

STUDY ON COMPRESSIVE BEHAVIOR OF LASER-ARC WELDED TUBE-IN-TUBE S355 STEEL COLUMNS

Ming-Yang Li ¹, De-Hong Huang ², Zi-Yi Zeng ³, Yao-Peng Liu ^{2,*} and Siu-Lai Chan ^{2, 4}

¹ School of Civil Engineering, Southwest Jiaotong University, Chengdu, China

² School of Civil Engineering and Transportation, South China University of Technology, Guangzhou 510641, China

³ Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, China

⁴ State Key Laboratory of Subtropical Building and Urban Science, South China University of Technology, Guangzhou 510641, China

* (Corresponding author: E-mail: yaopengliu@scut.edu.cn)

ABSTRACT

This paper presents an experimental and numerical study on the axial compression behavior of laser-arc hybrid welded tube-in-tube steel columns made of S355. Three different cross-sectional configurations, i.e. square-in-square (SS), circular-in-square (SC) and conventional square hollow section (S), were investigated through monotonic tension tests and axial compression tests. Digital Image Correlation (DIC) was employed to analyze deformation patterns. Results demonstrate that the ductility of composite SS and SC columns has been significantly improved compared to single hollow-section columns, effectively delaying local buckling and mitigating strength degradation. Moreover, numerical simulations using finite element method (FEM) were conducted and validated against experimental results. Parametric studies were conducted to evaluate the influence of column slenderness on axial load-bearing capacity, highlighting that current design codes (EN 1993-1-1:2022 and GB 50017-2017) provide conservative predictions. Findings suggest adopting the class a₀ curve from EN 1993-1-1:2022 or the class a curve from GB 50017-2017 for the design of such composite columns. This study provides essential data and practical guidance for the structural application of laser-arc welded tube-in-tube composite columns.

ARTICLE HISTORY

Received: 12 November 2024
Revised: 20 February 2025
Accepted: 1 March 2025

KEYWORDS

Laser-arc hybrid welding;
Tube-in-tube steel column;
Finite element method;
Compressive behavior;
Initial geometric imperfections

Copyright © 2025 by The Hong Kong Institute of Steel Construction. All rights reserved.

1. Introduction

Modular construction has gained increasing attention and application both domestically and internationally due to its advantages of fast construction speed, high engineering quality, low labor consumption, energy efficiency, and environmental protection [1, 2]. However, due to spatial constraints, the cross-sectional dimensions of modular construction members are limited. To overcome these limitations, this study proposes two new types of steel column cross-sections: square hollow section column nested within square hollow section column and circular hollow section column nested within square hollow section column, both formed through laser-arc hybrid welding.

Currently, scholars have conducted relatively limited research on hollow section columns. Wang et al. [3] conducted material tensile tests and local buckling tests on RHS/SHS stub column specimens of varying strengths and evaluated existing design provisions in the Eurocode 3 for such structural columns. Ma et al. [4] provided a comprehensive review on high-strength steel hollow sections, highlighting gaps in design rules. Yang et al. [5] proposed a new equation for deriving the cross-sectional slenderness of SHS and RHS considering the influence of corner radius. Li et al. [6] studied flexural and interactive buckling of 7A04-T6 high-strength aluminium RHS columns, offering improved design methods based on test and FE results. Zhu et al. [7] studied the behavior and design of hot-rolled carbon steel circular hollow sections (CHS) under the effect of moment gradients. Lin et al. [8] conducted a numerical study on high-strength steel welded box columns and proposed new column curves incorporating yield strength and width-to-thickness ratio to improve design accuracy beyond existing codes. Yan et al. [9] conducted low-temperature compression tests and simulations on stainless-steel tubular stub columns, revealing enhanced strength but reduced ductility with decreasing temperature. Meng et al. [10] investigated the buckling behavior of axial compressive hollow sections members, encompassing CHS, SHS, and RHS sections. Wang et al. [11, 12] conducted experimental and numerical studies on S890 and S960 CHS members under combined and eccentric loading, and evaluated the applicability of existing design codes, highlighting their varying accuracy for different section classes. Yin et al. [13] conducted tests and simulations on cold-formed HSS SHS columns, and proposed modified buckling curves for design.

Some studies have been conducted by researchers on the axial compressive performance and design methods of composite cross-sections. Li et al. [14] conducted experimental and numerical investigations on the local buckling behavior of cold-formed steel built-up box-section columns and revealed the built-up interaction mechanism between C- and U-section components. Zhao et al. [15] proposed a new type of cold-formed stainless-steel spliced rectangular tubular column and demonstrated through tests and FE analysis that V-shaped

stiffeners significantly enhance its axial and compression-bending capacities. However, systematic research on structural members with square-circular composite cross-sections remains relatively limited.

Traditional arc welding techniques, while widely used in structural fabrication, suffer from several well-recognized limitations, including high heat input, significant welding deformation, large heat-affected zones (HAZ), and low welding efficiency [16–21]. These drawbacks are particularly detrimental when applied to thick-section or high-performance steels, where dimensional control and material integrity are critical. For example, Sokolov et al. [22, 23] observed that conventional welding methods tend to induce excessive thermal distortion and broad HAZs in thick S355 structural steel, adversely affecting dimensional precision and mechanical performance. Similarly, Zhong et al. [24] emphasized that traditional fusion welding introduces considerable membrane residual stresses and geometric imperfections in stainless steel T-sections, which may compromise structural stability.

In contrast, laser welding presents a high-precision, high-efficiency alternative, offering numerous advantages such as lower total heat input, narrower HAZ, reduced residual stresses, minimized distortion, and higher welding speeds [25–28]. These benefits stem from its concentrated energy delivery and non-contact nature. In addition, laser welding enables deep penetration and excellent process control, which is especially advantageous in joining thick or high-strength steel sections. For instance, Zhang et al. [17] demonstrated that with a 10 kW fiber laser, full penetration welding of thick stainless steel was achievable at high speeds, while also identifying the keyhole dynamics responsible for surface underfill defects, a challenge that is otherwise exacerbated in conventional methods.

Moreover, laser welding is readily integrable with robotic platforms, promoting automation and manufacturing repeatability. Sokolov and Salminen [29] conducted comparative trials and confirmed that laser welding maintains superior weld quality even under variable edge preparation conditions, underscoring its industrial robustness.

Building upon the merits of individual welding methods, laser-arc hybrid welding (LAHW) has emerged as a promising technique that combines the high precision and penetration of laser welding with the good gap-bridging ability and process stability of arc welding. Several researchers have explored the synergistic mechanisms of LAHW. Zhang et al. [26] quantified the “synergy effect” in LAHW of aluminum alloys using plasma spectroscopy, confirming that laser energy enhances arc stability and increases the material’s laser absorptivity, while the arc assists with broadening the fusion zone and improving melt flow. Likewise, Yin et al. [16] demonstrated that in LAHW of low-strength high-toughness steel, the increased cooling rate due to the combined heat source promoted the formation of bainite and fine acicular ferrite in the weld metal, thereby enhancing both hardness and low-temperature

toughness.

In light of the limited research in the existing literature on the application of LAHW to square and circular hollow section (SHS/CHS) members, as well as composite steel members, this study aims to investigate the axial compressive performance of ultra-high-power LAHW composite section steel columns, with the goal of providing experimental data and theoretical support for the practical engineering application of such novel structural systems.

In this research, axial compression tests were first conducted on laser-welded composite section columns to obtain their structural response under axial loads, including load–displacement curves, deformation and failure modes, as well as global buckling behavior. The comparison between the influences of different internal tube configurations on load-bearing capacity and failure mechanisms was performed. Subsequently, a finite element model was developed in ABAQUS and validated against the experimental results. A parametric study was then performed to investigate the influence of slenderness ratio on the axial capacity of columns with the two composite section types. Finally, by comparing the simulation results with predictions from Chinese specification (GB 50017-2017 [30]) and European specification (EN 1993-1-1:2022 [31]), the applicability of each code to these composite sections was evaluated, and corresponding design recommendations were proposed.

2. Experimental study

2.1. Specimen preparation and experimental procedure

This experimental investigation comprises tensile coupon tests and axial compression tests on steel columns with various cross-sectional configurations. The columns, fabricated using ultra-high-power LAHW, were made of grade S355J0 steel.

2.1.1. Monotonic tension test

To investigate the material properties of the steel used in this study, monotonic tension tests were conducted. Given that the tested hollow section columns tested had a wall thickness of 10 mm, the tensile specimens were also prepared with the same thickness. As illustrated in Fig. 2(c), the specimens were designed and fabricated in accordance with ISO 6892-1:2019 [32], and were cut from the same batch of steel using a wire cutting process. All specimens complied with the specified dimensional and quality requirements. The experimental procedure followed the guidelines of ISO 15609-1:2019 [33], and the tests were carried out using an electro-hydraulic servo fatigue testing machine, as shown in Fig. 2(a).

2.1.2. Column specimens and test setup

The axial compression tests included three types of steel column cross-sections, two of which were composite sections. The composite cross-sections consisted of one square hollow section nested within another square hollow section (SS), and one circular hollow section nested within a square hollow section (SC). The third type was a conventional square hollow section (S). For each section type, four identical specimens were fabricated using LAHW, resulting in a total of 12 test specimens. The section dimensions — including outer column diameter (d_1), outer column thickness (t_1), inner column diameter (d_2), inner column thickness (t_2), cross-sectional area (A), specimen length (L), and effective buckling length (L_{cr}) — are summarized in Table 1. Cross-sectional configurations and weld locations are illustrated in Fig. 1. The specimen labeling follows a consistent format, e.g., ‘SS-1’ denotes the first specimen of the SS column group.

Table 1
Geometric dimensions of the test specimens

Type	d_1 (mm)	d_2 (mm)	t_1 (mm)	t_2 (mm)	A (mm ²)	L (mm)	L_{cr} (mm)
SS	200	143	10	10	120.5	1200	1840
SC	200	178	10	10	124.4	1200	1840
S	200	/	10	/	76	1200	1840

Note : $L_{cr} = L + 640\text{mm}$

The loading setup is shown in Fig. 3(a). An electro-hydraulic 1500-ton testing machine was used to apply axial compressive loading, with a loading rate of 1 mm/min. Once the applied load dropped to 80% of the peak load, the test was terminated and the load was removed. A knife hinge as shown in Fig. 3(c) is arranged at each end of the test specimen, which allowed the in-plane rotation about one axis, with 320mm hinge offset per end.

Fig. 4 shows strain gauges positioned at three column heights (3L/8, L/2, 5L/8) and both ends. Composite-section columns required dual gauges straddling the mid-length weld seam, while square hollow sections used single gauges. LVDTs monitored deformations: DT1–DT2 (in-plane lateral), DT3 (out-of-plane), DT4–DT5 (axial), and DT6–DT9 (end rotations via knife hinges).

The deformation of the steel columns was monitored using 2D-DIC technology during the experiment as shown in Fig. 3(b). The surface of the steel column specimens without attached strain gauges was designated as the 2D-DIC measurement area. This surface received a uniform coat of matte white paint followed by the application of a black speckle pattern using hydro transfer printing to enable digital image correlation analysis.

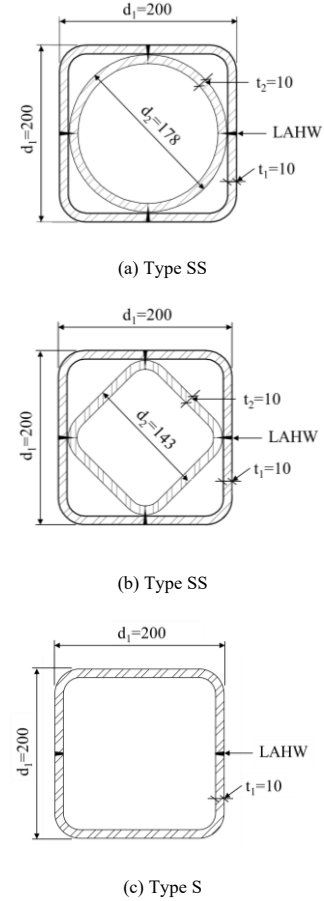


Fig. 1 Cross-sections of Steel Columns: Types SS, SC and S

2.1.3. Measurement of initial geometric imperfections

The initial geometric imperfections on both sides of the member along the weak axis direction were measured using a combination of vernier calipers, a spirit level, a plumb line, and the string-line method, following the approach proposed by Li[6], as illustrated in Fig. 5. A plumb line was first suspended from the end plate. The distances from the column surface to the plumb line were then measured at the top, bottom positions to define the virtual reference plane, as indicated by the blue dashed line in Fig. 5. The initial geometric imperfections were measured at the mid-height, 1/4, and 3/4 height positions along the column. At each location, measurement points were placed on two opposing faces of the column, spaced at 140 mm intervals. The deviations between the measured values and the ideal (imperfection-free) positions were calculated based on geometric relationships, yielding values denoted as Δv_{ai} , Δv_{bi} , Δv_{ci} and Δv_{di} , as shown in Fig. 5. The maximum value among Δv_1 , Δv_2 , and Δv_3 was taken as the initial geometric imperfection of the specimen, denoted as v_0 . The calculation formulas for Δv_1 , Δv_2 , and Δv_3 are shown in Eq. (1), and the results are summarized in the accompanying table.

$$\Delta v_i = (\Delta v_{ai} + \Delta v_{bi} + \Delta v_{ci} + \Delta v_{di})/4 \quad (1)$$

where $i = 1, 2, 3$.

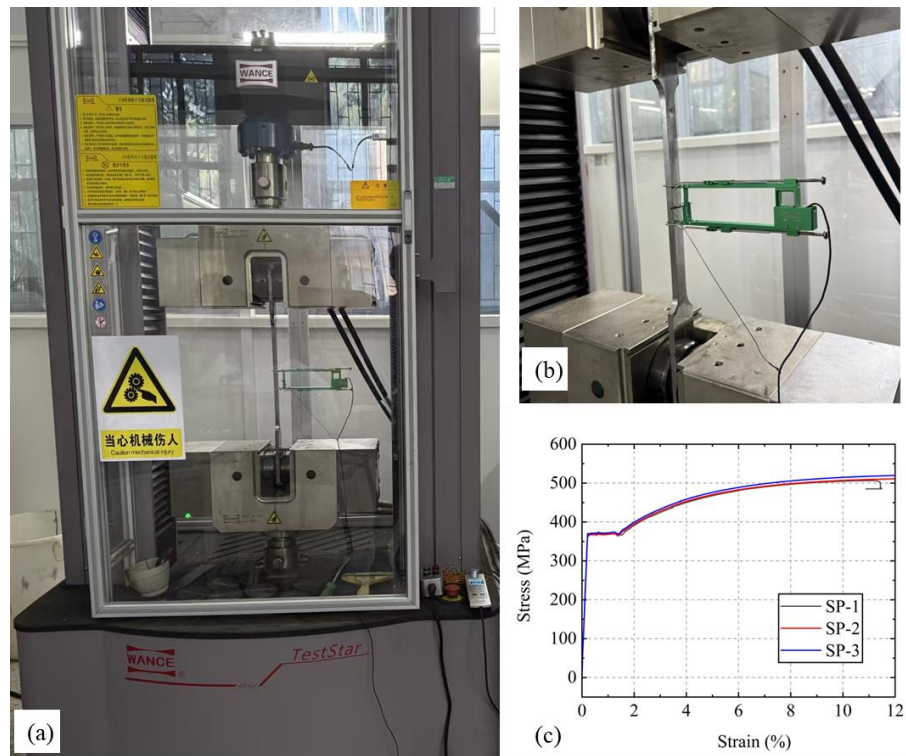


Fig. 2 Experimental setup of monotonic tension tests: (a) Test device; (b) The extensometer set up; (c) Stress-strain curve of monotonic tension tests;

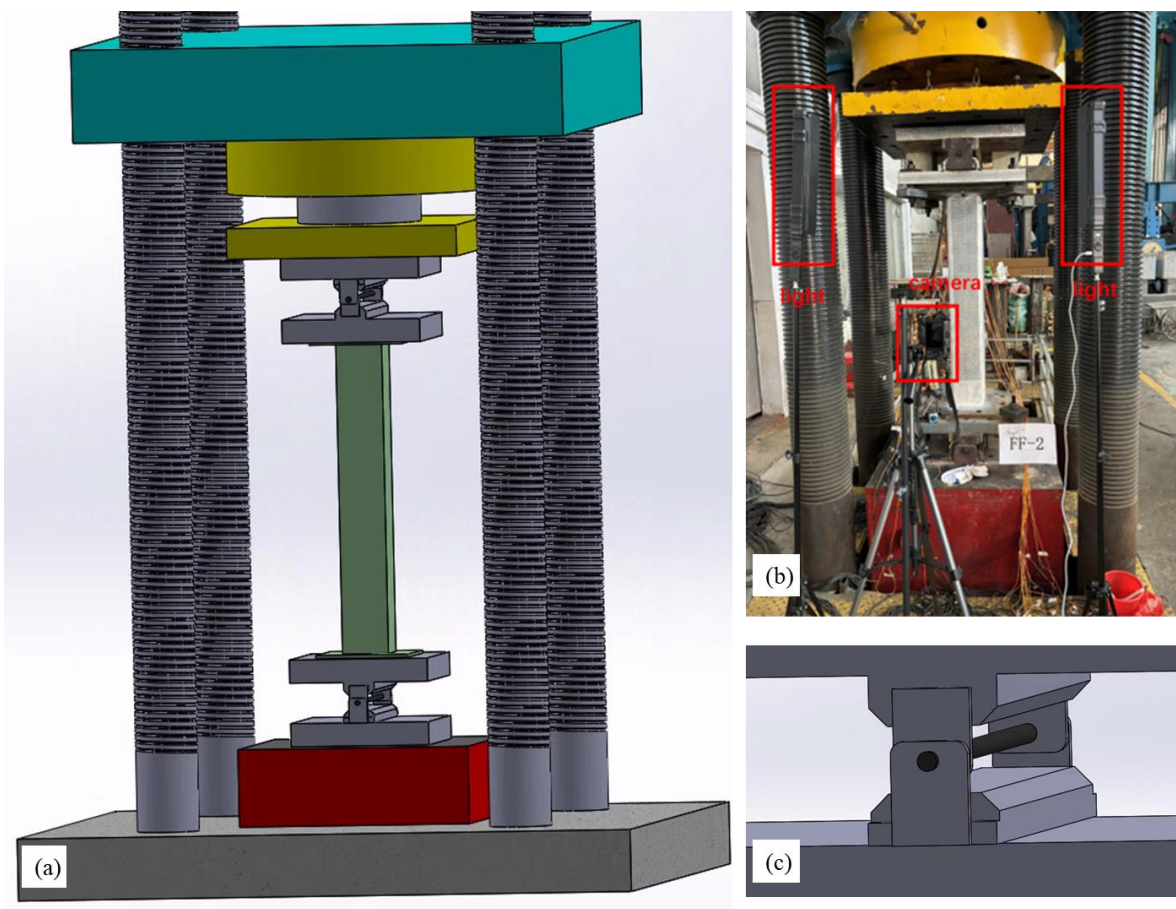


Fig. 3 Experimental setup of compressive test: (a) 1500 ton. loading machine; (b) 2D-DIC monitor; (c) Knife hinge

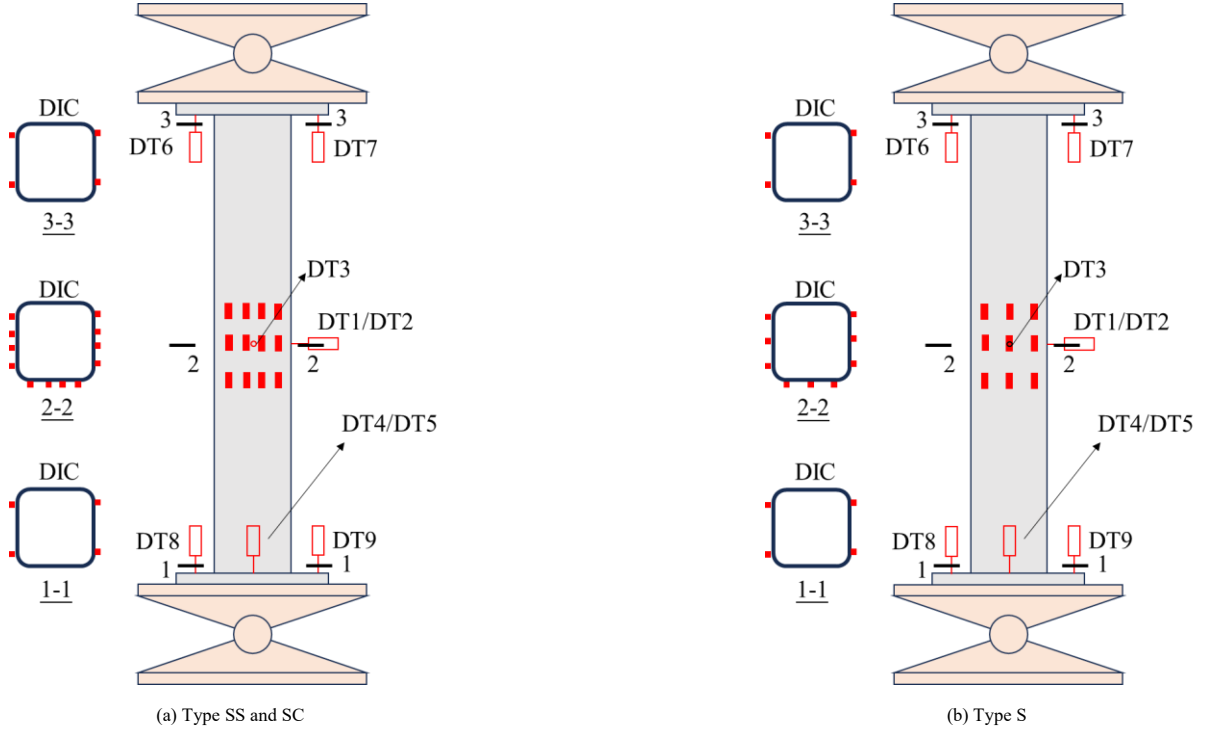


Fig. 4 Layout of measurement points for compressive members

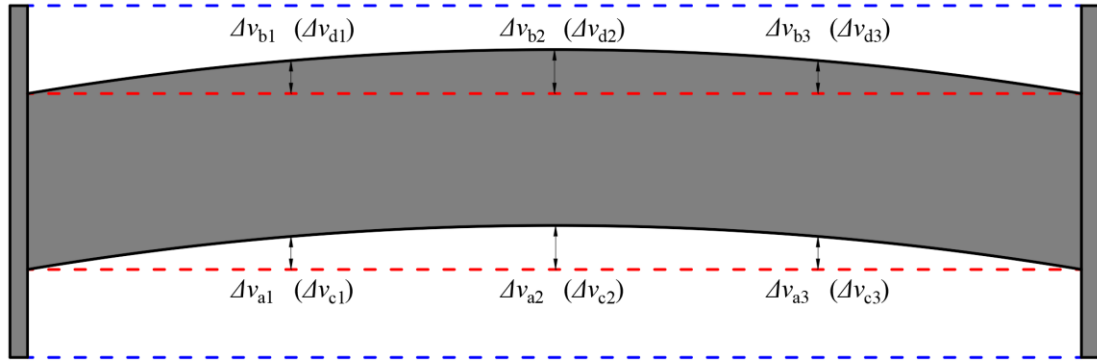


Fig. 5 Measurement procedure of initial geometric imperfections

The initial eccentricities at the top (e_{0t}) and bottom (e_{0b}) of the specimens were calculated retrospectively based on the strain gauge readings at the column ends and the applied axial load, following Eq. (2). To ensure that all specimens were subjected to elastic and stable axial compression, the readings corresponding to a vertical load of $0.15 N_u$ were used in the calculations, where N_u denotes the axial compressive strength of the specimen. The specific formulas for calculating the end eccentricities are provided below, and the results are summarized in Table 3.

$$e_0 = \frac{\varepsilon_1 + \varepsilon_2 - \varepsilon_3 - \varepsilon_4}{4} \cdot \frac{EW}{0.15N_u} \quad (2)$$

In Eq. (2), e_0 denotes the end eccentricity of the column; ε_1 to ε_4 represent the absolute values of the strains measured by the four strain gauges installed at the column end; E is the experimentally measured Young's modulus; W is the measured section modulus of the specimen; and N_u is the axial compressive strength of the specimen.

In summary, the equivalent initial geometric imperfection can be calculated using $e = v_0 + (e_{0b} + e_{0t})/2$, and the results are presented in Table 3.

2.2. Experimental results and discussion

2.2.1. Results of Monotonic tension test

Through monotonic tension tests on three standard material specimens, the stress-strain curves shown in Fig. 2(c) were obtained. The Young's modulus (E), yield strength (σ_y), ultimate tensile strength (σ_u), and elongation after fracture (δ) of the steel are summarized in Table 2. The results indicate that the yield strength (σ_y) of the S355J0-grade steel used in this study was measured to be 367.8 MPa, the ultimate tensile strength (σ_u) was measured to be 510.04 MPa, and the average elongation after fracture is 38.4%. These material properties were subsequently used in the numerical simulations and parameter analysis.

Table 2
Results of monotonic tension tests

Specimens	E (N/mm ²)	σ_y (MPa)	σ_u (MPa)	δ (%)
Sp-1	200399.06	369.04	506.28	36.4
Sp-2	204331.7	366.27	512.32	38.3
Sp-3	195757.38	368.07	511.53	40.2
Average	200162.71	367.8	510.04	38.4

Table 3
Initial geometric imperfections of test specimens

Specimen	Global geometric imperfections				Initial eccentricity		$e/L(\%)$
	Δv_1 (mm)	Δv_2 (mm)	Δv_3 (mm)	v_0 (mm)	e_{0b} (mm)	e_{0t} (mm)	
SS-1	0.114	0.18	0.1625	0.180	1.32×10^{-5}	-4.2×10^{-6}	0.150
SS-2	0.271	0.355	0.326	0.355	-1.1×10^{-6}	1.09×10^{-6}	0.296
SS-3	0.315	0.333	0.130	0.334	5.05×10^{-8}	3.41×10^{-6}	0.277
SS-4	0.294	0.248	0.260	0.294	-5.2×10^{-6}	-4.7×10^{-6}	0.294
SC-1	0.179	0.194	0.185	0.194	-2.2×10^{-5}	-7.2×10^{-6}	0.162
SC-2	0.245	0.189	0.326	0.326	-7.4×10^{-6}	-1.1×10^{-6}	0.272
SC-3	0.496	0.491	0.328	0.496	-4.6×10^{-6}	-4.2×10^{-6}	0.414
SC-4	0.180	0.166	0.21	0.210	-3.9×10^{-7}	-1.0×10^{-5}	0.175
S-1	0.341	0.331	0.261	0.341	-5.7×10^{-6}	/	0.2845
S-2	0.155	0.066	0.186	0.186	-6.6×10^{-7}	-2.8×10^{-6}	0.155
S-3	0.231	0.152	0.240	0.240	-1.7×10^{-6}	6.8×10^{-7}	0.200
S-4	0.131	0.228	0.224	0.228	-3.2×10^{-6}	-4.3×10^{-6}	0.190

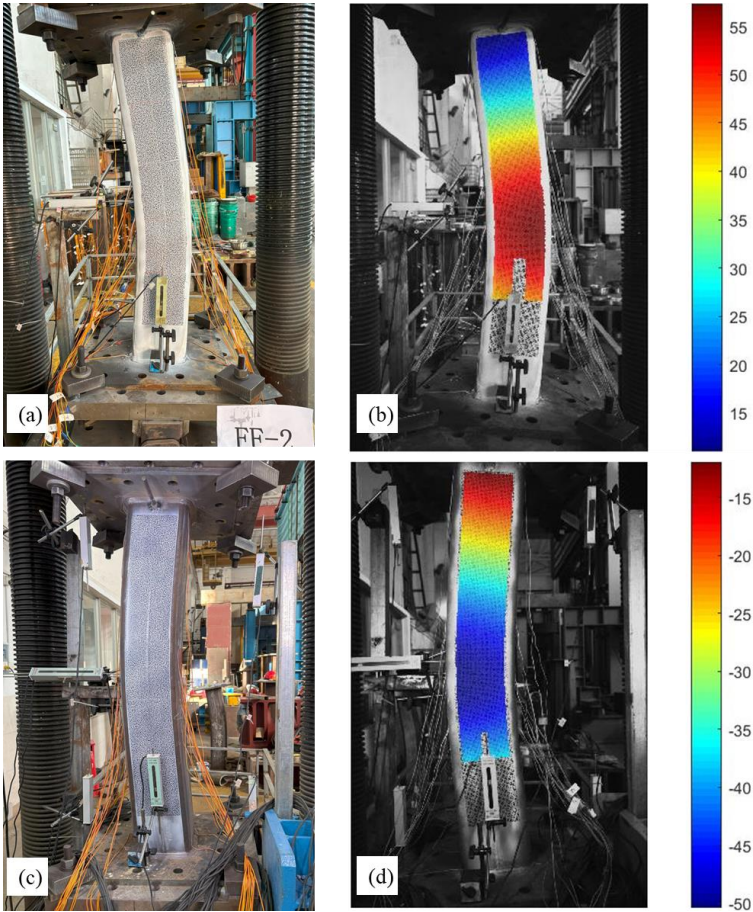


Fig. 6 Typical failure mode of SS/SC specimens and DIC results:(a) Failure mode of type SS; (b) DIC result of type SS; (c) Failure mode of type SC; (d) DIC result of type SC

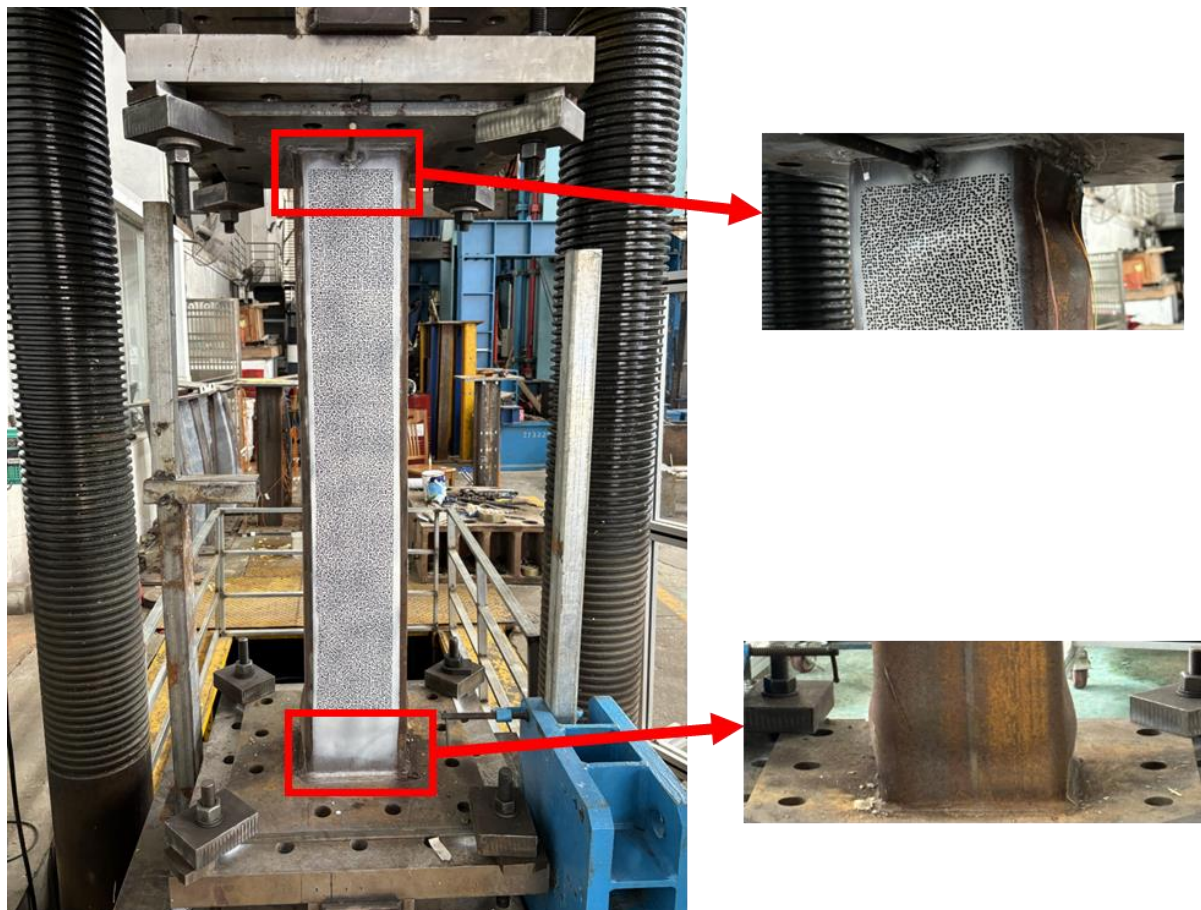


Fig. 7 Typical failure mode of type-S specimens

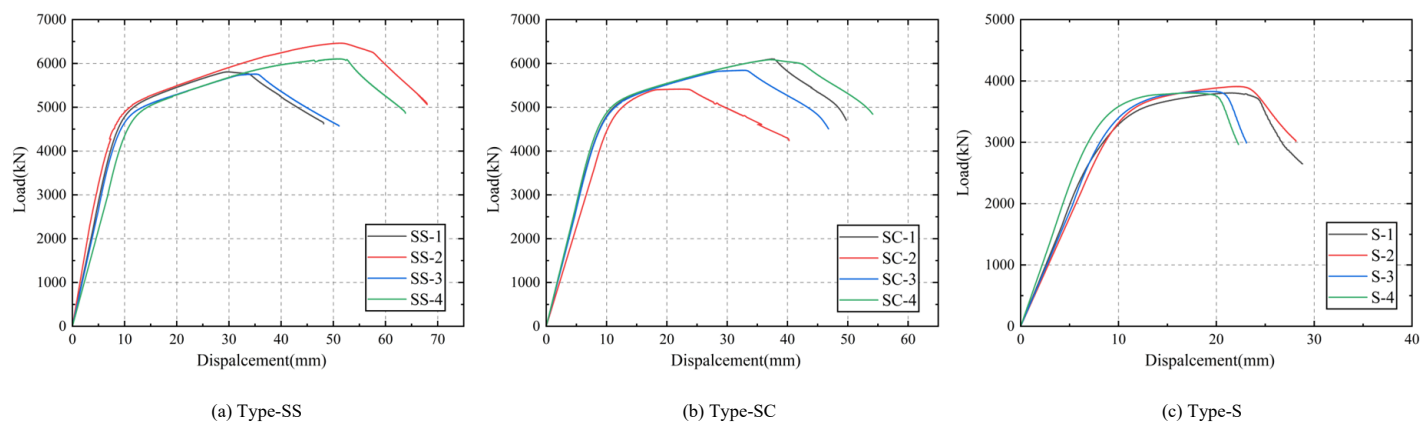


Fig. 8 Load-axial displacement curves from experimental tests

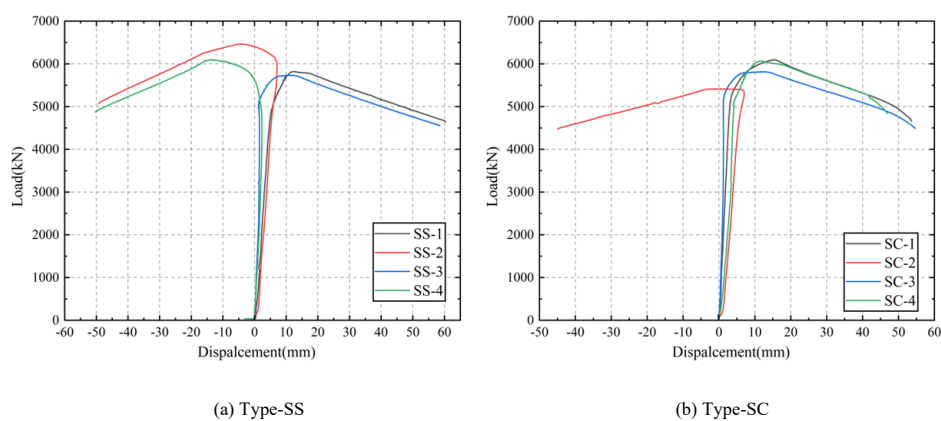


Fig. 9 Load-lateral displacement curves from experimental tests

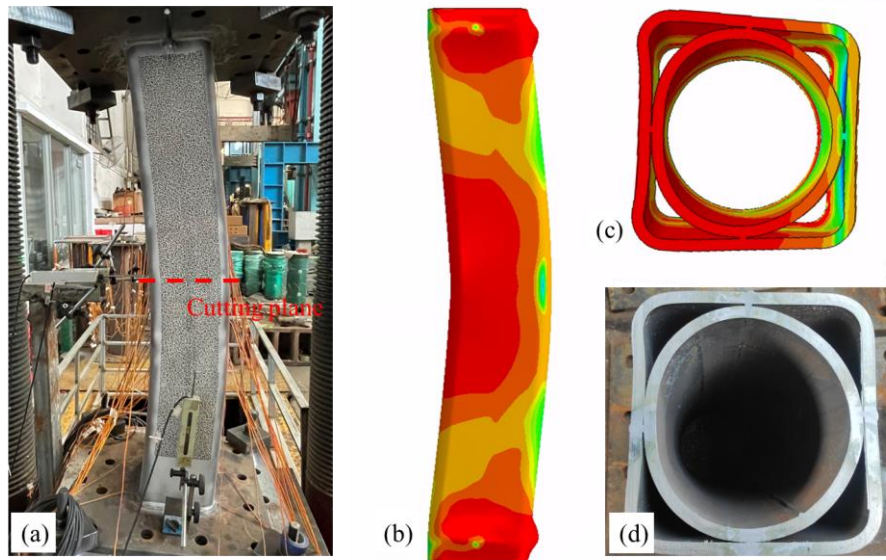


Fig. 10 Comparison of failure modes of type-SS column: experiment vs. FE simulation: (a) Experimental failure mode; (b) FE simulation – side view of displacement contour; (c) FE simulation – section view of displacement contour; (d) Cross-sectional deformation after test.

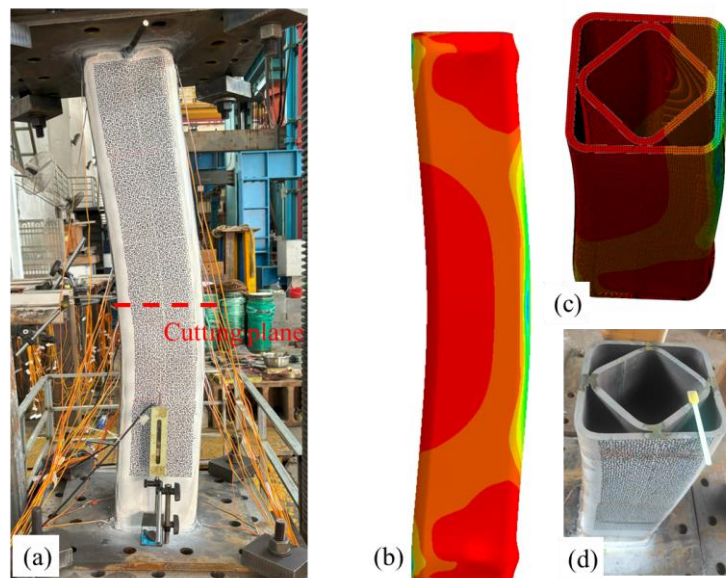


Fig. 11 Comparison of failure modes of type-SC column: experiment vs. FE simulation: (a) Experimental failure mode; (b) FE simulation – side view of displacement contour; (c) FE simulation – section view of displacement contour; (d) Cross-sectional deformation after test.

2.2.2.2. Results of axially compressive tests

The typical failure modes and in-plane deformation contours obtained via 2D-DIC are shown in **Fig. 6**, while the load–displacement curves for the type-SS and SC specimens are presented in **Fig. 8**. Specimens consistently exhibited three-phase responses: elastic stage, strain hardening, progressive softening, confirming material strength-dominated failure behavior.

At the initial stage of loading, all specimens exhibited an elastic load–displacement response, characterized by predominant axial compression and negligible cross-sectional deformation. As the load increased, lateral bending gradually developed in the type-SS/SC columns, accompanied by rotation at the rotational hinges. In contrast, local buckling at both loaded ends was observed in the type-S columns, as shown in **Fig. 7**. Moreover, the unloading slope K_{un} of the type-S columns was noticeably steeper than that of the type-SS/SC columns as shown in **Table 4**, indicating a more abrupt loss of strength. The failure modes are summarized in **Table 4**. It can be observed that all composite-section specimens exhibited global buckling as the primary failure mode, whereas the specimen without an inner tube experienced local buckling failure.

These observations suggest that the composite SS/SC columns effectively prevent premature local buckling and exhibit a slower strength degradation after peak load, maintaining a certain load-bearing capacity even under large deformations.

Fig. 9 presents the load–lateral displacement curves for the type-SS and type-SC columns. The lateral displacement initially exhibited a linear increase of approximately 5 mm before reaching the peak load. As global deformation developed, the lateral displacement abruptly increased in different directions, due to initial imperfections and variations in column placement orientation. At the point of unloading, the average lateral displacement reached 57.7 mm for the type-SS columns and 47.6 mm for the type-SC columns, indicating that both types of composite columns experienced significant global bending deformation during the failure process.

In addition, the post-failure cross-sectional deformation characteristics observed through wire-cutting are also presented. **Fig. 10** and **Fig. 11** compare the cross-sectional deformation patterns of type-SS and type-SC columns. It can be seen that the inner circular tube in the SC configuration experiences more significant deformation than that in the SS configuration. This observation is consistent with the load–displacement curves shown in **Fig. 8**, where the type-SS columns exhibit a longer ascending branch and an average ultimate load approximately 3% higher than that of the type-SC columns (6027.50 kN vs. 5847.86 kN). These results indicate that the square inner tube in the SS configuration provides more effective confinement and strengthening compared to the circular inner tube in the SC configuration.

Since the 2D-DIC system is limited to capture in-plane deformations, only

the DIC results for the type-SS and type-SC columns are reported, as shown in Fig. 6(b) and Fig. 6(d). These figures display the lateral displacement contour plots of two representative specimens, SS-2 and SC-1. It can be observed that

the deformation patterns are generally consistent with the load–lateral displacement curves presented in Fig. 9.

Table 4

Comparison of load-bearing capacities among experiment, FE Analysis and code-based calculations

Specimens	$N_{j,EXP}/kN$	$N_{u,EXP}/kN$	N_{EU}	N_{GB}	$N_{u,EXP}/kN$	$N_{u,FE}/kN$	$N_{u,EXP} / N_{u,FE}$	$N_{u,EXP} / N_{EU}$	$N_{u,EXP} / N_{GB}$	K_{int}	Failure mode
SS-1	4930.0	5817.37					1.01	1.34	1.38	25.19	G
SS-2	4954.1	6463.92	4326.79	4210.6	6027.50	5780.75	1.12	1.49	1.54	20.88	G
SS-3	4760.0	5734.40					0.99	1.33	1.36	23.59	G
SS-4	4870.8	6094.31					1.05	1.41	1.45	19.56	G
SC-1	4995.0	6095.84					1.03	1.37	1.41	28.43	G
SC-2	4866.9	5411.79	4439.20	4329.8	5847.86	5891.14	0.92	1.22	1.25	29.64	G
SC-3	4967.4	5816.91					0.99	1.31	1.34	29.02	G
SC-4	5061.0	6066.92					1.03	1.37	1.40	23.40	G
S-1	3311.0	3796.3						1.39	1.42	38.29	L
S-2	3501.0	3894.59	2725.40	2682.88	3823.98	/	/	1.43	1.45	31.36	L
S-3	3435.8	3814.65						1.40	1.42	36.46	L
S-4	3418.0	3790.39						1.39	1.41	37.09	L
Average							1.02	1.37	1.40		
Variance							0.003	0.004	0.004		

Note: “G” denotes global buckling and “L” denotes local buckling

2.2.3. Comparison of load-bearing capacity against design codes

A comparison between the experimental results and the resistances calculated according to EN 1993-1-1:2022 and GB 50017-2017 is presented in Table 4.

The axial load capacities in both design codes can be expressed using a reduction factor, with the calculation methods detailed as follows: First, the normalized slenderness ratio was calculated using Eq. (3) and (4), where L_{cr} is the effective length, i is the radius of gyration about the relevant axis, determined based on the properties of the gross cross-section; E is the elastic modulus, and f_y is the yield strength of the steel.

For EN 1993-1-1:2022, the reduction factor χ was computed using Eq. (5) and (6), where the imperfection factor α depends on the cross-section class.

$$\lambda_n = \frac{L_{cr}}{i} \frac{1}{\lambda_1} \quad (3)$$

$$\lambda_1 = \pi \sqrt{\frac{E}{f_y}} \quad (4)$$

$$\chi = \frac{1}{\Phi + \sqrt{\Phi^2 - \lambda_n^2}} \quad \text{but } \chi \leq 1.0 \quad (5)$$

$$\Phi = 0.5[1 + \alpha(\lambda_n - 0.2) + \lambda_n^2] \quad (6)$$

For GB 50017-2017, when the normalized slenderness $\lambda_n \leq 0.215$, the reduction factor χ is calculated using Equation (7); when $\lambda_n > 0.215$, χ is determined by Eq. (8). The coefficients α_1 , α_2 , and α_3 depend on the cross-section type.

$$\chi = 1 - \alpha_1 \lambda_n^2 \quad (7)$$

$$\chi = \frac{1}{2\lambda_n^2} [(\alpha_2 + \alpha_3 \lambda_n + \lambda_n^2) - \sqrt{(\alpha_2 + \alpha_3 \lambda_n + \lambda_n^2)^2 - 4\lambda_n^2}] \quad (8)$$

According to the EN 1993-1-1 classification, type-SS and type-SC columns were compared with cross-section class a_0 , while type-S columns were classified as class a . Accordingly, in Eq. (6), the imperfection factor α was taken as 0.13 for curve a_0 and 0.21 for curve a . In contrast, under the GB 50017-2017 specification, all column types were compared with cross-section class a . Based on the Chinese code, the coefficients α_1 , α_2 , and α_3 used in Eq. (7) and (8) were taken as 0.41, 0.986, and 0.152, respectively.

It can be observed that the design resistances specified by both the Eurocode and the Chinese code are significantly lower than the experimental results.

This discrepancy can be primarily attributed to the higher manufacturing precision achieved through laser welding. As shown in Table 3, the maximum measured initial geometric imperfection is 0.41%, whereas GB 50017-2017 recommends a geometric imperfection of 1/1000, and EN 1993-1-1:2022 suggests an equivalent imperfection in the range of 1/150 to 1/100. The lower initial geometric imperfection allows the member to reach the yield stress before significant instability occurs, enabling the material to enter the strain hardening stage. As a result, the stress continues to increase beyond yielding, leading to an ultimate strength higher than the nominal yield capacity.

3. Numerical study

To further investigate the axial compression behavior of the laser-welded composite columns (type-SS and type-SC), numerical simulations and parametric analysis were conducted. A finite element (FE) model was developed using the commercial software ABAQUS. The model was calibrated and validated against the experimental results described earlier.

The FE model incorporates the measured initial geometric imperfections reported in Section 2.1.3, and adopts the same boundary conditions and loading scheme as used in the experiment study.

After validating the FE model, a series of parametric analyses were performed to study the influence of slenderness on axial load capacity by varying the effective length of the columns. For each case, both a first-order linear elastic buckling analysis and a nonlinear static analysis with initial imperfections were carried out.

Initial geometric imperfections were introduced into the model by modifying the ABAQUS input keywords.

3.1. Material properties, element type and boundary conditions

In the finite element model, the steel was modeled using the classical metal plasticity model with isotropic hardening, and the material parameters were derived from the aforementioned tensile test results. Eight-node linear brick elements with reduced integration (C3D8R) were employed for the mesh discretization. To accurately capture the local buckling and bending behavior of the plate elements under axial compression, the global mesh size was refined to 3 mm, corresponding to three elements through the plate thickness.

Since the column ends were welded to end plates in the experiments, and the end plates were fitted to the knife-edge supports, the same boundary condition was replicated in the FE model. All nodes on the end cross-sections were coupled to reference points located 0.32 m away from the end face

centroids, representing the distance between the knife hinge rotation center and the support plane. All degrees of freedom at the reference points were constrained except for the rotation about a single axis and the axial translation (Z-direction) at one of the reference points. The finite element models of both type-SS and type-SC columns are shown in **Fig. 12**.

The axial load was applied via displacement-controlled loading, enabling precise determination of both the peak load and post-peak behavior. The load-displacement curves were obtained by extracting the reaction force and displacement at the reference points.

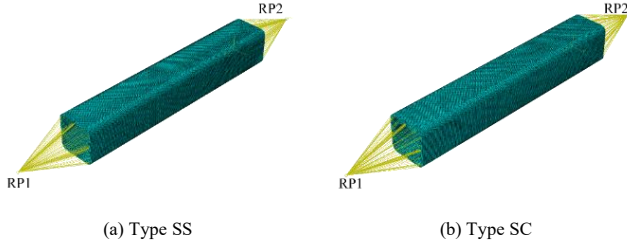


Fig. 12 Finite element model of columns

3.2. Initial geometric imperfections

During the application of initial geometric imperfections in the validation of the finite element model, the imperfection amplitude was set equal to the maximum measured value for each specimen group, as reported in Section 2.1.3. The imperfection shape was taken as the lowest-order global buckling mode obtained from linear elastic buckling analysis. Specifically, the buckling mode shape was imported into the nonlinear axial compression model via the ABAQUS input file, and the imperfection amplitude was scaled according to the effective length of each column. For the type-SS columns, the applied imperfection amplitude was 0.30‰, while for the type-SC columns, it was 0.41‰.

In the subsequent parametric analysis, in order to evaluate and compare the performance of laser-welded composite columns with existing design codes, the imperfection amplitude was uniformly set to $L/1000$, where L is the effective length of the column, as recommended by GB 50017-2017. The imperfection shape followed the first global buckling mode derived from linear buckling analysis.

3.3. Validation of finite element model

Table 5
Parametric analysis results for type SS and SC with different slenderness

Section type	L/mm	$\bar{\lambda}$	$N_{u,FEA}/\text{kN}$	γ_{FEA}	$\gamma_{EU,a0}$	$\gamma_{GB,a}$	$\gamma_{FEA}/\gamma_{EU,a0}$	$\gamma_{FEA}/\gamma_{GB,a}$
SS	1200	0.39	4326.79	0.976	0.972	0.950	1.00	1.03
	1800	0.51	4211.96	0.951	0.948	0.922	1.00	1.03
	2400	0.64	4109.63	0.927	0.916	0.884	1.01	1.05
	3000	0.77	3901.69	0.880	0.869	0.833	1.01	1.06
	3600	0.89	3530.78	0.797	0.801	0.763	1.00	1.04
	4200	1.02	3062.11	0.691	0.711	0.678	0.97	1.02
	4800	1.15	2495.64	0.563	0.613	0.588	0.92	0.96
	5400	1.27	2259.88	0.510	0.523	0.505	0.97	1.01
	6000	1.40	1997.22	0.451	0.447	0.433	1.01	1.04
	6600	1.52	1726.60	0.390	0.384	0.374	1.02	1.04
SC	1200	0.38	4495.90	0.989	0.974	0.952	1.02	1.04
	1800	0.50	4357.25	0.958	0.951	0.925	1.01	1.04
	2400	0.62	4243.88	0.933	0.921	0.891	1.01	1.05
	3000	0.75	4050.00	0.891	0.879	0.843	1.01	1.06
	3600	0.87	3898.51	0.857	0.816	0.778	1.05	1.10
	4200	0.99	3426.81	0.754	0.732	0.697	1.03	1.08
	4800	1.11	3037.17	0.668	0.637	0.610	1.05	1.10
	5400	1.24	2486.05	0.547	0.547	0.527	1.00	1.04
	6000	1.36	2207.07	0.485	0.469	0.455	1.03	1.07
	6600	1.48	1881.46	0.414	0.404	0.393	1.02	1.05
Average							1.01	1.04

Table 4 presents the results of the finite element (FE) analysis in terms of axial resistance, showing a maximum error of 12% for the type-SS columns and 8% for the type-SC columns. The average error across all specimens is approximately 2%, indicating good agreement in predicting the bearing capacity.

Fig. 10 and **Fig. 11** compare the deformation patterns of typical type-SS and type-SC columns observed in the experiments and those predicted by the finite element (FE) model.

The results demonstrate that the FE model successfully reproduces the global deformation behavior of the columns, as well as the local buckling of the outer wall plates (**Fig. 10a, b**), and the deformation of the inner steel tube (**Fig. 10c, d**). These findings confirm that the FE model is capable of accurately capturing the key deformation and failure mechanisms under axial loading of laser-welded composite columns.

3.4. Parametric study

To assist engineers in selecting appropriate design curves for the effective use of laser-welded composite columns, a series of axial compression simulations were conducted using the validated finite element (FE) model to investigate the performance of composite columns with varying slenderness ratios.

The actual column lengths ranged from 1200 mm to 6600 mm, at intervals of 600 mm. For each length, a finite element (FE) analysis was conducted to determine the ultimate axial load capacity, with the initial imperfection amplitude set to $L/1000$. Based on the results, the reduction factor (defined as the ratio of the ultimate load to the yield load) was calculated. The corresponding normalized slenderness ratios were determined using the section moment of inertia, radius of gyration, and effective length.

The results were compared with the design curves specified in EN 1993-1-1:2022 and GB 50017-2017, as shown in **Fig. 13** and **Fig. 14**. It is observed that, under EN 1993-1-1:2022, the ultimate axial capacities of type-SS columns closely align with the resistance curve for cross-section class a_0 , while those of type-SC columns slightly exceed this curve. In contrast, under GB 50017-2017, the ultimate strengths of both type-SS and type-SC columns are consistently higher than the class a design curve.

Table 5 summarizes the selected column lengths, the calculated normalized slenderness ratios, and the corresponding reduction factors. It also presents the detailed results of the parametric analysis, including a comparison between the reduction factors obtained from finite element simulations and those predicted by the design codes. It is evident that both design codes provide conservative estimates compared to the FE results, with EN 1993-1-1:2022 showing closer agreement than GB 50017-2017.

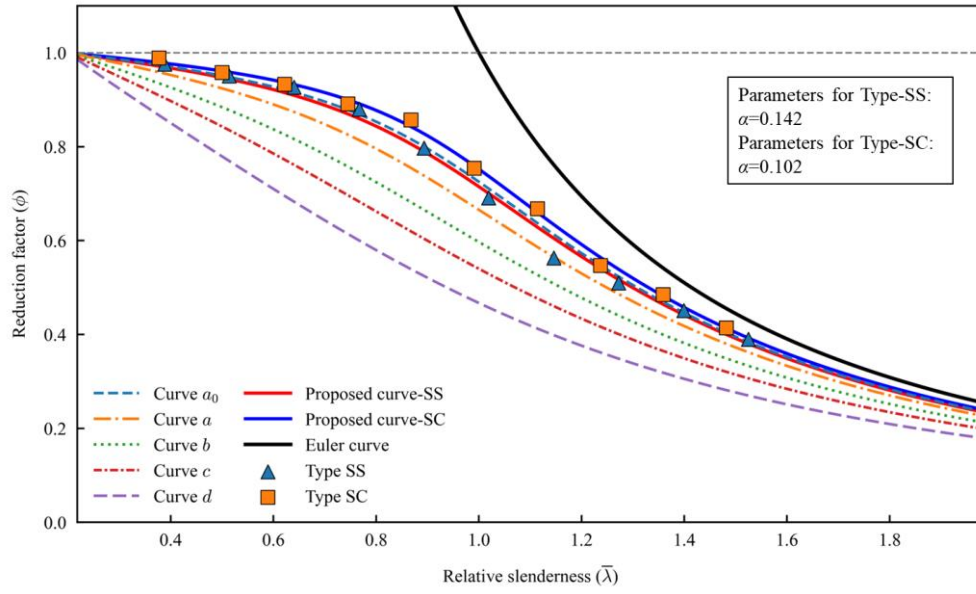


Fig. 13 Comparison of reduction factor between FE results and EN 1993-1-1:2022

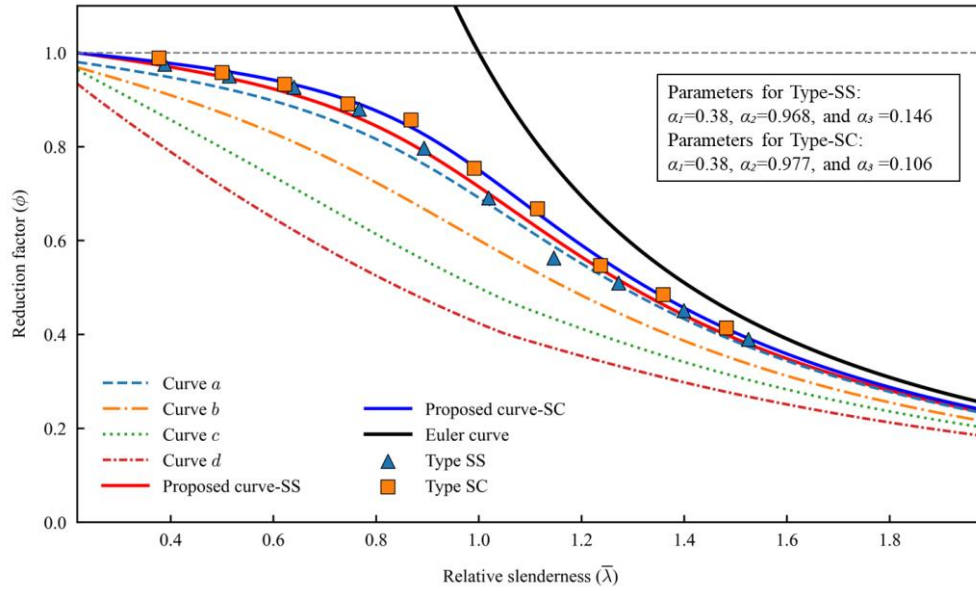


Fig. 14 Comparison of reduction factor between FE results and GB 50017-2017

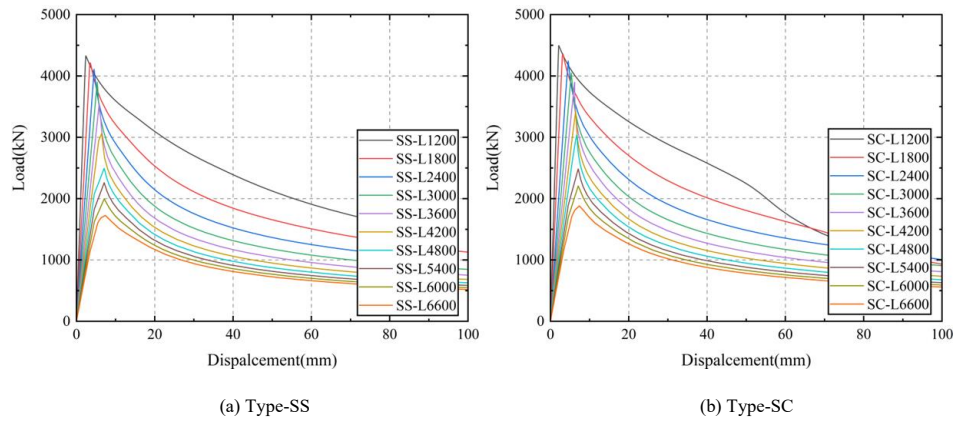


Fig. 15 Load-displacement curves with different lengths

As both design codes exhibit varying degrees of conservatism in predicting the bearing capacities of the two composite cross-sections, a regression analysis was conducted to minimize the error (in terms of R-squared) with respect to the

parametric FE results. Based on this analysis, the following optimized parameters were obtained:

For the calculation method proposed in EN 1993-1-1:2022 (Eq. 5-6), the

recommended imperfection factor α is 0.142 for type-SS columns and 0.102 for type-SC columns. For the calculation method specified in GB 50017-2017 (Eq. 7-8), the recommended values of α_1 , α_2 , and α_3 for type-SS columns are 0.38, 0.968, and 0.146, respectively; for type-SC columns, the corresponding values are 0.38, 0.977, and 0.106. The curves of regression fitting results are also illustrated in Fig. 13 and Fig. 14.

Fig. 15 presents the load–displacement curves obtained from FE analysis for type-SS and type-SC columns with various lengths. As the column length increases, the ultimate load capacity gradually decreases, while the displacement corresponding to the peak load increases.

Notably, under the assumption of an initial imperfection amplitude of $L_{cr}/1000$, the type-SC columns exhibit higher ultimate strengths than the type-SS columns at the same length. This trend is in contrast to the results obtained from simulations using the measured imperfections, as well as from the experimental tests. This discrepancy may indicate that the square-in-square (type-SS) composite configuration is more sensitive to global imperfections. Further investigation into this behavior is therefore recommended.

4. Conclusions

This study conducted experimental investigations and numerical simulations to evaluate the compressive behavior of LAHW tube-in-tube composite steel columns made from S355J0 steel. Key conclusions from this research are summarized as follows:

- (1) Both composite column types (square-in-square and circular-in-square) demonstrated superior post-peak behavior compared to the traditional single square hollow section columns, effectively preventing premature local buckling and exhibiting gradual strength degradation after peak load.
- (2) Composite columns fabricated by LAHW exhibited minimal initial imperfections, significantly lower than the values recommended by

current design standards, thereby achieving higher precision and improved axial load performance.

- (3) Finite element models validated by the experiments accurately predicted the ultimate loads and failure modes, including global and local deformation behavior, confirming their suitability for structural analysis and design applications.
- (4) The parametric analysis showed that the normalized slenderness significantly affects the ultimate strength of composite columns. Both the EN 1993-1-1:2022 and GB 50017-2017 standards provided conservative predictions compared to experimental and numerical results, with EN 1993-1-1:2022 offering slightly better agreement.
- (5) Under a uniform initial imperfection amplitude assumption ($L/1000$), numerical simulations indicated that circular-in-square (SC) columns exhibited marginally higher ultimate strengths than square-in-square (SS) columns for identical lengths. This finding contrasts with the experimental outcomes and highlights the potential sensitivity of SS configurations to global imperfections, warranting further investigation.

In summary, this study suggests that the class a_0 curve from EN 1993-1-1:2022 or the class a curve from GB 50017-2017 can serve as suitable design curves, balancing safety and structural economy for LAHW composite steel columns.

Acknowledgements

This work was supported by grants from the Basic and Applied Basic Research Foundation of Guangdong Province (Grant No. 2025A1515010443). The authors also gratefully acknowledge Peak Kong Special Steel Company Limited for providing the experimental materials and conducting the welding procedures.

References

- [1] Ferdous, W., Y. Bai, T. D. Ngo, A. Manalo, and P. Mendis, “New advancements, challenges and opportunities of multi-storey modular buildings – a state-of-the-art review”, *Engineering Structures*, 183, 883–893, 2019.
- [2] Boyd, N., M. M. A. Khalfan, and T. Maqsood, “Off-site construction of apartment buildings”, *Journal of Architectural Engineering*, 19, 51–57, 2013.
- [3] Wang, J., S. Afshan, N. Schillo, M. Theofanous, M. Feldmann, and L. Gardner, “Material properties and compressive local buckling response of high strength steel square and rectangular hollow sections”, *Engineering Structures*, 130, 297–315, 2017.
- [4] Ma, J.-L., T.-M. Chan, and B. Young, “Tests on high-strength steel hollow sections: A review”, *Proceedings of the Institution of Civil Engineers - Structures and Buildings*, 170, 621–630, 2017.
- [5] Yang, L., F. Yin, J. Wang, A. Bilal, A. H. Ahmed, and M. Lin, “Local buckling resistances of cold-formed high-strength steel SHS and RHS with varying corner radius”, *Thin-Walled Structures*, 172, 2022.
- [6] Li, B., Y. Wang, X. Zhi, Y. Zhang, and C. C. Baniotopoulos, “Testing, modelling and design of 7A04-T6 high-strength aluminium alloy RHS columns under axial compression”, *Journal of Building Engineering*, 57, 104910, 2022.
- [7] Zhu, Y., Z. Yang, S. Su, Y. Chen, M. Zhang, and G.-Q. Li, “Cross-sectional behaviour and design of hot-rolled carbon steel circular hollow section beams under moment gradients”, *Thin-Walled Structures*, 215, 113454, 2025.
- [8] Lin, Y.-J., K.-Q. Liu, T.-J. Li, and Y. Zhou, “Numerical study and design method of high strength steel welded box columns”, *Advanced Steel Construction*, 17, 127–135, 2021.
- [9] Yan, J.-B., B. Zhang, J.-Y. Feng, Y.-S. Du, Y.-B. Luo, and Y.-D. Shi, “Low-temperature compression behaviour of circular stub stainless-steel tubular columns”, *Advanced Steel Construction*, 18, 670–678, 2022.
- [10] Meng, X., S. Whitfield, S. Boudjabeur, and L. Gardner, “Stability of hot-finished and cold-formed steel hollow section columns: A comparative study”, *Structures*, 68, 107192, 2024.
- [11] Wang, Y., A. Su, H. Yang, J. Zhao, and Y. Wang, “S890 hot-rolled ultra-high strength steel (UHSS) seamless circular hollow section beam-columns: Testing, modelling and design”, *Thin-Walled Structures*, 197, 111583, 2024.
- [12] Wang, Y., H. Yang, Y. Wang, and A. Su, “Testing, numerical modelling and design of S890 and S960 ultra-high strength steel circular hollow sections under combined loading”, *Thin-Walled Structures*, 192, 111102, 2023.
- [13] Yin, F., J. Wang, L. Yang, N. Kang, and F. Elliott, “Testing and design of cold-formed high strength steel square hollow section columns”, *Journal of Constructional Steel Research*, 213, 108394, 2024.
- [14] Li, Y.-C., Y. Lu, A.-H. Han, W.-H. Li, X.-W. Wang, and Z.-L. Wu, “Local buckling mechanism of cold-formed steel built-up columns: Experimental and numerical investigation”, *Advanced Steel Construction*, 21, 218–230, 2025.
- [15] Zhao, J., Y. Peng, H.-X. Li, X.-X. Zhang, and J. Dong, “Structural properties of cold-formed thin-walled rectangular high-strength stainless-steel spliced tubular columns under axial compression and compression-bending”, *Advanced Steel Construction*, 21, 182–193, 2025.
- [16] Yin, F., X. Li, C. Chen, L. Zhao, Y. Peng, and Z. Tian, “Microstructure and mechanical properties of weld metal in laser and gas metal arc hybrid welding of 440-MPa-grade high-strength steel”, *Journal of Iron and Steel Research International*, 28, 853–861, 2021.
- [17] Zhang, M., Z. Zhang, K. Tang, C. Mao, Y. Hu, and G. Chen, “Analysis of mechanisms of underfill in full penetration laser welding of thick stainless steel with a 10 kW fiber laser”, *Optics & Laser Technology*, 98, 97–105, 2018.
- [18] Yan, R.-Z., C.-L. Zhang, S. Wang, J.-Q. Liu, and T. Sun, “Distribution of residual stress in the sphere-pipe connection welds of welded hollow spherical joints”, *Advanced Steel Construction*, 19, 262–272, 2023.
- [19] Wang, J.-X., X.-G. Shi, Z.-L. Liu, T. Ding, Q.-Z. Xiang, and Z.-H. Huang, “STUDY ON FRACTURE BEHAVIOR OF CHS-X JOINTS WITH WELD DEFECTS”, *Advanced Steel Construction*, 21, 253–264, 2025.
- [20] Liu, X.-Y., Y.-Q. Wang, Y.-D. Bu, and Y. Guan, “Study on micromechanical fracture models of structural steel and its welds”, *Advanced Steel Construction*, 17, 104–126, 2021.
- [21] Jie, Z.-Y., W.-J. Wang, P. Zhuge, Y.-D. Li, and X. Wei, “Fatigue properties of inclined cruciform welded joints with artificial pits”, *Advanced Steel Construction*, 17, 20–27, 2021.
- [22] Sokolov, M., A. Salminen, V. Somonov, and A. F. H. Kaplan, “Laser welding of structural steels: Influence of the edge roughness level”, *Optics & Laser Technology*, 44, 2064–2071, 2012.
- [23] Sokolov, M., A. Salminen, M. Kuznetsov, and I. Tsubilskiy, “Laser welding and weld hardness analysis of thick section S355 structural steel”, *Materials & Design*, 32, 5127–5131, 2011.
- [24] Zhong, Y., Y. Liang, and O. Zhao, “Membrane residual stresses and compressive behaviour of laser-welded stainless steel T-sections”, *Thin-Walled Structures*, 189, 110741, 2023.
- [25] Yang, S., D. Wang, L. Yang, F. Zhang, C. Zhang, B. Zhou, C. Liu, and G. Huang, “Effects of laser-arc hybrid welding on microstructure and mechanical properties of dissimilar steel joint”, *Optik*, 268, 169795, 2022.
- [26] Zhang, C., M. Gao, and X. Zeng, “Influences of synergy effect between laser and arc on laser-arc hybrid welding of aluminum alloys”, *Optics & Laser Technology*, 120, 105766, 2019.
- [27] Hu, B. and G. Den Ouden, “Synergetic effects of hybrid laser/arc welding”, *Science and Technology of Welding and Joining*, 10, 427–431, 2005.
- [28] Hu, B. and G. Den Ouden, “Laser induced stabilisation of the welding arc”, *Science and Technology of Welding and Joining*, 10, 76–81, 2005.
- [29] Sokolov, M. and A. Salminen, “Experimental investigation of the influence of edge morphology in high power fiber laser welding”, *Physics Procedia*, 39, 33–42, 2012.
- [30] Design standard for steel structures: GB50017-2017, Beijing: China Construction Industry Press, Beijing, 2017.
- [31] Eurocode 3. Design of steel structures. Part 1-1, general rules and rules for buildings, British Standards Institution, London, 2023.
- [32] Metallic materials — Tensile testing — Part 1: Method of test at room temperature, the International Organization for Standardization, Geneva, Switzerland, 2019.
- [33] Specification and qualification of welding procedures for metallic materials — Welding procedure specification — Part 1: Arc welding, International Organization for Standardization, Geneva, Switzerland, 2019.