined Transfer Five      | 2.4173           | 2.2463           | 1.9991           | 0.8270          |
| Inclined Transfer Five      | 2.4259           | 2.2538           | 2.0038           | 0.8260          |
| Inclined Transfer Seven     | 2.4339           | 2.2609           | 2.0085           | 0.8252          |
| Solid-Web Beam Transfer     | 2.4857           | 2.3092           | 2.0725           | 0.8338          |

Table 3 shows the natural vibration period of the first three modes of the overall structure of inclined column transfer and solid-web beam transfer. It can be seen from the above that the structural cycle ratio of inclined column transfer and solid-web beam transfer does not meet the requirement of 0.85. The natural vibration period of the solid web beam above is slightly greater than that of the inclined column transfer indicating that the inclined column transfer can provide better overall stiffness. For the inclined column transfer structure, as the length of inclined column increases, the cycle decreases and the overall stiffness of the structure becomes stronger.

### 3.3.2 The horizontal displacement of the structure

Figure 7 and Figure 8 show the horizontal displacement of the structure under earthquake and wind load respectively. XZ represents inclined column transfer and SFZH represents solid-web transfer. It can be seen from the figures that under earthquake and wind loads, the horizontal displacements of the solid-web transfer in the X direction and Y direction are all greater than those of the inclined column, which indicates that the overall stiffness of the inclined column transfer structure is better. In the inclined column transfer structure, the displacement of X and Y directions decreases with the reduction of the cross section of the inclined column under earthquake and wind loads.
(a) Structural horizontal X-direction displacement under earthquake
(b) Structural horizontal Y-direction displacement under earthquake
Fig.7 The horizontal displacement of the structure under earthquake

(a) Structural horizontal X-direction displacement under wind load
(b) Structural horizontal X-direction displacement under wind load
Fig.8 Structural horizontal displacement under wind load

3.3.3 The ratio of equivalent shear stiffness between the transfer layer and its adjacent upper structure

Tab.4 The equivalent shear stiffness of the transfer layer and its adjacent upper layer (Unit: 10^7kN/m)

| Shear Stiffness Transfer Form | Equivalent Shear Stiffness of the Transfer Layer | Equivalent Shear Stiffness of the adjacent upper layer | Stiffness Ratio |
|-------------------------------|-----------------------------------------------|-----------------------------------------------|----------------|
|                               | X Direction       | Y Direction       | X Direction       | Y Direction       | X Direction       | Y Direction       |
| Inclined Column Transfer One  | 4.3733            | 5.4788            | 3.4335            | 4.2161            | 1.2737            | 1.2995            |
| Inclined Column Transfer Two  | 4.1845            | 5.2410            | 3.4335            | 4.2161            | 1.2187            | 1.2431            |
| Inclined Column Transfer Three| 4.0108            | 5.0222            | 3.4335            | 4.2161            | 1.1681            | 1.1912            |
| Inclined Column Transfer Four | 3.9246            | 4.9136            | 3.4335            | 4.2161            | 1.1430            | 1.1654            |
| Inclined Column Transfer Five | 3.9688            | 4.9694            | 3.4335            | 4.2161            | 1.1559            | 1.1787            |
It can be seen from Table 4 that the shear stiffness ratios of the two transfer forms all satisfy the requirement of no less than 0.5. The equivalent shear stiffness of the upper layer is basically the same for the same structural arrangement above the transfer layer. As it can be seen from the table, the arrangement of the inclined columns in the inclined column transfer structure can significantly increase the shear stiffness of the transfer layer, and the ratio of the stiffness of the upper and lower layers of the transfer layer is greater than 1 to meet the requirements of the corresponding specifications.

### 3.3.4 Section size of transfer girders

Table 5 shows the section size of transfer girders in the two transfer forms. It can be seen that the section size of transfer girders are significantly reduced after the inclined columns are arranged, so that more space can be obtained.

**Tab.5 Comparison of section size of transfer girders between the inclined column transfer and the solid-web transfer (Unit:mm×mm)**

| Transfer Type                | Section Size |
|------------------------------|--------------|
| Inclined Column Transfer Six | 850×1000     |
| Inclined Column Transfer Seven| 900×1800     |

### 3.3.5 Shear-Weight Ratio

The shear-weight ratio of the two transfer forms in X and Y directions is shown in Figure 9. The project is located in the 6 degree zone, and the basic period of the structure is less than 3.5s. According to the requirements of literature [26] and [27], the minimum seismic shear force on any floor of the structure shall not be less than 0.8%, the floor gravity load representative value (minimum shear-weight ratio). As seen from the table, the ratio of shear-weight to inclined column transfer is not much different from that of the solid-web transfer, and both meet the requirements. It can be concluded that the vertical layout of the structure is reasonable.

![Shear-weight ratio in X direction](image1.png)

![Shear-weight ratio in Y direction](image2.png)

Fig.9 Shear-weight ratio between X- and Y-directions of inclined column transfer and solid-web transfer
4. Conclusion

This chapter first introduced the concept and principles of seismic design for high-rise buildings with transfer floors, and detailed description of the structural stiffness ratio combined with relevant specifications, especially the stiffness ratio of the transfer layer to its adjacent upper layer, which is key to the structural design and scientific analysis. Then, a real project was calculated using solid-web beam transfer and inclined column transfer respectively to make comparison and analysis from the aspects of the overall structure cycle, displacement, stiffness ratio, section size of transfer girders, and shear-weight ratio. The following conclusions are:

(1) In terms of the overall structure cycle, the natural vibration period of the inclined column transfer is slightly smaller than that of the solid-web transfer, indicating that the inclined column transfer can provide greater overall stiffness. The horizontal displacement of the inclined column transfer is smaller than that of the solid-web transfer structure under the action of earthquake, which shows that the inclined column transfer can obtain a better seismic response than the solid-web transfer structure; while under the action of wind load, two transfer forms demonstrate no big difference.

(2) The more direct and clear transfer force of the inclined column transfers can obviously improve the lateral stiffness ratio of the upper and lower layers of the transfer layer, thereby avoiding the formation of a weak layer at this point.

(3) The inclined column transfer can effectively reduce the section size of transfer girder, making it into a flexible space with more spaces for building use.

References

[1] Fu Xueyi. Applied Structural Design of Tall Building (second edition) [M]. Beijing: China Architecture & Building Press, 2010.
[2] Tang Xingrong, He Ruoquan. The Current Situation and Development of Transfer Floor Structure in High-rise Buildings. J. Suzhou Institute of urban construction and environmental protection, 2001, 14 (3): 31-37
[3] Zhang Weibin. Analysis of Structural Design of Reinforced Concrete Belt Transfer Story and Engineering Example [M]. Beijing: China Architecture & Building Press, 2008.
[4] Zhao Xian. High-rise building structure practical design method (third edition) [M]. Beijing: China Architecture & Building Press, 1998.
[5] Tang Xingrong. High-rise building transfer story structure design and construction [M]. Beijing: China Architecture & Building Press, 2002.
[6] Luo Di, Luo Zhaohui. Some problems of tall building with transfer stories [J]. Journal of Tianjin Institute of Urban Construction, 1999, 15 (3): 41-45.
[7] Yang Chaoce, Zhong Shusheng, Lin Huanwen. An experimental Research of Vertically--Loaded RC Joint of Local Transfer from Straight Wall to Inclined Column [J]. Chongqing Architecture, 2005: 22-25.
[8] Qian Shusheng, Wang Zhanghao, Caolin. Experimental Research of Vertically Loaded RC Joint of Local Transfer From Inclined Column with Different Angle to Beeline Shaped Short Shear Wall [J]. Journal of Chongqing University, 2005, 28 (7): 35-38.
[9] Qian Shusheng, Cao Lin, Luying. A study of vertically-loaded transfer RC joint from inclined column to framed short shear wall [J]. Sichuan Building Science. 2005, 31 (1): 22-26.
[10] Qian Shusheng, Qi Yong, Ni Zhong. Experimental Research on the Seismic Behavior of the Haunched Beam Transfer Structure with Frame-supported Short-leg Shearwall [J]. Journal of Chongqing Jianzhu University, 2007, 29 (6): 31-37.
[11] Qian Shusheng, Shi Shilun, Lu Ting, Jiang Fan. Experimental Study on Seismic Behaviors of Transfer Floor from Inclined Column to Framed Short-leg Sher Shear Wall [J]. Journal of Chongqing Jianzhu University, 2007, 29 (1): 44-47.
[12] Liang Ying. Research and Application of Matching Stiffness Ratio of Transition Column and Inclined Column of Inclined Column Structure in Frame-supported Shear Wall Structure [D].
Guizhou: Guizhou University, 2013.

[13] Wang Zhanghao. Experimental Research on Inclined Column Transfer Structure of Framed Short Shear Wall under Low-cyclic Reversed Loads [D]. Chongqing: Chongqing University, 2005.

[14] Jiang Fan. Experimental Study on Seismic Behavior of Inclined-pillar Structures in Frame-supported Short-limb Shear Wall Structures [D]. Chongqing: Chongqing University, 2005.

[15] Yang Chunling. Mechanical Behavior and Elasto-Plastic Analysis of Sloping Column Type and Beam Type Transition Structures in Framed Short-Shaft Shear Walls [D]. Chongqing: Chongqing University, 2007.

[16] Huang Miao. Experimental Study on Seismic Behaviors of Inclined Column-shaped Transfer Floor of Framed Short-leg Shear wall Structures with Varied Heights of Transfer Beam [D]. Chongqing: Chongqing University, 2008.

[17] Qi Yong. Experimental Study on Seismic Behaviors of Inclined Column-shaped Transfer Floor Structures of Frame-supported Short-leg Shearwall with Varied Ratio of Thickness. [D]. Chongqing: Chongqing University, 2008.

[18] Zhou Hao. Experimental Study on Seismic Behaviors of Inclined Column Transfer Structure with Short-leg Shear Wall with Different Axial Compression Ratios [D]. Chongqing: Chongqing University, 2009.

[19] Li Shiming. Experimental Study on Seismic Behaviors of Inclined Column-shaped Transfer Floor of Frame Short-leg Shearwall Structures in Varied Angle of Inclined Column. [D]. Chongqing: Chongqing University, 2009.

[20] Nie Jianguo, Liu Ming, etc. Steel-concrete composite structure [M]. Beijing: China Architecture & Building Press, 2005.

[21] Technical specification for steel reinforced concrete composnte structures [S]. Beijing: China Architecture & Building Press, 2002.

[22] Zheng Shansuo, Li Lei. Basic Performance and Design of Steel High Strength and High Performance Concrete Structures [M]. Beijing: Science Press, 2012.