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CONSTRUCTION TECHNOLOGY AND APPLICATION OF FRAME COLUMNS SUBJECTED TO ALTERNATING TENSION AND COMPRESSION FORCES USING THE REVERSE CONSTRUCTION METHOD

RuiDa Zong[1,2], JiaLi Cao[1,2*], XiaoXia Zhao[1,2], TianCi Zhu[1,2], BaoAn Zhang[1,2]
[1]*China Construction Fourth Engineering Bureau Co., Ltd., Guangzhou 51000, Guangdong, China.*
[2]*China Construction Fourth Engineering Bureau Construction Investment Co., Ltd., Shanghai 200000, China.*
[*]*Corresponding Author: JiaLi Cao*

Abstract: Based on a museum project along the Beijing-Hangzhou Grand Canal in China, this paper proposes a reverse construction technique for frame columns at beam-slab-column intersections where deformation differences exhibit irregular dynamic changes under loading. Based on finite element analysis of the stress characteristics of the frame columns and their connected beams and slabs, the reinforcement of the frame beams connected to the frame columns is strengthened to meet both the original design requirements and serve as temporary cantilever beams. The main structure outside the frame columns is constructed first, allowing the beams and slabs connected to the top and bottom of the frame columns to deform independently to a stable state. Finally, the frame columns are constructed. This technique effectively solves the quality problems caused by alternating tensile and compressive stresses in the frame columns due to deformation differences at the top and bottom; avoids the need for long-term temporary supports for beams and slabs, reducing construction difficulty and costs; eliminates the additional pressure transmitted to the bottom beams and slabs of the frame columns, improving structural safety redundancy; and accelerates the early interweaving of secondary structures and mechanical and electrical installations, shortening the overall construction period.
Keywords: Alternating tensile and compressive stress; Frame column; Reverse construction

1 INTRODUCTION

With the rapid development of my country's construction industry, various large-span, high-clearance, and heavy-load buildings are becoming increasingly common, posing higher demands on the structural mechanics, construction techniques, and construction safety of complex structures. The conventional construction method for building frame columns is the sequential method, where construction proceeds layer by layer from bottom to top. The pressure gradually increases with each added layer, and the columns remain under compression, consistent with their structural mechanical properties. However, when there is a significant difference in deformation between the top and bottom of the frame column during construction, and this deformation difference changes dynamically with each added layer, the frame column experiences tensile and compressive stress reversals due to the constraints from the beams and slabs at its top and bottom. Using the conventional sequential method can lead to the following problems: when the deformation at the top of the frame column is less than the deformation at the bottom, the frame column undergoes tensile failure and develops horizontal cracks; when the deformation at the top of the frame column is greater than the deformation at the bottom, the frame column buckles and becomes unstable under compression, and the pressure is transmitted downwards, causing additional pressure on the beams and slabs at the bottom of the frame column. To effectively shorten the construction period, reduce the impact on the surrounding environment during construction, and protect surrounding building structures, the top-down construction method is usually adopted [1-3].
Regarding the research on slab-column node areas in top-down construction, many scholars at home and abroad have achieved certain results. Dawn et al. studied the design method of concrete-filled steel tube (CFT) and reinforced concrete foundation nodes and designed a new type of node, finding that this new node has excellent ductility and plastic deformation capacity under seismic action compared to ordinary concrete columns[4]. Jiho et al. established an analytical model of a concrete-filled steel tube column-foundation node, finding that the seismic performance of the column node is enhanced with increasing foundation embedment depth, diameter-to-thickness ratio, axial compression ratio, and pile foundation concrete strength[5]. Kanvinde et al. studied the seismic performance of exposed hollow steel columns on base plate nodes, concluding that all specimens exhibited excellent deformation capacity and stable hysteretic response[6]. Fang Xiaodan, Zhou Ying et al. conducted low-cycle repeated load tests on concrete column ring beam nodes, finding that the ring beam nodes have good plastic deformation capacity and energy dissipation capacity[7-10]; Zou Yun et al. proposed a new type of beam-column connection node, concluding that the specimens ultimately underwent bending failure in the ideal plastic hinge zone at the beam end, exhibiting good ductility and energy dissipation performance[11-14]. The aforementioned studies mainly focus on underground structures or foundation engineering, leaving a significant gap in the field of above-ground building structures. Based on this, this paper proposes a reverse construction technique for frame columns subjected to alternating tensile and compressive forces. This technique aims to avoid the effects of tensile-compressive force conversion within the frame columns,

reduce additional stress, ensure project quality, and facilitate convenient construction, thus possessing significant importance and practical relevance.

2 PROJECT OVERVIEW

The project for a museum along China's Grand Canal consists of a podium and a tower, forming a comprehensive single building integrating a museum and a cultural exchange center. It has two underground levels and fifteen above-ground levels. The outer ring of levels 1-8 forms the podium, while the inner ring of levels 1-15 forms the mountain-shaped tower. The total building height is 73.5m, and the total construction area is approximately 175,650 m². The building structure has a safety rating of Level 1, a seismic design intensity of 7 degrees, and a basic design seismic acceleration of 0.10g. The architectural rendering is shown in Figure 1. The 9th to 15th floors of the mountain-shaped tower feature an atrium, with an inwardly sloping mountain-shaped frame structure that, together with the outer mountain-shaped cylinder and the core cylinder, forms a lateral force-resisting frame system. To complement the overall spatial layout of the mountain-shaped tower's column-frame structure system, the mountain-shaped frame utilizes a ring-shaped, large-span steel-concrete composite truss structure system, with a maximum span of 35m and a height of 31m, composed of upper chords, lower chords, horizontal chords, and vertical web members, see Figure 1.

Figure 1 Rendering of the Hangzhou Grand Canal Museum

3 TECHNICAL PRINCIPLES

Based on finite element analysis of the stress characteristics of frame columns and their connected beams and slabs during the layered construction loading of the main structure, the reinforcement of the frame beams connected to the frame columns is strengthened to meet the original design requirements and also serve as temporary cantilever beams. This ensures that the main structure can safely and reliably support itself during the construction process without the support of the frame columns. The construction of the main structure outside the frame columns is prioritized, supplemented by full-process monitoring and analysis of the structural stress state, ensuring that the beams and slabs connected to the top and bottom of the inverted frame columns deform independently. After the deformation of the adjacent beams and slabs stabilizes, the frame columns are constructed using pre-reserved reinforcement, enabling them to work collaboratively with the adjacent beams and slabs. This strengthens the overall bearing capacity and stability of the main structure, and is more conducive to bearing subsequent decorative and variable loads, see Figure 2-3.

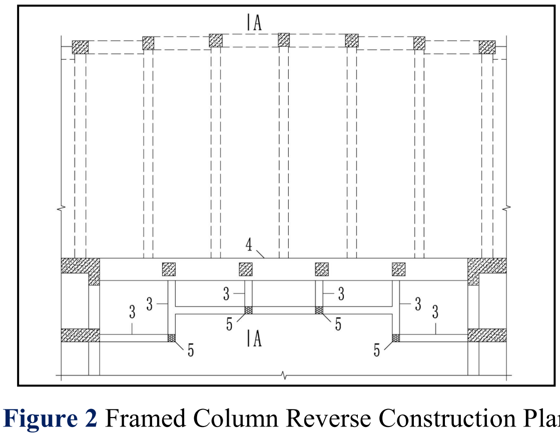


Figure 2 Framed Column Reverse Construction Plan

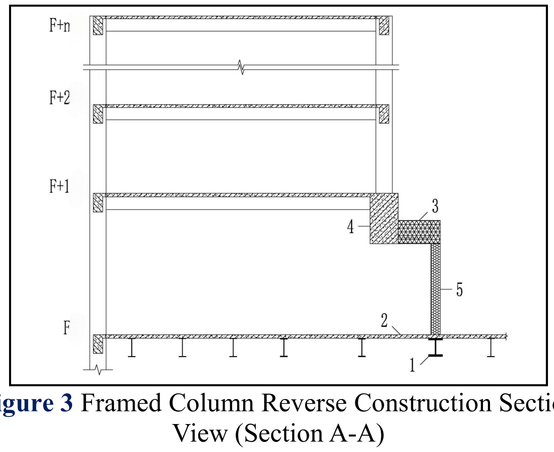


Figure 3 Framed Column Reverse Construction Section View (Section A-A)

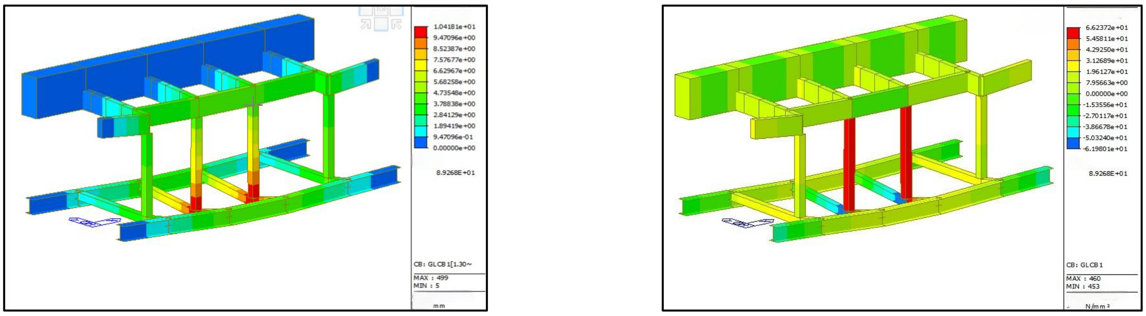
Note: 1-Frame column base beam; 2-Frame column base plate; 3-Frame column top beam; 4-Transfer beam; 5-Top-down construction frame column

4 TECHNICAL PROCESS AND KEY OPERATING POINTS

To avoid the influence of tensile and compressive stress conversion in the frame columns, reduce additional pressure, and ensure efficient and convenient construction, the bottom frame columns of the stacked hollow trusses in the mountain-shaped tower's inner courtyard are constructed using the reverse construction method. This mainly includes: scheme optimization design → construction of the bottom floor of the frame columns → construction of the top floor of the frame columns → layered construction and loading of the upper structure → reverse construction of the frame columns.

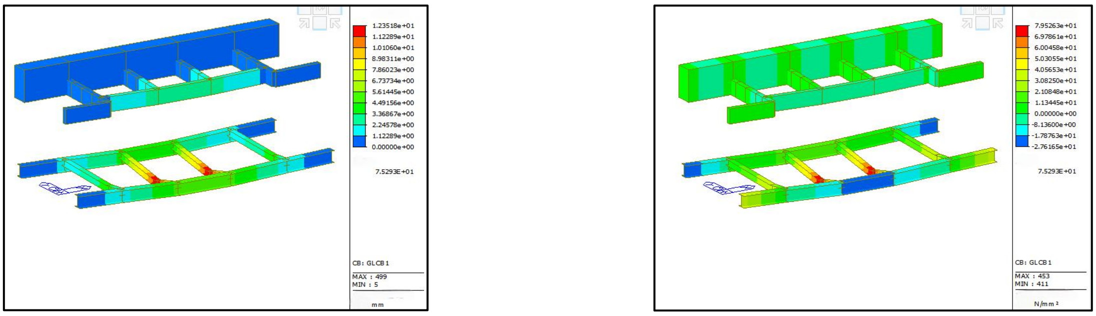
4.1 Scheme Optimization Design

Finite element software is used to simulate and analyze both forward and reverse construction methods for the frame columns. The structural stress states of the two schemes under different working conditions are compared, and the optimal construction scheme is selected. For the forward construction method, layered construction and loading are adopted; for the reverse construction method, the frame columns are not constructed initially. The reinforcement of the frame beams connected to the reverse-constructed frame columns is strengthened according to the envelope principle (taking the larger value), so that they meet the original design requirements and can also serve as temporary cantilever beams. This ensures that they can withstand the structural self-weight and construction loads without frame column support. The frame columns are then constructed after the stress state stabilizes, see Figures 4-7.



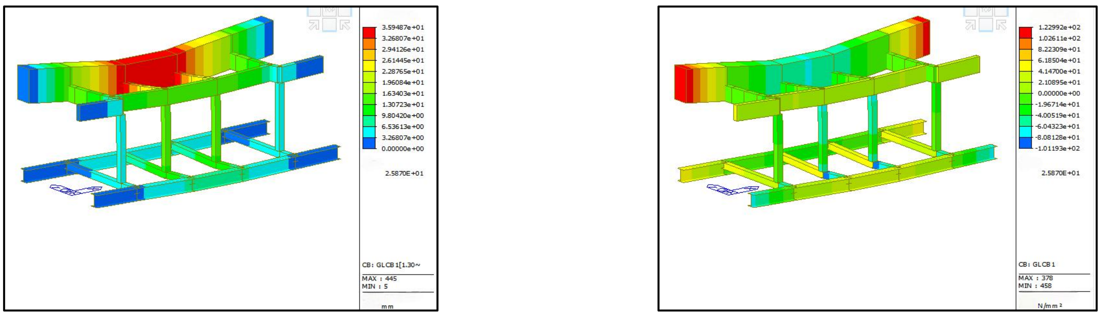
(a) Deformation (b) Stress

Figure 4 Construction Condition During Sequential Construction up to the Top Floor of the Frame Column



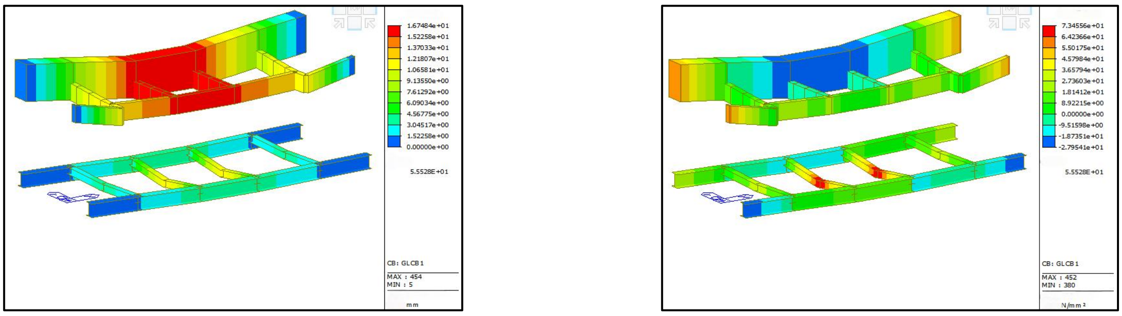
(a) Deformation (b) Stress

Figure 5 Construction Condition up to the Top Floor of the Frame Column Using the Top-down method



(a) Deformation (b) Stress

Figure 6 Construction Condition Using the Conventional Method up to the Roof Level



(a) Deformation (b) Stress

Figure 7 Construction Condition Using the Top-down Method up to the Roof Level

Table 1 Statistical Analysis of Structural Stress States under Different Construction Conditions for Frame Columns using Conventional and Top-down Methods

Construction condition	Location	Scheme		Limit Value
		Conventional method	Inverted method	
Construction up to the top floor of the frame columns	Maximum deformation of beam and slab at the top of the frame column	3.94mm	2.63mm	*L*/400=30.15mm
	Maximum deformation of beam and slab at the bottom of the frame column	10.42mm	12.35mm	
	Maximum tensile stress of the frame column caused by deformation difference	15MPa	0MPa	C60=2.04MPa
Construction to the roof level	Maximum deformation of the beam and slab at the top of the frame column	15.82mm	16.72mm	*L*/400=30.15mm
	Maximum deformation of the beam and slab at the bottom of the frame column	12.80mm	11.70mm	
	Maximum compressive stress in the frame column caused by the deformation difference	10MPa	0MPa	C60=60MPa

As shown in the above Table 1, when using the conventional construction method, the frame columns are constructed first. When the structure is constructed to the top floor of the frame columns, the maximum deformations of the top and bottom beams of the frame columns are 3.94 mm and 10.42 mm, respectively (≤30.15 mm). The maximum tensile stress in the frame columns caused by the difference in top and bottom deformation is 15 MPa (≥2.04 MPa), at which point the frame columns experience irreversible cracking due to severe tensile stress exceeding the limit. Furthermore, when the subsequent structure is constructed to the roof level, the maximum deformations of the top and bottom beams of the frame columns are 15.82 mm and 12.80 mm, respectively (≤30.15 mm), and the maximum compressive stress in the frame columns caused by the difference in top and bottom deformation is 10 MPa (≤60 MPa). In contrast, when using the reverse construction method, the frame columns are constructed last. When the structure is constructed to the top floor of the frame columns, the maximum deformations of the top and bottom beams are 2.63 mm and 12.35 mm, respectively (≤30.15 mm). When the subsequent structure is constructed to the roof level, the maximum deformations of the top and bottom beams are 16.72 mm and 11.70 mm, respectively (≤30.15 mm). After the frame structure system (excluding the reverse-constructed columns) reaches a stable state of stress and deformation, the bottom frame columns are constructed, at which point they are not affected by the difference in top and bottom beam deformation. Comparing the two construction methods, it is found that for this alternating tension and compression stress region, the reverse construction method for frame columns exhibits superior stress characteristics and stability compared to the conventional construction method.

4.2 Construction of the Ground Floor of the Frame Columns

The construction of the ground floor of the frame columns involves the installation of the steel structure, erection of support frames and formwork, positioning and layout marking of the frame column bases, welding of the upper flange of the steel beams to the connecting plates, and welding of the connecting plates to the reserved longitudinal reinforcement of the frame column bases according to design requirements. Reinforcement bars are then tied and concrete is poured for the floor slab, see Figures 8-9.

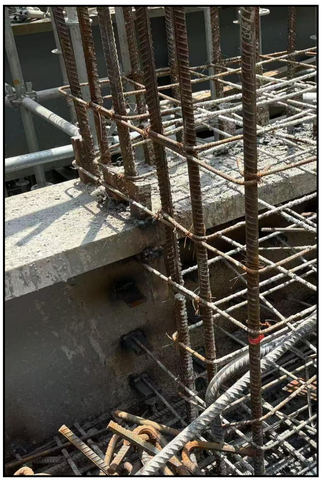


Figure 8 Longitudinal Reinforcement Connection at the Bottom of the Frame Column

Figure 9 Floor Concrete Pouring

4.3 Construction of the Top Floor of the Frame Columns

This involves the installation of the steel structure for the top floor of the frame columns using the top-down construction method, erection of supporting scaffolding and formwork, positioning and layout marking of the frame column tops, tying of floor reinforcement and pre-leaving longitudinal reinforcement for the frame columns extending downwards, and concrete pouring, see Figures 10-11.

Figure 10 Construction of the Top Floor of the Frame Column

Figure 11 Installation of Beam Stress and Strain Sensors

4.4 Step-by-Step Construction and Loading of the Superstructure

The superstructure is constructed layer by layer using the sequential construction method. When the concrete strength of the frame columns at the top and bottom floors reaches the design value, the corresponding floor support frames and formwork are removed. The beams and slabs at the top of the frame columns bear the load layer by layer until the roof layer is completed and the stress reaches its peak, see Figure 12-13.

During the step-by-step construction of the structure above the frame columns, the transfer beams should be monitored throughout the entire process to observe the strain and cracks at the beam supports at both ends, and the cracks and deflection at the bottom of the beam at mid-span. Monitoring frequency: once before concrete pouring for each floor, once every 15 minutes during pouring, once every 30 minutes within 6 hours after pouring, and once a day for the rest of the time, see Figure 14-15.

The monitoring data collected during the step-by-step construction and loading should be summarized and analyzed in a timely manner, compared with theoretical calculation values, warning values, and alarm values, to assess the stress state of the main structure and ensure that it meets the design requirements, providing a basis for decision-making for the next construction process.

Figure 12 Reserved Longitudinal Reinforcement for the Frame Column

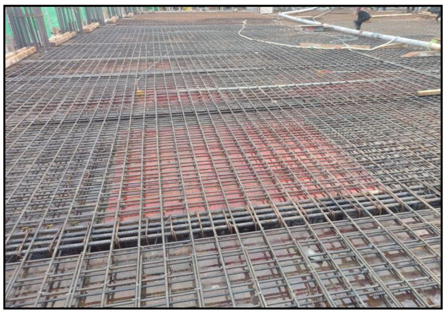


Figure 13 Roof Level Construction

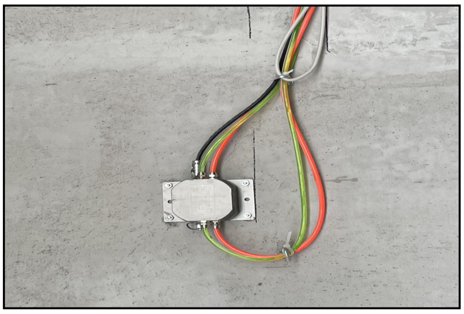


Figure 14 Differential Pressure Level Gauge for Beams

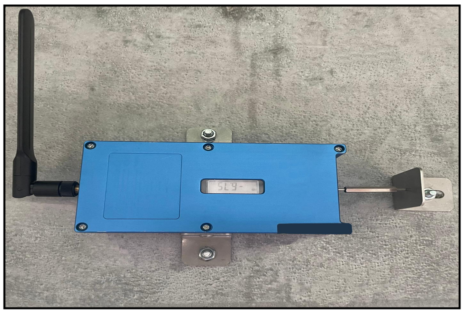


Figure 15 Surface Crack Gauge for Beams

4.5 Reverse Construction of Frame Columns

After the upper structure construction is completed, and the load-bearing capacity of the top and bottom beams and slabs of the reverse-constructed frame columns reaches its peak and the deformation stabilizes, scaffolding is erected to tie the reinforcement of the frame columns. The formwork is then installed and concrete is poured. The formwork is removed and curing is carried out according to specifications, thus completing the reverse construction of the frame columns. After the reverse construction of the frame columns is completed, they work in conjunction with the adjacent beams and slabs, and the overall structure enters a stage of internal force redistribution. Strain, cracks, and deflection should be continuously monitored, and the corresponding magnitude and rate of change should be analyzed until all data reaches a stable state,see Figures 16-17.

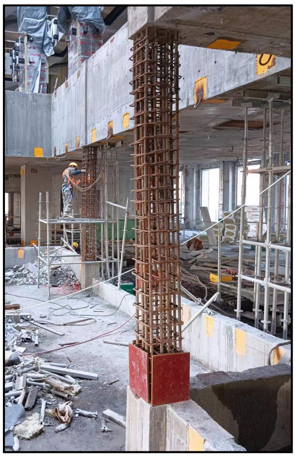


Figure 16 Frame Column Reinforcement Binding

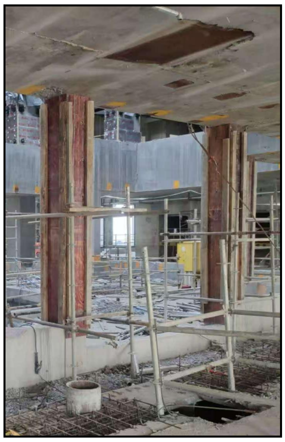


Figure 17 Frame Column Formwork

5 Cost-Benefit Analysis

This paper uses the Binjiang Kaixuanmen (Kaixuan Binjiang Garden) project as an example, where the tower area has 12 frame columns subjected to alternating tensile and compressive forces.

5.1 Conventional Construction Method

The scaffolding for the floor slabs weighs approximately 70 kg/m2, and the relevant area of the frame columns at the top and bottom floors is approximately 350 m2. The rental cost of scaffolding is approximately 150 yuan/ton/day. The construction of the structure above the frame columns takes approximately 100 days. The total cost of scaffolding and shoring for this project is 70/1000 × 350 × 150 × 100 = 367,500 yuan.

Because scaffolding is used for shoring at the top and bottom floors of the frame columns, secondary structure and electromechanical installation work cannot be carried out concurrently, resulting in a serious delay of 100 days. The resulting costs for lost work time, finished product protection, and personnel management amount to approximately 700,000 yuan.
Total: 367,500 + 700,000 = 1,067,500 yuan.

5.2 Top-Down Construction Method

The unit price of rebar is approximately 6000 yuan/ton. The reinforced frame beams connected to the top-down frame columns require approximately 6 tons of rebar, resulting in a reinforcement cost of 6000 × 6 = 36,000 yuan.
The labor costs for rebar rust prevention and removal, and surface preparation at the joints of the top-down frame columns, as well as the cost of adding micro-expanding agent to the concrete, amount to approximately 15,000 yuan.
Total: 36,000 + 15,000 = 51,000 yuan.
Based on the above analysis, the cost savings are: 1,067,500 - 51,000 = 1,016,500 yuan.

6 CONCLUSION

For beam-slab-column joints where deformation differences exhibit irregular dynamic changes under loading, this paper presents a reverse construction technique for frame columns under alternating tensile and compressive forces. This technique primarily involves using adjacent annular reinforcing beams and slabs to independently cantilever and support the upper load until structural stability is achieved, ensuring that the top and bottom of the lower frame columns are not affected by tensile or compressive stresses. This successfully addresses the structural deformation stability in areas subjected to alternating tensile and compressive forces. This technique not only avoids the risk of column cracking that might occur with conventional construction methods but also eliminates additional pressure on the beam-slab at the base of the frame column, further improving the safety redundancy of the frame structure system.

COMPETINGINTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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