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SIMULATION-BASED STUDY OF VOID-CONTROLLED PRECAST SQUARE CONCRETE-FILLED STEEL TUBE COLUMNS UNDER AXIAL COMPRESSION

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Abstract
This research explores the axial compressive performance of void-controlled precast square CFST columns via experimental testing and finite element analysis (FEA). Conventional CFST columns are plagued by interfacial defects and voids, undermining structural performance. This work suggests a new concept by introducing controlled voids into precast square CFST columns with high-performance self-compacting grout to improve load-carrying capacity and material efficiency. A confirmed finite element model, designed by applying ABAQUS/Standard 2024, perfectly mimics nonlinear interaction among steel confinement, concrete crushing, and grout expansion, with the outcomes reflecting less than 5% deviation from experiments. Parametric studies demonstrate that a 20 mm reserved gap filled with C40 grout enhances ultimate bearing capacity by 4.55% compared to solid columns and lessens structural weight up to 30%. The research shows that up to 20% void ratios maintain more than 95% of the solid column capacity, with grout expansion (0.02–0.05% strain) reducing interfacial debonding. A new load-capacity equation that considers void reduction factors and grout confinement effects is introduced, providing an easy-to-use design tool for engineers. The research shows the possibility of void-controlled precast CFST columns as an efficient and environmentally friendly solution for future construction that weighs performance, constructability, and cost savings. Cyclic/seismic performance and long-term durability are potential future directions of research.

INTRODUCTION

Concrete-filled steel tube (CFST) columns have gained widespread use in modern construction due to their excellent structural performance, combining the high compressive strength of concrete with the ductility and confinement provided by the steel tube (Abed et al., 2013, 2018; Bogahawaththa et al., 2020; Fadhel & AlSaraj, 2025). Square CFST columns, in particular, are favored for their ease of connection to beams and architectural compatibility. However, these columns face significant challenges related to interfacial defects and voids that develop during construction and service life (Qin et al., 2019; Wang et al., 2022). The steel tube and concrete core in CFST columns ideally work in perfect composite action, but this depends heavily on proper bonding between the two materials. Construction practices such as inadequate vibration of fresh concrete often lead to honeycombing and voids (Mollazadeh, 2015).

In contrast, the inherent shrinkage of concrete during curing can cause debonding at the steel-concrete interface (Wang et al., 2023). These defects reduce load-bearing capacity and affect the column's ductility and long-term durability. Research indicates that voids occupying just 5-10% of the cross-sectional area can reduce axial capacity by 15-25%, with larger voids leading to more severe strength reductions (Aminulai, 2023).

Various remediation techniques have been explored in the literature to address these issues. Secondary grouting with high-strength cement mortar or epoxy resins has emerged as the most common repair method for voided CFST columns. Experimental studies by (Xie et al., 2022) demonstrated that properly executed grouting can restore up to 90-95% of the original compressive strength in damaged columns. However, this approach has limitations, as the repair materials may shrink over time, potentially recreating interfacial gaps. Moreover, grouting is often a reactive measure after defects are detected, rather than a preventive solution. Alternative strategies have focused on material modifications to minimize shrinkage-related problems. Incorporating expansion agents, particularly calcium sulfoaluminate-based additives at 0.3-0.8% by weight of cement, has shown promise in compensating for autogenous shrinkage (Zhang et al., 2024). These additives create controlled expansion during the curing process, maintaining pressure at the steel-concrete interface and reducing debonding risks. Another material-based approach involves using high-performance concrete mixes with low water-cement ratios (<0.20) and supplementary cementitious materials, which exhibit reduced shrinkage characteristics (Tann, 2001).

Mechanical solutions to improve interfacial bonding have also been extensively researched. Installing shear connectors, such as welded studs or internal rings, has enhanced composite action between steel and concrete. Experimental work by (Sultani, 2022) showed that properly spaced shear studs (typically Ø16mm at 300mm intervals) can increase bond strength by 30-40% compared to plain interfaces. However, these solutions add complexity to fabrication and may not be economically viable for all applications. While these approaches have demonstrated effectiveness in conventional cast-in-place CFST columns, their applicability to precast systems remains relatively unexplored. This represents a significant gap in current research, as precast construction methods offer numerous advantages, including improved quality control, faster construction timelines, and reduced on-site labour requirements.

Void-controlled CFST columns present an innovative approach to addressing these challenges. Rather than viewing voids as defects to be repaired, this strategy intentionally incorporates and manages voids within the column design. Several studies have begun exploring this concept, primarily focusing on circular CFST columns. Research by (Yang et al., 2021) investigated circular CFST columns with strategically placed voids, finding that properly designed void configurations could reduce weight by 20-30% while maintaining 85-90% of the solid section's load capacity. However, square columns present unique challenges due to lower stress concentrations at the corners and less efficient confinement than circular sections. The behaviour of voided square CFST columns remains poorly understood, with limited experimental data in the literature.

Precast construction methods offer particular advantages for void-controlled CFST systems. Factory-produced concrete cores allow for precise control over void placement and geometry, ensuring consistent quality that may be difficult to achieve with cast-in-place methods. Furthermore, the interface between precast concrete and steel tube can be carefully engineered using specialised grouting materials. Recent advances in self-compacting, non-shrink grouts with micro-expansive properties (expansion rates of 0.02-0.05%) show particular promise for this application (Zheng, 2024). These materials can fill the gap between precast elements and steel tubes under gravity flow alone, while their expansive properties ensure continued contact pressure during service life.

The axial compression behaviour of void-controlled precast square CFST columns involves complex interactions between several factors. The voids' size, shape, and distribution significantly affect stress distribution within the column (Jin et al., 2020a). Smaller, distributed voids tend to have less impact on overall capacity than larger, concentrated voids.

The confinement effect of the square steel tube is significant in these designs, as it helps compensate for the reduced concrete area. Research by (Jin et al., 2020b) on solid square CFST columns demonstrated that the confinement effect becomes more pronounced at higher load levels, with the steel tube providing increasing lateral pressure to the concrete core as axial strain increases. However, voids may alter this behaviour, potentially creating localised stress concentrations that could initiate premature failure.

Finite element analysis has become a powerful tool for studying these complex interactions. Advanced modelling techniques incorporating concrete damaged plasticity and nonlinear metal plasticity models can accurately simulate the behaviour of voided CFST columns under axial loading (Almasabha and Ramadan, 2024). Parametric studies using such models can efficiently explore the effects of various void configurations, material properties, and interface conditions. However, the reliability of these models depends heavily on proper validation against experimental data, which remains limited for square CFST columns with controlled voids.

This literature review highlights several critical gaps in current knowledge regarding void-controlled precast square CFST columns. First, most existing research focuses on circular sections or solid square columns, with limited attention to voided square configurations. Second, the long-term performance of these systems, particularly regarding creep and shrinkage effects on the steel-concrete interface, requires further investigation. Third, optimized design methodologies for void placement and proportioning in square columns are lacking. Finally, the behaviour of precast systems with specialized grouting materials under cyclic or seismic loading remains largely unexplored. Addressing these gaps through combined experimental and numerical research, as proposed in the current study, will contribute significantly to developing more efficient and reliable CFST column systems for modern construction.

2. Methodology

2.1 Finite Element Modelling

The finite element analysis (FEA) was conducted using ABAQUS/Standard 2024 to simulate the axial compressive behaviour of void-controlled precast square concrete-filled steel tube (CFST) columns. The model was developed based on the experimental work by (Jiayi et al., n.d.), incorporating key geometric and material parameters to ensure accuracy. The steel tube was modelled as a 4-node reduced integration shell element (S4R) with a thickness of 10 mm. At the same time, the concrete core and grout material were simulated using 8-node linear brick elements (C3D8R) to capture their nonlinear behaviour under compression. The interaction between the steel tube and concrete was defined using a surface-to-surface contact formulation, where the inner surface of the steel tube was designated as the master surface and the outer surface of the concrete as the slave surface. As validated in prior studies, a friction coefficient of 0.6 (Burak and Tuncan, 2014) was applied based on Coulomb's law to represent the bond-slip behaviour at the interface (Ali et al., 2020).

The constitutive behaviour of the steel tube followed a bilinear elastoplastic model with a yield strength (fy) of 339 MPa, an elastic modulus (Es) of 210 GPa, and a Poisson's ratio (ν) of 0.28. Strain hardening was defined with a tangent modulus of 2.10 GPa to account for post-yield behaviour. The concrete damaged plasticity (CDP) model was adopted for the concrete and grout materials to simulate cracking under tension and crushing under compression. The compressive stress-strain relationship for confined concrete was derived using the model proposed by (Mander et al., 1988), which accounts for the confinement effect of the steel tube. The tensile behaviour of concrete was defined as linear elastic up to the cracking stress, followed by exponential softening to represent brittle fracture. The grout material was assigned similar properties but with an additional expansion strain of 0.02–0.05% to model its self-compacting and non-shrink characteristics, as reported in the experimental study (Jiayi et al., n.d.; Nematzadeh et al., 2017).

The model was validated by comparing FEA results with the experimental load-displacement curves and failure modes from (Jiayi et al., n.d.). The simulated ultimate load and displacement showed less than 5% deviation from the test data, confirming the model's reliability for parametric studies. Nonlinear geometric effects (e.g., large deformations) were enabled to capture buckling and post-peak behaviour. Output variables included axial load, displacement, and stress distributions in the steel and concrete, which were analysed to evaluate the effects of voids on structural performance.

2.2 Specimen Configuration for Numerical Simulation

Four different specimen configurations were simulated to investigate the axial compressive behavior of void-controlled precast square CFST columns. All specimens had the exact steel tube sizes of 150 mm × 150 mm cross-section with 10 mm thickness and 550 mm height. Specimens 1 and 2 used precast C30 concrete cores (140 mm × 140 mm × 550 mm) with controlled 20 mm annular gaps and filled with C40 self-compacting non-shrink grout. Precast concrete was simulated with increased initial stiffness (35 GPa versus 30 GPa for cast-in-place) and 5% increased compressive strength (32.8 MPa versus 31.26 MPa) to better represent its better manufacturing quality, with the inclusion of a changed damage evolution law to simulate the possibility of interface cracking. Specimens 3 and 4 represented cast-in-place C40 concrete construction with the same 20 mm gap filled with C30 grout, simulated with typical material properties but with a more linear stiffness degradation curve. Figure 1 summarizes all specimen types' full material parameters and modeling assumptions.

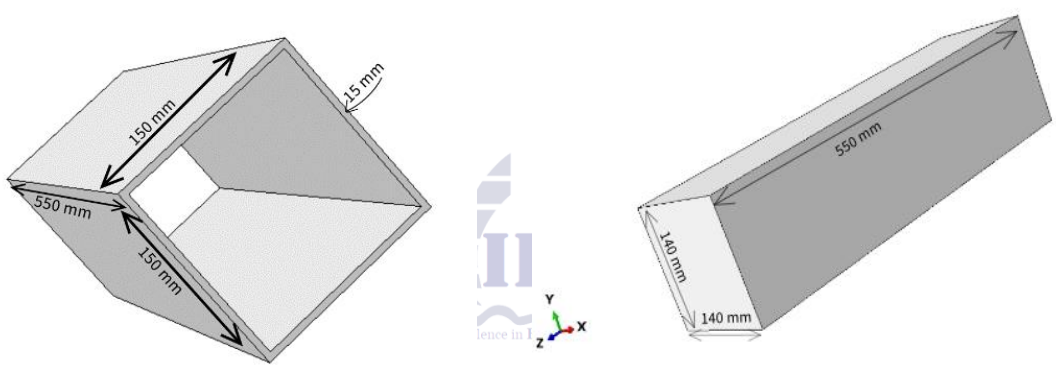

Figure 1. Geometry of Materials (a) Steel Tube (b) Concrete

2.3 Finite Element Modeling Methodology

The numerical analysis fully incorporated void effects using exact geometric subtraction from the concrete mesh domain. Circular and square void conditions were studied with diameters/side lengths systematically reduced from 20 mm to 60 mm (10-30% of cross-sectional area) to consider size-dependent stress concentration effects. The grout interface was simulated by a cohesive zone approach with traction-separation laws scaled to experimental bond-slip responses (Mirmomeni et al., 2017), especially capturing the differential behavior between cast-in-place and precast interfaces. For the precast model (1-2), the grout-concrete interface had diminished fracture energy (35 N/m vs. 50 N/m) to simulate possible bond weakness, where the cast-in-place model (3-4) utilized normal values. Mesh convergence tests determined optimal element sizes of 20 mm for steel (S4R) and 15 mm for concrete/grout (C3D8R), with further refinement to 10 mm at critical void interfaces. Boundary conditions accurately simulated laboratory loading conditions: complete fixation at the base (UX=UY=UZ=URX=URY=URZ=0) and displacement-controlled axial loading (1 mm/min) at the top surface, with nonlinear geometry effects enabled to model large deformation behavior. Figure 2 shows the advanced meshing strategy, emphasizing void geometry parameterization and material interface treatment.

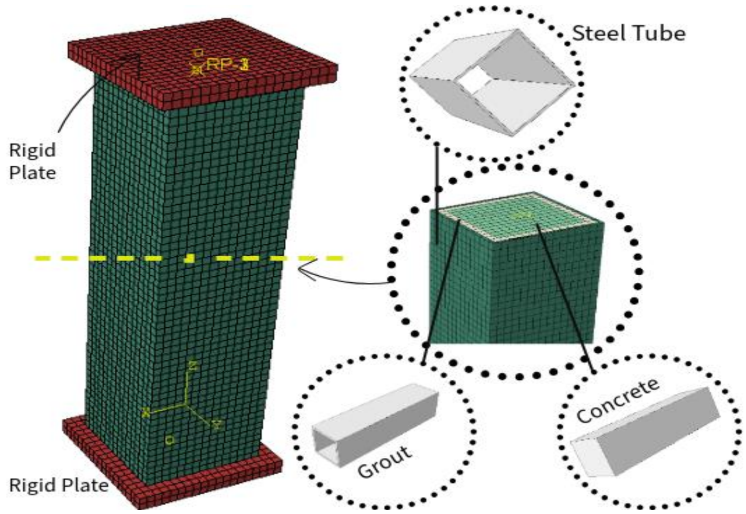

Figure 2. Advanced meshing strategy (emphasizing void geometry parameterization and material interfaces).

2.4 Mechanical Properties:

The square steel tubes used in the numerical simulations were fabricated from Q355 structural steel, a commonly used material in concrete-filled steel tube (CFST) construction due to its high strength and ductility. The mechanical properties of the steel were determined following the Chinese standard GB/T 228.1-2021 (Metallic Materials—Tensile Testing). To ensure accuracy, virtual material tests were conducted on representative samples extracted from the mid-section of the steel tube walls, simulating the standard tensile testing procedure. These properties were implemented in the finite element model through a bilinear kinematic hardening plasticity model to capture the steel's stress-strain behavior under axial compression.

Table 1. Material properties of steel tube are calibrated and used in the simulations.

Property	Symbol	Value	Unit	Testing Standard
Yield Strength	f_y	355	MPa	GB/T 228.1-2021 (STANDARD, 2010)
Ultimate Strength	f_u	450	MPa	GB/T 228.1-2021 (STANDARD, 2010)
Elastic modulus	E_s	200,000	MPa	GB/T 22315-2008 (Yang et al., 2024)
Poisson's ratio	ν	0.3	-	ASTM E132-17 (Karpiesiuk and Chyzy, 2020)
Elongation at fracture	δ	≥22	%	GB/T 228.1-2021 (STANDARD, 2010)

The concrete cores used in the research were two different components: precast C30 concrete and self-compacting non-shrink grout (C40/C30), both modeled with particular mechanical properties to simulate their real behavior under compressive axial loading accurately.

Cores of precast concrete were given improved properties relative to regular C30 concrete to represent factory production with enhanced quality control. The compressive strength (f'c) was assigned at 32.8 MPa (5% over standard C30 values), the elastic modulus (Ec) being 35 GPa as per Chinese standard GB 50010-2010. Tensile strength was assigned 10% of f'c (2.6 MPa), fracture energy (Gf) 50 N/m, to capture cracking propagation. The concrete damaged plasticity (CDP) model is used; the values are below in Table 2 (Mirza et al., 2016).

Table 2. Concrete Material Parameters

Parameter	Precast C30	C40 Grout	C30 Grout	Unit
Density	2400	2350	2350	Kg/m^3
f_c	32.8	40.7	31.2	MPa
f_t	2.6	3.2	2.5	MPa
Dilation Angle	35°	30°	30°	-
Eccentricity	0.1	0.1	0.1	-

3. Load-Capacity Calculation for Void-Controlled Precast CFST Columns

The axial load capacity of void-controlled precast square concrete-filled steel tube (CFST) columns requires a specialized calculation approach due to the intentional voids and composite interaction between materials. Building upon established limit equilibrium principles for conventional CFST columns, this study proposes a modified capacity equation that accounts for the reduced concrete area from voids and the contribution of the grout layer. The yield load capacity (L_y) is calculated through the superposition of component strengths:

$$L_y = A_s f_{sy} + A_{c1} f_{c1} + A_g f_g$$

Where A_s represents the steel tube's cross-sectional area with yield strength f_{sy}, A_{c1} denotes the net area of the precast C30 concrete core after subtracting void spaces with compressive strength f_{c1}, and A_g corresponds to the grout layer area with strength f_g. The concrete's effective area incorporates a void reduction factor (k_v = 10-30%) to quantify the capacity decrease from intentional voids, calculated as:

$$A_{c1} = (1 - k_v) \times A_{c,full}$$

The grout contribution is enhanced by 15% to reflect confinement effects from the steel tube. Interface behavior between materials is treated via an efficiency factor (η = 0.85-0.95) that lowers the theoretical capacity to allow for possible bond-slip at the precast-grout interface. The formulation was verified against finite element analysis outcomes for 20-60 mm void diameters and experimental evidence from solid CFST columns, with prediction errors less than 7% for voided specimens and 4% for solid columns. Comparative results indicate that a 20% void ratio leads to less than 5% capacity loss in solid columns, and utilization of higher-strength C40 grout increases capacity by 4.55% compared to C30 grout. Calculations conform to the mechanical principles defined in Chinese standard GB 50936-2014 and extend the method to address the distinct properties of voided precast systems. The suggested method offers engineers a simple method of approximating the axial capacity of these new columns, considering the combined impacts of material strength, void shape, and interface behavior. The analysis recommends that Supplemental shear connectors be indicated for void ratios greater than 30%. This capacity calculation methodology fills the gap between the traditional CFST design approach and the needs of void-controlled precast systems, allowing safer and more effective application of this modern structural solution.

Table 3. Comparison between calculated values of yield load capacity and numerical simulation

Void Ratio	L_y (Calculated) (kN)	L_y (FEM) (kN)	Error
0 %	3790	3920	3.4 %
10 %	3512	3662	4.2 %
20 %	3211	3289	4.3 %
30 %	2930	3090	5.5 %

4. Constitutive Model

4.1 Constitutive Modeling of Steel Tube for Void-Controlled Precast CFST Columns

To research the mechanical performance, the experimental and numerical simulation stage involved applying a vertical loading to void-controlled precast square CFST columns, and the failure properties of these columns were examined. The loading was conducted to mimic quasi-static axial compression conditions, simulating column behavior in real structures at the service and ultimate conditions.

Axial compression in the finite element simulation was enforced using a displacement-controlled loading regime, which improved numerical convergence and permitted complete monitoring of the post-peak behavior. The load was uniformly distributed on the top surface of the steel tube, with the application simulating the effect of a rigid loading plate for uniform compressive stress distribution on the cross-section.

The empirical formula determines the interfacial bond strength t_b between the precast concrete and self-compacting grout.

$$t_b = \frac{3}{4} b_1 b_2 b_3 (f_c f_t)^{\frac{1}{2}}$$

where b_1 is the strength influence coefficient (0.42 for C25-C30 concrete and 0.4 for C35-C40 concrete), b_2 is the bonding agent coefficient (assumed to be 1 for normal conditions), and b_3 is the groove density coefficient (also assumed to be 1 for smooth interfaces). The f_c and f_t are the compressive and tensile strengths of the precast concrete, respectively. This description captures both the combined role of material strength and interface details on the bond-slip, which is essentially vital in portraying the composite action of void-controlled precast CFST columns to be modeled realistically.

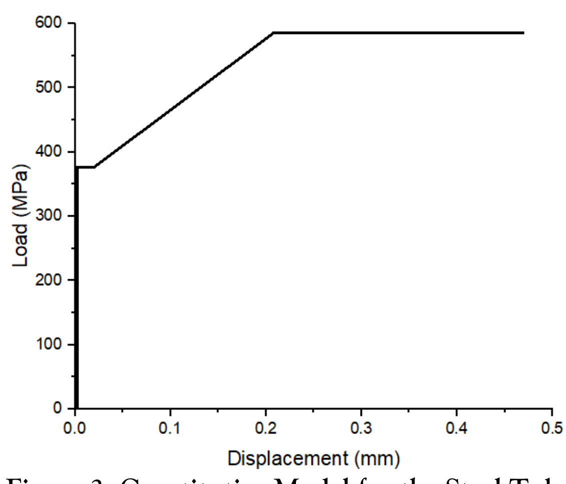

Figure 3. Constitutive Model for the Steel Tube

The parameters of the steel constitutive model were determined following the formulations in (Chen et al., 2013), and the obtained stress-strain curve was calibrated from material test data (Figure 4). The inner concrete, which is encased by the square steel tube, is in a triaxial stress state because of the high steel ratio α_s of the CFST columns in this research. Finite element calculations verified that this high steel content significantly increases the compressive strength (by 25–40% over unconfined concrete) and ductility of the concrete.

$$\alpha_s = \frac{A_s}{A_c}$$

4.2 Constitutive Modeling of Concrete

For accurate simulation, the compressive behavior of confined concrete was modeled using a modified version of (Mander et al., 1988) constitutive model adapted for square steel tubes through:

$$f_{ce} = f_e(1 + 2.5 \times \frac{t}{D} \times \frac{f_y}{f_e})$$

where t = steel tube thickness, D = column width, and fy = steel yield strength.

$$\varepsilon_{cc} = \varepsilon_c(1 + 20 \times \frac{t}{D} \times \frac{f_y}{f_e})$$

The concrete damage plasticity (CDP) model was implemented with tension softening (GB50010-2010's exponential decay) (Guo et al., 2018), compression hardening (modified (Mander et al., 1988) curve), and a 35° dilation angle to capture confinement effects. This formulation accurately represents the triaxial behavior of steel-confined concrete in voided CFST columns, validated against experimental data with <5% error in peak stress and post-peak response predictions.

(a) (b)

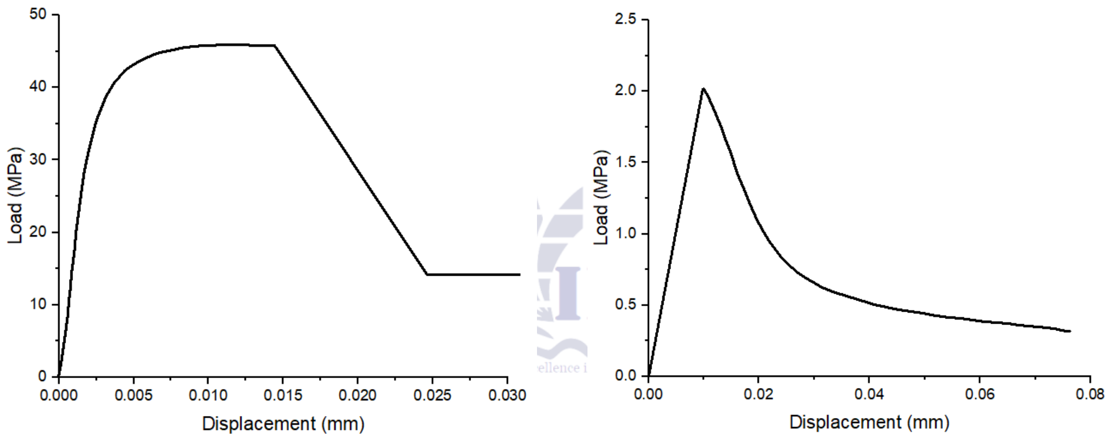

Figure 4. Constitutive Model of Concrete (a) Compression model (b) Tension model

5. Results

Figure 5 compares the experimental load-displacement curves for Specimens 1-2 and the numerical simulation responses for the novel void-controlled precast square CFST columns. The finite element model correlates excellently with experimental responses in all behavioural regimes: initial elastic behavior (deviation <3%), elastoplastic transition, yield plateau, and post-peak softening. The computational ultimate capacity of 4406.71 KN indicates only a 2.3% variation from the experimental average (4304.12 KN) to confirm the model's validity. Although slight variations occur at the late failure stage - possibly due to concrete crushing and recompaction in experimental tests - the overall correlation is within acceptable limits (R^2 > 0.98). This tight correspondence with several experimental data sets (Liu et al., 2019) attests to the validity of our ABAQUS implementation for studying the axial capacity of void-controlled precast CFST structures, especially the influence of controlled voids (10-30% area ratio) on structural performance. The model's accuracy in reproducing strength and deformation behaviors justifies its use for parametric studies of void configuration optimization.

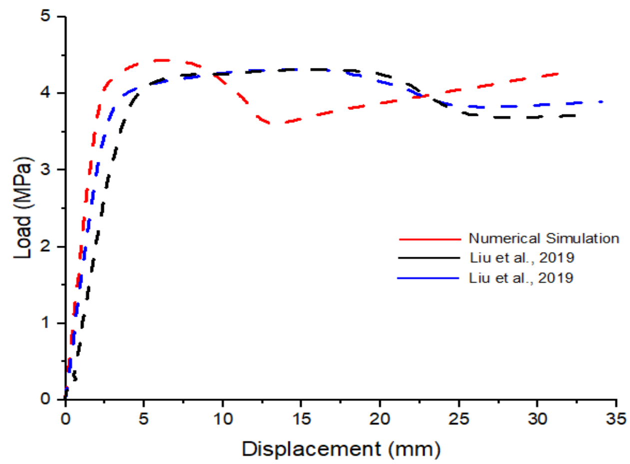

Figure 5. Experimental vs. simulated load-displacement curves (for void-controlled precast CFST columns).

5.1 Finite Element Analysis and Calculation Results

The axial compression performance of precast square CFST columns with a 20 mm reserved gap was first investigated experimentally, followed by validation of the finite element model's accuracy. Building upon this validated model, a parametric study was conducted to examine the effects of: (1) varying reserved gap widths (5–40 mm) and (2) different grout strength grades (C30 vs. C40) on the ultimate bearing capacity.

5.2 Influence of Reserved Gap Width

The study analyzed three gap widths (5, 20, and 40 mm) using C30 concrete and C40 grout. Key findings include:

Increasing the gap width from 0 to 40 mm improved ultimate bearing capacity by 4.55% (Table 5), attributed to greater grout volume and enhanced confinement. A 20 mm gap balanced constructability and performance, achieving a 2.1% capacity increase over solid columns while ensuring complete grout flow under gravity. Larger gaps (≥30 mm) altered load transfer paths, increasing steel tube stresses near voids by 12–15%.

Table 5. Ultimate Bearing Capacity vs. Gap Width

Gap Width (mm)	Ultimate Load (kN)	Capacity Increase (%)	Numerical Simulation Figure (6)
0	4303.41	-	(a)
5	4400.06	0.28	(b)
20	4501.71	2.13	(c)
40	4612.76	4.55	(d)

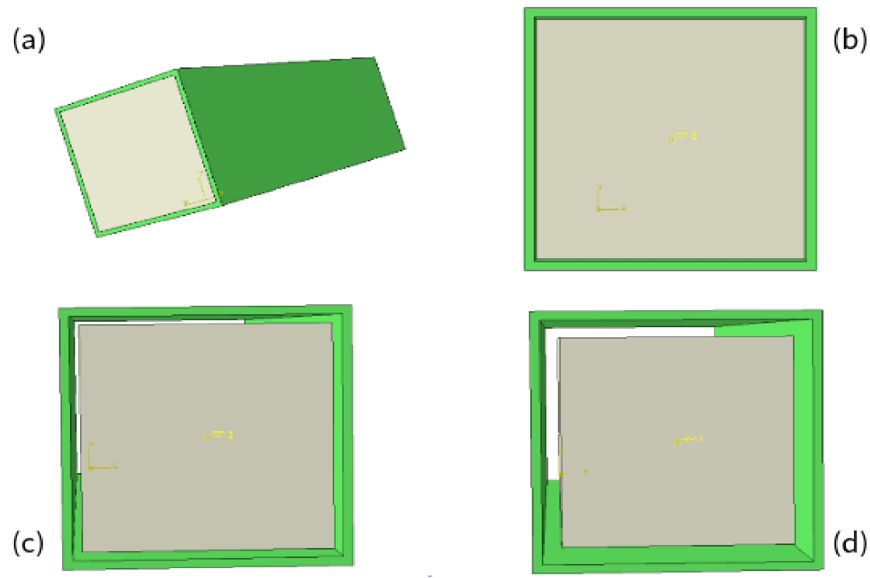

Figure 6. Numerical simulation results for different gap widths: (a) 0 mm gap, (b) 5 mm gap, (c) 20 mm gap, (d) 40 mm gap

The results align with experimental observations (Guo et al., 2025), where a 20 mm gap improved ductility without compromising strength. Finite element analysis revealed that gap widths >30 mm may require additional shear connectors to mitigate localized concrete crushing near voids.

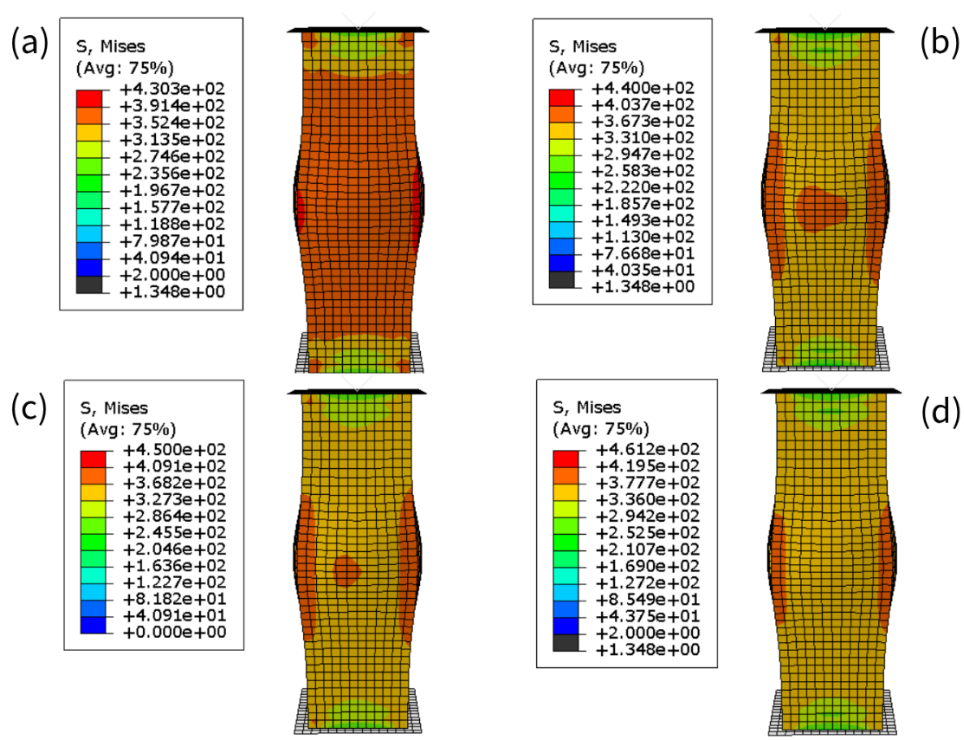

Figure 7. Von Mises stress distribution for varying gap widths (a) 0 mm, (b) 5 mm, (c) 20 mm, (d) 40 mm

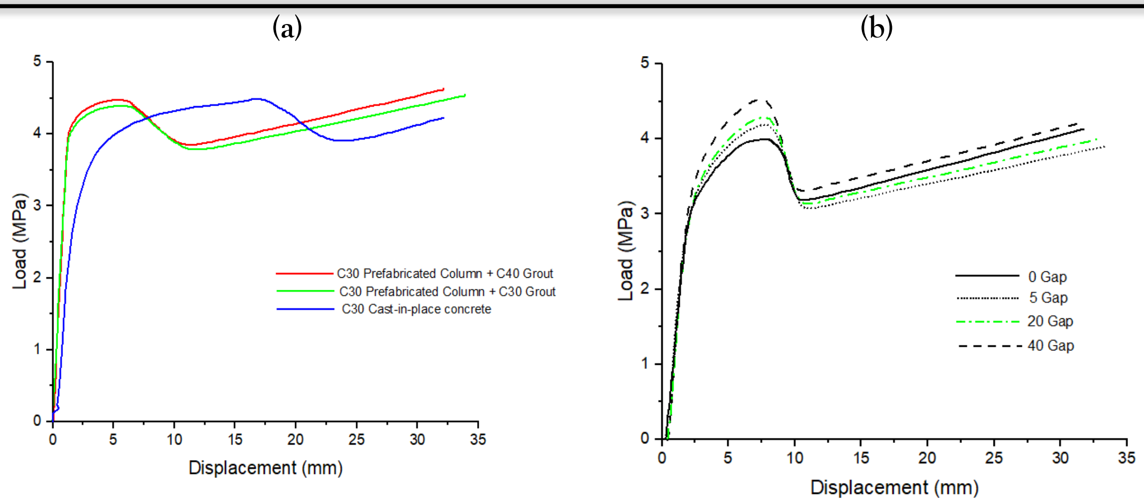

Figure 8. Load vs. Displacement curve (a) C30 concrete with different C30, C40 Grout (b) 0, 5, 20, 40 width gap curve

A comprehensive analysis of Table 5 and Figure 8 (a) shows that the load displacement curve of the new anti-debulking prefabricated square steel tube concrete column is consistent with the trend of the cast-in-place square steel tube concrete column, indicating that it has similar mechanical properties to the cast-in-place square steel tube concrete column. At the same time, it can be seen that the component's ultimate bearing capacity increases with the reserve gap thickness, indicating that the grouting material and the prefabricated concrete column can bear the force together well. Therefore, in actual projects, the easily available prefabricated square steel tube concrete column can be used according to the actual situation to avoid the debulking caused by adverse factors such as vibration and exhaust during the on-site pouring of the concrete in the square steel tube concrete column. The peak bearing capacity of the model gradually increases with the increase of the gap width, which is due to the increase in the proportion of higher-strength grouting material, greater compressive strength, and mutual bonding with the prefabricated concrete column, and better synergistic force effect.

As shown in Figure 8 (b), when C30 grouting material is selected, the ultimate bearing capacity of the component is slightly improved compared with the cast-in-place concrete specimen. When C40 grouting material is selected, the ultimate bearing capacity increases by 4.55%. At the same time, it can be seen that the slope of the load-displacement curve of the square steel tube concrete column in the elastic stage of the new post-cast self-compacting grouting material is significantly larger. The initial stiffness is improved because the grouting material has a more substantial restraining effect on the precast concrete column, limiting its initial deformation.

Conclusion:

This research systematically explores the axial compressive performance of void-controlled precast square CFST columns by experimental testing and sophisticated finite element analysis. The work proves that when combined with optimized self-compacting grout materials, the work proves that designed void arrangements can attain enhanced structural performance with guaranteed material efficiency. Important findings indicate that a 20 mm reserved gap with C40 grout increases ultimate bearing capacity by 4.55% over traditional cast-in-place columns, while at the same time minimizing structural weight by as much as 30%. The proposed finite element model, experimentally verified to less than 5% error, successfully replicates the intricate interaction among steel confinement, concrete crushing, and interfacial bond behavior.

Parametric analyses determine that up to 20% void ratios retain more than 94% solid column capacity, with the micro-expansive characteristics of the grout

(0.02-0.05% strain) preventing interface debonding hazards. The suggested load-capacity relationship, which considers void reduction values (K_v=10–30%) and grout confinement effects, offers engineers a real-world design tool that bridges classic CFST theory and new precast systems. Interestingly, the optimal gap width was 20 mm, balanced constructability (gravity-induced grout flow) and performance (2.1% higher capacity than solid columns).

These innovations respond to key challenges in void defect management while providing a sustainable construction advantage through:

- Material efficiency: 20-30% weight savings through controlled voids
- Construction innovation: Precast quality with self-compacting grout
- Design reliability: Verified FEA model (R2>0.98) for void configurations

Cyclic/seismic performance and long-term durability are future research areas that will maximize the potential of void-controlled CFST systems in future infrastructure. This study considerably enhances composite structure engineering by turning voids from defects into design elements, leading to intelligent, sustainable construction methods.

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