Research on Proper Height of the New External-shearing and Internal-framing Structure

Cheng Jianwei¹, Wang Yong¹, Peng Qichao¹, and Jiang Qing²

(¹Xuzhou College of Industrial Technology, Xuzhou, 221100 ²Hefei University of Technology, Hefei, 230000)

Author's Brief Introduction: Cheng Jianwei (1972 -) Male, Master, Professor, Research Direction: Building Industrialization

Abstract: This study proposes a new external-shearing and internal-framing structure, and introduces the merits and application scenarios of this new structure. With a one-staircase six-house pagoda-style residential building as the study case, we tested mechanical and seismic indicators of the proposed new structure, including the floor rigidity, the shear bearing capacity, the shear-weight ratio, the floor displacement ratio and the floor displacement angle, under different degrees of seismic fortification intensity. The test result shows that the new external-shearing and internal-framing structure has good mechanical performance when applied to pagoda-style residential buildings, the structural control indicators meet the standards and the structure can be widely used in buildings below 33 floors with a degree of seismic fortification intensity ranging from 6 to 7.

1. Introduction

Assembled steel structure has the characteristics of the whole process of industrial product production [1]. At present, the most frequently applied assembled steel structures include steel frame structure, steel frame-support structure, steel frame-core tube structure, steel frame-steel shear wall structure, etc. They have their own advantages and disadvantages; for example, steel frame structure lacks lateral rigidity, thus limiting the applicable height of the building; the steel frame-support structure and the steel frame-core tube structure are not flexible in layout, thus lowering the utilization of the building space. In addition, the external wall panels of the building are poor in waterproof performance. External scaffolding is required during construction, and there are also problems such as leakage beams and columns in the residential buildings. Based on the above-mentioned shortcomings, this paper puts forward the concept of New structural systems of external shear-inner frame assembly and studies the structural calculation data of different heights under different seismic intensities by combining the advantages of concrete-filled steel tube structure and the assembled concrete shear wall structure. This paper clarifies the optimum height of the structural system under different seismic intensities, thereby providing reference for engineering practice.

2. New structural system of outer shear-inner frame assembly

New structural system of outer shear-inner frame assembly refers to the structure in which the surroundings of the building adopt sandwich prefabricated shear for bearing while the inside adopts the inner frame combing the steel tube concrete column and the structural steel beam. The sandwich prefabricated shear wall panels are connected by cast-in-place concrete joints, and its reinforcement layer at the bottom and top layer are cast-in-place concrete shear walls, which are designed based on...
the theory of Equivalent Cast-In-Place. The inner frame is made of rectangular flat long steel-tube concrete columns with its long side in the transverse direction of the building and the short side in the longitudinal direction. The inner frame steel beam and the concrete shear wall are connected by concealed steel columns, the cast-in-place concrete is connected by rigid joints [2], and the inner frame steel beam is connected by concrete-filled steel tube columns. The 8m+ load shear wall of the gable and the separating walls should be separated using precast concrete slabs. This structure is able to realize full assembly and construction, and is flexible in the industrialization degree and the layout. In addition, it can solve the problems including the leakage of rain in the external wall panel of the steel frame structure and leakage beam and column in the steel structure of residential buildings.

3. Mechanical and seismic performance analysis of the mixed structural system of outer shear-inner frame assembly

3.1 Calculation model of New structural system of outer shear-inner frame assembly

This paper takes a six-story tower-type high-rise residential building with New structural system of outer shear-inner frame assembly as the object, and respectively establishes the calculation models with 18, 25 and 33 floors. The outer walls are the 200mm-thick load-bearing sandwich prefabricated shear walls, which are connected by I-shaped, T-shaped and L-shaped cast-in-place concrete joints, and the vertical steel bars are connected using grout sleeves. The inside of the building adopts a steel tube concrete frame, whose steel beams are rigidly connected using concealed steel columns with cast-in-place T-nodes of the prefabricated shear walls. The partition wall is made of strip-shaped panels, and the stairs are made of prefabricated slabs made of truss laminated plates. The building layout is shown in Figure 1, and the architectural rendering is shown in Figure 2.

Fig. 1 Plane layout of a new structure with outer shear-inner frame

![Fig. 1 Plane layout of a new structure with outer shear-inner frame](image1)

Fig. 2 Architectural effect drawing of new structure with outer shear-inner frame

![Fig. 2 Architectural effect drawing of new structure with outer shear-inner frame](image2)

3.2 Calculation and result analysis of New structural system of outer shear-inner frame assembly

3.2.1 Related information about New structural system of outer shear-inner frame assembly with 7-degree seismic intensity

The construction site here belongs to Category II, the third earthquake group, with $T_g$, the site characteristic period of 0.45s, $\alpha_{\text{max}}$, the maximum earthquake impact coefficient of 0.08, the wind load
of 0.35KN/m², and Class C ground roughness. For the gravity load representative value, its live load combination coefficient is 0.5, the period reduction factor is 0.75, and the structural damping ratio is 0.05. The seismic action analysis is performed by adopting the total rigidity analysis method. This case project uses SATWE to perform finite element analysis on the computational model.

1) Information about the floor

The materials selected for the engineering components are shown in Table 1.

Table 1 Materials selected for the plate column walls

| Floor | Roof beam | Column | Plate | Shear wall (250mm thick) |
|-------|-----------|--------|-------|--------------------------|
|       | Structural steel | Steel tube | Concrete | Conc | Horizontally distributed reinforcement | Vertically distributed reinforcement | Minimum ratio of reinforcement distribution | Concrete | edge member |
| 26-33 | Q345 | Q345 | C40 | C30 | 360 | 270 | 270 | 0.3% | C40 | 270 |
| 19-25 | Q345 | Q345 | C40 | C30 | 360 | 270 | 270 | 0.3% | C40 | 270 |
| 1-18  | Q345 | Q345 | C40 | C30 | 360 | 270 | 270 | 0.3% | C40 | 270 |

2) Information about quality

The total mass of the engineering structure in this case includes the dead load, the mass produced by the live load and by the additional load. Calculation shows that the mass ratio of each floor is less than 1.5, indicating that the quality of each floor is evenly distributed along the height, which meets the requirements stipulated in Technical Specification for Concrete Structures of Tall Building 3.5.6.

3) Information about wind load

The downwind direction is used in the calculation of the wind load. For the maximum wind load and the maximum bending moment of each floor, see Figure 3 and Figure 4. The change of the shear force of the floor and the downwind bending moment is curve-shaped, which meets the design requirements.

![Fig. 3 Shear diagram of downwind floor](image-url)
3.2.2 Mechanical analysis of New structural system of outer shear-inner frame assembly in the 7-degree seismic zone

The reinforced concrete prefabricated shear wall is used for the outer walls, while the concrete-filled steel-tube frame is used for the inside. The former one is the main component for lateral load resistance. The lateral movement of its centroid, the standard value of lateral displacement between layers, and the earthquake impact coefficient shall comply with the current Technical Specification for Concrete Structures of Tall Buildings \[3\].

3.2.2.1 Floor rigidity (floor shear/interlayer displacement)

(1) Lateral shear rigidity of the floor

The lateral shear rigidity of the floor is \( K_i / K_{i-1} \), or the ratio of the shear rigidity of the layer to that of the next corresponding floor \[4\]. The lateral rigidity ratios of the models with 18, 25, and 33 floors are shown in Table 2. The lateral shear rigidity of the models with 18, 25 floors are in compliance with the specifications, with no lateral rigidity irregularity \[5\], while that of the 16th floor of the model with 33 floors is lower than that of the 18 and 25 floors in terms of shear rigidity ratio.

Table 2 Lateral rigidity ratio of three floor structures

| Calculation model | Floor | Ratx | Raty |
|-------------------|-------|------|------|
| 18 floor          | 4-18  | 1.00 | 1.00 |
|                   | 3     | 0.95 | 0.95 |
|                   | 1-2   | 1.00 | 1.00 |
| 25 floor          | 9-25  | 1.00 | 1.00 |
|                   | 8     | 0.81 | 0.82 |
|                   | 7     | 1.04 | 1.04 |
|                   | 1-6   | 1.00 | 1.00 |
| 33 floor          | 17-33 | 1.00 | 1.00 |
|                   | 16    | 0.70 | 0.71 |
|                   | 1-15  | 1.00 | 1.00 |

Note: Rat is the lateral rigidity ratio of the floor.

(2) Rigidity ratio of the floor

The floor rigidity ratios can be divided into rigidity ratio of 1 and rigidity ratio of 2. The rigidity ratio of 1 is generally meaningful only to the frame structure, so this paper will not list the values related to it. The rigidity ratio of 2 refers to the ratio of the product of the lateral rigidity of the floor to
its height and the product of the lateral rigidity of the upper corresponding floor and its height. The rigidity ratio of 2 can be used to measure the vertical regularity of the structure, so as to avoid the existence of weak layers. The ratio of rigidity of 2 is shown in Figure 5. It can be seen from the curve that the rigidity ratio of the embedded layer is 1.46, slightly less than 1.5, and that of the other layers is 2, greater than 0.8, indicating that the lateral rigidity irregularity does not exist in the structure, and that the structural facade is regular [6]. The changes of the rigidity ratio of 2 of the three models are basically the same, which means that the floor rigidity ratio is stable as the number of floors increases.

![Fig. 5 Comparison of multi-directional stiffness ratio 2 of three models](image)

### 3.2.2.2 Ratio of shear-load bearing capacity of the floor

The ratio of shear-load bearing capacity of the floor is the ratio of the bearing capacity of the floor to that of the upper floor, and its control is mainly for avoiding the appearance of the weak floor caused by vertical change of the shear capacity of the lateral-resistant structure [7]. Calculation results show that the floor shear capacity ratio of the three calculation models is greater than 80%, without any abrupt change, thus meeting the requirements of A-level high-rise building, whose interlayer shear capacity of the lateral-resistant structure should be no larger than 80%, and no less than 65% of the shear capacity of the adjacent upper layer [6].

### 3.2.2.3 Structure cycle ratio and direction of vibration mode

The structural cycle ratio is the relative relationship between the lateral rigidity and the torsional rigidity of the control structure, whose purpose is to make more reasonable planar arrangement of the lateral force-resisting components, so as to avoid excessive torsional effect of the structure. The lateral force-resisting components surrounding the structure contribute the most to the torque of the structure. The first and second vibration modes should be translational motion, and the torque cycle should appear after the third vibration mode [8]. Calculation shows that the most unfavorable direction angle of the 18-storey building under the seismic effect is -0.38 degree, that of the 25-storey building is -0.04 degree, and that of the 33-storey building is 0.53 degree. The above results show that the most unfavorable direction angles of all the structures are small, which is beneficial to earthquake resistance. From vibration mode calculation, the torque cycles of the structure appear in the third and the seventh vibration mode, indicating that the plane layout of the outer shear-inner frame assembly structure reasonable [6].

In addition, for the 18-storey building, the effective mass coefficient of the first seismic direction EX is 97.84%, and that of the second seismic direction EY is 96.82%; for the 25-storey building,
97.06%, and 95.75%; for the 33-storey building, 96.59%, and 95.07%. The sum of the participating mass of each mode should not be less than 90% of the total, so 15 participating modes is sufficient.

3.2.2.4 Structural shear-to-weight ratio under earthquake action

The shear-to-weight ratio, or the minimum shear coefficient \( \lambda_{\text{min}} \), is the ratio of the shear force of the floor to the sum of the representative values of the gravity loads on each layer. Its purpose is to limit the minimum seismic shear force of each floor and bear sufficient seismic effect. The minimum shear force coefficient of the floor is appropriate to be used to ensure the long-term structural safety under the seismic effect [9]. Based on the results of finite element analysis, the shear-to-weight ratios of each condition are shown in Figure 6. It can be seen that the shear-to-weight ratios of the three models are all greater than 1.60%, meeting the requirements of the specification [5]. In addition, the more the number of floor is, the lower the shear-to-weight ratio is.

![Figure6](image)

Figure6. A sketch of shear-weight ratio for each working condition of an earthquake

3.2.2.5 Floor displacement ratio/displacement angle

The floor displacement ratio refers to the ratio of the maximum elastic horizontal displacement (or interlayer displacement) of the floor to the average of the elastic horizontal displacement (or interlayer displacement) at both ends of the floor under the assumption that all floors are rigid, the purpose of which is to control the structural torque [10]. The calculation results show that the maximum displacement ratio of the 18-storey model is 1.18 (the sixth layer), and its maximum interlayer displacement ratio is 1.19 (the third layer); the maximum displacement ratio of the 25-storey model is 1.16 (the tenth layer), and its maximum interlayer The displacement ratio is 1.16 (the third layer); the maximum displacement ratio of the 33-storey model is 1.14 (fourth layer), and its maximum interlayer displacement ratio is 1.14 (fourth layer), all of which meet the requirements of the specification [6].

The interlayer displacement angle refers to the ratio of the maximum interlayer displacement to the floor height based on the elastic method. Based on the finite element calculation, the maximum interlayer displacement angles of the three models are shown in Figure 7. It can be seen that \( \Delta u/h \), the ratio of the maximum interlayer horizontal displacement to the layer height is less than 1/800, indicating the interlayer displacement angles all meet the requirements of the specification [6].
Figure 7 Comparison of Maximum Interlayer Displacement Angles

3.2.2.6 Overall rigidity-to-gravity ratio

The rigidity-to-gravity ratio refers to the ratio of the lateral rigidity of the structure to the design value of the gravity load, which is used to measure the gravity second-order effect of the structure and to determine whether the overall structural stability meets the requirements [11]. The rigidity-to-gravity ratios of the three models are shown in Table 3. It can be seen that their overall stability meets the requirements, without taking into consideration the gravity second-order effect [6].

Table 3 The rigidity-to-gravity ratios of the three models

| Model  | Working condition | Verification formula | Checking value under earthquake | Checking value under wind load |
|--------|-------------------|----------------------|---------------------------------|-------------------------------|
| 18-storey | X direction | EJ₀/GH² | 35.87 | 45.17 |
|         | Y direction | EJ₀/GH² | 31.69 | 34.99 |
| 25-storey | X direction | EJ₀/GH² | 24.44 | 29.82 |
|         | Y direction | EJ₀/GH² | 18.37 | 19.99 |
| 33-storey | X direction | EJ₀/GH² | 18.04 | 21.46 |
|         | Y direction | EJ₀/GH² | 11.16 | 12.09 |

3.2.2.7 Ratio of axial compression stress to strength

The ratio of axial compression stress to strength refers to the ratio of the design value of the axial pressure of the column (wall) to the product of the total cross-sectional area of the column (wall) and the design value of the concrete axial compressive strength. It reflects the pressure of the column (wall) and the ductility of the control structure. The ratios of axial compression stress to strength of the three floor structures are shown in Table 4, and all of them meet the requirements.

Table 4 Ratio of axial compression stress to strength and the conformity

| Model  | Component type | Size of section (mm) | Seismic grade | Calculated ratio of axial compression stress to strength | Allowable ratio of axial compression stress to strength | Conformity |
|--------|----------------|---------------------|--------------|--------------------------------------------------------|------------------------------------------------------|------------|
| 18-storey | Steel tube concrete column | — | Third | 0.35 | 0.85 | Yes |
|         | Shear wall | 200 | Second | 0.30 | 0.75 | Yes |
| 25-storey | Steel tube | — | Second | 0.41 | 0.75 | Yes |
3.2.3 Analysis of mechanical properties of New structural system of outer shear-inner frame assembly in the 8-degree seismic zone

This paper designs the Second Earthquake Group, Class II Site, with $T_g$, the seismic characteristic period of 0.40s, and the horizontal seismic influence coefficient maximum value based on the 0.168 (0.2g)-degree seismic zone. An 8-layer computing model is established to conduct finite element analysis. The results show that the maximum displacement ratio of the whole building under X-direction positive eccentric static vibration condition is 1.19 (at the first tower of the seventh floor), the displacement ratio is close to 1.2, or the specified limit, and the multi-directional rigidity ratio of 2 has reached the limit. It can be seen that New structural system of outer shear-inner frame assembly in the 8-degree seismic zone is not suitable for buildings higher than 8 floors. In order to further explore its application height, this project establishes a 25-storey model with 350mm-thick cast-in-place concrete shear walls at the elevator shaft and 350mm-thick prefabricated shear walls surrounding it, so as to lift the strength of the shear wall and concrete filled steel tube to C45 for finite element analysis. Results show that it meets the specifications. However, this kind of treatment is difficult for the production and hoisting of prefabricated shear wall components, resulting in a significant increase in construction costs.

4. Suitable height of the building with outer shear-inner frame assembly

4.1 Structural calculation to determine the appropriate height

Based on the above structural analysis results and the analysis of the control indexes of structural design of common tower houses with 18, 25 and 33 floors, it is concluded that the suitable height of mixed structure of outer shear-inner frame-assembly in the 6- and 7-degree seismic zones is below 100m, while that in 8-degree seismic zone is below 24m.

4.2 Appropriate height based on specifications

In Technical Specifications for Rectangular Steel Tube Concrete Structures (CECS 159:2004), with reference to the structure requirements for the frame-concrete shear wall, the suitable maximum height of the building in the 6-degree seismic zone is 220m, that in 7-degree seismic zone is 190m, and that in the 8-degree seismic zone is 150m. In Technical Specifications for High-Rise Civil Building Steel Structures (JGJ99-98), with reference to the steel frame-concrete shear wall structure, the suitable maximum height of the 6-and 7-degree seismic zones is 180m, and that of the 8-degree seismic zone is 100m. In Technical Standard for Assembled Steel Structures (GB0017-2017), with reference to applicable height of the frame-shear wall structure, the suitable maximum height of the 6-degree seismic zone is 130m, that of the 7-degree seismic zone is 120m, and that of the 8-degree seismic zone is 80m. Therefore, for New structural system of the outer shear-inner frame assembly, its applicable height in the 6-and 7-degree seismic zones should be less than 100m, while that in the 8-degree seismic zone should be less than 80m.

4.3 Suitable height based on maximum aspect ratio

In Technical Specifications for Rectangular Steel Tube Concrete Structures (CECS 159:2004), with reference to the reinforced concrete-shear wall structure, the maximum aspect ratio of the building in the 6-degree seismic zone is 7, that in the 7-degree seismic zone is 7, and that in 8-degree seismic zone is 6. In the Technical Specifications for High-Rise Civil Building Steel Structures (JGJ99-98), with reference to the steel frame-shear wall structure, the maximum aspect ratio of the building in the 6-
and 7-degree seismic zones is 5, and that in 8-degree seismic zone is 4. In the Technical Standard for Assembled Steel Structures (GB0017-2017), with reference to frame-shear wall structure, the maximum aspect ratio of the building in the 6- and 7-seismic zones is 6, and that of the building in the 8-degree seismic zone is 5. Therefore, the maximum aspect ratio for New structural system of the outer shear-inner frame assembly is 6 in the 6- and 7-seismic zones, and 4 in the 8-degree seismic zone.

5. Conclusion
Based on the finite element analysis and summary of specifications of the tower house with New structural system of the outer shear-inner frame assembly, the following conclusions can be drawn:
1) The concept of New structural system of the outer shear-inner frame assembly is a supplement to the high-rise steel structure system, which helps to solve the problems of insufficient rigidity of the floors in the high-rise steel structure, leakage of hanging plates in the outer wall, and the inflexible space arrangement of the outer frame-inner barrel structure.
2) When New structural system of outer shear-inner frame assembly system is applied to the tower house, the suitable height in the 6- and 7-seismic zones is 100m or less with a maximum aspect ratio of 6. The suitable height of the 8-degree seismic zone is 24m or less with a maximum aspect ratio of 4, which is not suitable for high-rise buildings.
3) New structural system of outer shear-inner frame assembly is high in the industrialization degree, but it needs further study and research for engineering applications.

Acknowledgment
Fund project: Xuzhou key R&D project (KC17135)

Reference
[1] Yang Jianxing. Research and Application on Industrial The Hierarchical Assembly of Steel Industrialized Housing System[J]. Steel Structures, 2012, (5): 15-18.
[2] Liu Jian Pan Peng Li Donglun. Research on seismic behavior for steel beams-reinforced concrete shear walls with new type connection joints [J]. Journal of Civil Engineering, Volume 2014, 47 Supplement (1): 66-67.
[3] JGJ-99-98 Technical Specification for Steel Structures of High-rise Civil Buildings [S]. Beijing Publishing House, 1988.
[4] Yang Xuelin. Discussion on some problems about new revised structure codes and review of buildings exceeding code limits [J]. Architectural Structure, 2012, 42 (8): 157-158.
[5] Code for Seismic Design of Buildings GB 50011-2010 [S]. Beijing: China Construction Industry Press, 2010.
[6] JGJ3-2010 Technical Specifications for Concrete Structures of High-rise Buildings [S]. Beijing: China Construction Industry Publishing House, 2010.
[7] Zhang Weijie. Design Frame-Shear Wall Structure Based On PKPM Program[J]. Low temperature building technology, 2017, (1): 71-72.
[8] Ban Qizhi. Analysis the Influence of Irregular Plane High-rise Shear Wall Layout Form On Structural Performance [J]. Architectural structure, 2018 (S2): 98-101.
[9] WANG Fu-ming, SHEN Pu-sheng. Study of the Basic Structural Period of Tall Structure Systems Satisfying Shear-gravity Ratio of Chinese Codes [J]. Journal of Hunan University (Natural Science Edition), 2015, 42 (09): 8-13.
[10] Bai Ruobing. Control strategies on storey drift ratio of high-rise shear wall structures [J]. Architectural structure, 2018, 48 (24): 63-69.
[11] Huang Jifeng, Xu Peifu, Chen Fusheng. Overall stability checking of flexural tall buildings under uneven vertical loads [J]. Architectural Structure, 2018, 48 (24): 53-57.