Research Article

Bearing Capacity of Light-Steel Compound Section and Steel Columns under Axial Compression

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In the international trend of vigorously developing low-carbon economy and green buildings, environmental protection and conservation have received increased attention in the construction field. Light steel, as an environmental protection material, has gradually become a key direction in the architectural field. The axially compressed columns forming the wall skeleton in the light steel structure usually adopt two cross-sectional forms, namely, cold-formed thin-walled steel built-up cross-section and independent profiled steel cross-section. The cold-formed thin-walled steel cross-section is divided by the splitting method into two types, namely, open type and closed type. This paper analyzes two cold-formed thin-walled steel composite sections and independent section columns. The theoretical calculation, experimental test, and finite element simulation were used, and the multidimensional calculation results were compared to obtain the mechanical properties of axial compression columns. Based on the comparison between the experimental results and the calculation results, it is found that the specification is conservative. The experimental results show that it is more flexible to use composite cross-section columns in the middle of the light steel skeleton; steel columns in the corner of the frame are more conducive to the structure’s overall stability.

1. Introduction

A light steel structure system has the advantages of low construction pollution, recyclable materials, and good seismic performance, which is in line with the green building and sustainable development strategy. The light steel keel system is lightweight, has high strength, and is used for new buildings and reconstruction. When used for addition, special treatment on the original structure and its foundation is unnecessary [1].

Many experts and scholars have carried out specific research on split members in recent years to study the bearing performance of light steel split columns. They have developed a light steel building system, mainly analyzing the bearing capacity influencing factors and calculation methods. LaBoube and Stone [2] conducted axial compression test research on I-shaped split-section split-columns connected by screws, using spherical hinge bearings. The research showed that American Iron and Steel Institute norms have smaller calculated values for thicker members. Young and Chen [3] carried out the theoretical calculation and experimental study on axial compression of two high-strength cold-formed thin-walled steel web ribbed composite columns. The comparison of the calculation results of national codes with the experimental results shows that the direct strength method can more reasonably calculate the bearing capacity of composite members. Peters [4] studied the screw spacing of the double-limbed box column. In a specific range, the larger screw spacing indicates a smaller initial bending moment at the end of the column and greater ultimate bearing capacity. Zhou et al. [5] presented a new analytical approach to establish a computing method for the flexural buckling bearing capacity of the CFS built-up back-to-back section column. In addition, shear panels are employed at the location of screws to consider the discrete shear deformation restraint effect. The study of Dar et al. [6, 7] was performed on CFS built-up battened columns under axial compression. By changing the thickness and
height of the channel of the composite column, the behavior change of the composite column caused by these changes is studied. Anbarasu and Darb [8] studied the axial capacity and the nonlinear deformation response of pin-ended CFS built-up. In the study of Waheed et al. [9], experimental and numerical investigations were focused on the seismic performance of CFS columns. A full-scale built-up battened column was subjected to quasi-static cyclic loading, and its response was recorded. Columns under axial loading were applied concentrically. In this paper, new design equations for the reliable design strength predictions of the CFS built-up column component of lipped channels with spacers were proposed. Sun et al. [10] studied the mechanical performance and design method of cold-formed rectangular steel columns with thick walls. The study found that indirect cold-formed rectangular steel columns have lower cold-formed effects than direct cold-formed rectangular steel columns. Chen et al. [11] experiment on back-to-back channels with edge-stiffened holes to understand the effects of composite actions between the CFS back-to-back channels on the axial strength of such channels. The test results show that for the case of back-to-back channels with edge-stiffened holes, the axial strength increased by 6.6% on average. Anbarasu and Venkatesan [12] studied the effects of the plate slenderness, member slenderness, chord slenderness, and slenderness of batten plates on the compression behavior and strength of cold-formed steel composite slab box columns. Test results including the compression resistances, the load versus displacement responses, and the deformed shapes were presented.

Based on the design scheme of the actual layering project, the two cold-formed thin-walled steel segmented columns and the corresponding steel axial compression columns of the main load-bearing components in the light steel keel system are studied, and a reference for enterprise engineering applications is provided.

2. Experimental Research

According to the standard engineering practice provided by the enterprise, the four-limb open composite column (4C type), four-limb closed composite column (CU type), and special-shaped steel column (ZF type and CF type) composed of C and U single limbs are designed. The 4C type corresponds to the same rotational inertia as CF type, CU type, and ZF type. The material is Q235 cold-formed thin-walled steel, according to the engineering structure practice. The finite element analysis model has the same size as the test specimen, which is a 1:3 scale specimen. The single-leg U-shaped steel is U170 × 70 × 1 mm; the C-shaped steel is C160 × 60 × 2 × 1 mm; and the column height is 1.2 m, according to the requirements of specification for cold-formed thin-walled steel [13, 14]. For the cross-section column, the screw spacing along the longitudinal direction of the component is 300 mm, and screws are encrypted within 300 mm at both ends of the column, with a spacing of 100 mm. The end plate is 360 × 280 × 3 mm.

To further study the axial compression performance of light steel built-up column and profiled steel column, 4 groups of 12 scaled specimens were fabricated and tested. The working conditions of the specimens are shown in Table 1.

2.1. Test Design

2.1.1. Test Specimens. Fabrication of built-up section column specimens: U- and C-shaped steels are used in the built-up section of this test. M4.8 × 19 self-tapping screws connect the built-up section. To uniformly transmit force at the loading end of the specimen, the upper and lower welded end plates are strengthened (as shown in the theoretical section of the specific design) [15, 16].

Fabrication of the profiled steel section column specimen: the profiled steel section column is welded after cutting the steel plate.

2.1.2. Measuring Point Position. In this experiment, displacement gauges were arranged on each specimen, and the arrangement positions of all specimens were the same. Two displacement gauges were arranged on the upper surface of the upper end plate of the column, and two displacement gauges were arranged on the upper surface of the lower end plate of the column [17]. The specific arrangement positions are shown in Figure 1. Different orientation marks are attached on the four sides of the specimen to determine its deformation and failure direction. The location diagram is shown in Figure 2.

2.2. Test Procedures

2.2.1. Material Properties Test. Cold-formed thin-walled steel and square steel sections are made of Q235 steel. Considering that the steel of the assembled column is relatively thin, the steel performance test is carried out on the profile used for cold-formed thin-walled steel with a thickness of 1 mm, number 5. The specimens of the steel performance test are made according to the "metal material-tensile test method" (GB/T228-2010) [18], and the plane size is shown in Figure 3. The test loading equipment is a 100 kN electronic universal testing machine; the loading rate is 10 MPa/s; and the DH3821 data acquisition system measures the deformation. The experimental stretching device is shown in Figure 4.

The measured yield strength, tensile strength, and Poisson’s ratio of steel are shown in Table 2, and the stress-deformation curve of steel obtained according to the experimental data is shown in Figure 5. The finite element simulation analysis can be simplified as the double broken line strengthening model of steel, as shown in Figure 6.

2.2.2. Fabrication of Combined Section Column Specimens. The single-limb components used in the combined section of this test are U-shaped steel (specification 170 × 70 × 1 mm) and C-shaped steel (specification 160 × 60 × 20 × 1 mm). The cross-section forms are shown in Figures 7(a) and 7(b). The combined section is composed of M4.8 * 19 self-tapping
Table 1: Specimen conditions.

<table>
<thead>
<tr>
<th>Specimen classification</th>
<th>Length (mm)</th>
<th>Slenderness ratio $\lambda$</th>
<th>Thickness (mm)</th>
<th>Number of specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>4C type</td>
<td>1200</td>
<td>18.52</td>
<td>Figure 1</td>
<td>3</td>
</tr>
<tr>
<td>CU type</td>
<td>182</td>
<td>18.2</td>
<td>Figure 2</td>
<td>3</td>
</tr>
<tr>
<td>ZF type</td>
<td>227.7</td>
<td>3.7</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>CF type</td>
<td>242</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

Note. Multiple parts constitute each fragment type; each segment is called a type and represented by letters. Arabic numerals represent the specimen number. For example, in CU-1, CU represents the built-up cross-section column of a closed box, and 1 represents the first specimen of this type of section.

Figure 1: Diagram of the displacement gauges: (a) lower part of the upper end plate and (b) upper part of the lower end plate.

Figure 2: Location diagram.

Figure 3: Plate sample ruler.
screws. According to the requirements of the “cold steel specification” and the screw spacing in the relevant specifications of cold-formed thin-walled steel at home and abroad, the screw spacing is determined [19, 20]. The screw spacing is 300 mm along the longitudinal length of the component. At the distance of 300 mm between the two ends of the column of the combined section, it is divided into three equal points to strengthen two self-tapping screws as shown in Figures 7(c)–7(e). The combination section is shown in Figures 7(f) and 7(g). In order to ensure the uniform force transmission and sufficient stiffness of the loading end of the assembled specimen and square steel during the test, the end plate of $360 \times 280 \times 3$ mm in length, width, and thickness is welded at the upper and lower ends of the column, as shown in Figure 7(h).

Before the test, the end of the test piece is polished by using an angle grinder to ensure that the end plate is in close contact with the column as much as possible to reduce initial defects.

2.2.3. Fabrication of Square Steel Section Columns. The sizes of square steel are $138 \times 132 \times 3.7$ mm and $172 \times 120 \times 3.7$ mm. The square steel specimen is welded after cutting the square steel plate. The cross-section forms are shown in Figures 8(a) and 8(b).

2.2.4. Test Device. The test was completed in the structural laboratory of Changchun Institute of Technology. The vertical load was applied by the static high-pressure testing machine and the reaction gantry. The reaction gantry was composed of left and right screws and upper beams, and the top was a hydraulic jack, as shown in Figure 9. Before the test loading, the upper and lower nuts are fixed, and the pad block is adjusted to keep the beam immobile. The hydraulic jack is connected to the high-pressure testing machine through the tubing. The top jack is moved downward by controlling the hydraulic system (Figure 10) to adjust the flow pressure, and then the loading is realized. A sensor (Figure 11) is placed on the lower support, connected with the force measuring display (Figure 12) for real-time observation of the load value during the loading process. The deformation acquisition is carried out by the DH3821 acquisition system (Figure 13), and the dial indicator carries out the displacement acquisition. The boundary conditions of the column end are set as welded steel plates on both sides of the column end, and the two ends are hinged.

2.2.5. Test Loading System. Before the test, the geometric alignment of the specimen was carried out. The flat and assembled test specimen at the end was placed on the thick steel plate, and the geometric alignment was carried out with
the load sensor at the lower part of the steel plat and the upper Jack.

Then, the DH3821 data acquisition system was connected, and the displacement meter was set up after the system debugging. Finally, the vertical load was applied to the specimen. The load controlled the loading in this experiment. The loading was divided into preloading and formal loading, as follows:

Preloading: pre-pressure of 3 kN is applied to the specimen to test whether the readings of the dial gauge and DH3821 data acquisition system and the dynamometer are regular, the stability of the deformation gauge is checked, and the physical alignment of the specimen is rechecked. After checking the normal work of each part, the displacement meter is cleared to prepare for the formal loading test.

Figure 7: Fabrication of assembled section: (a) C-shaped steel, (b) U-shaped steel, (c) splicing plane diagram, (d) screw, (e) splicing indication, (f) 4C series, (g) CU series, and (h) end reinforcement.
Since there are many specimens in the test, the predicted axial compression ultimate load by theoretical calculation is quite different. Therefore, the manual controlled static high-pressure testing machine is selected for continuous and slow loading. When the load reaches each level of loading, the load is maintained for 2 min. After the load is stable, the deformation is collected by DH3821, and the displacement meter reading of the dial gauge is read. Then the next level of loading is carried out. When the load decreases significantly, it indicates that the specimen reaches the ultimate bearing capacity state. The stable pressure of the throttle is controlled until the specimen is damaged. Finally, the testing machine is unloaded and closed:

1. Formal loading of CU series box-type assembled components

   Formal loading: in the formal loading to load control, loading speed is 25 kN per level of load; loading time is 2 minutes, expected 10–12 level loading, close
to the theoretical failure load each level loading 5 kN, until the column appears noticeable yield stop loading.

(2) Official loading of ZF square steel

Formal loading: when formal loading to load control, loading speed is 40 kN per stage; loading time is 2 minutes, expected 10–12 level loading, close to the theoretical failure load each stage loading 5 kN, until the column appears obvious yield stop loading.

(3) Formal loading of 4C series assembled openings

Formal loading: in the formal loading to load control, the loading speed is 25 kN for each level of load; the loading time is 2 minutes, expected 10–12 level loading, close to the theoretical failure load each level loading 5 kN, until the column appears obvious yield stop loading.

(4) Formal loading of CF square steel

Formal loading: when the formal loading is to the load control, the loading speed of each stage is 40 kN, and the loading stage is 5 kN near the theoretical failure load until the apparent yield of the column stops loading.

2.3. Test Results

2.3.1. Buckling Behavior and Ultimate Load of the Test Members

(i) 4C-type column

(1) The specimen has no apparent change at the initial stage of 4C-1 loading. When loaded to 190 kN, the top 10 cm away from the top is convex; the column head rotates around the weak axis; and the flange expands outward. When approaching the ultimate load, the deformation increases evidently. When loaded to 265.2 kN, local failure occurs, and the failure mode is shown in Figure 14.

(2) At the initial stage of 4C-2 loading, no significant change was found in the specimen. When loaded to 85 kN, the flange bulged; the splicing gap became more significant; and apparent local buckling deformation appeared 30 cm away from the lower end. The south side bulged evidently, and the east and west flanges expanded outward. When approaching the ultimate load, the web of the failure point collapsed, and the lower end column was bent to the weak axis direction. The local failure occurred when loading to 290.3 kN. The failure mode is shown in Figure 15.

(3) At the initial stage of 4C-3 loading, the specimen did not change significantly. When the loading was approximately 100 kN, the splicing gap of the specimen increased. When the loading was 230 kN, the flanges on both sides of the specimen at 20 cm from the upper end expanded, and the splicing gap increased. When the loading was close to the ultimate load, the specimen at 20 cm from the upper end was convex, and the compression bending of the column head was biased toward the weak northern axis. When the loading was 280.7 kN, local failure occurred. The failure mode is shown in Figure 16.

(ii) CU-type column

(1) The local top collapse of the CU-1 specimen occurs, and the test phenomenon is not ideal. When loaded to 180 kN, the specimen is destroyed, as shown in Figure 17.

(2) The CU-2 specimen has an unnoticeable change at the initial stage of loading. When the load is 120 kN, the middle flange of the specimen is outsourced by a U-shaped steel, and local buckling occurs. When the load is increased to approximately 195 kN, the upper end of the column bends southward. When the load is 217 kN, the deformation increases, and the upper end of the east and west sides of the outward bulge is severe. When the load is added to 230 kN, the upper end of the column bends southward, and the local failure occurs when the load is 235.3 kN. The failure mode is shown in Figure 18.

(3) In the early stage of the CU-3 specimen, the specimen has no apparent change. When the load is 95 kN, the U-shaped steel flange on the west side expands. When loaded to 131 kN, the east and west sides bulge. The upper part of the south side bulges when the load reaches 206 kN. When the load is close to the ultimate load, the specimen bends southward, and local failure occurs when the load reaches 240.6 kN. The failure mode is shown in Figure 19.

(iii) CF-type column

(1) At the beginning of CF-1 loading, the specimen has no evident deformation. A slight bulge
Figure 14: 4C-1 failure mode: (a) south, (b) east, and (c) west.

Figure 15: 4C-2 failure mode: (a) south, (b) east, and (c) west.

Figure 16: 4C-3 failure mode: (a) south, (b) east, and (c) west.
Figure 17: CU-1 failure mode.

Figure 18: CU-2 failure mode: (a) south, (b) east, and (c) west.

Figure 19: CU-3 failure mode: (a) south, (b) east, and (c) west.
appears in the middle of the south when the load is 200 kN. When the load is 400 kN, the bottom of the specimen is up to 10 cm, and the east and west sides bulge outward. The specimen slightly tilts to the north to produce local buckling. When the load is close to the ultimate load, the specimen suddenly bends to the north, and the local damage occurs when the load reaches 423.6 kN. The failure mode is shown in Figure 20.

(2) At the initial stage of CF-2 loading, the specimen has no evident deformation. When loaded to 295 kN, the lower end of the south column bulges outward. When loaded to 430 kN, the south column bulges outward at 20 cm above the specimen. When the ultimate load is reached, the upper end of the column collapses in the east and west sides, and the south column bulges out. Local damage occurs when loading to 452.4 kN. The failure mode is shown in Figure 21.

(3) At the beginning of CF-3 loading, no evident deformation of the specimen is observed. When loaded to 300 kN, the upper end of the south column is concaved inward at 10 cm. With increasing load near the ultimate load, the upper end of the column is convex on both sides of the east and west, and local damage occurs when loading to 431.2 kN. The failure mode is shown in Figure 22.

(iv) ZF-type column

1) At the initial stage of ZF-1 loading, the specimen has no evident deformation. When loaded to approximately 360 kN, the south side at 10 cm above the column bulges outward, and the east and west sides collapse. When loaded to approximately 420 kN, the upper column head bends southward, and the deformation increases. When loaded to approximately 423.4 kN, local damage occurs. The failure mode is shown in Figure 23.

2) In the early stage of ZF-2 loading, the specimen has no evident deformation. When loaded to approximately 380 kN, the upper end of the column at 16 cm bulges outward from the north, and the east and west sides are depressed inward. When loaded to 430 kN, the upper end of the column bends north, and the deformation increases. When loading to 441.6 kN, local failure occurs. The failure mode is shown in Figure 24.

3) At the initial stage of ZF-3 loading, the specimen has no evident deformation. When loaded to approximately 385 kN, the upper part of the southern column is convex at 13 cm. When loaded to 430 kN, the east and west sides are concave, and when loaded to 440.8 kN, local damage occurs. The failure mode is shown in Figure 25.

2.3.2. Test Data Analysis

(1) Load versus Axial Displacement Curves. The load-displacement curve is shown in Figure 26. This part has two linear ascending stages at the beginning of loading. The main
reason is that parts produce specific errors when spliced. At continuous loading, the welding gap or the length of the limb of the specimen is compacted; the curvature of the load-
displacement curve increases rapidly; and the curve main-
tains a linear relationship. When loading to the near ultimate bearing capacity, the curve has a slight bending, and the
specimen's stiffness decreases. When the ultimate bearing capacity is reached, the curve decreases rapidly, and the specimen is damaged.

(2) Bearing Capacity Analysis. The bearing capacity of columns is compared with different section forms. The average ratio of the bearing capacity \( (P_{u}) \) and the ratio of the cross-section area of the built-up section and the profiled steel section are calculated, as shown in Table 3.

Table 3 shows that the ratio of CF type to 4C type is 1.56, and the area ratio is 1.64. Therefore, the bearing capacity of the 4C-type column specimen is better than that of the CF-type column after area conversion. The bearing performance of the ZF type and CU type is opposite.

### 3. Theoretical Analysis

#### 3.1. Component Design and Theoretical Calculation

3.1.1. Theoretical Analysis of the Built-Up Column. The structures of 4C and CU built-in columns are shown in Figures 27 and 28, respectively.

Moment of inertia of single-leg C-shaped steel: 

\[ I_x = 1.27 \times 10^6 \text{ mm}^4 \quad \text{and} \quad I_y = 1.66 \times 10^5 \text{ mm}^4 \]  

\( (x \text{ is the strong axis, and } y \text{ is the weak axis}) \). The rotational inertia of the 4C built-in column is derived from the parallel translation formula, as follows: 

\[ I_x = 5.24 \times 10^6 \text{ mm}^4 \quad \text{and} \quad I_y = 9.04 \times 10^6 \text{ mm}^4 \]

In the same way, the moment of inertia of the CU-type built-up column is obtained as follows: 

\[ I_x = 5.43 \times 10^6 \text{ mm}^4 \quad \text{and} \quad I_y = 5.81 \times 10^6 \text{ mm}^4 \]
3.1.2. Theoretical Analysis of the Profiled Steel Column.
According to the principle of equal inertia moment, we designed shaped steel columns corresponding to 4C composite columns. The cross-section is $120 \times 172 \times 3.7 \text{mm}$, as shown in Figure 29. The inertia moment of the $X$- and $Y$-axis is obtained as follows: $I_x = 5.19 \times 10^6 \text{mm}^4$ and $I_y = 9.04 \times 10^6 \text{mm}^4$, respectively.

We also designed steel columns corresponding to CU composite columns, namely, ZF type. The cross-section is $132 \times 138 \times 3.7 \text{mm}$, as shown in Figure 30. The inertia moment of the $X$- and $Y$-axis is obtained as follows: $I_x = 5.39 \times 10^6 \text{mm}^4$ and $I_y = 5.78 \times 10^6 \text{mm}^4$, respectively.

### Table 3: Comparison of test values between built-up section and profiled steel section.

<table>
<thead>
<tr>
<th>Specimen classification</th>
<th>Length (mm)</th>
<th>Experiment average (kN)</th>
<th>Area (mm$^2$)</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>4C type</td>
<td>1,200</td>
<td>237.9</td>
<td>1,248</td>
<td>Local compression failure</td>
</tr>
<tr>
<td>CU type</td>
<td></td>
<td>278.7</td>
<td>1,278</td>
<td>Local compression failure</td>
</tr>
<tr>
<td>ZF type</td>
<td></td>
<td>435.3</td>
<td>1,943</td>
<td>Local compression failure</td>
</tr>
<tr>
<td>CF type</td>
<td></td>
<td>435.7</td>
<td>2,106</td>
<td>Local compression failure</td>
</tr>
<tr>
<td>$P_{CF}/P_{4C}$</td>
<td>—</td>
<td>1.56</td>
<td>1.64</td>
<td>—</td>
</tr>
<tr>
<td>$P_{ZF}/P_{CU}$</td>
<td>—</td>
<td>1.8</td>
<td>1.56</td>
<td>—</td>
</tr>
</tbody>
</table>

3.2. Theoretical Calculation

3.2.1. Calculation of the Bearing Capacity of the Built-Up Section Column. In the technical specification of low-rise cold-formed thin-walled steel buildings (JGJ227-2011) [21], the bearing capacity of cold-formed thin-walled steel members with a slenderness ratio less than 50 is multiplied by the number of sections. The calculation formula is as follows:

$$N_u = \sum_{i=1}^{n} \phi A_y f.$$  

(1)
Here, $N_u$ – ultimate bearing capacity, $n$ – number of sections, $\phi$ – stability factor, $A_e$ – effective sectional area, and $f$ – design value of steel strength.

The slenderness ratio of the CU-type section column is less than 50, which satisfies the use conditions of formula (1). The bearing capacity $N_u$ of a single C steel and U steel under the same member height and deformation conditions is calculated. The effective heights of the component are as follows: $l_{0x} = l_{0y} = 1.2$ m, $I_x = 1.27 \times 10^6$ mm$^4$, $I_y = 1.66 \times 10^5$ mm$^4$, and $A = 316$ mm$^2$. Then, the slenderness ratio of the component to the $X$- and the $Y$-axis is obtained as follows: $\lambda_x = l_{0x}/i_x = 22.77$ and $\lambda_y = l_{0y}/i_y = 52.2$. The corresponding stability coefficient is checked according to the specification $\phi = 0.963$, $N_{ZF}^u = 0.963 \times 1943 \times 215$ kN. Similarly, the bearing capacity of the single-leg U-shaped steel is $N_{4C}^u = 55.3$ kN.

According to formula (1), the bearing capacity of the CU-type column is as follows: $N_{CU}^u = 55.3 \times 2 + 57.545 \times 2 = 225.69$ kN. Similarly, the bearing capacity of the column with 4C type is as follows: $N_{4C}^u = 57.545 \times 4 = 230.18$ kN.

3.2.2. Calculation of the Bearing Capacity of the Profiled Steel Column. The ZF-type column is calculated by integral force, $l_{0x} = l_{0y} = 1.2$ m, $i = \sqrt{I/A}$. The slenderness ratio of the $X$- and $Y$-axis is obtained as follows: $\lambda_x = l_{0x}/i_x = 22.77$ and $\lambda_y = l_{0y}/i_y = 52.2$. The corresponding stability coefficient is checked according to the specification $\phi = 0.963$, $N_{ZF}^u = 0.963 \times 1943 \times 215$ kN. Similarly, the bearing capacity of the column with CF type is as follows: $\phi = 0.956$, $N_{4C}^u = 0.963 \times 1943 \times 215 = 432.867$ kN.

4. Finite Element Simulations

4.1. Finite Element Model

4.1.1. Selection of Structure Unit Types. When the size or thickness of one direction of the structure is smaller than that of other parts, the shell element should be used to simulate the components, and the finite element includes two types of shell elements: conventional shell and continuous shell. Because the specimen used in this paper
2.06 Poisson’s ratio is 0.3; and the elastic modulus is 2.06 × 10^5 MPa.

4.1.2. Component Creation and Material Properties. The component module is based on the true size of the test specimen, drawing a two-dimensional plane diagram of the component (single-limb U-shaped steel, C-shaped steel section, and end plate) and then selecting the discrete shell component module. The analysis adopts Q235 steel; Poisson’s ratio is 0.3; and the elastic modulus is 2.06 × 10^5 MPa.

4.1.3. Component Assembly and Meshing. Each component is created in its coordinate system, independent of each other. Each component entity is assembled into a whole assembly by moving, rotating, and other functions in the overall coordinate system. A parametric study was performed to evaluate a suitable mesh size for the FE model. After several adjustments, the appropriate global size is found [22, 23]. The global division size of C- and U-type steel is defined as 10 mm; the end plate size is 20 mm; and the element shape is quadrilateral. The assembled components and the meshing model are shown in Figure 31.

4.1.4. Interaction, Boundary Conditions, and Loading

(1) Interaction. Under the action of load, the specimen will buckle, and the areas of the internal and external surfaces of the component will contact other areas, so interaction needs to be set. Because the component element is the shell element, in order to reduce the impact of assembly intrusion, the general contact is selected. The property of the interaction between the assembled single-limb components is set to hard contact (“penalty” friction). It can ensure that each surface can transfer pressure and not invade the other. For more effective simulation of screw connection and welding between end plate and column, MPC constraint and binding constraint are adopted, respectively. In the nonlinear buckling analysis, in order to effectively simulate the axial compression load so that the load can be uniformly transmitted and the data extraction is convenient, the upper and lower ends of the section are coupled with the central reference point of the upper-end plate [26, 27] as shown in Figure 33.

4.1.5. Initial Defects and Residual Stresses. When using ABAQUS [28] to analyze the axial force performance of light steel assembled section column and square steel, there are some initial defects in the model due to the residual stress analysis results in the process of steel plate welding into square steel and the cutting and assembling. Therefore, according to the relevant references, in the numerical simulation process, 25% wall thickness is taken as the initial defect amplitude [26, 27], Square steel corner residual stress is 0.4fy. The residual stress of the plate is 0.2fy [27, 29].

4.2. Comparison of Finite Element and Test

4.2.1. Comparison of Failure Modes and Deformation Characteristics. As shown in Figure 34, for the 4C-type members, with the appearance of the outward expansion of the C-shaped steel with the outer edge of the roll, the finite element simulation finally fails at 300.3 kN, and the failure mode is a local failure.

As shown in Figure 35, the failure modes of the CU-type specimens are the same; all failures are classified as local buckling and finally as a bending failure, accompanied by a large number of ripples. The finite element simulation is finally destroyed at 253.2 kN.

As shown in Figures 36 and 37, the failure modes of the ZF- and CF-type specimens are the same, that is, local buckling at the end of the component. This finding is consistent with the failure mode of the test. The finite element simulations of the ZF- and CF-type specimens are finally destroyed at 448.6 and 456.4 kN, respectively.

The failure mode obtained by the finite element analysis is the same as that of the test, and the finite element analysis is highly consistent with the test.

4.2.2. Load-Displacement Curve Comparison. Four types of specimens are compared in Figure 38. The figure shows that the rising slope of the curve obtained by finite element simulation and test is the same, and the curves are in good agreement. This finding indicates that the finite element simulation and test are in line with the elastic theory before reaching the bearing capacity failure.

4.2.3. Load-Deformation Curve. Due to the small slender-ness of the specimen, the failure mode of the specimen is mainly local failure. During initial loading, the load is small and has no obvious deformation, and the slope of the curve is stable. Since the position of the buckling waveform of each specimen is relatively random and there is no accurate position, if the location of the deformation gauge is not above the peak and valley of the local buckling waveform, the turning point is not obvious. Therefore, for the 4C, CF, and ZF series, the local buckling load of the specimen should be determined by combining the test phenomenon of the specimen and the load-axial displacement curve.
Figure 31: Load-axial displacement curve: (a) 4C series, (b) CU series, (c) CF series, and (d) ZF series.

Figure 32: Interaction property settings: (a) screw simulation, (b) end binding constraints, and (c) end coupling.
series components, as the load increases, the plate will produce buckling ripples. The concave side deformation increases faster, and the convex side deformation gradually changes from compression to tension. Therefore, the local buckling load of the specimen can be roughly judged according to the bifurcation inflection point of the deformation. Load-deformation curves are shown in Figures 39–42.

4.3. Comparison of the Test, Finite Element, and Theoretical Calculation of the Built-Up Section. The average test value, finite element simulation value, and theoretical calculation value of the built-up section column are compared and analyzed, as shown in Table 4.

The comparative analysis indicates that the ultimate bearing capacity obtained by finite element analysis is in good agreement with the experimental value, and the theoretical calculation is conservative.

4.4. Comparison of Finite Element Bearing Capacity of Built-Up and Profiled Steel Columns. Comparative analysis of axial compression bearing capacity of the built-up column and profiled steel column is shown in Table 5.

Table 5 shows that the ratio obtained by ABAQUS is close to the test. The comparison of the ratio and the area shows that the ratio of the bearing capacity of CF type and 4C type is less than that of the area ratio, and the bearing capacity of the 4C-type section is approximately 1.08 times

Figure 33: End plate constraint schematic: (a) lower end plate constraint and (b) upper end plate constraint.

Figure 34: 4C-type failure mode: (a) front elevation and (b) side elevation.
Figure 35: CU-type failure mode: (a) front elevation and (b) side elevation.

Figure 36: CF-type failure mode: (a) front elevation and (b) side elevation.
Figure 37: ZF-type failure mode: (a) front elevation and (b) side elevation.

Figure 38: Continued.
Figure 38: Comparison of load-displacement curves: (a) 4C type, (b) CU type, (c) CF type, and (d) ZF type.

Figure 39: 4C series load-strain curves: (a) 4C-1, (b) 4C-2, and (c) 4C-3.

Figure 40: CU series load-strain curves: (a) CU-1, (b) CU-2, and (c) CU-3.
Figure 41: ZF series of load-strain curves: (a) ZF-1, (b) ZF-2, and (c) ZF-3.

Figure 42: CF series load-strain curves: (a) CF-1, (b) CF-2, and (c) CF-3.

Table 4: Test values, finite element analysis, and theoretical calculation analysis.

<table>
<thead>
<tr>
<th>Specimen classification</th>
<th>Length (mm)</th>
<th>Experiment average (kN)</th>
<th>Finite element (kN)</th>
<th>Theoretical value (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4C type</td>
<td>1,200</td>
<td>278.7</td>
<td>300.3</td>
<td>230</td>
</tr>
<tr>
<td>CU type</td>
<td></td>
<td>237.9</td>
<td>253.2</td>
<td>225.6</td>
</tr>
</tbody>
</table>

Table 5: Comparison of the finite element between built-up and profiled steel columns.

<table>
<thead>
<tr>
<th>Specimen classification</th>
<th>Length (mm)</th>
<th>Finite element (kN)</th>
<th>Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CU type</td>
<td></td>
<td>253.2</td>
<td>1248</td>
</tr>
<tr>
<td>4C type</td>
<td>1,200</td>
<td>300.3</td>
<td>1278</td>
</tr>
<tr>
<td>ZF type</td>
<td></td>
<td>448.6</td>
<td>1943</td>
</tr>
<tr>
<td>CF type</td>
<td></td>
<td>456.4</td>
<td>2106</td>
</tr>
<tr>
<td>( P_{CF}/P_{CU} )</td>
<td></td>
<td>1.52</td>
<td>1.64</td>
</tr>
<tr>
<td>( P_{a}/P_{CU} )</td>
<td></td>
<td>1.77</td>
<td>1.56</td>
</tr>
</tbody>
</table>
that of the CF-type section. Therefore, after the area conversion, the bearing capacity of the 4C type is better than that of the CF type, and the relationship between the CU type and ZF type is opposite.

5. Conclusion

On the basis of the test, numerical simulation, and current standards, the mechanical properties of light steel columns with four cross-section forms are studied, and design methods for practical engineering are proposed. The following conclusions can be drawn:

(1) In the axial compression test and finite element simulation of cold-formed thin-walled steel built-up section and profiled steel section column, when the slenderness ratio is small, the failure modes include local buckling.

(2) The slope of the load-displacement curve obtained by the finite element simulation of the two cross-section columns is stable, and the shape is similar. This finding indicates that the material has typical elastic-plastic properties and conforms to the material properties of steel. The two columns have the same working process and mechanical properties.

(3) Considering the influence factors of the area of the built-up section and profiled steel section, as well as the area conversion, CF and 4C columns are found to have better bearing capacity because of their more developed structure and considerable stiffness. ZF-type columns have better overall performance and mechanical performance than CU-type columns.

(4) The use of the built-up section column is recommended for columns in the middle part of the light steel skeleton. This approach is convenient for connecting wall plates on both sides and can satisfy the bearing capacity requirements. The use of profiled steel section column in the corner of the light steel frame is recommended due to the increase in load, thereby increasing the structure’s overall stability.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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