

# Research on The Force Analysis and Application of Slender Stainless Steel Column Sections

Yufan Yu \*

School of Physical Science and Technology, Soochow University, Suzhou, China

\* Corresponding Author Email: 2122402009@stu.suda.edu.cn

**Abstract.** Stainless steel, as a green building material, has many advantages, including aesthetically pleasing shapes, good corrosion resistance, stable mechanical properties, long service life, low cost, and easy maintenance. It is often used in structural construction, such as buildings and infrastructure. One of the typical cross-sectional forms of stainless steel used in construction is the slender stainless steel section. Slender stainless steel columns have high strength, which is consistent with the high material hardness and obvious stress hardening characteristics of stainless steel. Therefore, they are widely used in stainless steel components. Stainless steel has a non-linear stress-strain relationship, and among them, open slender cross-section stainless steel members are more prone to developing local and distortion section instability, so these members have complex non-linear instability behavior. This paper reviews the current status and future prospects of the force analysis and application research of slender stainless steel column sections. This paper analyzes the bending load-bearing capacity and stability analysis results of stainless steel materials using finite element models by several different teams, and compares the advantages and disadvantages of the effective width method and direct strength method in section calculation. Finally, the application route of slender stainless steel column is analyzed, and the application prospect in people's production and life in the future is put forward.

**Keywords:** Stainless steel; Slender section; Buckling capacity; Stability analysis.

## 1. Introduction

In recent years, the global output of stainless steel has witnessed a rapid increase, and the application scope of stainless steel materials has been gradually expanding. Its role in the construction industry has evolved from traditional decorative components to structural load-bearing ones. The mechanical properties of stainless steel differ significantly from those of ordinary low-carbon steel [1]. Due to this factor, the design expressions of stainless steel components vary considerably from those of ordinary low-carbon steel. Simultaneously, with the extensive application of stainless steel structural components in recent years, the design methods of stainless steel structural components have become a focus of attention for researchers and designers both domestically and internationally.

The nonlinear characteristics of stainless steel materials render the bending buckling capacity and stability issues of stainless steel components as the key problems influencing the design of stainless steel structures. Stainless steel materials typically possess considerable strain hardening capabilities, enabling the utilization of their post-buckling strength after local buckling of plate members to achieve more economical and rational section designs. Once local buckling occurs in the constituent plate members, the section of the component partially fails, and the overall stability bearing capacity of the entire stainless steel component is directly affected and weakened, namely, local and global correlated buckling occurs. The stability of components has always been a hot topic in the field of structural engineering research. Due to its unique and excellent material properties, stainless steel components have attracted numerous scholars to conduct analyses and research. Currently, some scholars have carried out partial studies on the local and global correlated stability performance of stainless steel structural components.

At present, there is scarce research on the relevant buckling of slender cross-section stainless steel compression members both at home and abroad. The slender cross-section is a crucial parameter for



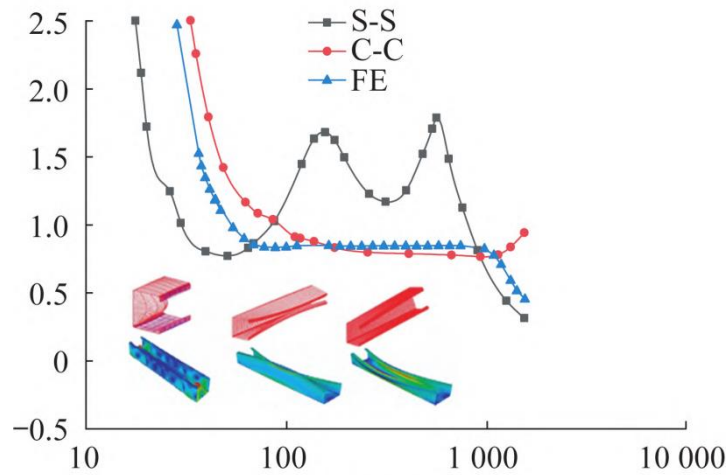
depicting the deformation degree of structures or components under loading conditions. The concept of the slender cross-section is extensively applied in multiple domains such as materials science, structural engineering, and mechanical design. It is mainly employed to measure the extent of deformation perpendicular to the force direction when a component is subjected to axial force. Specifically, the slender cross-section is associated with the length, cross-sectional dimensions, and constraints at both ends of the component. For instance, when the length of the component increases or the cross-sectional size reduces, or the constraints at both ends of the component weaken, the value of the slender cross-section will increase, indicating that the stability of the component deteriorates. The slender cross-section is frequently utilized to assess the stability of a component under compressive loads. By calculating the value of the slender cross-section, engineers can determine whether a component is likely to experience instability and adopt corresponding design measures to ensure the safety and stability of the structure. Simultaneously, the slender cross-section is also employed to simplify three-dimensional equations into two-dimensional ones, especially when the ratio of the total length to the maximum thickness of the object is greater than 10, the complete equation can be simplified to a two-dimensional equation for solution. The improvement of design specifications related to slender cross-section stainless steel components still requires a comprehensive theoretical foundation and accurate experimental data for support. Based on the above background, this paper reviews the research taking slender cross-section stainless steel columns as the object of study, analyzes the pros and cons of combining experimental research and numerical simulation analysis methods, and summarizes and reveals the failure process and failure mechanism of the relevant buckling.

## 2. Analysis of Flexural Capacity

In the research of Liu Meijing's team at Southeast University, they investigated the relevant stable bearing capacity of slender cross-section stainless steel columns by establishing finite element models that could accurately simulate welding residual stresses, geometric initial imperfections, and nonlinear material characteristics. Moreover, they carried out systematic parametric analyses of the main influencing factors and compared and analyzed the summarized experimental and finite element calculation results with theoretical calculation methods [2].

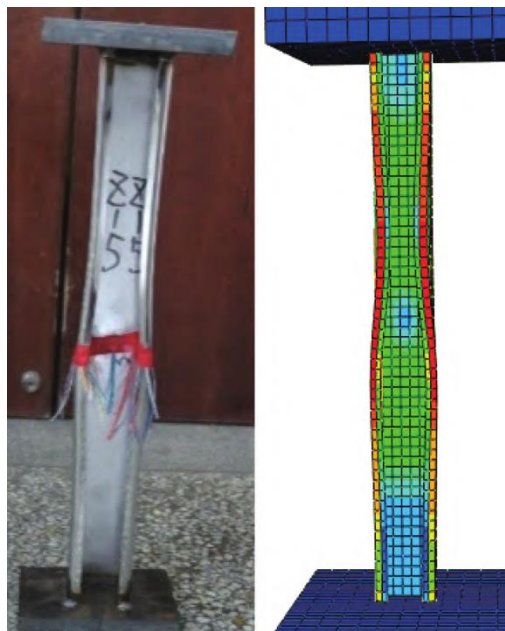
To study the buckling capacity of slender stainless steel columns under axial compression with distortion, he and his team first calculated the elastic buckling critical stress of slender stainless steel columns using ABAQUS and CUFSM softwares and combined three boundary conditions to determine a more reasonable calculation method. Then, they conducted finite element numerical analysis using a verified finite element model to obtain a large amount of data results.

Fig. 1 shows a comparison of the elastic buckling critical load factor of slender stainless steel members under axial compression with different boundary conditions. The vertical axis represents the load factor, and the horizontal axis represents the length, measured in millimeters. S-S and C-C represent the elastic buckling critical load obtained with the two end hinges and two end fixed conditions in the CUFSM software, respectively, and FE represents the actual test member's elastic buckling critical load calculated using the ABAQUS software. The length of the member in the ABAQUS software is the actual length, while the length of the member in the CUFSM software is not the actual length but the envelop curve obtained from different half-waves.



**Figure 1.** Relationship curves of load factor vs. member length [2]

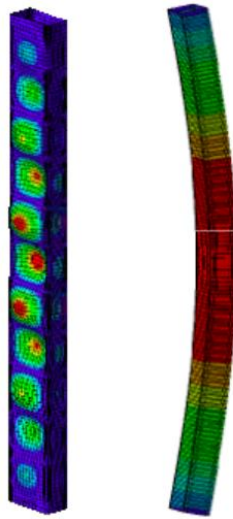
The comparison in Fig. 2 illustrates the congruity between the distortion buckling failure mode obtained through finite element simulation of the slender section stainless steel column conducted by our team and the experimental failure mode. It is evident from the Fig. 2 that both the finite element model and specimen exhibit distortion buckling failure, deviating from a straight line, with consistent distortion buckling failure modes observed across all component parts.



**Figure 2.** Comparison of failure modes between test and finite element results [2]

The first Technical Specification of Stainless Steel Structure in China has successfully completed the axial center loading test on 8 full-size welded slender box section stainless steel columns. The final failure mode observed in the specimens is a combination of associated instability, involving both local buckling of the plate and overall buckling of the member [3]. The research team responsible for this code has conducted specialized experimental research on the size and distribution of welding residual stress within slender specimen cross sections. They have proposed a simplified distribution model for residual stress. Prior to conducting the loading test, measurements were taken to determine the amplitude of local and global geometrical initial defects (referred to as  $w_0$  and  $v_0$  respectively). A finite element model was established using ABAQUS software, with mechanical properties determined based on longitudinal tensile test results. During finite element analysis, control reference nodes were established at both ends of the component, with their distance from the end face set equal to that between the rotation center of hinge support and end point in testing. To apply eccentricity to initial load at column's end, translation along coordinate axis was used by adjusting position of

reference node. As depicted in Fig. 3, lowest order local and global buckling modes are considered as distribution patterns for local and global geometric initial defects respectively. These two geometric defects are linearly superimposed according to measured defect amplitudes from specimen [3].



**Figure 3.** Shapes of initial local and global geometric imperfections [3]

A total of 110 numerical examples were utilized to analyze the influence of geometric initial defects, with the regularized slenderness ratio of components ranging from 0.22 to 1.62. The analysis reveals that for components with relatively small length and thickness, the impact of initial defects on the overall performance is minimal. However, for components with larger dimensions and fineness, the effect of local initial defects can be approximately disregarded. In contrast, for members falling within the range of medium-length columns in terms of slenderness ratio, both local and global geometric initial defects have a significant influence on stability capacity. An increase in defect amplitude substantially reduces both local and global stability capacity related to these members.

The presence of welding residual stress and geometric initial defects in elongated stainless steel members also significantly diminishes their actual local buckling stress but allows them to continue bearing loads after buckling due to considerable strain hardening ability inherent in stainless steel materials. Nevertheless, considering the adverse impact plate buckling has on overall member stability, it is advisable to calculate effective plate width or employ direct strength methods to reduce loadings. The direct strength method treats the entire section as a whole rather than calculating individual plates separately. This approach simplifies calculations for complex-shaped sections while better accounting for component part constraints compared to effective width methods. However, the direct strength method also has certain limitations. Firstly, accurately calculating the elastic buckling stress of the entire cross-section is rather complicated and requires the application of methods such as the finite strip method. Secondly, when the cross-section contains plate components with a large width-to-thickness ratio, due to their low elastic buckling stress, the calculation results of the direct strength method tend to be conservative. In such cases, the effective width method should be adopted instead.

The failure processes related to local and distortional buckling in each specimen are fundamentally similar. All specimens initially experience distortional buckling, and local buckling occurs when the load approaches the extreme point. The half-wave length of local buckling in each specimen is significantly shorter than that of distortional buckling [4]. Before the load reaches the extreme point, the amplitudes of local and distortional buckling deformations of the specimens are relatively small. During the stage of load carrying capacity decline, the local and distortional buckling deformations of each specimen develop rapidly. For specimens with rotations around the weak axis of the cross-section at both ends, the distortional deformation of the flanges on both sides develops rapidly during the stage of load carrying capacity decline. The local buckling wave of the web is covered by the web

bulging caused by the distortional deformation, resulting in an insignificant local buckling deformation in the final failure mode of the specimen. Specimens that undergo failure related to local and distortional buckling all exhibit distortional buckling first, and local buckling occurs when the load is close to the extreme point. After buckling, the post-buckling strength of the specimens is very small or even approaches zero, and the buckling failure of most specimens is sudden.

In conclusion, based on the experiments and investigations, the local and distortional buckling bearing capacity of slender cross-section stainless steel columns is negatively correlated with the amplitude of the initial geometric defects of the components and positively correlated with the proportion of the cross-sectional area in the corner zone and the nominal yield strength of the stainless steel material.

### **3. Stability Analysis**

The team led by Yuan Huanxin employed the effective width method and direct strength method to account for the adverse effects of local buckling on the overall stability of the member, and subsequently calculated the corresponding stable bearing capacity. The design curves derived from these two methods were compared against experimental and finite element calculation results [3]. The comparison revealed that the Perry-effective width method overestimated both local and global relative stability capacities of welded stainless steel box columns by 12% when compared to experimental and finite element results. On average, the calculated strength obtained through Perry-direct strength method was found to be 1.03 times higher than that determined through testing and finite element calculations. This discrepancy can be attributed to neglecting welding residual stress in theoretical calculations, as such stress significantly weakens relevant stable bearing capacities within sections. Additionally, complications arise during application due to complex calculation processes associated with initial defect item.

In accordance with European specification EN 1993-1-4, reference values for material strength index and strain hardening index are provided for commonly used Austenitic and biphasic stainless steels. This allows determination of normalized yield strength and strain hardening index ranges applicable to these materials. Finite element calculations encompassed both types of stainless steel by considering a range of values for these coefficients. Based on test data alongside numerical results from finite element analysis, appropriate modifications were made to original defect coefficient as well as slenderness ratio limit value. A comparison between design curves obtained using modified formulas against experimental data and finite element calculations demonstrated improved accuracy when compared with existing theoretical calculation methods.

### **4. Applied Researches**

The slender column structure is widely used in the industrial field. In various fields of precision equipment, the slender column structure is often used as the pile leg of the platform and mainly bears the axial pressure [5]. At the same time, the slender stainless steel column has a wide range of applications in modern production and life because of its corrosion resistance, high strength and beautiful features. In modern architecture, slender stainless steel columns are often used as support structures, such as stair railings, balcony guardrails, curtain wall supports. Its high strength and corrosion resistance ensure the safety and durability of the building. At the same time, the gloss and texture of stainless steel also add a modern feel to the building. In modern furniture design, slender stainless steel columns are also often used to make the legs or frames of tables and chairs. This design is not only stable and durable, but also simple and generous, in line with modern aesthetic trends. Stainless steel is also easy to clean and maintain, making furniture more practical. In the field of medical devices, slender stainless steel columns can be used to make the handle portion of surgical instruments, providing stable support and precise operation. Its corrosion resistance also ensures that surgical instruments can maintain good performance after a long time of use. In some industrial equipment, the slender stainless steel column can be used as a drive shaft or support rod. Its high strength and wear resistance ensure the stable operation and long-term use of the equipment. At the

same time, stainless steel is also easy to clean and maintain the equipment. In addition to practicality, slender stainless steel columns also have a wide range of applications in the field of decoration. It can be made into a variety of exquisite crafts or decorations, such as sculptures, screens, to add a unique beauty to the indoor environment. Slender stainless steel columns are widely used in practical production and life, covering many aspects such as construction, furniture, medical treatment, industry and decoration. Its excellent performance and beautiful appearance make it an indispensable part of these fields.

With the continuous progress of science and technology and the continuous development of industry, the application prospect of slender stainless steel column in future production will be broader. In the field of intelligent manufacturing, slender stainless steel columns can be used as key components of robots or automation equipment, such as robotic arms, conveyor belt supports. With the popularization of artificial intelligence and automation technology, the demand for high-performance, high-reliability parts will continue to increase, and slender stainless steel columns with their excellent performance and durability will play an important role in this field. In the new energy industry, such as wind power generation, solar power generation and other fields, slender stainless steel columns can be used to make brackets or towers, providing a strong guarantee for the stable operation of new energy equipment. With the continuous development and promotion of new energy technologies, the demand for high-performance, corrosion-resistant stainless steel materials will continue to grow. In the aerospace field, slender stainless steel columns can be used to make structural components of aircraft, rockets and other aircraft, such as wing skeleton, tail support. Due to the extremely high requirements for lightweight, high strength and corrosion resistance of materials in the aerospace field, slender stainless steel columns will be widely used in this field with their unique advantages [6]. At the same time, in environmental protection projects, slender stainless steel columns can be used to make support structures for environmental protection facilities such as sewage treatment equipment and waste incinerators. Its corrosion resistance and strength will ensure the long-term stability of these facilities even in harsh environments.

In summary, the application prospect of slender stainless steel tower in future production is very broad. With the continuous progress of science and technology and the continuous development of the industry, it is believed that it will play an important role in more fields, bringing more convenience and well-being to human production and life.

## **5. Conclusion**

The primary focus of this paper is to investigate the bending bearing capacity and stability analysis of slender stainless steel sections, as well as discuss its application research. The following conclusions have been drawn:

- (1) In terms of bending capacity, the finite element numerical model accurately simulates the mechanical properties of nonlinear stainless steel materials, including the residual stress from cross-section welding, initial defects in local and global geometry, and eccentricity in initial loading. It has been observed that welding residual stress and variations in local and global geometrical initial defects significantly affect the relative bending ultimate bearing capacity of the member.
- (2) Regarding stability analysis, it is crucial to consider the influence of material strength index and strain hardening index on component stability. Parametric analysis was conducted to examine various factors such as initial geometric defect distribution mode, amplitude of geometric defects, strain hardening coefficient of stainless steel material, cold working effect, and relative bending slenderness ratio on component mechanical properties. Results indicate that parameters like initial geometric defect amplitude, material cold working effect, and particularly relative bending slenderness ratio play significant roles in determining component stability.
- (3) In terms of applied research, slender stainless steel columns are extensively utilized across diverse fields. With continuous advancements in science and technology expected in future

developments, slender stainless steel columns will find increased applications within high-tech industries.

## References

- [1] G.P. Shu, B.F. Zheng, S.G. Fan, X.M. Shen, Study on flexural stability of stainless steel columns under axial loading, *Journal of Building Structures* 34.11 (2013) 116-122
- [2] M.J. Liu, M.H. Chen, G.M. Pan, et al. Edge stainless steel column C shape section distortional buckling direct strength method, *Progress in Steel Building Structures* 25.05 (2023) 70-74
- [3] H.X. Yuan, Y.Q. Wang, Y.F. Zhu, et al. Behavior of interactive buckling in welded stainless steel box section columns, *Engineering Mechanics* 32.09 (2015): 84-91.
- [4] C.X. Li. Study on local distortion related buckling of rolled C-section stainless steel column, Nanjing: Southeast University, 2021.
- [5] L.H. Wang, J. Feng and W.X. Tang, Multimodal buckling characteristics of stainless steel column shell with initial defects, *China Offshore Platform* 38.02 (2023) 84-90+96.
- [6] D. Liang. Study on integral distortion related buckling of rolled C-section stainless steel beams, Nanjing: Southeast university, 2023.