Design Method and Finite Element Analysis of Prefabricated Steel-concrete Composite Lattice Column

Xiaofan Fu¹, Xiaotong Peng¹*, Xu Zhang¹ and Chen Lin²
¹ School of Civil Engineering and Architecture, University of Jinan, Jinan, Shan Dong, 250022, China
² School of Architecture and Landscape Design, Shandong University of Art & Design, Jinan, Shan Dong, 250014, China
*Corresponding author’s e-mail: pengxito@163.com

Abstract. In order to solve the problem of exposed column, a new prefabricated steel-concrete composite lattice column (SCLC) in residential building was proposed. The SCLC consists of concrete filled steel tubes, which are connected by channel steel and lace plates. The finite element simulations of six infilled SCLC with different cross-section (L-shaped, T-shaped and X-shaped) were performed under monotonic loading by using ABAQUS, in which the carrying capacity, ductility, stiffness and energy dissipation were analysed. The results indicate that the infilled concrete can improve the strength and stiffness of SCLC, while the ductility decreases slightly. X-shaped SCLC has the best carrying capacity and poor ductility. The SCLC with T-shaped has the best comprehensive performance.

1. Introduction
It has become an inevitable trend to build economically high-rise buildings on limited urban land. The current steel structure buildings have become relative mature, but there are still problems such as exposed column, inflexible structural layout, and low standardization of components. The development of prefabricated steel structure has been restricted. In view of that, this paper combines the advantages of lattice columns to form a new fabricated Steel-Concrete Composite Lattice Column (SCLC). At present, scholars at home and abroad have done a lot of research on prefabricated steel structure and steel lattice column system [1-5], but there are still few research results on prefabricated steel-concrete lattice column. Therefore, it is of great significance to research SCLC’s performance and its structural system.

2. Design of steel-concrete composite lattice column
2.1. Steel-concrete composite lattice column (SCLC) structure
The SCLC consists of concrete filled steel tubes, which are connected by channel steel and lace plates, and can be divided into L-shaped, T-shaped and X-shaped according to the cross-section form. The seamless square steel tubes are used as the steel tube columns. The steel tube and the web of the channel steel are connected by long screw bolts, and the bolts can deep into the square steel tube to a certain length, which is convenient for strengthening the coordination of them. Thin strip steel plate is used as the lace plate, which is connected to the flange of the channel steals by bolt. The cavity, formed by the channel steel and the lace plate, can be filled with autoclaved light-weight concrete.
blocks. The filling provides certain support for the channel steel and the lace plate, which can appropriately increase the lateral stiffness of the SCLC in construction and restrain the out-of-plane buckling of the lace plates. The SCLC model diagram is shown in figure 1.

![SCLC model diagram](image)

(a) L-SCLC  (b) T-SCLC  (c) X-SCLC

Figure 1. SCLC model diagram

2.2. Design method of steel-concrete composite lattice column (SCLC)
SCLC is divided into two types of structures: lace-plate SCLC and lace-plate-concrete SCLC. Each of them has three types: L-shaped, T-shaped, and X-shaped, a total of 6 models. The square steel tube and channel steel are 160 × 160 × 10mm and 160 × 80 × 10mm. The lace plate is made of 380 × 200 × 10mm steel plate, arranged along the top of the column with an interval of \( l_v = 600 \) mm, and the distance between the two square steel tube columns is 400mm. The lace-plate SCLC is a pure steel lattice column, and the square steel tubes are not filled with concrete (figure 2). The lace-plate-concrete SCLC has the same size as the lace-plate SCLC, but the square steel tubes are filled with concrete to form a concrete-filled steel tube structure. At the same time, the restraining effect of the block on the out-of-plane buckling of the lace plate is regarded as the safety reserve of the component and is not considered in design (figure 3).

![Lace-plate SCLC](image)

![Lace-plate-concrete SCLC](image)

Figure 2. Lace-plate SCLC  Figure 3. Lace-plate-concrete SCLC

3. SCLC performance analysis

3.1. Establishment of finite element models
In this paper, the steel members are all made of Q345 grade steel and the concrete is C35 grade. The steel is analysed by the elastoplastic theory, using the Mises yield criterion and the isotropic hardening model. The elastic modulus of the hardening section is 0.01E. Concrete uses damage-plasticity model (CDP model) [6]. Zeng Yu’s calculation method [8] of concrete plastic damage constitutive model parameters was adopted, as shown in table 1.

| Compressive stress (MPa) | Nonlinear strain (mm) | Compression damage factor | Tensile stress (MPa) | Cracking strain (mm) | Tensile damage factor |
|-------------------------|-----------------------|---------------------------|----------------------|---------------------|----------------------|
| 24.019                  | 0                     | 0                         | 1.78                 | 0                   | 0                    |
| 29.208                  | 0.4                   | 0.1299                    | 1.46                 | 0.1                 | 0.3                  |
| 31.709                  | 0.8                   | 0.2429                    | 1.1                  | 0.3                 | 0.55                 |
| 32.358                  | 1.2                   | 0.3412                    | 0.96                 | 0.4                 | 0.7                  |
| 31.768                  | 1.6                   | 0.4267                    | 0.8                  | 0.5                 | 0.8                  |
| 30.379                  | 2                     | 0.5012                    | 0.536                | 0.8                 | 0.9                  |
| 28.507                  | 2.4                   | 0.566                     | 0.359                | 1                   | 0.93                 |
| 21.907                  | 3.6                   | 0.714                     | 0.161                | 2                   | 0.95                 |
| 14.897                  | 5                     | 0.8243                    | 0.073                | 3                   | 0.97                 |
| 2.953                   | 10                    | 0.9691                    | 0.04                 | 5                   | 0.99                 |

In this paper, SOLID elements are used to model concrete and steel lattice columns. The element type is C3D8R, and STRUCTURED mesh generation is used. It is assumed that there is no relative displacement between concrete and steel tubes, and the Tie command is used to bind.

In the models, a combination of displacement loading and force loading is used: the vertical load is calculated by PKPM, and N = 400kN is taken, the horizontal displacement is $\varepsilon = 150$mm. In this paper, the consistent mode imperfections method is used to simulate the initial defect of the component. The buckling eigenvalue of the structure is analysed to obtain the elastic buckling mode of the SCLC component, and 0.4% of the first-order buckling mode is taken as the deformation value of the initial defect.

### 3.2. SCLC model design

In order to evaluate the influence of concrete and cross-section form on the carrying capacity of SCLC, combining the above elements in different forms, a total of six lattice column models of lace-plate SCLC (L-lace-plate, T-lace-plate, X-lace-plate) and lace-plate-concrete SCLC (L-concrete, T-concrete, X-concrete) were designed. The specific dimensions are shown in table 2.

| Component name      | Dimensions of square steel tube (mm) | Dimensions of channel steel (mm) | Dimensions of lace plate (mm) | sectional area ($mm^2$) |
|---------------------|--------------------------------------|---------------------------------|------------------------------|-------------------------|
| L-lace-plate        |                                       |                                 |                              | 37200                   |
| T-lace-plate        |                                       | 380x200x10mm                    |                              | 52800                   |
| X-lace-plate        |                                       | 160x160x10mm                    | 160x80x10mm                  | 68400                   |
| L-concrete          | 160x160x10mm                         | 160x80x10mm                     |                              | 56800                   |
| T-concrete          |                                       | 380x200x10mm                    |                              | 72400                   |
| X-concrete          |                                       |                                  |                              | 82000                   |

### 3.3. SCLC ductility and carrying capacity analysis

The ductility coefficient $\mu$ is used to indicate the ability of structural plastic deformation. The ductility coefficient is the ratio of the ultimate displacement $\Delta \mu$ to the yield displacement $\Delta y$, where the
ultimate displacement $\Delta \mu$ is the displacement when the carrying capacity is reduced to $0.85V_{\text{max}}$. If the carrying capacity has not reduced to $0.85V_{\text{max}}$, the maximum displacement of the model is taken as the ultimate displacement. The yield displacement method is the geometric construction method proposed by Guo Zhenhai [8]. In order to explore the lateral performance of SCLC, the ductility and carrying capacity of 6 kinds of components are analysed. The load-displacement curves of all components are shown in figure 4.

3.3.1. Influence of infilled concrete

In order to study the influence of infilled concrete on the ductility and carrying capacity of SCLC, the models with the same cross-section form were divided into a group for analysis. The load-displacement curves of the L-shaped, T-shaped and X-shaped SCLC models under monotonic loading are shown in figure 5, figure 6 and figure 7 respectively. The loading results and indicators of the six models are listed in table 3.

| Model       | $V_{\text{max}}$ (kN) | $V_y$ (kN) | $\Delta \mu$ (mm) | $\Delta y$ (mm) | $\mu$   |
|-------------|------------------------|------------|-------------------|-----------------|---------|
| L-lace-plate| 627.3                  | 498.96     | 150               | 27.3            | 5.49    |
| L-concrete  | 956.66                 | 677.87     | 150               | 40.8            | 3.68    |
| T-lace-plate| 1024.29                | 839.69     | 150               | 25.98           | 5.77    |
| T-concrete  | 1488.32                | 1118.38    | 150               | 39.85           | 3.76    |
X-lace-plate 1221.45 1044.12 150 30.74 4.88  
X-concrete 1738.36 1323.34 150 43.28 3.47  

In summary, when the cross-section form is the same, the carrying capacity and yield displacement of the filled concrete are improved significantly compared to the unfilled concrete, indicating that the concrete has improved the stiffness, carrying capacity and deformation performance of the SCLC model, but the ductility is reduced. The concrete SCLC models of various cross-section forms can meet the requirements of the ductility, indicating that the energy dissipation capacity of the SCLC in the application is guaranteed.

3.3.2. Influence of cross-section shape

The SCLC models with different cross-section are compared. The load-displacement curves of the lace-plate and lace-plate-concrete SCLC models are shown in figure 8 and figure 9 respectively. The loading results and indicators of the six models are listed in table 3.

![Figure 8. Load-displacement curves of the lace-plate SCLC models](image)

![Figure 9. Load-displacement curves of the lace-plate-concrete SCLC models](image)

In summary, the X-shaped cross-section has the highest carrying capacity when the filled concrete is the same. However, due to the restraining effect of the columns on both sides on the middle column, the ductility coefficient is the smallest, and the deformation performance is not as good as the L-shaped section and the T-shaped section. The T-shaped cross-section has the highest stiffness and the largest increase in carrying capacity. The square steel tube column perpendicular to the loading direction plays an appropriate restraining role. The ductility is the best and the square steel tube columns are most efficient. T-shaped cross-section is the most recommended cross-section in the project.

4. Conclusion

The finite element simulations of six infilled SCLC with different cross-section (L-shaped, T-shaped and X-shaped) were performed under monotonic loading by using ABAQUS, in which the carrying capacity, ductility, stiffness and energy dissipation were analysed, and the conclusions are as follows:

- For SCLC with the same cross-section form, the carrying capacity of the lace-plate-concrete SCLC members is higher than that of the lace-plate SCLC members, which is increased by about 31.78%. The stiffness of the lace-plate-concrete members is also improved, while the ductility is reduced obviously.
- For SCLC with the same infilled material, X-shaped cross-section has the largest carrying capacity and the smallest ductility, and the deformation performance is not as good as the L-shaped and T-shaped. The carrying capacity of the T-shaped is smaller than that of the X-
shaped, but it is improved significantly compared to the L-shaped. The T-shaped SCLC has the best comprehensive performance.

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