Two Calculation Methods for Overall Stability Coefficients of Stainless Steel Welded I-section Beams

L. Yang[a], *Y.Q. Wang*[b,*], *B. Gao*[c], *Y.J. Shi*[b], *H.X. Yuan*[b]

[a]*The College of Architecture and Civil Engineering, Beijing University of Technology, Beijing 100124, PR China*
[b]*Key Laboratory of Civil Engineering Safety and Durability of China Education Ministry, Department of Civil Engineering, Tsinghua University, Beijing 100084, PR China*
[c]*China Southwest Architectural Design and Research Institute Co. , Ltd. , Chengdu 610081, PR China*

Abstract

The present investigation studies the overall stability bearing capacity of stainless steel welded I-section beams. Experimental tests of 8 specimens have been conducted. In addition, an finite element method (FEM), of which the validity has been verified by experimental results, is introduced to calculate the overall stability bearing capacity. Based on results of the FEM and experimental investigation and comparison of design standards for overall stability coefficients calculation of structural stainless steel, two calculation methods for overall stability coefficients of welded I-section beams are proposed. One is the modification of Chinese Code for design of steel structures, the other is the regression analysis results based on finite element analysis. Both methods have simple form and enough emergency capacity for engineering design.

Keywords

Stainless steel flexural member; Welded section; Overall stability coefficient; Calculation method

1 Introduction

Because of the high initial cost of stainless steel, the material has been traditionally regarded as extravagant for use as structural material in regular engineering structures [1]. Nonetheless, because of its high corrosion resistance, good fire resistance, ease of maintenance, good durability, aesthetics, and particularly low cost in whole life cycle, the use of stainless steel in civil engineering structures has been steadily growing in the past 15~20 years.

In comparison to carbon steel, the essential difference of stainless steel is the non-linear stress-strain curve [2-5]. Therefore, the structural design codes for carbon steel should not be applied directly to stainless steel because of its special strength and stiffness properties [6]. Nowadays, some countries/regions have published their national design code for stainless steel structures. But, such design standard has not been established in China yet.

When considering the overall buckling of steel beams, the overall stability coefficients is adopted for the convenience to calculate the ultimate loading capacity. And for stainless steel welded beams, it is necessary to take into account the effect of the low proportional limit, residual stresses and the gradual yielding behaviour of the material [7-16].

In this paper, two calculation methods for overall stability coefficients of stainless steel welded I-section beams are proposed. The base thinking is improved the existing calculation methods for carbon steel beams, which is the same to the existing codes and most researches. The finite element model is established and analyzed by using ANSYS, and its validity is verified by experimental test of eight specimens. Based on the experimental and finite element analysis results, two calculation methods for overall stability coefficients of stainless steel welded I-section beams are proposed and compared to that in EC3[17].

2 Numerical method and experimental validation

2.1 Finite element model

The numerical method has been used to study the flexural behaviour and the non-linear deformation of the stainless steel beams effectively [2,4]. In this paper, the finite element code ANSYS is used to investigate the overall stability capacity and the ultimate moment.

Stainless steel is a typical non-linear metal material, and the non-linear stress-strain relationship will influence the flexural behaviour of stainless steel beams. The stress-strain relationship is presented by using Ramberg-Osgood equation [18] in the FE model, as illustrated in Eq.(1):

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$$\varepsilon = \frac{f}{E_0} + 0.002\left(\frac{f}{f_{0.2}}\right)^n \quad f \le f_{0.2}$$

$$\varepsilon = \frac{f - f_{0.2}}{E_{0.2}} + \left(0.008 - \frac{f_{1.0} - f_{0.2}}{E_{0.2}}\right)\left(\frac{f - f_{0.2}}{f_{1.0} - f_{0.2}}\right)^{n'_{0.2,1.0}} + \varepsilon_{0.2} \quad f_{0.2} < f \le f_u \tag{1}$$

where E_0 is the initial Young's Modulus;

$f_{0.2}$ is the 0.2% proof stress;

$f_{1.0}$ is the 1.0% proof stress;

n denotes a constant, which can be given by $n=\ln(20)/\ln(f_{0.2}/f_{0.01})$;

$E_{0.2}$ is the tangent modulus corresponding to $f_{0.2}$;

$n'_{0.2,1.0}$ is the strain-hardening coefficient, which is expressed as[19]:

$$n'_{0.2,1.0} = 12.255\left(\frac{E_{0.2}}{E_0}\right)\left(\frac{f_{1.0}}{f_{0.2}}\right) + 1.037 \quad \text{for tension}$$

$$n'_{0.2,1.0} = 6.399\left(\frac{E_{0.2}}{E_0}\right)\left(\frac{f_{1.0}}{f_{0.2}}\right) + 1.145 \quad \text{for compression} \tag{2}$$

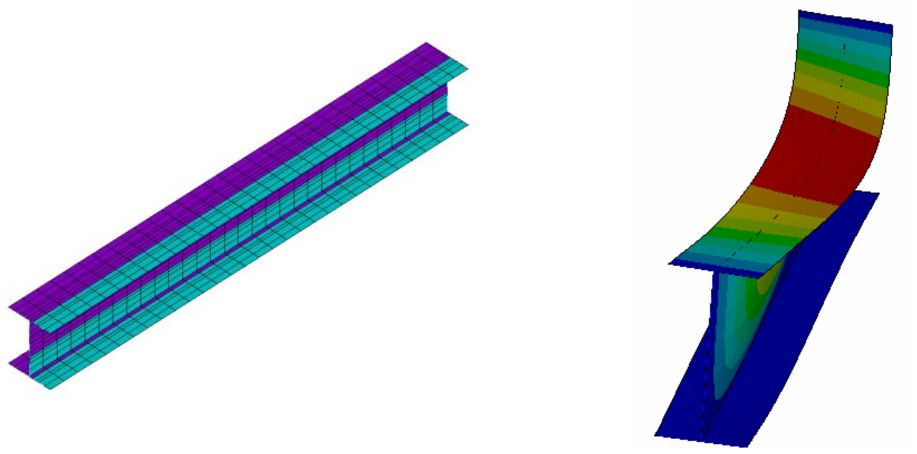
Since the welded I sections are used in the study, the welding residual stress need to be considered. As shown in Figure 1a), the model of residual stress distribution proposed by Gardner L [10] is adopted. The Figure 1b) shows the simplified model of residual stress distribution in the FE model.

a) Proposed residual stress model for stainless steel fabricated I sections[10]

b) Distribution of residual stress for the FE model

Figure1 Distribution of residual stress

The first buckling mode (with an maximum initial deformation of L/1000, where L is the length of specimen) of the specimen is included in the FE model as initial imperfection, and the FE model is shown in Figure 2.



a) Element meshing **b) Initial imperfection**

Figure 2 The element meshing and initial imperfection of the FE model

2.2 Experimental validation of numerical method

In order to testify the validity of the numerical method, tests of a set of 8 specimens have been conducted. The Geometry characteristic of the specimens is shown in Table 1**,** and Figure 3 shows the test stress-strain curves, which are closed to that obtained from Eq.(1) and Eq.(2).

Table 1 Measured geometrical details for the specimens

Specimen	Beam length	Laterally unbraced length	Compression flange		Tension flange		Web	
			Width	Thickness	Width	Thickness	Height	Thickness
	L (mm)	L_b (mm)	b_{fc} (mm)	t_{fc} (mm)	b_{ft} (mm)	t_{ft} (mm)	h_w (mm)	t_w (mm)
S-1	3599	1749.0	100.26	7.50	101.29	7.50	247.98	5.64
S-2	3299	1598.5	100.86	7.50	100.51	7.50	248.96	5.64
S-3	2999	1455.5	100.94	7.50	99.76	7.50	249.50	5.64
S-4	2405	1157.5	101.30	7.50	100.80	7.50	248.64	5.64
S-5	2200	1056.5	101.12	7.50	100.36	7.50	248.44	5.64
S-6	1998	956.5	100.08	7.50	100.87	7.50	248.48	5.64
S-7	2200	1055.0	99.56	7.50	130.13	7.50	200.52	7.50
S-8	2000	956.5	100.28	7.50	130.50	7.50	201.52	7.50

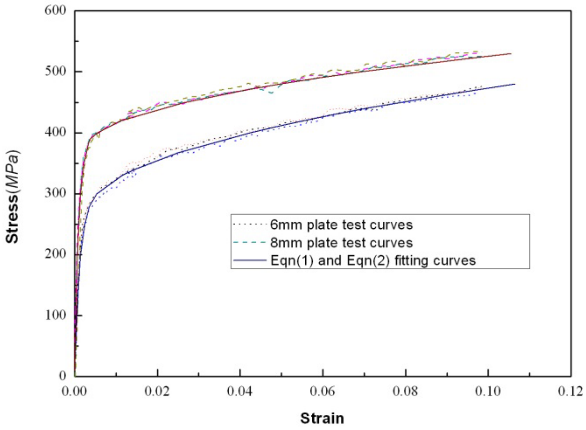


Figure 3 Comparison between measured stress-strain curves and fitting curves

The test scene is shown in Figure 4.

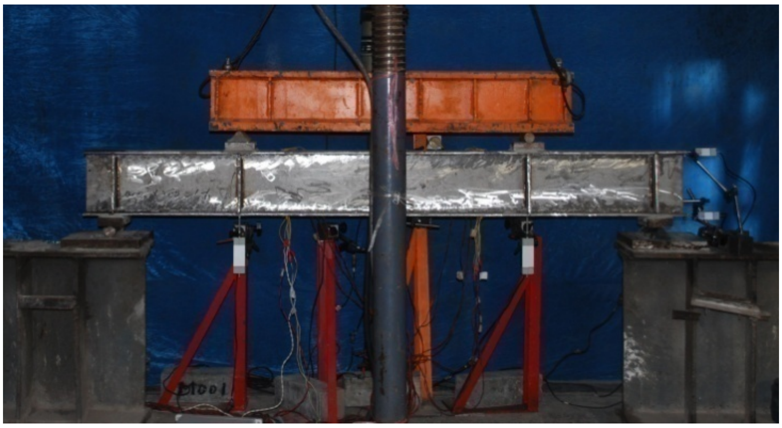


Figure 4 Test scene

The FE model is shown in Figure 5, in which the actual constraining conditions, loading procedure have been simulated.

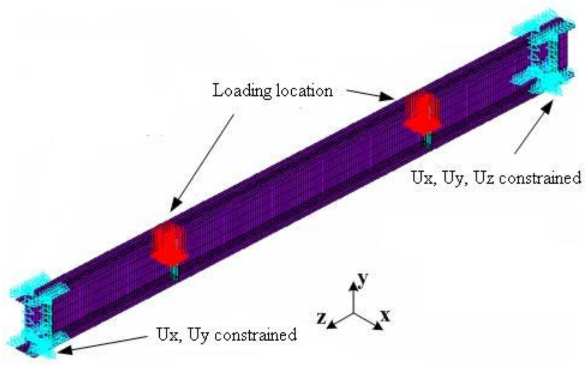
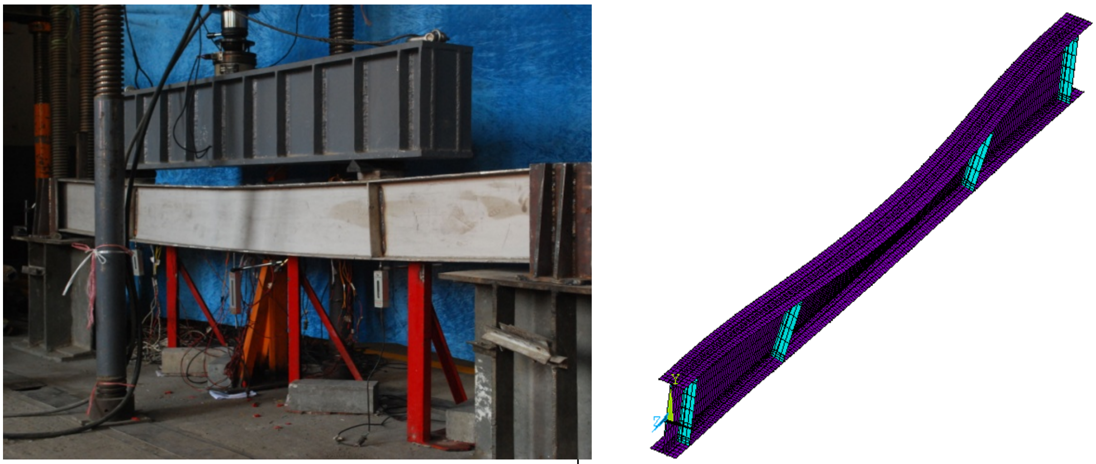


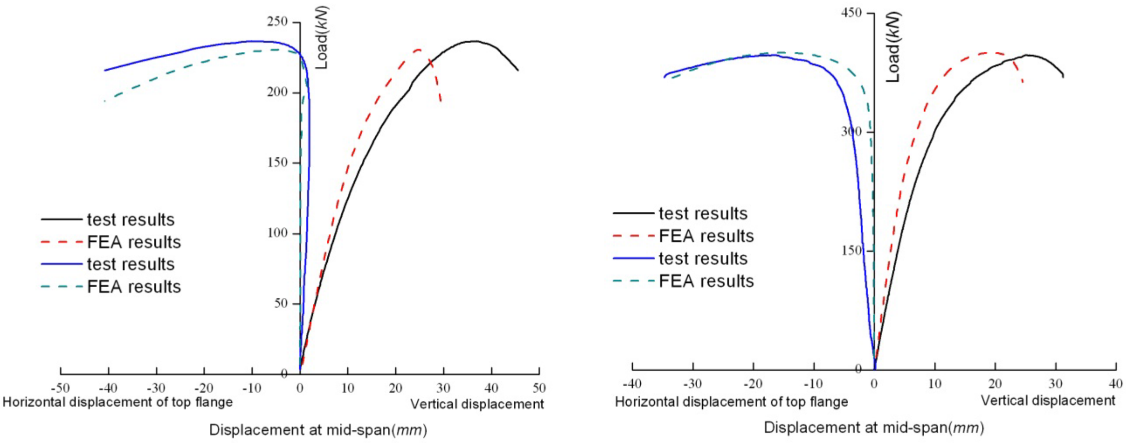
Figure 5 FE model

Figure 6 shows the comparison of failure modes by the experimental test and FEA. The comparison of load-displacement curves for typical specimens are shown in Figure 7, and the comparison of ultimate moments are illustrated in Table 2.



a) **Failure mode of experimental test** b) **Failure mode of FEA**

Figure 6 Comparison of experimental and finite element analysis failure modes



a) S-2 b) S-5

Figure 7 Comparison of experimental and finite element analysis load-deformation curves at mid-span for typical specimens

Table 2 Comparisons of ultimate loads between test results and FEA results

Specimen	Test result P_{Exp}(kN)	FEA result P_{rs}(kN)	P_{Exp}/P_{rs}	FEA result P_{nr}(kN)	P_{Exp}/P_{nr}
S-1	184.17	175.02	0.95	187.08	1.02
S-2	236.54	230.57	0.97	226.31	0.96
S-3	262.92	246.59	0.94	257.48	0.98
S-4	333.92	342.88	1.03	351.63	1.05
S-5	397.04	400.45	1.01	407.70	1.03
S-6	442.68	447.43	1.01	453.58	1.02
S-7	346.91	335.14	0.97	347.28	1.00
S-8	428.32	443.95	1.04	460.82	1.08
		AVG	0.99	*AVG*	1.02

Note: P_{rs} denotes the FEA results with residual stress considered, and P_{nr} denotes the FEA results without residual stress considered.

According to Table 2, the residual stress has an effect on the ultimate load of stainless steel welded I-section beams, but the effect is limited.

As illustrated in Figure 6, Figure 7 and Table 2, the failure modes, load-displacement curves and ultimate moments obtained from FEA results all coincide well with that obtained from experimental tests. The validation of the numerical method adopted in this work has been verified.

2.3 Parametric analysis

In order to ensure the effectiveness of proposed calculation methods, a total of 315 specimens with typical sections (as shown in Figure 8 and different slenderness ratio under different load forms have been investigated by FEA.

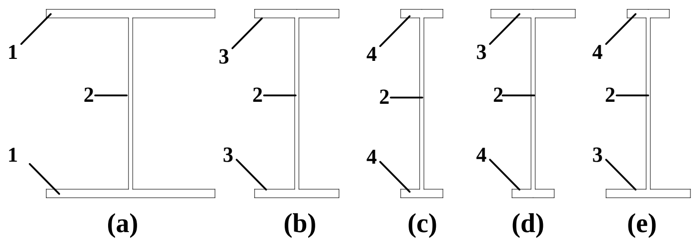


plate 1- 400mm×20 mm; plate 2 - 400 mm×10 mm；

plate 3 - 200mm×20 mm; plate 4 -100 mm×20 mm

Figure 8 Typical sections

Different load types and load positions considered in the FEA, which are shown in Figure 9.

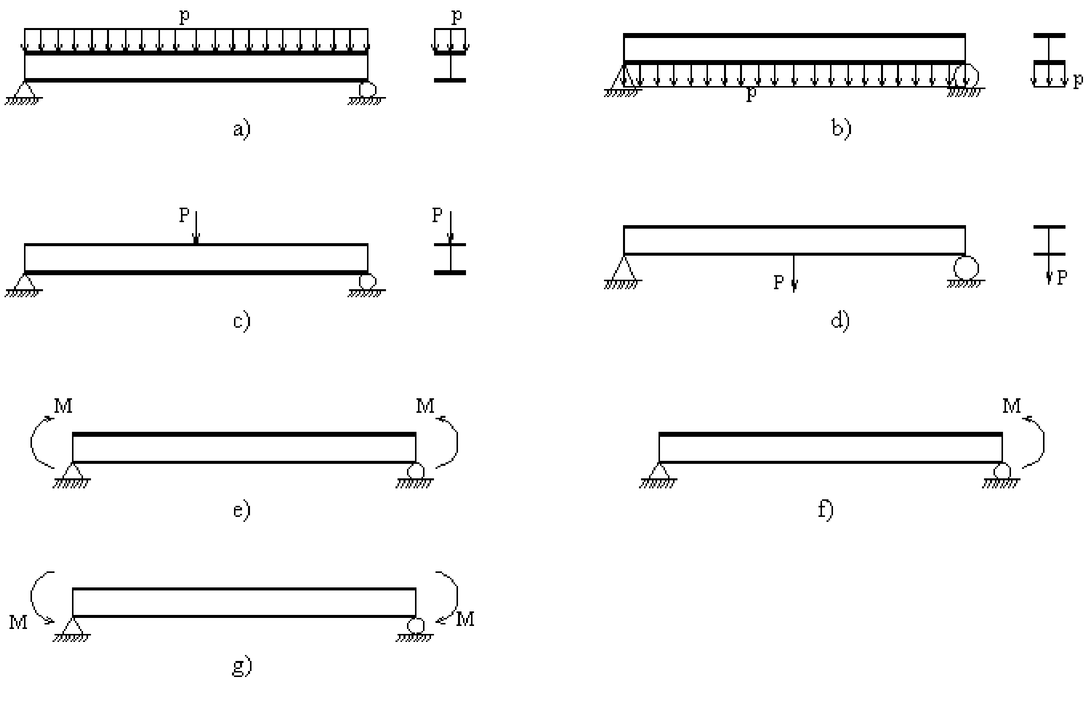


Figure 9 Load situations

Three main parameters, cross section, load situation and slenderness ratio, are combined, and a total of 315 specimens have been analyzed in the FEA. The overall stability coefficient of the specimen can be derived from the ultimate moment obtained by the FEM.

3 Existing standard methods and proposed methods

3.1 Existing standard methods

Europe

According to EC3 [17], the cross section are classified by the susceptibility to local buckling and their rotation capacity. In this study, the ultimate moment of the specimens, M_{Ed} can be calculated by Eq.(3):

$$M_{Ed} \leq \frac{\chi_{LT} M_{pl}}{\gamma_{M1}} \tag{3}$$

where: M_{pl} is the plastic moment of the section;

γ_{M1}=1.1, is the partial factor;

χ_{LT} is the reduction factor, which is given by:

$$\chi_{LT} = \frac{1}{\varphi_{LT} + \sqrt{\varphi_{LT}{}^2 - \lambda_{LT}{}^2}} \leq 1 \tag{4}$$

where: $\varphi_{\mathrm{LT}}=0.5(1+\alpha_{\mathrm{LT}}(\lambda_{\mathrm{LT}}-0.4)+\lambda_{\mathrm{LT}}{}^2)$ and $\lambda_{\mathrm{LT}}=(W_{\mathrm{y}}f_{\mathrm{y}}/M_{\mathrm{cr}})^{0.5}$。

in which: α_{LT} is the imperfection factor, α_{LT} =0.34 for cold formed sections and hollow sections,

or α_{LT} =0.76 for welded open section;

λ_{LT} is the limiting slenderness;

W_{y} is the plastic section modulus;

f_{y} is the yield strength;

M_{cr} is the elastic critical moment for lateral torsional buckling.

US/Australia and New Zealand

The approach in the SEI/ASCE [20] Specification is adopted in the AS/NZS [21] Specification. The non-linear behaviour of stainless steel is taken into account. The tangent modulus E_t and tangent shear modulus G_t are adopted to replace the initial elastic modulus E_0 and initial shear modulus G_0. Therefore, an iterative approached is required to determine the elastic critical moment M_{cr}.

China

So far, there is no special specification for stainless steel structures. With reference to the provisions for carbon steel structures [22], the overall stability coefficient φ_{b} can be defined by elasticity theory:

$$\varphi_b = \beta_b \frac{4646}{\lambda_y^2} \frac{Ah}{W_x} \left[\eta_b + \sqrt{1 + \left(\frac{\lambda_y t_1}{4.4h} \right)^2} \right] \frac{205}{f_{0.2}} \frac{E_0}{193000} \tag{5}$$

where: β_{b} is the equivalent bending moment coefficient;

A is the area of the section;

h is the height of the section;

t_1 is the thickness of the compression flange;

W_{x} is the elastic section modulus;

λ_y is the slenderness ratio of the weak axis;

η_{b} is the reduced coefficient of asymmetrical cross-section.

If $\varphi_{\mathrm{b}} > 0.6$, the member will be considered to come to inelastic state, and φ_{b} needs to be modified by:

$$\varphi_{\mathrm{b}}' = 1.07 - 0.282/\varphi_{\mathrm{b}} \leq 1.0 \tag{6}$$

Apparently, non-linear behaviour of stainless steel is not considered in the calculation method for carbon steel structures.

Comparison

Since the Ramberg Osgood parameter *n* has significant effect on the buckling curve, in the comparison of different standard method, the value of parameter is set to be 4.15 (which is obtained from the material property test). Figure 10 shows the comparison of buckling curves between different standard methods and the FEA results. In the FE model, the dimension of welded I-section is 840mm×400 mm×20mm×20mm and a uniform load applies on the top flange of the specimen.

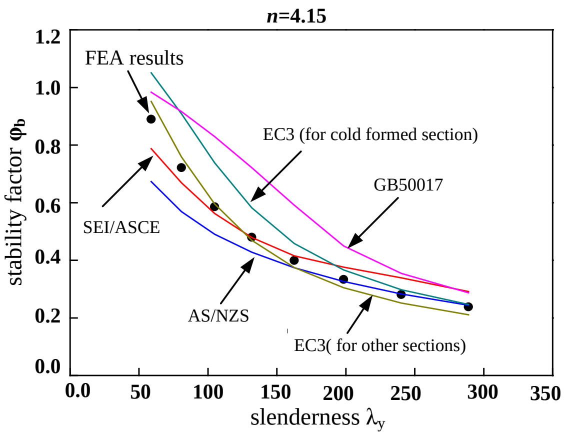


Figure 10 Comparison between the results of different standards and the FEA results

According to Figure 10, the results calculated based on EC3 are very close to the FEA results. Since the SEI/ASCE Specification and AS/NZS Specification are applied on to cold worked material, the corresponding results have obvious differences between the FEA results. For Chinese Standard for carbon steel structures, the differences are even greater, because the non-linear property of stainless steel is not taken into account.

3.2 Proposed calculation method I

Because the material non-linearity is not considered in Eq.(6), the proposed calculation method I makes reference to the method of strength reduction, and the overall stability coefficient φ_b calculated by Eq.(5) should be modified by:

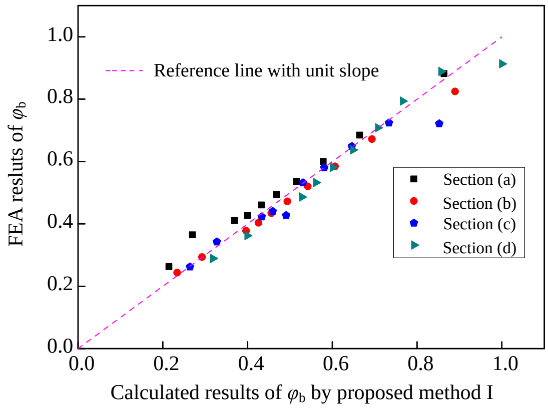
$$\varphi_b' = \varphi_b \Big/ \left(1 + m\varphi_b^n\right)^{\frac{1}{n}} \leq 1.0 \tag{7}$$

where m and n are correction coefficient $m=n=0.8$ for stainless steel welded section.

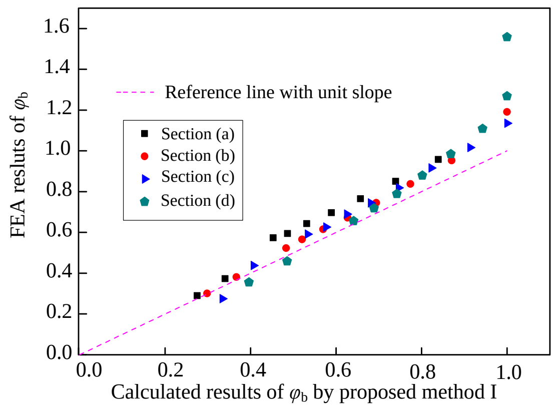
The comparison between proposed method I and the FEA results is illustrated in Figure 11, in which the overall stability coefficient of FEA results is calculated by:

$$\varphi_b = M_{cr}/M_y \tag{8}$$

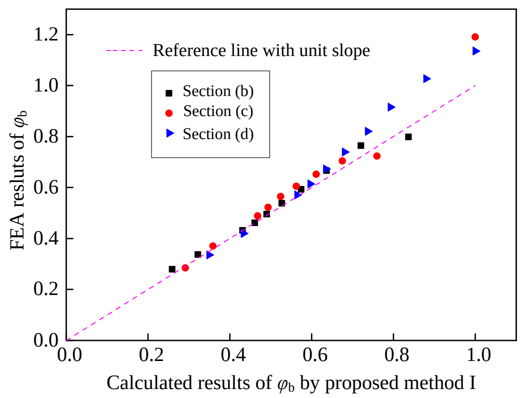
where: M_y is the yield moment of the section.



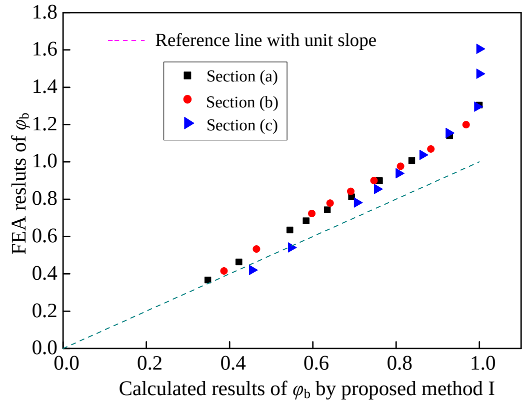
a) Results of load situation a)



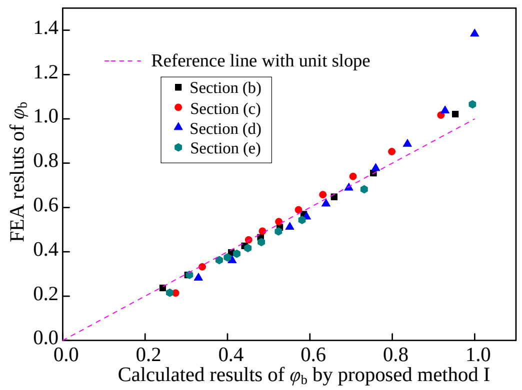
b) Results of load situation b)



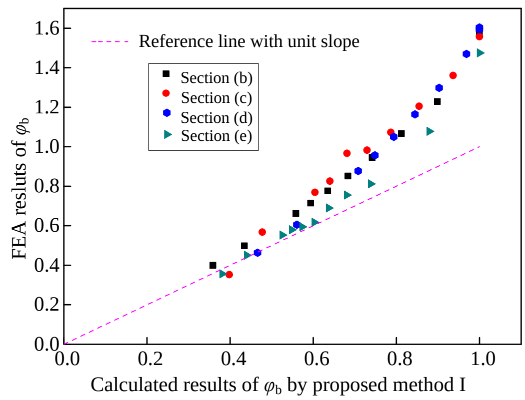
c) Results of load situation c)



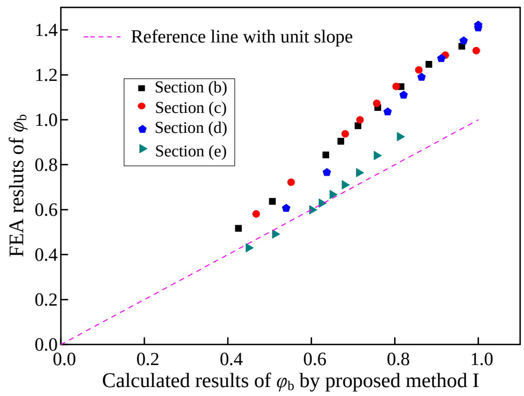
d) Results of load situation d)



e) Results of load situation e)



f) Results of load situation f)



g) Results of load situation g)

Figure 11 Comparison between the FEA results and the results calculated by proposed method I

According to Figure 11, the results calculated by proposed method I are close to that of the FEA and are conservative on the whole.

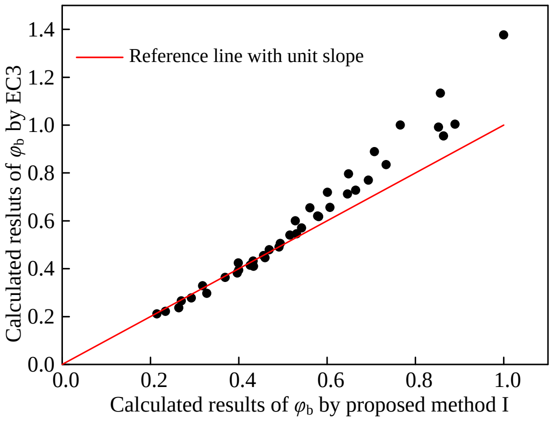


Figure 12 Comparison between the EC3 and the proposed method I

The comparison between the results calculated by the proposed method I and that by EC3 are shown in Figure 12. Both results are close to each other and the results calculated by proposed method I are relatively conservative.

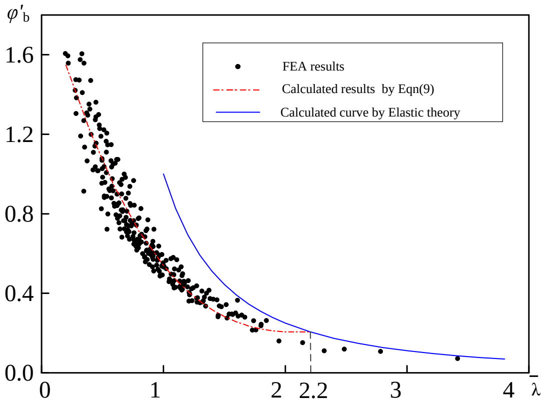
3.3 Proposed calculation method II

Currently, the normalized slenderness ratio is used to present overall stability coefficient the in some national standards for its simple form. In proposed calculation method II, the regression analysis method is used to fit the FEA results, as shown in Figure 13[23].

According to the regression results, the authors proposed the overall stability coefficient could be calculated by Eq.(9)[23]:

$$\varphi_b' = M_{cr}/M_y = 1.9516 - 2.1917\bar{\lambda} + 0.8993\bar{\lambda}^2 - 0.1199\bar{\lambda}^3 \qquad \bar{\lambda} \le 2.2$$
$$\varphi_b' = M_{cr}/M_y = 1/\bar{\lambda}^2 \qquad \bar{\lambda} > 2.2 \qquad (9)$$

where: $\bar{\lambda} = (M_y/M_{cr})^{0.5}$, is the normalized slenderness ratio.



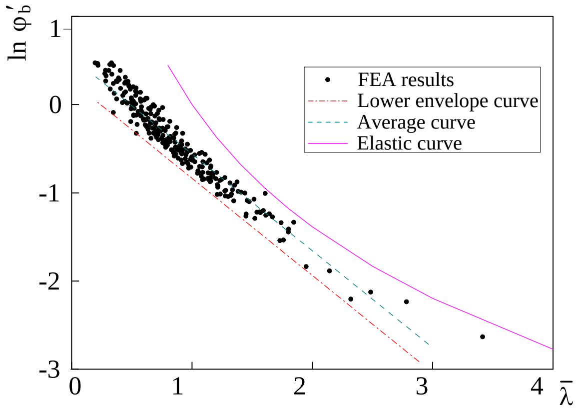


Figure 13 The FEA results and proposed curve **Figure 14 The FEA results and proposed curve**

Based on Figure 13, the natural logarithm of the overall stability coefficient is shown in Figure 14, and the regression results of average value between the overall stability coefficient and the normalized slenderness ratio is given by Eq.(10).

$$\varphi_b = e^{0.5358 - 1.097\bar{\lambda}} \le 1.0 \qquad (10)$$

Since the effect of residual stress, the FEA results of overall stability coefficient are lower than that of elasticity theory. Therefore, the lower envelop equation for engineering design is suggested as:

$$\varphi_b = e^{0.2661-1.102\bar{\lambda}} \leq 1.0 \tag{11}$$

The comparison between the results calculated by Eq.(11) and that by FEA are shown in Figure 15[23]. According to Figure 15, Eq.(11) can be applied for engineering design and assure the safety and reliability.

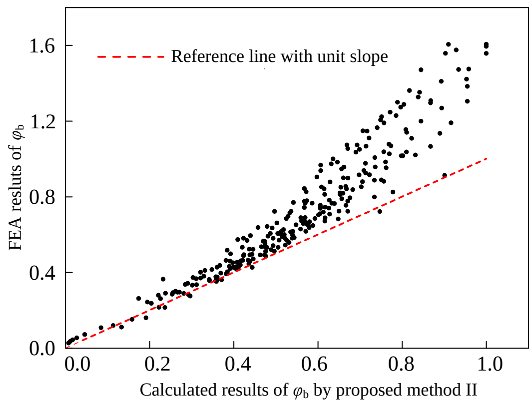


Figure 15 Comparison between results calculated by FEA and that by Eq.(11)

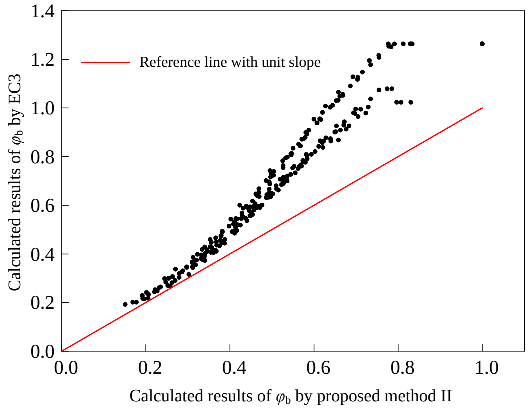


Figure 16 Comparison between the results calculated by EC3 and that by Eq.(11)

The comparison between the results calculated by Eq.(11) and that by EC3 are shown in Figure 16[23], and the results calculated by Eq.(11) are relatively conservative.

3.4 Comparison

Both proposed calculation methods are applied to calculate the overall stability coefficients of the eight specimens, and the results are compared with that of experimental test and specifications of EC3, as illustrated in Table 3.

According to Table 3, the results of proposed calculation methods are close to that of EC3 and are conservative to experimental results. Both of the propose calculation method can be applied for engineering design and assure the safety.

Table 3 Comparison of overall stability coefficients

Speci-men	Test result φ_{EXP}	EC3 φ_{EN}	Proposed method I φ_{I}	Proposed method II φ_{II}	$\varphi_{EXP}/\varphi_{EN}$	$\varphi_{EXP}/\varphi_{I}$	$\varphi_{EXP}/\varphi_{II}$
S-1	0.95	0.32	0.40	0.36	2.98	2.38	2.64
S-2	1.10	0.36	0.44	0.40	3.07	2.49	2.76
S-3	1.10	0.41	0.49	0.44	2.70	2.25	2.49
S-4	1.08	0.55	0.61	0.55	1.98	1.77	1.98
S-5	1.17	0.61	0.66	0.59	1.91	1.76	1.98
S-6	1.17	0.68	0.71	0.63	1.73	1.64	1.85
S-7	1.21	0.60	0.62	0.55	2.02	1.96	2.19
S-8	1.32	0.66	0.67	0.59	1.99	1.98	2.22
					AVG	2.03	2.26

4 Conclusion

Due to the non-linearity of stainless steel, the structural design standards for carbon steel should not be applied to stainless steel directly. In this paper, the overall stability bearing capacity of stainless steel welded I-section beams is studied and two calculation methods for overall stability coefficients of stainless steel welded I-section beams are proposed, by improving the existing calculation methods for carbon steel beams.

A finite element method to analyze the overall stability bearing capacity of stainless steel welded I-section beams is proposed, in which the non-linear stress-strain relationship of material, distribution of residual stress and initial deformation of the specimen are taken into account. The validity of the finite element method has been verified by a series of experimental tests on eight specimens.

Based on results of the finite element analysis and experimental investigation and comparison of design standards for overall stability coefficients calculation of structural stainless steel, two calculation methods for overall stability coefficients of welded I-section beams are proposed. One is the modification of Chinese Code for design of steel structures, the other is the regression analysis results based on finite element analysis. The results of proposed calculation methods are close to that of EC3 and are conservative to experimental results, and both methods have simple form and enough emergency capacity for engineering design.

Acknowledgement

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