Research Progress and Review of Stainless Steel Civil Architecture

Xuan Chang*, Hong-gang Lei*

College of Civil Engineering, Taiyuan University of Technology, Taiyuan 030024, China

*email:844355710@qq.com

*Corresponding author’s e-mail: leihonggang@tyut.edu.cn

Abstract: Compared with carbon steel, stainless steel has a series of excellent characteristics, such as beautiful shape, corrosion resistance and ductility. China as a large stainless steel production, but in the face of the study of stainless steel in the building is not thorough, in order to better use of stainless steel in the building structure, we need to increase the study of stainless steel. Through a large number of retrieval of domestic and foreign relevant scholars research, in this paper, the research achievements and progress of stainless steel civil building are reviewed from two aspects: stainless steel material and stainless steel connection. By comparing the similarities and differences between Chinese and European stainless steel codes, this paper finds out the shortcomings, and finally puts forward some suggestions on the application and research of stainless steel in civil buildings.

1. Introduction

Stainless steel entered people's field of vision as early as the 1820s because of its beautiful appearance, strong corrosion resistance, good impact toughness, easy maintenance, and high comprehensive cost-effectiveness. At that time, due to the lack of understanding of stainless steel materials, the application of stainless steel in construction engineering was limited to very few occasions [1]. For example, it is used as a non-structural component in very small building components, such as doors and windows, wall panels, and floors. The Chrysler Building (Figure 1), which was completed in 1930, uses stainless steel as its exterior decoration. In the past 20 years, stainless steel structures have been widely used in airports, railway stations, shopping malls, etc. Many typical stainless steel buildings have also appeared at home and abroad, such as (Figure 2).
Table 1 lists typical buildings since the development of stainless steel. It can be seen from the table that foreign research on stainless steel structures is relatively mature. The application of stainless steel materials in the structure in my country is mainly limited to exterior decoration. Although the application of stainless steel materials in my country has become more and more normal in recent years, such as the entrance hall of the Great Hall of People in Haikou and Datong Local Taxation Bureau. As the world's largest producer of stainless steel, my country has not yet matured theories. The use of stainless steel structures in the main body of buildings or the main force-bearing components is subject to many restrictions. It is urgent to increase the research on stainless steel.

| Building name                      | Year | Address          | Structure form          |
|-----------------------------------|------|------------------|-------------------------|
| London's Savoy, The grand hotel   | 1929 | London           | Non-load bearing member |
| Sydney Opera House                | 1998 | Sydney           | Load-bearing member     |
| Shanghai Jin Mao Tower            | 1999 | Shanghai         | Non-load bearing member |
| The arched pedestrian viewing bridge of the York Group | 2001 | United Kingdom   | Non-load bearing member |
| Appet Bridge                      | 2005 | Stockholm, Sweden| Load-bearing member     |
| Gala Galdana Bridge               | 2005 | Menorca, Spain   | Load-bearing member     |
| Stonecutters Bridge, Hong Kong    | 2008 | Hong Kong        | Load-bearing member     |
| Guangzhou Asian Games Gymnasion   | 2010 | Guangzhou        | Non-load bearing member |
| Helix bridge                      | 2010 | Singapore        | Load-bearing member     |
| Sheik Zayed Bridge                | 2010 | UAE              | Load-bearing member     |
| Hong Kong-Zhuhai-Macao Bridge     | 2018 | Guangdong Province | Load-bearing member    |
| Qingshan Yangtze River Bridge     | 2019 | Wuhan            | Load-bearing member     |

This article briefly introduces stainless steel materials and stainless steel connections, combines European norms and Chinese norms, finds out the similarities and differences, and summarizes the content that is lacking in domestic and foreign stainless steel norms. Finally, the problems facing my country's stainless steel structure are reviewed.

2. Stainless steel material

2.1. Classification of stainless steel materials

There are many varieties of stainless steel, considering the heat treatment production process, classification according to microstructure and heat treatment characteristics is more practical. It is divided into five categories: martensite, ferrite, austenite, duplex and precipitation hardening [2]. Among them, martensitic stainless steel and precipitation hardening stainless steel cannot be used in structural engineering due to their poor welding and cold working properties. Due to the brittleness
tendency of ferritic stainless steel, this serious limitation has become the difficulty and key to its
development. Commonly used stainless steels are austenitic S30403, S30408, S31603, S31608 and
duplex stainless steels S22253 and S22053.

According to the formula provided in the technical regulations for stainless steel structure CECS
410:2015, the stress-strain curve of commonly used stainless steel is drawn:

![Stress-Strain Curve Diagram](image)

**Figure 3. Stress-Strain Curve Diagram**

### 2.2. Research on stainless steel materials at home and abroad

Since the Taiyuan Iron and Steel Company produced the first furnace of stainless steel in September
1952, my country has started the production of stainless steel. After nearly 70 years of development,
my country has become the largest country in stainless steel production. In the 20th century, my
country's stainless steel development has entered the fast lane. China's stainless steel crude steel
output accounted for 56.3% of it. Scholars at home and abroad have also begun to study stainless steel
materials.

The world’s important stainless steel design codes include European standards: ENV1993-1-4 ,
and European standards EN 1993-1-4 (hereinafter referred to as European standards) , the American
Standard ASCE/SEI 8-02, AS/NZS in the Australian/New Zealand standard 4673:2001 "Cold-formed
stainless steel structure", in addition to Sweden (SIS), United Kingdom (BSI), Germany (DIN) and
other countries regarding stainless steel design provisions. At present, the domestic CECS 410: 2015
"Technical Specification for Stainless Steel Structures" has been officially promoted and used in
December 2015.

This section compares the classification and properties of stainless steel materials in the European
standard EN1993-1-4 [3] and the Chinese stainless steel design code CECS 410:2015 (fu is the
ultimate tensile strength and fy is the yield strength). The ultimate tensile strength and yield strength
of cold-rolled steel strip, hot-rolled steel strip, hot-rolled steel plate, steel bar, steel bar and section
steel are divided in detail in the European standard, but the Chinese standard (hot-rolled, cold-rolled)
steel pipe, The ultimate tensile strength and yield strength of steel strips are uniformly specified.

| CECS 410: 2015 Austenitic stainless steel (Commonly used) |
|----------------------------------------------------------|
| S30408 | S30403 | S31608 | S31603 | S22053 | S22253 |
| fy | fu | fy | fu | fy | fu |
| 205 | 515 | 170 | 485 | 205 | 515 |

| EN1993-1-4 Austenitic stainless steel (Hot rolled steel strip) |
|---------------------------------------------------------------|
| 1.4301 | 1.4306 | 1.4401 | 1.4404 | 1.4362 | 1.4462 |
| fy | fu | fy | fu | fy | fu |
| 210 | 520 | 200 | 520 | 220 | 530 |

Table2. Commonly used Chinese and European austenitic and duplex stainless steel (N/mm²)
It can be seen from the table that the ultimate tensile strength and yield strength of the two specifications specified in the Eurocode for duplex stainless steel and the Chinese specification are close, while the yield strength and ultimate tensile strength of the austenitic stainless steel in the Eurocode are both greater than Austenitic in Chinese specifications. Shows that China's stainless steel specifications are more conservative.

3. Stainless steel connection

3.1. The status quo of stainless steel joint connections

In many major earthquakes at home and abroad, ordinary carbon steel structures suffered brittle fracture at the first-level welds at the beam-column connection, and the seismic performance was not very satisfactory. Therefore, domestic and foreign scholars began to explore the joints through high ductility stainless steel materials.

3.2. Research on stainless steel connection at home and abroad

3.2.1. Research on stainless steel connection in domestic and foreign standards

The yield strength and ultimate tensile strength of stainless steel bolts are consistent with the values specified in the European standard [3] and the Chinese standard [2].

| Specification | Tensile capacity | Shear capacity |
|---------------|------------------|----------------|
| CECS 410: 2015 | $N_r \leq N^b_r$ | Shear at the thread; $N^b_v = 0.86k_dn_v \pi d^2 f^b_v$ $N^b_c = d_c \sum f^b_c$ |
| EN1993-1-4    | $f_{u,red} = \frac{\pi d^2 f_v}{4}$ | Shear at non-thread; $N^b_v = k_dn_v \pi d^2 f^b_v$ $N^b_c = d \sum f^b_c$ |

The formula for calculating the tensile bearing capacity of stainless steel bolts in China and Europe is shown in Table 3. In EN-1993-1-4, the support strength is calculated by using the reduction value $f_{u,red}$ obtained by $f_{u,red} = 0.5f_y + 0.6f_u$ instead of $f_u$. The stainless steel bolts whose shear force reaches EN ISO 3506 performance classes 50, 70 and 80 are regarded as bolts of class 4.6, 5.6 and 8.8. In calculating the shear bearing capacity of stainless steel bolts, the ultimate tensile bearing capacity of stainless steel is taken as the ultimate bearing capacity, and the gross cross-sectional area of stainless steel bolts is also considered. Clearly stated in this specification: If the shear plane passes through the unthreaded part of the bolt, then $\alpha = 0.5$; If the shear surface passes through the threaded part of the bolt, then $\alpha = 0.6$.

According to the relevant regulations on the shear capacity of stainless steel bolts given in the above two specifications. Calculate the shear bearing capacity of the austenitic stainless steel bolt M39 and the bolt with performance class 50 in the two specifications.

| Specification | Shear capacity at thread (N) | Shear capacity at non-thread (N) |
|---------------|-----------------------------|-------------------------------|
| CECS 410: 2015 | 155A_e | 133.3A_e |
| EN1993-1-4    | 240A | 200A |
In comparison with the table, the shear capacity obtained in EN1993-1-4 is about 1.5 times that calculated in CECS 410:2015. Through the comparison of the mechanical and physical properties of stainless steel and stainless steel bolts, the calculation of the bolt shear bearing capacity shows that the shear bearing capacity of the bolts specified in the Eurocode is stronger than that of the Chinese stainless steel code.

3.2.2. Research on fatigue of stainless steel joints in domestic and foreign codes
Although stainless steel has good ductility, in real life, fatigue and fracture problems caused by repeated cyclic loads sometimes occur. For example, the structure is repeatedly swayed under the action of strong earthquakes, the bridge structure on the sea is affected by the waves, and the crane beam is affected by the crane. Therefore, in recent years, domestic and foreign scholars have carried out research on stainless steel fatigue.

3.2.3. Research on stainless steel connections by domestic and foreign scholars
In the overall stability of components, Yang Lu [5-17] and others have more than 20 papers on the overall stability of stainless steel components. It is concluded that the slenderness ratio is the main factor affecting the bearing capacity of the components. Zheng Baofeng, Shu Ganping [18-23] and others conducted finite element analysis on the axially compressed components of cold-formed rectangular tube section, and concluded that the larger factor affecting the overall stability of the component is the overall defect of the component, not the section of the component. On this basis, it is refined to the experimental research of cold-formed stainless steel tube axial compression column, and the influence of slenderness ratio and width-thickness ratio on axial compression failure is analyzed. In terms of local stability, Wang Yuanqing, Yuan Huanxin [24-30] and others analyzed the local stability performance of axial compression and related stability performance for welded box-section stainless steel columns, short columns and I-shaped short columns, and based on this Numerical analysis of the shear buckling performance of stainless steel welded thin web beams.

In terms of bolt connection, Guan Jian, Wang Yuanqing [31-36] and others, Get the influence factors of the pressure-bearing performance of the stainless steel high-strength bolt connection. In 2017, Wang Yuanqing [37] and others found that the hysteresis curves of all components have different degrees of slip and pinch phenomenon. E.L. Salih [38, 39] studied the failure of stainless steel bolted joints. Zou Ruomeng [40-42] and Wu Yaohua [43] compared Chinese and European and American stainless steel connection design specifications respectively, and provided a basis for the formulation of Chinese specifications, and concluded that the Chinese specifications for welding connection design are generally reasonable.

| Thesis Title | Author | Research Object | Conclusion |
|--------------|--------|----------------|------------|
| Experimental Study on Fatigue Life of 304 Stainless Steel Strain-hardened | Jiang Gongfeng and others | 304 stainless steel | Pre-strain strengthening can increase the design fatigue life of the structure. |
| Study on the Constitutive Relationship of Austenitic and Duplex Sainless Steel Materials Under Cyclic Loading | Chang Xiao | Austenitic stainless steel, duplex stainless steel | Proves the necessity of studying the fatigue performance of stainless steel materials |
| Experimental Research on High Cycle Fatigue of SUS301L Stainless Steel Welded Joints | Mi Congcong | SUS301L stainless steel | The higher the stress ratio, the shorter the fatigue life |
| Research Progress of Low-Cycle | Dai Xinyu | Austenitic | The key factors affecting material |
Fatigue Properties of Austenitic Heat-Resistant Steel[48] 

| Initiation and Propagation of Fatigue Cracks From Surface[49] | P. Cussac | 304L austenitic | The presence of surface irregularities greatly reduces fatigue life |
|-------------------------------------------------------------|----------------|----------------|-------------------------------------------------------------|

In the part of stainless steel connection, domestic and foreign scholars mainly study the load-bearing performance and deformation capacity of welding, bolted and bolt-welded mixed connections. The research on stainless steel fatigue mainly focuses on the low-cycle fatigue of stainless steel welded or bolt-welded connections under seismic loads and the fatigue life under cyclic reciprocating loads. Chen Zhihua [50] pointed out that the current domestic research on stainless steel structures is seriously lagging behind and lacks corresponding structural design methods. He analyzed the characteristics of stainless steel welded bolt joints, but did not involve the fatigue problem of stainless steel bolt joints. The fatigue failure of civil steel structure in normal use (except for special circumstances such as earthquakes) is mostly high-cycle fatigue failure. When it is broken, there is no obvious plastic deformation, and the failure is sudden and harmful. Although many models have been established for fatigue life prediction, there will be certain deviations for some new materials, and a suitable life prediction model needs to be established.

4. Summary and outlook

For stainless steel components, domestic mainstream stainless steel grades should be used as the main test materials to study the local stability of plates in compression, bending and shear, and provide as much test data as possible.

At present, there are few researches on the high-cycle fatigue failure and hysteretic properties of stainless steel at home and abroad. In the future, scholars should conduct in-depth research on high-cycle fatigue and stainless steel hysteretic properties to form a complete fatigue design specification for stainless steel.

Although more and more buildings at home and abroad use stainless steel structures, a complete stainless steel structure system has not yet been formed. This is the direction for the majority of scholars in stainless steel.

Acknowledgments

The author would like to thank the instructor for his patient guidance and colleagues for their enthusiastic help. Thank you for the strong support of the college, and finally thank Taiyuan University of Technology for your meticulous training.

References

[1] Y.Q. Wang, H.X. Yuan, Y.J. Shi, et al. (2010) Application and research status of stainless steel structure. Steel Structure. 25(02): 1-12.
[2] (2015). China Technical Regulations for Stainless Steel Structures.
[3] (2006). European design code for stainless steel structures: EN 1993-1-4 2006.
[4] (2017). Steel structure design standard.
[5] Y.A. Zhang, L.Yang, M.H. Zhao, et al. (2014) Research progress on the stability of stainless steel axial compression members. In: Hefei, Anhui, China: 10.
[6] L. Yang, D.C. Xu, F. Shang, et al. (2015) Experimental study on the overall stability of dual-phase stainless steel welded box-section axial compression members. Journal of Southeast University (Natural Science Edition). 45(02): 364-369.
[7] L. Yang, Y.A. Sun, K.Y. Ning, et al. (2019) Experimental study on the overall stability of hot-rolled stainless steel round tubular column axial compression members. Steel Structure (Chinese and English), 34(08): 10-16.
[8] L. Yang, K.Y. Ning, H.Y. Ban, et al. (2018) Experimental study on bending buckling of stainless steel welded box section compression members. Engineering Mechanics. 35(12): 143-150.

[9] F. Shang, L. Yang, M.H. Zhao, et al. (2016) Finite element study on overall stability of stainless steel I-shaped section axial compression members. Engineering Mechanics. 33(03): 112-119.

[10] L. Yang, F. Shang, M.H. Zhao, et al. (2017) Calculation method of overall stability bearing capacity of stainless steel box-shaped axial compression members. Journal of Harbin Institute of Technology. 49(06): 124-129.

[11] L. Yang, F. Shang, M.H. Zhao, et al. (2016) Calculation method for the overall stability of stainless steel I-shaped section members under axial compression. Journal of Hunan University (Natural Science Edition). 43(03): 55-65.

[12] F. Shang, L. Yang, M.H. Zhao, et al. (2016) Finite element study on the overall stability of stainless steel box section axial compression members. Building Structure., 46(06): 66-70.

[13] L. Yang, D.C. Xu, F. Shang, et al. (2015) Experimental study on the overall stability of duplex stainless steel welded I-shaped cross-section axially compressed columns. Journal of Building Structures. 36(07): 99-105.

[14] Y.H. Zhou, L. Yang, W.X. Zhang, et al. (2017) Summary of research on bearing performance of stainless steel tube concrete short columns under axial compression. Sichuan Architecture. 37(04): 177-179.

[15] L. Yang, D.C. Xu, F. Shang, et al. (2015) Experimental study on the overall stability of austenitic stainless steel welded I-section axial compression members. China Civil Engineering Journal. 48(11): 9-15.

[16] L. Yang Lu, D.C. Xu, Y.Q. Wang, et al. (2014) Experimental study on the overall stability of austenitic stainless steel welded box-section axial compression members. China Civil Engineering Journal. 47(08): 83-88.

[17] K.Y. Ning, L. Yang, H.Y. Ban. (2020) Research on seismic performance of stainless steel box-section columns. China Civil Engineering Journal. 53(04): 23-30.

[18] B.F. Zheng, G.P. Shu, X.M. Shen. (2011) Experimental study on the mechanical properties of stainless steel materials at room temperature. Steel Structure. 26(05): 1-6.

[19] G.P. Shu, B.F. Zheng, X.M. Shen. (2012) Research on calculation method of in-plane stability bearing capacity of stainless steel compression-bending members. Industrial Construction. 42(05): 41-44.

[20] B.F. Zheng, G.P. Shu, X.M. Shen. (2012) Finite element analysis of the section of stainless steel cold-formed tube under axial compression. Industrial Construction. 42(05): 12-20.

[21] G.P. Shu, B.F. Zheng, S.G. Fan, et al. (2013) Analysis of bending buckling bearing capacity of stainless steel axial compression columns. Journal of Building Structures. 34(11): 116-122.

[22] G.P. Shu, B.F. Zheng, X.M. Shen. (2013) Experimental study on cold-formed stainless steel tube axial compression column. Journal of Building Structures. 34(05): 87-95.

[23] R. Yang, B.F. Zheng, G.P. Shu. (2015) Current status of experimental research on stainless steel round pipe bending members and comparative analysis of specifications. Jiangsu Architecture. 01: 19-23.

[24] Y.Q. Wang, H.X. Yuan, Y.J. Shi, et al. (2013) Residual stress test and distribution model of stainless steel welded box section. Journal of Southeast University (Natural Science Edition). 43(05): 979-985.

[25] H.X. Yuan, Y.Q. Wang, X.X. Du, et al. (2015) Local stability of short column with stainless steel welded box section under axial compression. Journal of Southeast University (Natural Science Edition). 45(04): 769-775.
[26] Y.Q.Wang, H.X.Yuan, Y.J.Sheng, et al. (2012) Research progress on the stability of stainless steel structural members. Industrial Construction. 42(05): 1-11.

[27] H.X.Yuan, X.X.Du, Y.Q.Wang, et al. (2015) Calculation of the stable bearing capacity of stainless steel box columns considering relative buckling. Industrial Construction. 45(12): 18-22.

[28] Y.Q.Wang, H.X.Yuan, X.X.Du, et al. (2015) Local buckling analysis of stainless steel welded I-shaped section axial compression members. Industrial Construction. 45(12): 13-17.

[29] H.X.Yuan, Y.Q.Wang, X.X.Du, et al. (2015) Experimental study on local stability of stainless steel welded I-shaped short columns under axial compression. Journal of Building Structures. 36(05): 38-45.

[30] H.X.Yuan, Y.Q.Wang, Y.J.Sheng, et al. (2015) Experimental study on stability of stainless steel welded box-section column under axial compression. China Civil Engineering Journal. 48(02): 63-72.

[31] J.Guan, Y.Q.Wang, Y.Zhang. (2010) Research on stainless steel connection node and its engineering application. In: Ningbo, Zhejiang, China: 16.

[32] J.Guan Jian. Research on the residual stress of bolted joints and welded I-shaped sections of stainless steel components. Beijing Jiaotong University, 2012.

[33] J.Guan, Y.Q.Wang, Y.Zhang, et al. (2012) Influencing factors on the pressure-bearing performance of high-strength bolted joints of stainless steel members. Journal of Beijing Jiaotong University. 36(04): 115-120.

[34] J.Guan, Y.Q.Wang, Y.Zhang, et al. (2012) Comparison of design methods of bolted joints in stainless steel structures. Journal of Building Science and Engineering. 29(01): 115-120.

[35] Y.Q.Wang, J.Guan Jian, Y.Zhang Yong, et al. (2013) Anti-slip coefficient test of the friction surface of the bolt connection of stainless steel components. Journal of Shenyang Jianzhu University (Natural Science Edition). 29(05): 769-774.

[36] Y.Q.Wang, L.Yang, J.Guan, et al. (2015) Long-term test monitoring of strain relaxation of stainless steel bolts. Journal of Shenyang Jianzhu University (Natural Science Edition). 31(02): 201-208.

[37] Y.Q.Wang, X.L.Qiao, L.G.Jia, et al. (2018) Finite element analysis of seismic performance of stainless steel beam-column joints with different connection methods. Journal of Shenyang Jianzhu University (Natural Science Edition). 34(01): 1-10.

[38] E. L. Salih, L. Gardner, D. A. Nethercot. (2010) Numerical analysis of net section failure in stainless steel bolted connections. Steel Structure. 25(12): 83.

[39] E. L. Salih, L. Gardner, D. A. Nethercot. (2011) Study on the failure of stainless steel bolted joints. Steel Structure. 26(04): 84-85.

[40] R.M.Zou, J.Dong, J.X.Zhang. (2012) Comparison of design codes for stainless steel structure connection in the United States and Europe. Industrial Construction. 42(05): 63-66.

[41] X.L.Jin, R.M.Zou, J.Dong. (2013) Connection test of stainless steel fillet weld and design suggestions. Building Structure. 43(09): 78-82.

[42] R.M.Zou, J.Dong, X.L.Jin. (2013) Stainless steel butt weld connection test and design suggestions. Building Structure. 43(09): 83-87.

[43] Y.H.Wu, S.G.Qiu, Y.Zhang. (2015) Comparative analysis of stainless steel welding connection design methods between China and Europe and the United States. Building Structure. 45(15): 1-4.

[44] G.F.Jiang, L.Sun, G.Chen. (2014) Experimental research on fatigue life of 304 stainless steel strain-strengthening. Mechanical Strength. 36(06): 850-855.
[45] X.Chang, L.Yang, M.Wang, et al. (2019) Study on the constitutive relationship of austenitic and duplex stainless steel materials under cyclic loading. Engineering Mechanics. 36(05): 137-147.
[46] C.C.Mi. (2019) Research on High Cycle Fatigue Performance of SUS301L Stainless Steel Welded Joints. Southwest Jiaotong University.
[47] C.C.Mi, F.Q.Gao, H.L.Luo. (2020) Experimental study on high cycle fatigue of SUS301L stainless steel welded joints. Experiment Science and Technology. 18(02): 41-45.
[48] X.Y.Dai, X.D.Fang, F.H.Xu, et al. (2020) Research progress on low-cycle fatigue properties of austenitic heat-resistant steels. Iron and Steel. 55(03): 58-67.
[49] P. C, C. G, V. P, et al. (2019) Initiation and propagation of fatigue cracks from surface imperfections on 304L austenitic stainless steel. Procedia Structural Integrity. 19.
[50] Z.H.Chen, K.Weng, H.B.Liu, et al. (2012) Research status and engineering application of stainless steel in spatial grid structure. Industrial Construction. 42(05): 55-62.