Research on Hysteretic Behavior of Cold-Formed Thin-Wall Rolled Edge Channel Steel Flexural Members

Jiabao Yang¹, Yanli Guo¹,²*, Lipeng Yu¹, Chengli Hu¹ and Yafei Liu¹

¹School of Civil and Architectural Engineering, Nanchang Institute of Technology, Nanchang, 330099, China
²Jiangxi Province Key Laboratory of Hydraulic and Civil Engineering Infrastructure Security, Nanchang Institute of Technology, Nanchang 330099, China
*Email: 1160728289@qq.com

Abstract. The finite element software ABAQUS is used to calculate and analyze the mechanical performance of cold-formed thin-walled curved channel steel members under horizontal reciprocating load. Double nonlinear finite element model needs to be considered, the influence of geometric imperfection and residual stress. The accuracy of the results was verified by comparing with the relevant test results. On the basis of controlling the main parameters such as width-thickness ratio, axial compression ratio, slenderness ratio and buckling mode, the numerical simulation results of 9 hysteretic specimens were selected to research the influence of the above factors on the hysteretic performance of the flexural members. The analysis results show that the width to thickness ratio, axial compression ratio and slenderness ratio have great influence on the hysteretic performance of the flexural members. The larger the three main parameters are, the worse the bearing capacity, ductility and energy consumption of the members will be. Therefore, the design should avoid as far as possible to choose a larger width-thickness ratio and slenderness ratio section components.

1. Introduction
In recent years, with the development of China's industrialization level, cold-formed thin-wall steel industry also ushered in a rapid development, for light steel structure building, its dependence on high degree of component industrialization, light weight, high structural safety, good seismic performance, more suitable for the application of China's earthquake zone in the low-rise buildings. At present, there are many researches on cold-formed thin-wall steel structures, but the research on hysteretic behavior of cold-formed thin-wall rolled edge channel members is relatively limited in China. In view of this, through the establishment of ABAQUS finite element model, and on the basis of comparing with the existing test results and verifying the correctness of the model, select different width-thickness ratio, axial compression ratio and slenderness ratio for parametric analysis, get their hysteretic curve, so as to study the hysteretic performance of cold-formed thin-wall rolled edge channel steel bending members. It provides a reference for the optimization of seismic performance of cold-formed thin-wall rolled edge channel steel bending members.

2. Establishment and Verification of Finite Element Model
2.1. Finite Element Model Establishment
Parametric analysis was carried out with finite element analysis software ABAQUS, and S9R5, a nine-node reduced integral thin shell element, was selected to simulate channel steel members. Q345 steel
was selected, and the yield strength was $f_y = 345\text{MPa}$. Considering the Bauschinger effect, the bilinear follow-up strengthening model was selected, in which the elastic modulus $E = 2.06 \times 10^5 \text{MPa}$, the slope of the strengthening section was 1% of the elastic modulus, and the Poisson's ratio was 0.3. In order to analyze the influence of local buckling on the hysteretic performance of components, it is necessary to ensure that local buckling does not lead to overall instability of components, and the length of components must meet the requirements of $3d \leq L \leq 20i_{\text{min}}$. The constraints of the specimen model are shown in figure 1. Translational and rotational motion in all directions at the bottom are constrained to simulate complete consolidation at the bottom. Constant vertical load is applied along the Z direction according to different axial compression ratios at the top, and repeated horizontal push and pull displacement is applied along the Y direction to constrain translational displacement in the X direction and rotational displacement in the Y and Z directions. The mesh size of the model is divided by free mesh, and the mesh cell size is about $10\text{mm} \times 10\text{mm}$. In this case, relatively satisfactory calculation results can be obtained for the cell size. The finite element model is shown in figure 1.

2.2. Validation of Model Accuracy

According to Tongji University pay little super cold bending steel channel members in bending under circulating load of experimental results, using the finite element software ABAQUS to corresponding numerical simulation analysis and calculation of two component, the figure 2 and figure 3 shows that both hysteresis curve and failure mode, can be in agreement with the test results, show that the model is more accurate, It can be used to study the hysteretic behavior of cold-formed thin-wall rolled edge channel steel bending members.

![Figure 1. Finite element model.](image1)

![Figure 2. Finite element analysis results.](image2)

(a) C1-BC-L30-70-02  (b) C2-BC-L60-35-02
3. Parametric Model Analysis and Selection

On the basis of verifying the accuracy of the finite element analysis model, the effects of width to thickness ratio, axial compression ratio and slenderness ratio on the hysteretic performance and failure mode of the component were studied through parametric analysis. The selected specimens and parameters are shown in Table 1. The width-thickness ratio h/t is 40, 50, 60 and 70. The axial compression ratio n=0.1, 0.2, 0.3, 0.4; Take the slenderness ratio λ=30, 50, 70 three cases. In Table 1, the numbering rules of specimens are as follows: section number - force type - slenderness ratio - web width-thickness ratio - axial compression ratio.

Table 1. Details of the specimen.

| Specimen number | hxbxaxt/mm | fy(MPa) | h/t | L/mm | λ | n  | Δy/mm |
|-----------------|------------|---------|-----|------|---|----|-------|
| C1-BC-L30-40-01| 120x48x20x3| 345     | 40  | 720  | 30| 0.1| 4.34  |
| C1-BC-L30-40-02| 120x48x20x3| 345     | 40  | 720  | 30| 0.2| 3.86  |
| C1-BC-L30-40-03| 120x48x20x3| 345     | 40  | 720  | 30| 0.3| 3.38  |
| C1-BC-L30-40-04| 120x48x20x3| 345     | 40  | 720  | 30| 0.4| 2.89  |
| C1-BC-L50-40-01| 120x48x20x3| 345     | 40  | 1200 | 50| 0.1|12.06 |
| C1-BC-L70-40-01| 120x48x20x3| 345     | 40  | 1680 | 70| 0.1|23.63 |
| C2-BC-L30-50-01| 150x60x25x3| 345     | 50  | 900  | 30| 0.1|5.43  |
| C3-BC-L30-60-01| 180x72x30x3| 345     | 60  | 1080 | 30| 0.1|6.51  |
| C4-BC-L30-70-01| 210x84x35x3| 345     | 70  | 1260 | 30| 0.1|7.60  |

4. Finite element analysis

4.1. Hysteresis Curve Analysis

The hysteresis curve is a comprehensive reflection of the seismic performance of the structure. The ductility and energy dissipation capacity of the component can be judged according to the observation of the shape of the hysteretic curve. The skeleton curve extracted from the hysteretic curve can further observe the stiffness degradation and ductility coefficient of the component.

It can be clearly observed from figure 4 that for flexural members with small slenderness ratio under small axial compression ratio, width-to-thickness ratio has a great influence on the fullness degree of hysteretic curve. When the width-to-thickness ratio is large, although the bearing capacity of members increases slightly, the hysteretic curve is not full and energy dissipation capacity is poor. For the flexural member with small axial compression ratio and small width to thickness ratio, the slenderness ratio also has an effect on the fullness degree of hysteretic curve. The larger the slenderness ratio is, the more likely the member is to have global instability, and the worse the fullness degree of hysteretic curve is, the worse the seismic performance is. The axial compression ratio
mainly affects the peak value of hysteretic curve. For a member with the same section, the greater the axial compression ratio, the lower the ultimate bearing capacity of the member. For a member with a large slenderness ratio, the greater the axial compression ratio, the second order effect of the member is obvious, and the member is prone to collapse failure.

Figure 4. Hysteresis curve.

4.2. Skeleton Curve Analysis
Skeleton curve is the envelope of hysteretic curve. It can be clearly observed from the skeleton curve that the component changes from elastic deformation to yield point, and when the maximum load is reached, it begins to decline until instability or plastic failure.

(1) The influence of ratio of width to thickness
Figure 5 shows skeleton curves of components with the same slenderness ratio and different width-to-thickness ratios under the same coaxial pressure ratio. Figure 5 shows the influence of width-to-thickness ratio on the hysteretic performance of components: For the same component with the same slenderness ratio and axial compression ratio, the slope of skeleton curve is similar at the initial loading stage, indicating that the width-to-thickness ratio has little influence on the initial stiffness of components, mainly because the components are still in the elastic stage at the initial loading stage. As the width-to-thickness ratio increases, the strengthening stage of skeleton curve becomes shorter and shorter. When the width-to-thickness ratio is large, the strength of the component
decreases rapidly after reaching the ultimate bearing capacity, indicating that the ductility coefficient of the component is very small at this time and brittle failure is easy to occur. Although increasing the ratio of width to thickness increases the ultimate bearing capacity of the component, the ductility of the component with larger ratio of width to thickness decreases and the stiffness degradation speed accelerates.

Figure 5. Skeleton curves with different width-thickness ratios.

(2) The influence of ratio of the axial compression ratio

Figure 6 shows the skeleton curve of the same component under different coaxial pressure ratios. Figure 6 shows the influence of axial compression ratio on the hysteretic performance of components: When different pressures are applied to the same component, the slope of skeleton curve is similar at the initial loading stage, indicating that the axial compression ratio has little influence on the initial stiffness of components. Due to the difference in axial pressure, the four same members differ greatly not only in the position of the peak point, but also in the later rotation capacity, indicating that the axial pressure ratio has a great influence on the bearing capacity and rotation capacity of the members. This is because when the axial pressure ratio is large, the influence of the second-order effect becomes prominent with the increase of the later displacement.

Figure 6. Skeleton curves with different axial compression ratio.

(3) The influence of ratio of slenderness ratio

Figure 7 shows the influence of skeleton curve of slenderness ratio member. In the figure, $M_P$ is the plastic bending moment of full section member, relative radius $\phi = \delta / L \%$. For the flexural member with small slenderness ratio, the plasticity is given full play, hysteretic curve is full and energy dissipation capacity is strong in the process of strength failure. For the flexural member with medium slenderness ratio, the member is prone to in-plane instability. With the increase of loading times and loading displacement, the member is in elastic-plastic state when it fails, and the hysteretic curve is relatively full and the energy dissipation capacity is strong. For the flexural member with large slenderness ratio, the member is prone to out-of-plane instability, insufficient plastic development, low bearing capacity and poor energy dissipation capacity.
5. Conclusion
Based on verifying the correctness of the model, nine cold-formed thin-wall roll-side channel steel bending members with different width-thickness ratios, axial compression ratios and slenderness ratios were numerically simulated, and the following conclusions were obtained:

- Width-to-thickness ratio has a greater impact on the stiffness of the flexural member. The larger the width-thickness ratio, the earlier the local buckling of the flexural member.
- When the axial compression ratio is large, the second-order effect caused by axial force is obvious, the strength and stiffness of components are reduced, and the energy dissipation capacity is weakened.
- With the increase of slenderness ratio, the elastic stiffness of components decreases, the plasticity is not fully played, the bearing capacity decreases, and the overall instability is more likely to occur.

Acknowledgments
The author sincerely thanks the Natural Science Foundation of Jiangxi Province from Jiangxi Provincial Department of Science and Technology [No.20181BAB206040].

References
[1] He Z Q, Yang G, Zhou X H, Peng S Q 2021 Experimental study on distortion performance of Cold-formed Thin-wall Split H-shaped steel flexural member with Web stiffening Journal of Building Structures 1-11.
[2] Li Y Q, Xu H J 2019 Development status and prospect of cold-formed steel structure in China Building Structure 49(19): 91-101.
[3] Ren Z, Liu Q T, Wang B H, Dai L S 2020 Numerical analysis and design method for open-hole cold-formed thin-wall C-section steel flexural members Journal of Shanghai Jiaotong University 54(10): 1084-1093.
[4] Wang C G, Kong D L, Zhang Y C 2017 Comparative study on calculation methods of bearing capacity of cold-formed thin-wall steel members Progress in Steel Building Structures 19(06): 51-59.
[5] Yang N, Peng X 2015 Study on buckling mechanism and hysteresis model of cold-formed thin-wall Steel C members China Civil Engineering Journal 48(03):25-33.
[6] Wu S, Zhang H, Wang W 2010 Mechanical properties of a new type of cold-formed flange closed flexural member Journal of Guangxi University (Natural Science Edition) 35(01): 60-63.
[7] Zhang Z Q 1991 Stability calculation of cold-formed thin-wall steel flexural members Journal of Building Structures (02): 70-77.
[8] Ma R K, Li Y Q 2014 Finite element analysis of seismic performance of low-rise cold-formed thin-wall steel keel system building Journal of Building Structures 35(05): 40-47.
[9] Fu X C, Li Y Q, Shen Z Y 2016 Cold bending effect of cold - formed thick - wall steel with flanged groove section Journal of Tongji University(Natural Science) 44(12):1819-1827.