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BEHAVIOR OF STAINLESS STEEL LIPPED CHANNEL SECTIONS SUBJECTED TO ECCENTRIC COMPRESSION

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The design philosophy of stainless steel requires appropriate recognition of observed material nonlinearity and pronounced strain hardening. A rational method namely, the Continuous Strength Method (CSM) has recently been to incorporate these effects but, in its current form, CSM yields better results for stocky sections. Individual capacities (i.e., pure compression and pure bending) for all types of sections and cross-section resistance against combined loading (i.e. compression plus bending) for RHS and I-sections can be predicted using CSM. The current research numerically investigates the performance of stainless steel lipped channel (LC) sections subjected to compression and bending. Nonlinear finite element models are developed and validated using available experimental results, and are consequently used to generate additional results for a wide range of cross-sections through parametric studies. Current CSM guidelines are used to propose a new set of formulations for predicting the section resistance of lipped channel sections subjected to combined loading.

Keywords: Beam-column interaction; Continuous Strength Method; Finite element modeling; Stub column.

1 INTRODUCTION

Importance of stainless steel in construction is growing day by day as it can offer high corrosion resistance, better ductility, fire resistance, strength and attractive appearance. Stainless steel design methods are primarily based on analogies with carbon steel despite demonstrating significant nonlinear strain hardening unlike carbon steel. In order to exploit its beneficial properties, the Continuous Strength Method (CSM) was introduced for structural stainless steel design. CSM is a strain based approach, and is shown to predict section capacities more accurately when compared to those obtained using the existing international design guidelines (Afshan and Gardner, 2013). To date, major developments on CSM are limited to predicting section capacity under pure compression and bending. Formulations for combined bending and compression on rectangular hollow sections and I-sections have recently been proposed by Liew and Gardner (2014) and Zhao *et al.* (2014).

Current study aims to extend CSM formulations for lipped channel (LC) sections subjected to combined loading. As part of the current research, numerical models for LC stub columns are developed and validated against those presented in Fan *et al.* (2014), where stub columns were tested against both concentric and eccentric compression. A parametric study is undertaken using two of the validated cross-sections by altering the thickness of the section. Generated FE results are used to devise a new set of equation following CSM guidelines for predicting the interaction behavior of LC sections subjected to combined loading.

2 DEVELOPMENT OF NUMERICAL MODELS

2.1 Principle of Developing Numerical Models and Validations

Numerical models are developed using the finite element modelling software ABAQUS (2011) following techniques similar to those reported in Theofanous and Gardner (2009), Zhao *et al.* (2014) and Saadat *et al.* (2015). Following are the key aspects of the numerical modelling approach adopted in the current study:

- Four node shell element S4R with reduced integration is used.
- A uniform mesh size with element dimensions equal to the section thickness is adopted to maintain an optimum balance between accuracy and efficiency.
- Full range stress-strain material curves are used following compound Ramberg-Osgood material model proposed by Gardner and Ashraf (2006); required parameters were retrieved from experimental results.
- Lowest elastic buckling shape obtained by eigen mode buckling analysis is used to model the distribution of initial geometric imperfections.
- Two imperfection amplitudes — Modified Dawson–Walker model for stainless steel (Gardner and Nethercot, 2004) and 0.01t were used.
- Enhanced material strength at corner regions was appropriately included.
- For compression, ends were restrained against any movement except for the loaded end to be free against translation along the load direction. For eccentric loading, rotation was allowed at both ends in the axis of rotation to replicate pin ended boundary conditions.

Table 1 shows the performance of the developed FE models for the considered imperfection amplitudes. Results clearly show that both the chosen amplitudes perform fairly well in predicting the ultimate capacity although the ultimate deformation predictions are not quite accurate as those are affected by the post-buckling effects. For parametric studies, the modified Dawson–Walker model proposed for stainless steel was used to obtain the imperfection magnitude as it considers both material and geometric properties of a cross-section.

2.2 Parametric Studies

Parametric study has been conducted based on two selected LC sections chosen from the list of validated numerical models. The selected sections are C80×40×15×3 (T-6-A) and C120×40×15×3 (T-8-A) as reported in Fan *et al.* (2014). Nominal dimension of the sections were considered and the section thickness was varied in such a manner that the generated sections cover both stocky and slender cross-sections. Section thickness was varied between 2~6 mm with an increment of 1 mm, whilst internal radius was taken equal to the section thickness. Cross-section slenderness was varied between 0.28~0.71 for C80×40×15×t sections, and 0.43~1.09 for C120×40×15×t sections. In total there were 12 different section types. On each section eccentric loads were applied in 10 different eccentricities varying from 10-500 mm where 10 mm interval between 10-50 mm eccentricity and 100 mm interval is used between 100-50 0mm eccentricity. In total, 10 different loading types were applied on 12 different sections.

Table 1. Comparison between test and FE predictions for LC stub columns.

Source	Section ID	Dawson-Walker Model		t/100	
		$F_{u,test}/F_{u,FE}$	$\delta_{u,test}/\delta_{u,FE}$	$F_{u,test}/F_{u,FE}$	$\delta_{u,test}/\delta_{u,FE}$
Fan et al. (2014)	C80×40×15×3 (T-6-A)	1.08	0.74	1.08	0.74
	C80×40×15×3 (T-6-B)	1.00	0.79	1.00	0.79
	C80×40×15×3 (T-6-C)	0.98	1.35	0.98	1.35
	C80×40×15×3 (T-6-D)	1.16	1.15	1.16	1.15
	C100×40×15×3 (T-7-A)	1.07	0.70	1.07	0.69
	C100×40×15×3 (T-7-B)	0.97	1.14	0.97	1.14
	C100×40×15×3 (T-7-C)	0.94	1.05	0.94	1.05
	C120×40×15×3 (T-8-A)	1.07	0.99	1.06	0.97
	C120×40×15×3 (T-8-B)	1.03	0.91	1.02	0.89
	C120×40×15×3 (T-8-C)	1.03	1.57	1.02	1.57
	C120×40×15×3 (T-8-D)	1.01	1.72	1.01	1.72
	C160×60×15×3 (T-10-A)	1.00	1.13	1.01	1.09
	C160×60×15×3 (T-10-B)	1.01	1.06	1.01	1.02
	C160×60×15×3 (T-10-C)	0.99	1.39	1.01	1.40
	C160×60×15×3 (T-10-D)	1.00	1.59	1.01	1.66
	Average	1.04	1.15	1.03	1.15
	CoV	0.062	0.273	0.062	0.279

3 THE CONTINUOUS STRENGTH METHOD

The main feature of the Continuous Strength Method (CSM) is rational usage of strain hardening, and the use of a design base curve for obtaining the failure strain for a given section. The base curve establishes a relationship between the cross-section slenderness, λ_p and the strain ratio, $\varepsilon_{csm}/\varepsilon_y$. The equations for cross-section slenderness and base curve are given in Eqs. (1) and (2). However, it should be noted that the Eq. (2) is only valid for stocky sections with $\lambda_p \leq 0.68$. The critical elastic buckling stress, f_{cr} corresponds to the lowest local buckling shape of the section for a given load.

$$\bar{\lambda}_p = \sqrt{\frac{f_y}{f_{cr}}} \tag{1}$$

$$\frac{\varepsilon_{csm}}{\varepsilon_y} = \frac{3.6}{\bar{\lambda}_p^{0.25}} \tag{2}$$

Once the maximum strain, ε_{csm} is determined using the base curve, the corresponding failure stress f_{csm} is determined using the bilinear strain hardening material model, which allows calculating the capacity of the cross-section. Relevant formulations on cross-section capacities for stocky sections are available in Afshan and Gardner (2013). For slender sections, it was concluded that current codified formulations are capable of predicting section strengths accurately. However, existing codes still requires repetitive calculation of cross-section classifications for determining strength of the slender section which makes the process complicated. Recently Ahmed and Ashraf (2015) proposed a design rule to include slender sections in CSM. This method produced accurate results of section strength, meanwhile keeping the calculation process simple without cross-section classification. These formulations are used herein to calculate the capacity of slender sections.

4 DEVELOPMENT OF INTERACTION EQUATION FOR LIPPED CHANNEL SECTIONS

In this section, the data generated through the parametric study on C120×40×15×t and C80×40×15×t sections (t=2~6 mm) are used to develop an interaction formula for LC sections. A typical interaction equation similar to the proposal given by Liew and Gardner (2014) was adopted for uniaxial major axis bending plus compression loading of LC sections and it is presented in Eq. (3). Several sets of numerals for power *p* and *q* are investigated to suit LC sections. First method of performance evaluation was done by comparing the normalized P-M interaction curves produced by different coefficient values with a linear interaction curve, represents an ideal condition for beam-column interaction. Figure 1 compares the linear interaction curves to the normalized P-M interaction points. An alternative evaluation was done using the ratio of $R_{u,predicted}/R_u$, where, $R_{u,predicted}$ is the distance of an interaction point from the origin and R_u is the distance from origin to the corresponding point on the linear interaction curve. A value of $R_{u,predicted}/R_u$ greater than unity means the capacity is safely predicted. The variation of performance of the interaction equation by means of $R_{u,predicted}/R_u$ for various set of p and q are shown in Table 2.

$$\left(\frac{F}{N_{csm}}\right)^{p}+\left(\frac{M_{maj}}{M_{csm,maj}}\right)^{q}\leq 1 \qquad (3)$$

Table 2. Predictions for uniaxial bending plus compression resistances with varying interaction coefficients.

Set	p	q	C120×40×15×t		C80×40×15×t		All sections	
			Mean $R_{u,predicted}/R_u$	COV	Mean $R_{u,predicted}/R_u$	COV	Mean $R_{u,predicted}/R_u$	COV
a	1	1	1.12	0.11	1.11	0.09	1.12	0.10
b	1	0.5	1.21	0.14	1.18	0.12	1.20	0.13
c	1	1.5	1.06	0.12	1.06	0.11	1.06	0.12
d	1.5	1.5	0.97	0.13	0.98	0.14	0.98	0.14

By inspecting Table 2 and Figure 1(a) to 1(d) for both cases (C120×40×15×t and C80×40×15×t), the following summarization can be brought,

- From the normalized P-M interaction curve, for set ‘a’ all the points lie over the linear interaction curve with mean $R_{u,predicted}/R_u$ for all sections 1.12.
- In case ‘b’, the interaction points move further toward the conservative prediction away from the linear interaction curve and average $R_{u,predicted}/R_u$ has a value of 1.20 for all sections.
- In case ‘c’, the mean $R_{u,predicted}/R_u$ gives a value of 1.06 with a COV 0.12 which is found to be best suited till now.
- For case ‘d’, mean $R_{u,predicted}/R_u$ is less but closer to 1.0 while the predictions are quite scattered and the interaction curve clearly shows that a significant number of normalized interaction points lie on the unsafe zone.

Considering the points mentioned above it can be concluded that if value of unity for *p* and *q* (i.e. set ‘a’) in Eq. (3) is used, the formula produces conservative but safe predictions. However if the power over moment ratio is increased, as in set ‘c’ the average value of $R_{u,predicted}/R_u$ becomes more nearer to unity with the interaction points in P-M curve cover a narrow range of predictions with the linear interaction curve. Thus an interaction equation with coefficients *p*=1.0 and *q*=1.5 is suggested for LC stub columns subjected to compression and major axis uniaxial bending as given in Eq (4).

$$\frac{F}{N_{csm}} + \left(\frac{M_{maj}}{M_{csm,maj}} \right)^{1.5} \leq 1 \tag{4}$$

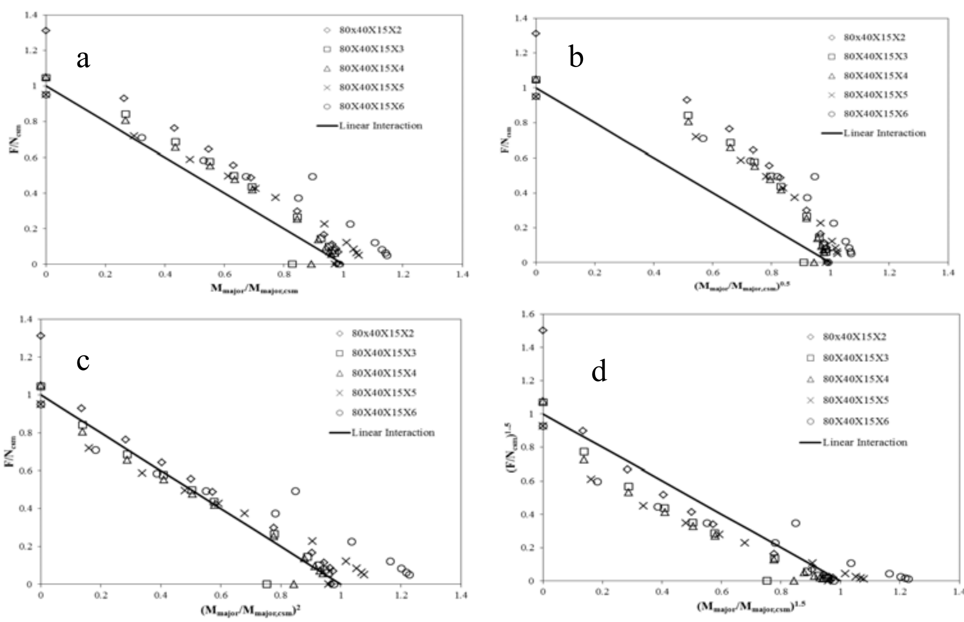

Figure 1. Normalized interaction curves for uniaxial bending plus compression for various set of coefficients (a) *p*=1 & *q*=1 (b) *p*=1 & *q*=0.5 (c) *p*=1 & *q*=1.5 and (d) *p*=1.5 & *q*=1.5.

5 CONCLUSION

A numerical investigation involving parametric study on 120 numerical models has been presented in this paper to investigate the behavior of beam-column interaction in lipped channel stainless steel stub column sections. Nonlinear FE models were subjected to eccentric compression producing bending about the major axis only. Recently proposed CSM interaction equations are tested for their suitability in predicting the behavior of lipped channel sections. Interaction equations with four separate sets of coefficients have been examined. Observed variations in predictions are summarized and consequently used to propose a new set of coefficients for LC sections. Further research is required to investigate the behavior against minor axis bending. Further research is currently underway to make more comprehensive investigations into the behavior of lipped channel stainless steel sections.

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