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STAINLESS STEEL I-SECTION BEAM-COLUMNS BEHAVIOR

Feber N.[*], Jandera M.[**]

Abstract: *The interaction between axial compression and major axis bending of welded stainless steel columns is being investigated at the Czech Technical University in Prague. This paper describes numerical modeling of welded stainless steel I-profile members loaded by a combined load (axial force and bending moment). The detailed finite element (FE) models were developed in software ABAQUS and subsequently validated against test results to simulate the interactive behavior and predict the ultimate capacity. The initial geometric imperfection modes, and amplitudes (global and local), and residual stress were considered to enhance the models accuracy. Material tensile coupon tests were also conducted. The aim of this work is to investigate the current design procedures for stainless steel beam-column members and compare them to the numerical results.*

Keywords: Stainless steel, Welded I-profile, Beam-column, Numerical study, Interaction factor.

1. Introduction

The use of stainless steels in construction has been increasingly spread in the last years as a result of their excellent corrosion resistance, easy maintenance, attractive surface finish, and good mechanical properties. Nevertheless, existing investigations regarding stainless steel beam-columns behavior are very limited. The existing procedures for the design of the stainless steel structure are mainly based on the carbon steel codes (EN 1993-1-1, 2005) with simple modifications (EN 1993-1-4, 2006) based mainly on engineering judgement as there was almost no experiment or numerical background available. However, stainless steel differs from carbon steel in a number of aspects, such as strain hardening, ductility, the shape of the stress-strain curve, etc. Therefore, the design procedures cannot be simply identical with the carbon steel ones and may also differ among the stainless steel families.

For stainless steel, significant research has been performed focusing on different fabrication processes, such as cold-formed (Jandera et al., 2008), laser welded (Bu, 2017) or conventional welded (Yuan et al., 2014) sections. The stability of stainless steel members has been investigated for various cross-section shapes, for instance, laser welded I-profiles (Bu, 2017), circular hollow sections (Burgan, Baddoo, & Gilsenan, 2000) and square and rectangular hollow sections (Židlický and Jandera, 2019).

In real structures, most of the members are subjected to combined compression and bending. The design formula for beam-columns involves the established beam and column resistances. However, the behavior of a member under combined loading is also significantly affected by the interaction between compression and bending, where only little experimental and numerical investigation exists. Design of stainless steel welded I-section loaded by axial force and bending moment is therefore the focus of the present study.

2. Current methods for beam-column behavior design

Currently, there are several available methods for design of stainless steel beam-columns. Design procedures for beam-column are also included in the European design code (EN 1993-1-4, 2006) and are largely following the interaction formulae for carbon steel (EN 1993-1-1, 2005) with modified interaction buckling factors k_i. According to the standard, members subjected to compression and major axis bending

[*] Ing. Nina Feber, PhD. student: Czech Technical University in Prague, Faculty of Civil Engineering, Thakurova 7; 160 00, Prague, CZ, nina.feber@fsv.cvut.cz

[**] Assoc. Prof. Ing. Michal Jandera, PhD.: Czech Technical University in Prague, Faculty of Civil Engineering, Thakurova 7; 160 00, Prague, CZ, michal.jandera @fsv.cvut.cz

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should satisfy expression (1). However, for the members with non-uniform moment distribution along their length and in the loading cases of dominant bending moment, conservative results could be expected.

There is also an American design guide (AISC, 2013), where the values of factor $1/\alpha_{ny}$ are almost the same as the corresponding correlation factor in the Eurocode. According to previous research (Bu, 2017) (Zheng et al., 2015), both codes provide conservative predictions.

$$\frac{N_{\mathrm{Ed}}}{N_{\mathrm{b,Rd,min}}} + k_y \left(\frac{M_{\mathrm{y,Ed}} + N_{\mathrm{Ed}} \cdot e_{\mathrm{N,y}}}{\beta_{\mathrm{w,y}} \cdot W_{\mathrm{pl,y}} \cdot \frac{f_{\mathrm{y}}}{\gamma_{\mathrm{M1}}}} \right) \leq 1 \qquad (1)$$

$$k_{\mathrm{y}} = 1 + 2\left(\bar{\lambda}_{\mathrm{y}} - 0.5\right) \cdot \frac{N_{\mathrm{Ed}}}{N_{\mathrm{b,Rd}}}; \quad \text{but } 1.2 \leq k_{\mathrm{y}} \leq 1.2 + 2\frac{N_{\mathrm{Ed}}}{N_{\mathrm{b,Rd}}} \qquad (2)$$

where $N_{\mathrm{Ed}}, M_{\mathrm{y,Ed}}$ are the design values of compression force and the maximal bending moment, respectively; $N_{\mathrm{b,Rd}}$ is the column resistance; $e_{\mathrm{N,y}}$ is the shift in the neutral axis when the cross-section is subject to uniform compression; $\beta_{\mathrm{w,y}} = 1{,}0$ for Class 1 or 2 cross-section, $\beta_{\mathrm{w,y}} = W_{\mathrm{el,y}}/W_{\mathrm{pl,y}}$ for Class 3 cross-section, $\beta_{\mathrm{w,y}} = W_{\mathrm{eff,y}}/W_{\mathrm{pl,y}}$ for Class 4 cross-section; $W_{\mathrm{el,y}}, W_{\mathrm{pl,y}}, W_{\mathrm{eff,y}}$ modulus of the cross-section; f_{y} is the proof stress; γ_{M1} is the partial safety factor.

An extensive study focused on the design procedure for stainless steel hollow section beam-columns was performed at Imperial College London (Zhao, 2015). In this work, the author considered also strain hardening for the section bending resistance by using the Continuous Strength Method (CSM) (Gardner, 2008 and Afshan and Gardner, 2013). The proposed design procedure (Zhao, 2015) is accurate and shows low COV for all structural stainless steel grades. But it is focused only on hollow sections. Therefore, further study and experiments are necessary to confirm its validity and verify its accuracy for welded I-sections.

An extensive experimental and numerical investigation (Bu, 2017) was carried out to design interaction curves for stainless steel beam-columns for a range of member slenderness values. An improved approach for design of stainless steel I-section beam-columns was proposed. The accuracy of the proposed procedure is demonstrated as very good but it is necessary to verify also on conventionally welded I-profiles.

More recently, based on 20 experiments and extensive parametric study, a new improvement was developed at the CTU Prague (Židlický and Jandera, 2019). The study deals with stainless steel SHS and RHS beam-column and provides safe and consistent predictions for austenitic, ferritic and duplex steels, and covers all cross-section classes (the interaction factor is dependent on section slenderness). Its suitability for the welded I sections has not been tested.

3. Beam-column tests

The experimental program contains material coupon tests, measurements of geometric (local and global) imperfections and beam-column tests. A total of 10 austenitic stainless steel welded I-sections were tested. The members were loaded by axial force and bending moment, exhibiting the major axis flexural buckling failure mode. The beam-column tests were performed using a 350 kN hydraulic jack. Pin-ended conditions at the top and bottom of the members were achieved through a pair of knife edges and wedge plates.

The required position and load eccentricity (distance between the specimen axis and the centerline of knife-edges) was set by oval holes in the wedge plates. Bracing system (lateral restrains) was used to prevent minor axis flexural and lateral-torsional buckling. The experiment setup is shown in 0.

4. Numerical study

An advanced numerical model was developed using the general-purpose FE analysis package ABAQUS to simulate the actual behavior of beam-column members and predict the ultimate capacity and failure mode. Geometrically and materially nonlinear analysis with imperfections (GMNIA) was used for the calculation. 3D models were created using the S4R element (four-node shell element with reduced integration).

Boundary conditions and loads were introduced using eccentric reference points that were coupled to all points at the respective end of the member by kinematic coupling function. The rotation about the bending axis at both ends and the longitudinal translation at the loaded end were released to simulate the pin-ended boundary conditions

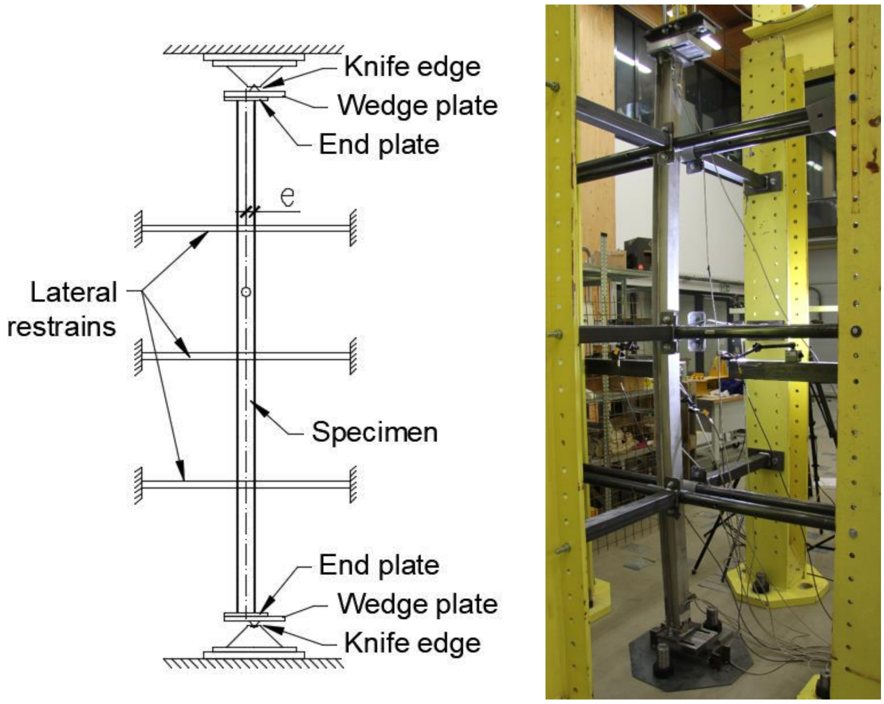

Fig. 1: Test set-up.

Boundary conditions and loads were introduced using eccentric reference points that were coupled to all points at the respective end of the member by kinematic coupling function. The rotation about the major axis bending axis at both ends and the longitudinal translation at the loaded end were released to simulate the pin-ended boundary conditions.

Both local and global geometric imperfections were introduced through the corresponding eigenmodes with measured amplitudes. Furthermore, residual stresses due to welding of the web and beam flanges were also considered in the models in accordance with a proposal (Yuan, Wang, Shi, & Gardner, 2014).

Fig. 2: Global and local geometric imperfection.

5. Conclusions

The main objective of the ongoing study is to investigate relevant interaction factors for stainless steel beam columns. The first important step was to create an accurate numerical model, which is presented in this paper. The ultimate loads obtained from the FE models N_{FEM} were compared to those from the corresponding experiments N_{TEST}, for beam-columns loaded by compression with range of three initial loading eccentricities to give a spectrum of bending moment-to-axial load ratios. The results are summarized in Tab. 1, where CS01-x is specimen ID for cross-section of 98 mm height, 90 mm width, 3 mm web thickness, 4 mm flange thickness, and CS02-x for of 100 mm height, 100 mm width, 4 mm web thickness, 5 mm flange thickness. L is the member length, e the load eccentricity and w_g the global geometric imperfection amplitude. All the specimens failed by a combination of bending and flexural buckling to the major axis, as shown in Fig. 1 for a typical specimen.

Tab. 1: Comparison of test and FE results with predicted strengths for beam-columns under compression plus major axis bending.

Specimen	L [mm]	e [mm]	w_g [mm]	F_{TEST} [kN]	F_{FEM} [kN]	F_{TEST}/F_{FEM}
CS01-a	2977	60	6.5	73.210	74.014	0.989
CS01-b	2976	30	6.91	98.661	97.513	1.012
CS01-c	2974	0	3.16	148.514	141.587	1.049
CS01-d	2976	60	7.38	73.324	74.232	0.988
CS01-e	2750	0	6.67	141.639	138.093	1.026
CS02-a	2976	30	7.62	120.238	114.120	1.054
CS02-b	2976	60	8.4	94.756	95.068	0.997
CS02-c	2977	30	7.94	122.556	132.457	0.925
CS02-d	2698	0	5.71	194.692	193.236	1.008
CS02-e	2700	0	6.3	190.582	190.869	0.998
Mean						1.004
COV						0.025

As can be seen from Tab. 1 the models show a very good agreement when compared to the tests results with the mean ratios F_{TEST}/F_{FEM} 1.004 and COV 0.025. The failure modes obtained from the FE models were also the same as those observed in the tests. Overall. the developed numerical models may be seen to represent the behavior of beam-columns accurately.

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