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Posted Date: November 17th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11446923/v1

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Additional Declarations: No competing interests reported.

Research on section matching design method for concrete-filled steel tubular composite columns

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ABSTRACT

Based on practical engineering optimization, a section matching design method for concrete-filled steel tubular (CFST) composite columns is proposed. With reference to current structural design codes and combining the existing section performance evaluation indicators of concrete-filled steel tube columns, including strength index (*SI*), ductility index (*DI*) and flexural-shear performance index (*SE*), the correlation between the section strength ratio ζ and these indices is analyzed. A standardized analytical process is also established to determine the suitable range for ζ. Leveraging the value ranges of each evaluation index provided by a data-driven model, the corresponding suitable intervals for cross-sectional parameters are identified. In addition, a case study of the Ganhaizi Bridge is proposed to introduce the specific application scenarios of the proposed section parameter matching intervals in the design calculation method and design process, with the aim of providing reference and guidance for the promotion and application of such CFST composite structures.

Keywords: CFST, Composite column, Optimize design, Evaluation index, Matching degree

Introduction

CFST composite structures are widely used in engineering due to their excellent compressive performance. This performance is evident in two key areas: first, the section strength of CFST composite structures has been improved[1-3]; second, the residual bearing capacity of CFST composite structures has been more effectively guaranteed[4]. As the strength of steel and concrete continues to rise, the range of available section parameter combinations for CFST composite structures has expanded significantly[5-6]. Even experienced designers often find themselves needing to perform multiple calcu-lations to identify an economically viable combination of section parameters, resulting in increased costs associated with trial calculations in structural design. Consequently, to enhance the design efficiency of CFST composite columns, extensive research on the design of section parameters is essential.

The encircling effect enhances the bearing capacity of CFST composite members beyond the sum of the actual section strengths. The magnitude of this effect relies on the optimal combination of the steel tube and core concrete section parameters. Moreover, the combined effect of CFST composite members not only increases bearing capacity but also improves ductility. Consequently, the degree of ductility enhancement can serve as an additional design constraint for section parameters, thereby reducing the number of preset parameters. Thus, the section parameter combinations of CFST composite members should consider both bearing capacity and ductility constraints across a broad range.

Currently, few studies address the matching analysis and evaluation of combined effects for cross-sectional parameter configurations in CFST composite columns. Existing research primarily focuses on the axial compressive behavior of CFST short columns[7–9]. Investigations into material strength compatibility mainly concern the necessary conditions for achieving

full confinement effectiveness, which requires the steel tube to reach plastic yielding before concrete crushing occurs[10]. However, limited attention has been given to potential mismatch issues that may arise from increased strength of the infilled concrete[11]. Although significant progress has been made in calculating the axial compressive capacity of CFST short columns, these studies remain fragmented and narrowly scoped[12-14]. The proposed estimation approaches generally apply only within specific parameter ranges. Ductility design methodologies for CFST members primarily focus on the component level, considering factors such as section geometry, axial compression ratio, and member slenderness[15]. These formulations are often complex and lack adaptability as ductility criteria for cross-sectional parameter design. Stiffness compatibility analyses have been performed only for specific shear wall elements with similar composite configurations[16, 17]. This review indicates that current research on the cross-sectional parameter design of CFST composite columns suffers from inadequate investigation into material strength compatibility, unclear performance evaluation metrics, and an absence of systematic design frameworks for integrating composite materials.

Engineering background

The Ganhaizi Bridge spans 1811 meters with a width of 24.5 meters, comprising 36 spans. Situated in a seismic intensity zone of 8 degrees, the bridge features a main girder constructed as a continuous beam of multiple-span steel tube trusses. The central girder stands at 440 cm in height, with sections spaced 440 cm apart. The bottom chord measures Φ813 mm in diameter, while the branch tube is 406 mm in diameter, both filled with C60 concrete. The bridge deck is a 20 cm thick prestressed reinforced concrete structure. The standard section's top beam has a cantilever width of 311 cm, with a distance of 533 cm between the two flanges. The longitudinal ribs on the sides are 70 cm high, while the mid-span height is 20 cm. Refer to Figure 1 for the cross-sectional layout of the main girder.

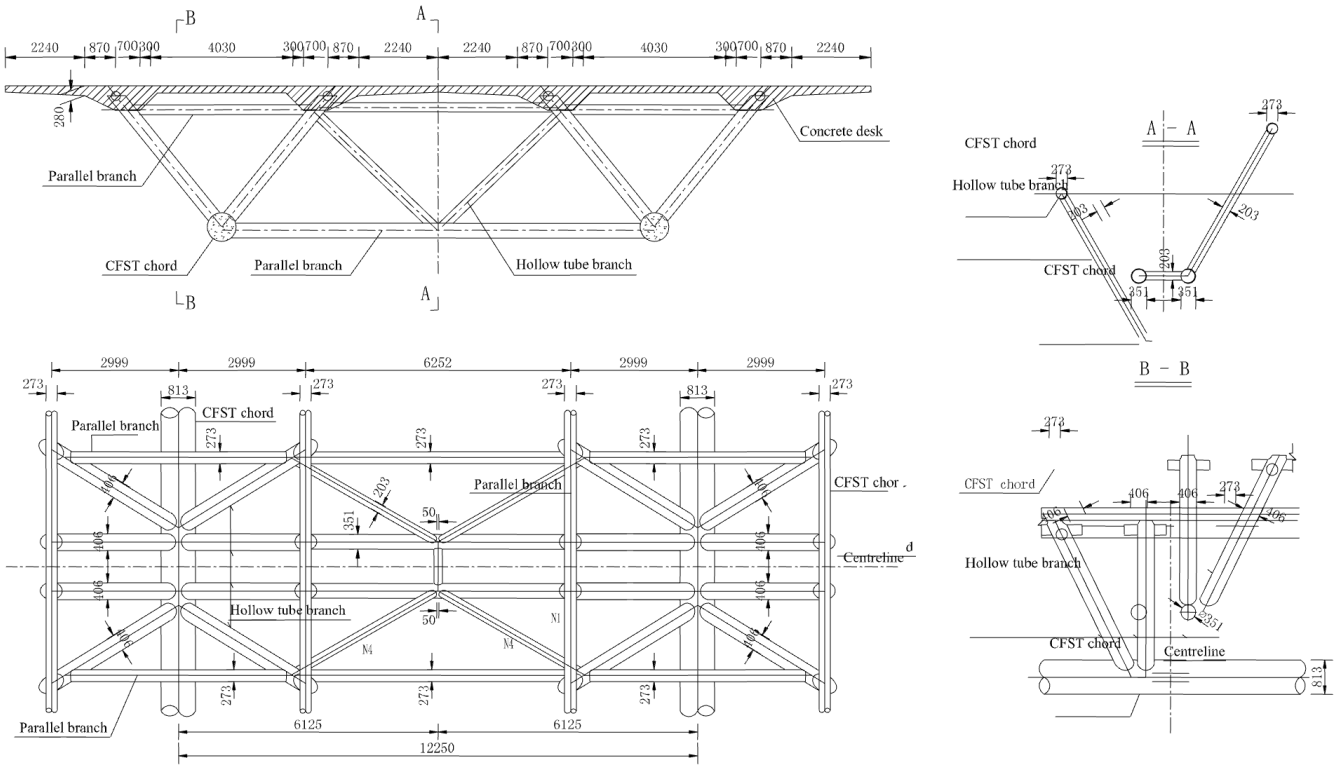


Figure 1. Ganhaizi bridge main beam structure layout (unit: mm).

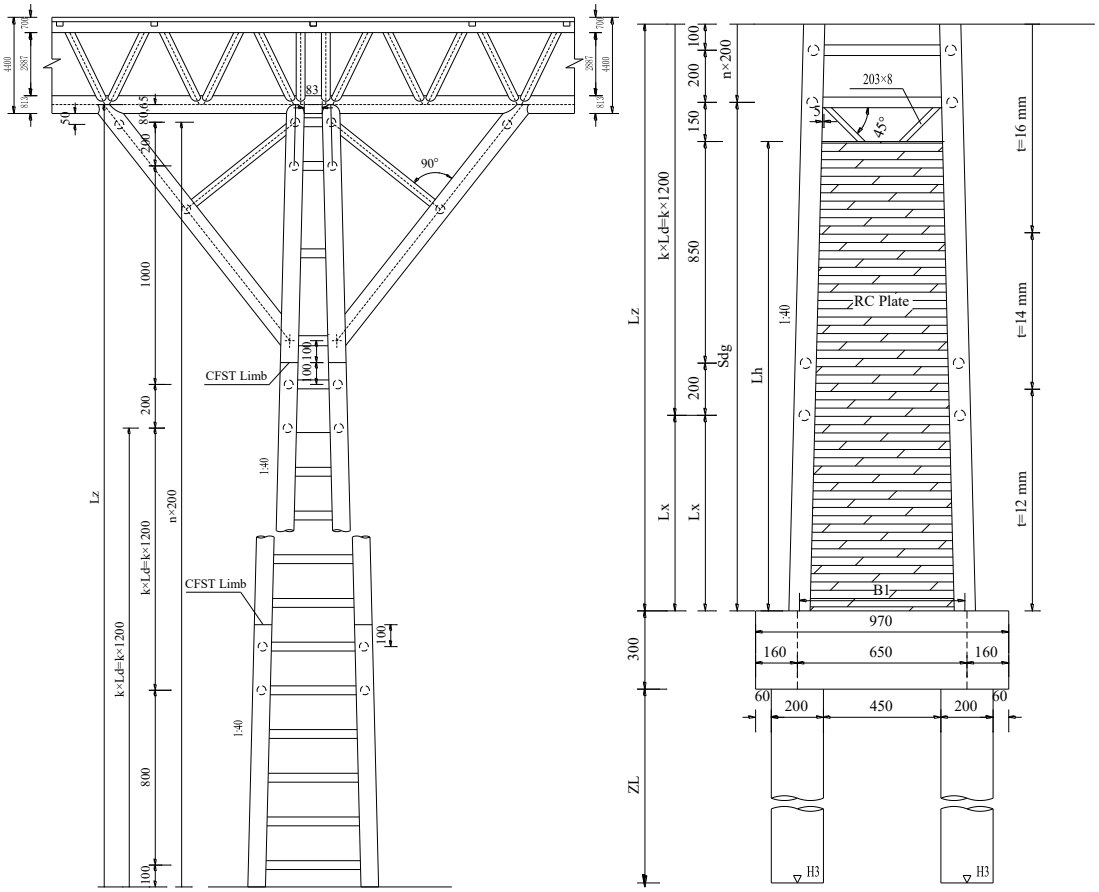
In the lower structure, 15 high piers, ranging from 20 m to 70 m, were constructed using lattice columns, while 10 high piers exceeding 70 m were built with mixed columns. This paper conducted finite element simulations for bridge piers 20#, 23#, and 25# based on the varying heights of the web plates. The specific layout is illustrated in Figure 2. The column limbs of the actual bridge utilize Q345 round steel tubes with an outer diameter of 813 mm and a wall thickness of 16 mm. The spacers also employ Q345 round steel tubes with an outer diameter of 457 mm and a wall thickness of 12 mm. Both the concrete in the column limbs and the web plate concrete are grade C50. Given that the mixed column piers in the actual

bridge have a variable cross-section, while this study focuses on a uniform cross-section, the variable cross-section structure is treated as equivalent to a uniform cross-section structure, following the method outlined in Ref.11. The calculation method is as follows:

$$\tan\left(\frac{a}{2}\ln\frac{I_0}{I_1}\right)=2a \tag{1}$$

$$\psi=(a^2+\frac{1}{4})\left(1-\frac{h_0}{h_1}\right)\frac{4}{\pi^2}\frac{I_1}{I_0} \tag{2}$$

where，I_1 denotes the moment of inertia of the small column head of the actual bridge composite column; I_0 denotes the moment of inertia of the large column head of the real bridge composite column; h_0 denotes the longitudinal spacing of the column limbs at the small column head of the actual bridge composite column; h_1 denotes the center distance of the column limbs at the cross-section of the large column head of the actual bridge composite column; h^* denotes the equivalent longitudinal spacing of the column limbs, calculated according to the formula.



a) upper CFST lattice column　　b) bottom CFST-RC composite column

Figure 2. Layout of CFST hybrid column of Ganhaizi bridge (unit : cm).

The longitudinal spacing of the equivalent limbs of 20 #, 23 #, and 25 # piers is calculated as 5.95 m, 5.80 m, and 5.60 m, respectively, based on the formula provided. All other structural parameters remain unchanged from the original design. Table 1 presents the key parameters of the equivalent bridge piers.

Main parameters	20# Pier	23# Pier	25# Pier
Height H(m)	106.9	101.8	94.8
Equivalent limb longitudinal spacing h_0(m)	5.95	5.80	5.60
Limb transverse spacing h_1(m)	12.3	12.3	12.3

Thickness of plate t_p(mm)	400	400	400
Diameter of tube D(mm)	813	813	813
Wall thickness of tube t(mm)	16	16	16
Parallel branch spacing (m)	2.0	2.0	2.0
Strength of infilled concrete	C50	C50	C50
Strength of plate concrete	C50	C50	C50
Strength of steel tube	Q345	Q345	Q345
Strength of reinforced steel	HRB400	HRB400	HRB400
Height of plate(m)	30.6	25.5	18.5
Ratio of height	0.29	0.25	0.20

Note: Ratio of height is the ratio of RC plate height to column height.

Table 1. Equivalent section parameters of Ganhaizi bridge pier

The substructure comprises reinforced concrete solid piers and straight abutments, providing support for the entire arch-girder system in an externally statically determinate configuration. The piers primarily resist axial forces and bending moments induced by the superstructure. At the springings of the leaning arches, independent pile caps are constructed and monolithically connected to the main pier caps. This integrated foundation system ensures that the horizontal thrust generated by the leaning arches is collectively resisted by all foundation piles, thereby enhancing the stability and load distribution capacity of the substructure.

Section parameter matching analysis

Main parameters on the strength and ductility

Performance results led to the definition of indices for comparing the ductility and strength enhancement of the CFST columns described by Han *et al.*[19], Portolés *et al.*[20], and Guler *et al.*[21]. For the steel tube confined STCU columns, identical per-formance indices, including *SE*, *SI*, and *DI*, were established to assess the degree of strength and ductility enhancement. These indices are defined as follows:

The strength enhancement index SI may be introduced to assess the load-carrying capacity of the composite section Nu relative to the sum of the strengths of the individual components and is expressed as follows.

$$SI = \frac{N_u}{f_c A_c + f_y A_y + f_p A_p} \tag{3}$$

Larger values of *SI* reflect a positive interaction between the steel tube and concrete core.

The ductility index DI was adopted to evaluate the level of ductility in STCU columns:

$$DI = \frac{\varepsilon_{85\%}}{\varepsilon_u} \tag{4}$$

where, $\varepsilon_{85\%}$ is the axial strain when the load falls to 85% of the axial bearing capacity, and ε_u is the axial strain at N_u. It should be noted that the ductility index *DI* as defined in Eq. (4) was introduced in most of the previous studies[22, 23] to assess the ability of STCU columns to sustain plastic deformation beyond the elastic limit.

The level of the shear force to the shear capacity of the specimen under unit horizontal load and eccentric load can be represented by the concrete contribution ratio *SE*.

$$SE = \frac{V_1}{V_0} \tag{5a}$$

$$V_1 = (M_u - N_u e_0)/L \tag{5b}$$

$$V_0 = V_{\mathrm{UHPC}} + \omega V_{\mathrm{CFST}} \tag{5c}$$

where, V_1 is the shear value corresponding to the shear benefit of the specimen in the horizontal direction under the action of unit horizontal force and eccentric load. V_0 is the ultimate shear capacity of CFST composite columns calculated based on the strut-and-tie model. V_{UHPC} can be calculated according to the calculation method of shear capacity of UHPC beams, proposed by Ma[24].

Consequently, this paper discusses the section parameter matching interval based on FE multi-parameter extended analysis of CFST composite columns. The discussion, as depicted in Figure 3, comprises two main aspects: 1) Defining the calculation method for each performance index and examining the appropriate value range for each index through parameter expansion analysis; 2) Investigating the strength ratio matching interval of the component section based on the value range of each performance index and providing recommendations for multiple sets of optimal solutions.

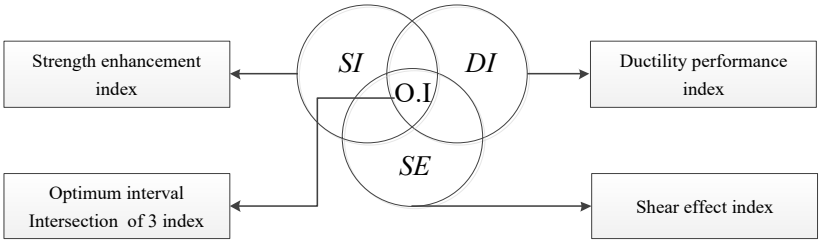


Figure 3. Matching analysis of section parameters.

Establishment of FE model

To facilitate the calculation of axial forces and bending moments in the main piers under ultimate bearing capacity conditions, this paper employs the finite element software MIDAS/Civil to model the Ganhaizi Bridge, as illustrated in Figure 4. The main girder and piers are represented using beam elements. The CFST box-type composite piers are modeled as equivalent rectangular sections based on their axial compression and bending stiffness. The boundary conditions reflect the actual conditions of the continuous rigid frame bridge. This approach is straightforward, efficient, and well-suited for the preliminary design stage.

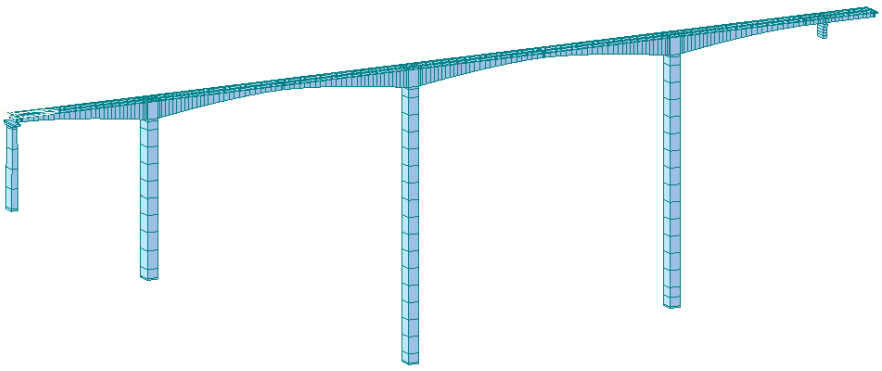
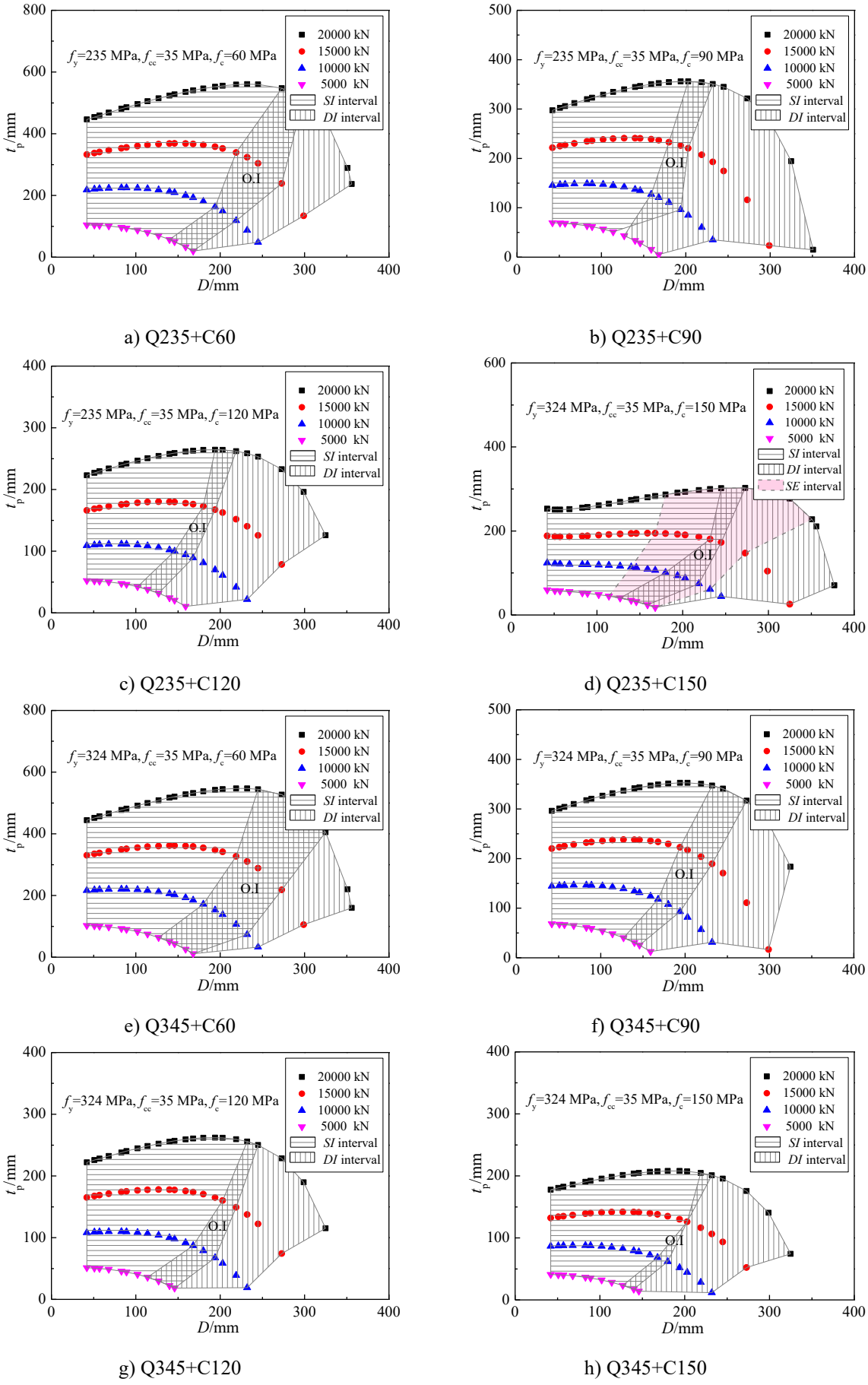


Figure 4. Spatial truss finite element calculation model of Ganhaizi bridge

Section parameter matching range

In engineering practice, ductility index requirements based on strain ratio are crucial. For CFST composite structures, *DI* should exceed 4.0, while for reinforced concrete structures, it should surpass 1.4. The analysis of performance indicators indicates that the *SI* index to some extent reflects the *DI* index. The cross-sectional area ratio p for CFST sections must not exceed the upper limit value pm. Within the range of $p \leq p_m$, both indices increase with the cross-sectional strength ratio. When $p = p_m$, the corresponding values of the bearing capacity index *SI* and the ductility index *DI* peak. Consequently, the suggested matching range for *DI* and *SI* is the cross-sectional strength ratio ζ corresponding to $p = p_m$, where *SI* is below 1.1, and *DI* exceeds 1.4.

Matching diagrams of geometric parameters for CFST composite column components with varying material strengths can be derived to meet different target bearing capacities. The recommended range for section strength ratio matching suggests a ductility index (*DI*) exceeding 1.4, a bearing capacity index (*SI*) below 1.1, and a flexural-shear performance index (*SE*) between 0.2 and 0.3. These diagrams are illustrated in Figures 5, 6, 7, and 8.



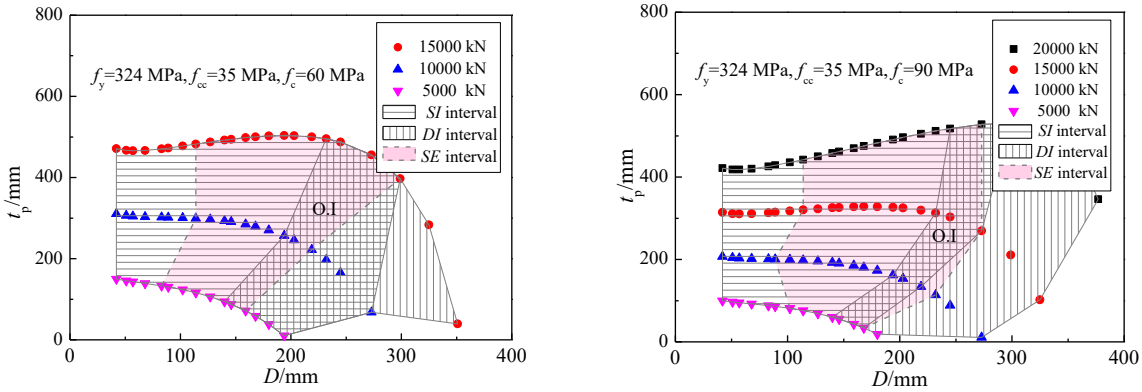
a) Q235+C60 b) Q235+C90

c) Q235+C120 d) Q235+C150

e) Q345+C60 f) Q345+C90

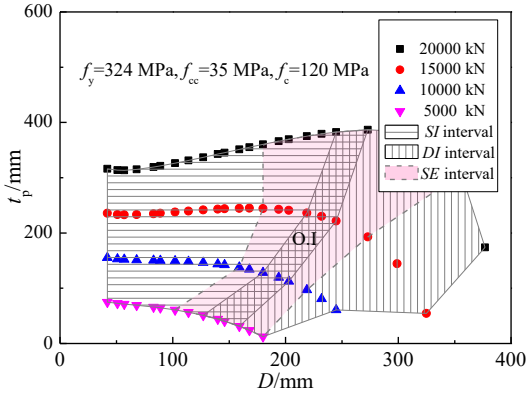
g) Q345+C120 h) Q345+C150

Figure 5. Parameter matching diagram of CFST composite short column under axial compression (λ≤8).

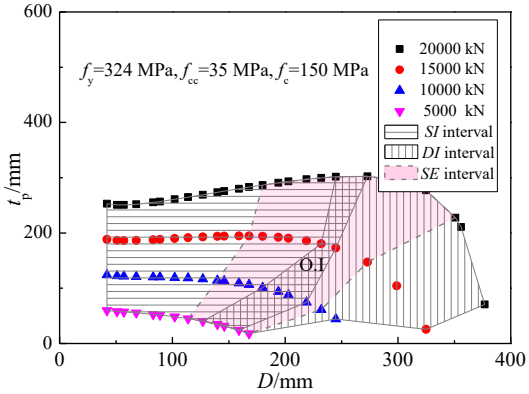


a) Q345+C60

b) Q345+C90

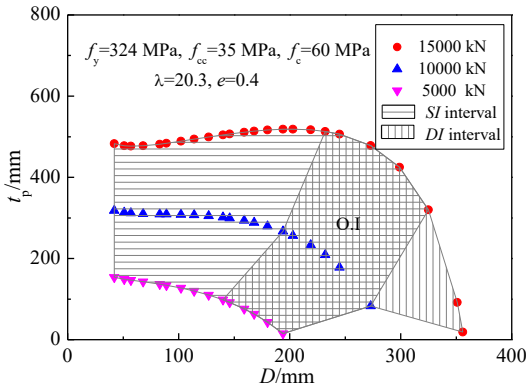


c) Q345+C120

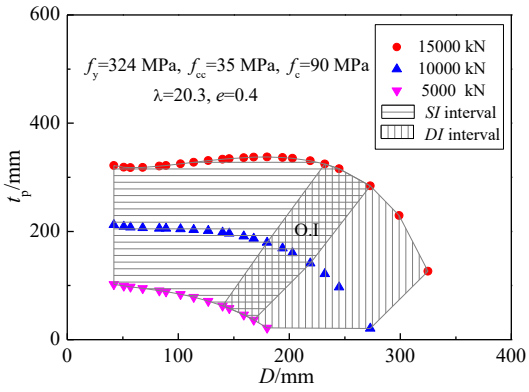


d) Q345+C150

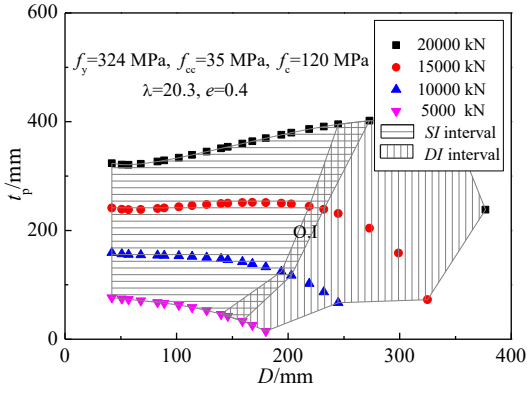
152 **Figure 6.** Parameter matching diagram of CFST composite short columns under eccentrically loaded (λ≤8).



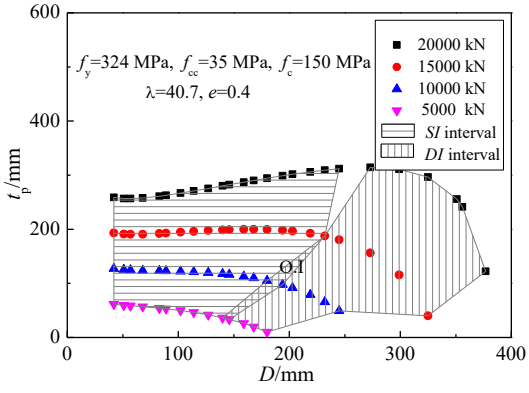
a) Q345+C60



b) Q345+C90

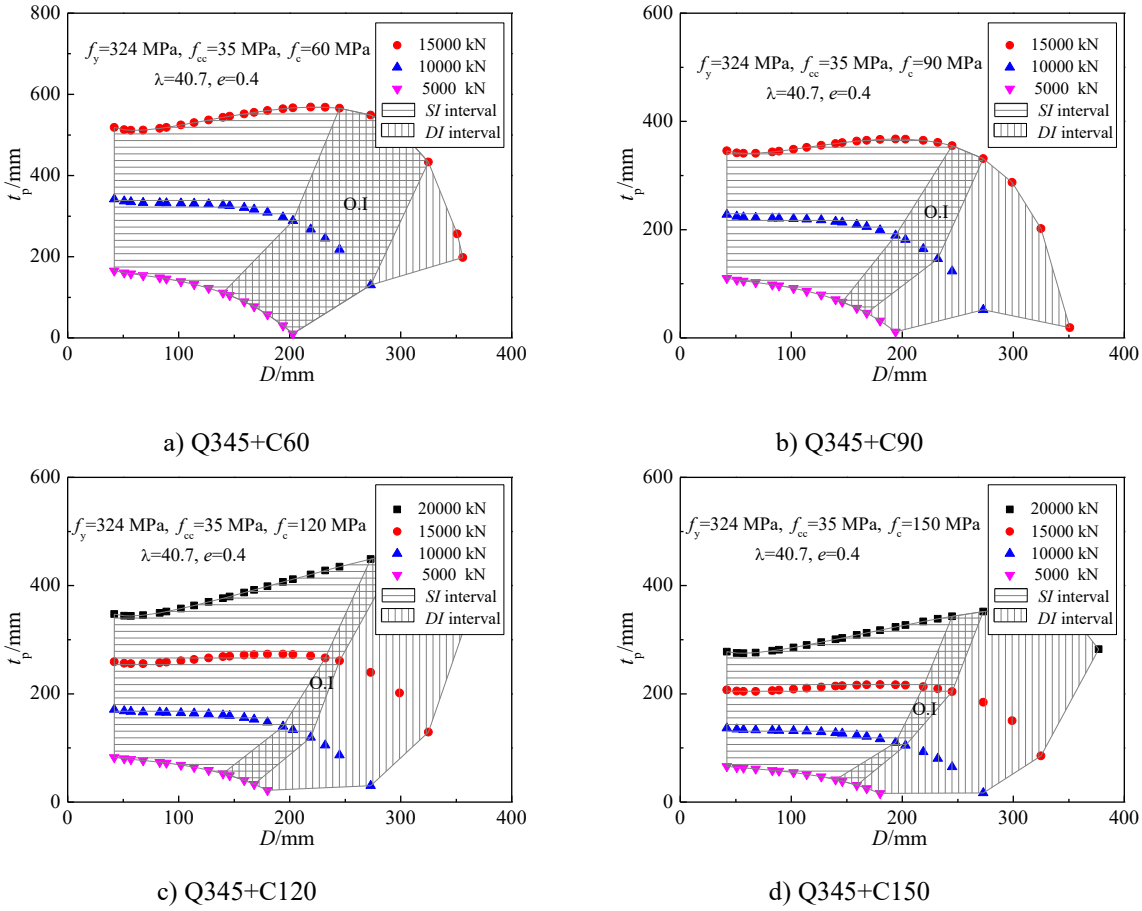


c) Q345+C120



d) Q345+C150

Figure 7. Parameter matching diagram of CFST composite intermediate column under eccentrically loaded (8<λ≤30).



a) Q345+C60 b) Q345+C90

c) Q345+C120 d) Q345+C150

Figure 8. Parameter matching diagram of CFST composite long column under eccentrically loaded (λ>30).

As shown in Figures 5-8, the shaded area O.I in these figures represents the optimal solution range for the CFST composite column specimens that simultaneously meet the bearing capacity index, ductility performance index, and flexural-shear performance index. The corresponding section strength coefficient ζ at this time is the matching range. Within this matching range, the bearing capacity, ductility performance, and flexural-shear performance of the CFST composite column specimens fulfill the structural design requirements.

Engineering Case application

Using the No. 20 # pier as an example, the axial force under dead load is determined by the self-weight of the superstructure. Structural design specifications require that the D/t ratio exceeds 20, and the design maintains the axial compression ratio of the pier at approximately 0.15 under dead load. Since the pier experiences eccentric compression in practice, an eccentricity value of 0.4 is adopted to ensure structural safety.

Figure 9 illustrates the parameter matching design process for CFST composite columns. These columns, meeting specific load-bearing targets, have a range of optional section parameters based on the strength enhancement index (*SI*) and ductility index (*DI*). By utilizing the matching intervals of *SI* and *DI*, designers can determine the suitable section parameters. Subsequently, multiple sets of CFST composite column parameters can be derived from the provided diagram to offer valuable design insights. To exemplify this, Ganhaizi piers 20, 23, and 25 were chosen to showcase the matching design process in comparison to the initial scheme.

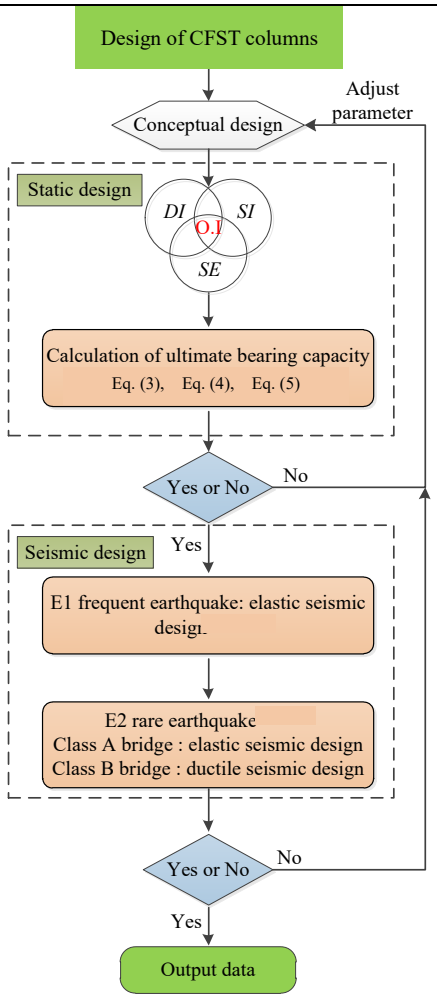
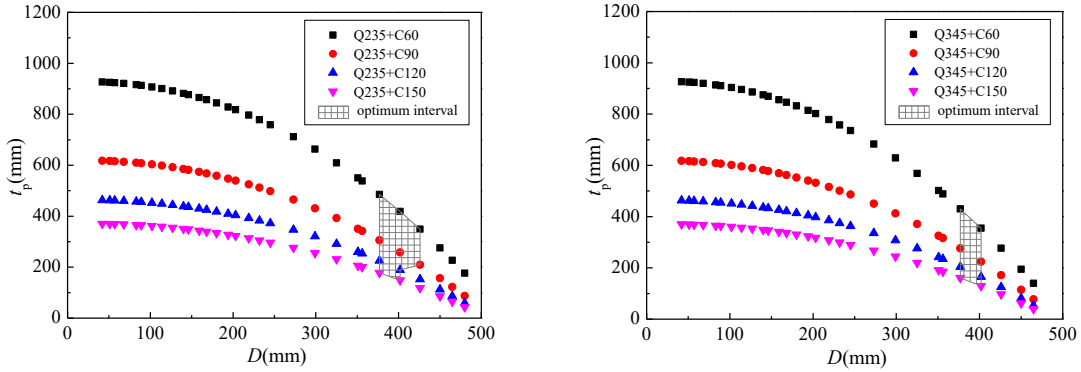
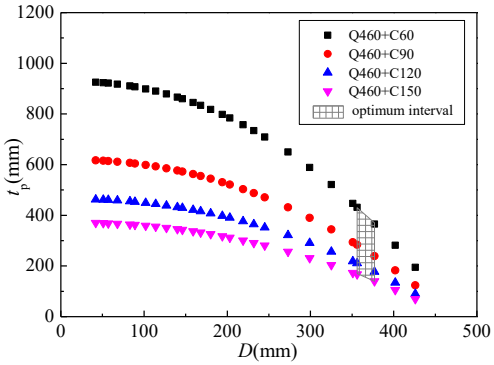


Figure. 9 Overall design flowchart of CFST composite columns.

The design methodology for component section parameters is established based on the cross-sectional parameter matching diagram. Initially, the material strength combination is chosen following standard specifications for steel tube models, conventional concrete strengths, and UHPC strengths, as depicted in Figure 10. Once the material strength combination is identified, designers can select appropriate geometric parameters from the matching range based on specific design needs. The compatible ranges for the outer diameter of the steel tube and the thickness of the UHPC plate are clearly indicated in Figure 10. For example, adhering to the minimum cross-sectional area criterion for the column, a composite column with Q460 steel and C150 concrete, featuring an outer diameter of D = 356 mm and UHPC plate thickness of t_p = 170 mm, is chosen.



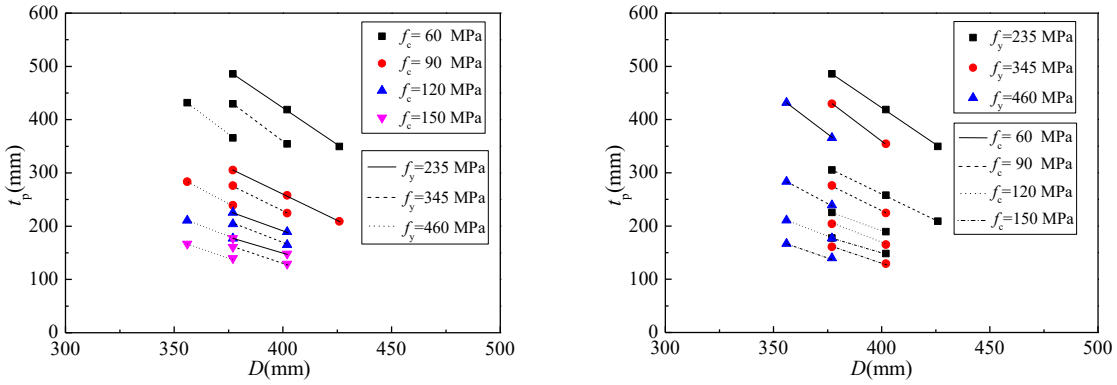
a) Q235 b) Q345



c) Q460

Figure 10. Parameters of cross section after matching and screening.

Figure 11 illustrates that multiple sets of optimal solutions within the matching interval are categorized based on the strength of the steel tube and the strength of the batten concrete. The designer can more efficiently identify the geometric parameters associated with these optimal solutions by considering the design requirements, enabling the selection of various design schemes.



a) different strength of concrete plate b) different strength of steel tube

Figure 11. Applicable range of CFST composite column matching design.

According to the above CFST composite column matching design method, combined with the design principle that the strength of the steel tube is consistent with the original scheme and the diameter-thickness ratio of the CFST limb is 40, the structural parameters of each pier when the CFST composite column scheme is adopted for the 20 #, 23 #,and 25 # piers of the Ganhaizi bridge can be obtained, as shown in Table 2.

Main parameters	20# Pier	23# Pier	25# Pier
Height H(m)	106.9	101.8	94.8
Equivalent limb longitudinal spacing h_0(m)	5.95	5.80	5.60
Limb transverse spacing h_1(m)	12.3	12.3	12.3
Thickness of plate t_p(mm)	170	222	211
Diameter of tube D(mm)	426	402	402
Wall thickness of tube t(mm)	10.65	10.05	10.05
Parallel branch spacing (m)	2.0	2.0	2.0
Strength of infilled concrete	C50	C50	C50
Strength of plate concrete	C120	C120	C120
Strength of steel tube	Q345	Q345	Q345
Strength of reinforced steel	HRB400	HRB400	HRB400

Height of plate(m)	106.9	101.8	94.8
Ratio of height*	1.0	1.0	1.0

Table 2. Section parameters of main pier matching design of Ganhaizi bridge

Summary and conclusions

This study systematically investigated the CFST section strength matching behavior through a comprehensive parametric analysis based on a three-dimensional finite element model. Based on the structural design requirements, the applicable range for the section parameter matching design is determined. This enables the intuitive and rapid design of the section parameters for CFST composite column components that achieve a certain target bearing capacity. The main conclusions can be summarized as follows:

1. The strength enhancement index (*SI*) of CFST composite columns exhibits a positive correlation with the section strength ratio (ζ) due to the confinement effect provided by the UHPC plate. To prevent catastrophic failure of the UHPC plate, the *SI* value is constrained to ≤1.10. This constraint ensures that the residual bearing capacity of the CFST composite column maintains ≥85% of its compressive strength bearing capacity when the ductility index (*DI*) ≥1.4.
2. For short columns under eccentric compression, the section strength ratio must satisfy a shear effect index (*SE*) within the range of 0.2-0.3. In contrast, eccentrically loaded intermediate and long columns exhibit *SE* values <0.2. Consequently, the design matching interval for these columns should focus exclusively on the strength enhancement index (SI) and ductility index (*DI*), with the SE excluded from the optimization criteria.

Data availability

All data supporting the findings in this study are available from the corresponding author upon reasonable request.

Use of AI tools

Large language models were used to assist with language editing and refinement of the manuscript. The use of these tools was limited to improving grammar, clarity, and academic style. All technical content, analyses, results, and conclusions were conceived, performed, and verified by the authors, who take full responsibility for the content of the manuscript.

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Funding

This research was supported by Jimei University Scientific Research Starting Foundation, grant number： No. ZQ2024109.

Competing interests

The authors declare no competing interests.