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Interactive failure mode and Design of Cold-formed Steel Closed Cross-section Built-up Columns

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Abstract
The structural behavior of Cold-formed Steel (CFS) built-up closed cross-section columns is investigated. The CFS built-up Closed Cross-Section columns are designed in various shapes with various slenderness ratios to verify the influence of intermediate fastener spacing and check the appropriateness of the Direct Strength Method (DSM) of AISI. A total of 595 axial compression test results were incorporated in this study with various end conditions, including the results from the literature. The design parameters such as local slenderness, global slenderness, intermediate longitudinal fastener spacing, and length of the column are varied. The failure modes of the column are summarized and the reason for them is explained. The influence of intermediate longitudinal connection spacing was observed in the axial loading capacity and failure modes. The investigation results indicated that the lesser value of intermediate fastener spacing to local buckling half-wavelength ratio increased the strength of the column while the higher ratio increased the vulnerability of local-global interactive buckling. The test results including ultimate load and failure modes were compared with the direct strength method design predictions of AISI and existing literature. A modified DSM approach is proposed with a new local slenderness expression to consider the influence of intermediate fastener spacing in the design strength of cold-formed steel built-up closed cross-section columns.

1. Introduction

Cold-formed steel structural members can be optimized into infinite cross-section shapes based on the need for construction. In other words, they can be formed into a built-up cross-section for higher loading capacities compared to traditional single-section members. A built-up cross-section with discrete connections along the length may fail in separation (failure of individual members) or buckle in interaction modes depending on the intermediate connection spacing (a) and slenderness (λ_l, λ_d, and λ_e). Interaction buckling can be defined as the simultaneous occurrence of two or more failure modes ($f_y >> f_{crl} = f_{crd} = f_{cre}$) resulting in erosion of individual critical load. The local-distortional interaction buckling ($f_y = f_{cre} >> f_{crl} = f_{crd}$) mode is notably one of the most thoroughly examined phenomena, through experimental, numerical, and design approaches (Yang and Hancock 2004; Young et al 2013; Dinis et al 2014; Anbarasu 2016 and Dar et al 2018). The local-global interaction ($f_y = f_{crd} >> f_{crl} = f_{cre}$) was well formulated for design applications using numerous experimental and numerical results by various researchers over several decades (Mulligan and Pekoz 1987; Dundu and Kemp 2006; Young and Chen 2008; Dubina et al 2013; Young et al 2013; Niu et al 2015; Martins et al 2017 and 2018a; Basaglia and

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Camotim 2012; Camotim and Basaglia 2014; Ye et al 2018; Zhang and Young 2015; Abbasi et al 2018; Zhang and Young 2018; Dinis and Camotim 2004; 2019; Selvaraj and Madhavan 2019; 2021b; 2021c; 2022b; Young and Yan 2002; Kwon et al 2009; Young and Rasmussen 1998; Van der Neut 1969; Dubina and Ungureanu 2002; Bai and Wadee 2015; and Shen and Wadee 2018a; 2018b). Fewer research investigation was carried out in the global distortional ($f_y = f_{crl} >> f_{crd} = f_{cre}$) and local-global distortional ($f_y >> f_{crl} = f_{crd} = f_{cre}$) of interactions, and further research is underway (Santos et al 2012; Young et al 2018; Kumar and Kalyanaraman 2018; Martins et al 2018a; 2018b; Martins et al 2018c). One of the recently discovered interaction modes is global-global interaction involving flexural-torsional (FTB) and minor-axis flexural (FB) buckling in intermediate angles, plain channel columns, and plain channel built-up columns (Dinis et al 2020, 2022; Selvaraj and Madhavan 2022). A detailed discussion about all possible interactive failure modes is summarized in Camotim et al. (2020a and 2020b). The method Erosion of Critical Bifurcation Load was developed by Dubina (2001); Dubina and Ungureanu (2004) and Dubina et al (2013). Overall Interaction Concept is also summarized by Li and Boissonnade (2022) and combined DSM with EC3 curves were investigated by Shen and Wadee (2019). Although there are established design methods for traditional CFS open sections, the design methods for the built-up cross-sections are currently under investigation. The simple connection methods for the CFS built-up closed cross-section column are proposed in Selvaraj and Madhavan (2023b).

Instability interactive failure modes can be highly challenging to predict and these interactions reduce the strength of the member significantly while comparing with the individual failure mode curve making the design predictions unconservative (design strength > actual strength). Various researchers have proposed different design approaches to account for the behavior of interaction and separation failures. The design approaches proposed by the various researchers for the design of built-up members and associated interactions is summarized in Selvaraj and Madhavan (2023a). After comparing and comprehensive analysis of the test results with the AISI design method, the paper presents a new DSM-based design approach, evidence of its simplicity and benefits compared with the current one.

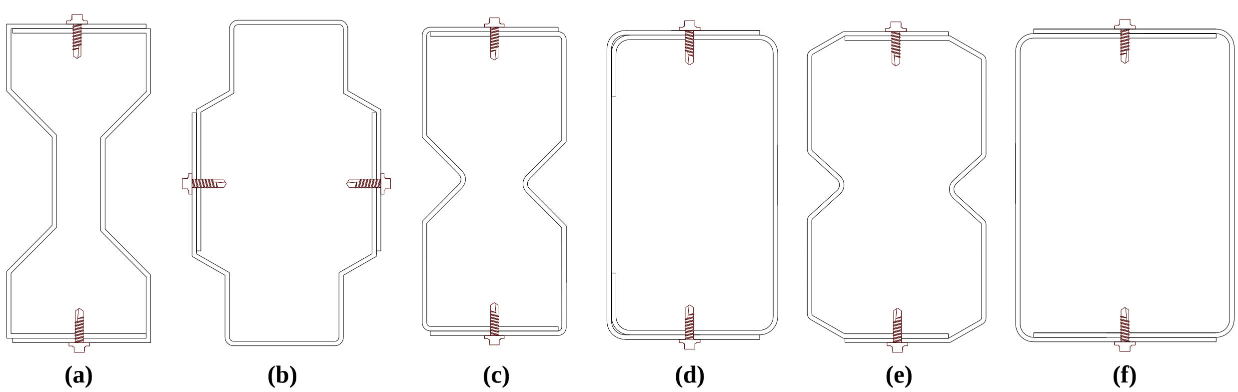

Fig. 1. Column test results database for local, global and local-global interactive buckling modes: (a) Closed Sections with Intermediate Stiffeners (Young and Chen (2008); (b) Closed Section Columns with Web Stiffeners - connected at the web - "O" Section (Zhang and Young 2018a and 2018b); (c) Closed Section Columns with Web Stiffeners - connected at the flange - "V" Section (Zhang and Young 2018a and 2018b); (d) Built-Up Closed Box Section (Nie et al. 2020 and Zhou et al. 2021); (e) Closed Section Columns with Web Stiffeners - connected at the flange - "CW" Section (Li and Young 2022a); (f) Face-to-face connected Closed Cross Section - connected at the flange (Selvaraj and Madhavan 2022).

Table 1. Built-Up Closed Cross-Section Column Test Results Database for Local, Global, and Local-Global Interactive Buckling Modes

Cross-section Figure – number of specimens*	Length (L) (mm)		$\lambda_{l\text{-}e}$		λ_e		a/L_{crl} (mm)		f_y (MPa)	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Fig. 1a - 17	298	2997.2	0.797	2.478	0.185	1.531	1.052	1.099	450	550
Figs. 1b-1c - 26	299.8	3199.8	1.904	5.639	0.104	1.285	1	1.052	500	550
Figs. 1b-1c - 252	400	4000	0.774	3.918	0.134	1.451	0.270	1.025	500	500
Fig. 1d - 80	270	3200	0.637	3.892	0.124	2.285	1	4.091	305.4	321.5
Fig. 1d - 68	526	2458	0.721	2.514	0.549	2.002	1.579	3	408.32	
Fig. 1e - 121	480	3580	0.346	4.862	0.265	2.089	0.625	2	611	
Fig. 1f - 31	1000	1800	1.258	1.911	0.350	0.98	0.833	9	377.4	
595 results	270 - 4000		0.346 - 5.639		0.104 - 2.285		0.270 - 9		305.4 - 611	

Note: *The test results summarized are corresponding to local, global and local-global interactive buckling only, the test results related to the distortional or, distortional-local or global-distortional buckling are removed. $\lambda_{l\text{-}e} = (P_{ne}/P_{crl})^{0.5}$; $\lambda_e = (P_y/P_{cre})^{0.5}$; L - length of the member; a - Intermediate fastener spacing; L_{crl} - Local buckling half-wave length determined from single cross-section using Thinwall software (Finite Strip Analysis) (Papangelis and Hancock 1995);

2. Column Test Results Database for Local, Global, and Local-Global Interactive Buckling Modes

A cold-formed steel built-up column test database was collected to facilitate the failure mode analysis, design results interpretation, and reliability analysis. The database is of 595 test results with vast parameters, including six types of built-up closed cross-sections (Fig. 1), various lengths ranging from 270 mm to 4000 mm, local-global interactive slenderness ($\lambda_{l\text{-}e}$) ranging from 0.346 to 5.639, global slenderness (λ_e) ranging from 0.104 to 2.285, a/L_{crl} ratio ranging from 0.270 to 9, material young's modulus ranging from 200 GPa - 218 GPa, and yield stress (fy) ranging from 305.4 MPa to 611 MPa. The column design parameters of the data collected and the corresponding references are summarized in Table 1.

3. Influence of Intermediate Fastener Spacing and Design Predictions

In general, the built-up closed cross-section columns shown in Fig. 1 are subjected to three possible failure modes: (1) overall global buckling; (2) local-global interactive failure; (3) pure local buckling due to highly slender unstiffened elements (web or flange). The accurate prediction of either of these three failure modes and corresponding design strength is a difficult task with the current AISI design approach (see AISI S100) due to the following; (i) overall global buckling influenced by the local buckling of the unstiffened elements, if the intermediate fastener spacing is larger or equal to $0.5r_i(KL/r)_o$; (ii) the built-up closed cross-section (face-to-face connection forms) will have an overlapping local buckling feature on the connected elements (either flange or web) due to the interlocking/pairing effect (elements overlapping each other owing to the method of formation of closed-cross-section) which will increase the local buckling strength. This overlapping local buckling feature is significantly affected by the ratio of the fastener spacing to the local buckling half wavelength (a/L_{crl}). In fact, it is a general perception (Selvaraj and Madhavan 2022 and Craveiro 2022) that the overlapping feature would restrain the local buckling of the unstiffened elements (imagine two elements acting together -

double thickness effect leading to $f_{crl} >> f_{cre}$) and consider only the overall global buckling, ignoring the local-global interactive and pure local buckling modes, this situation is possible only if the intermediate fastener spacing is very close thus inhibiting the local buckling of the individual elements.

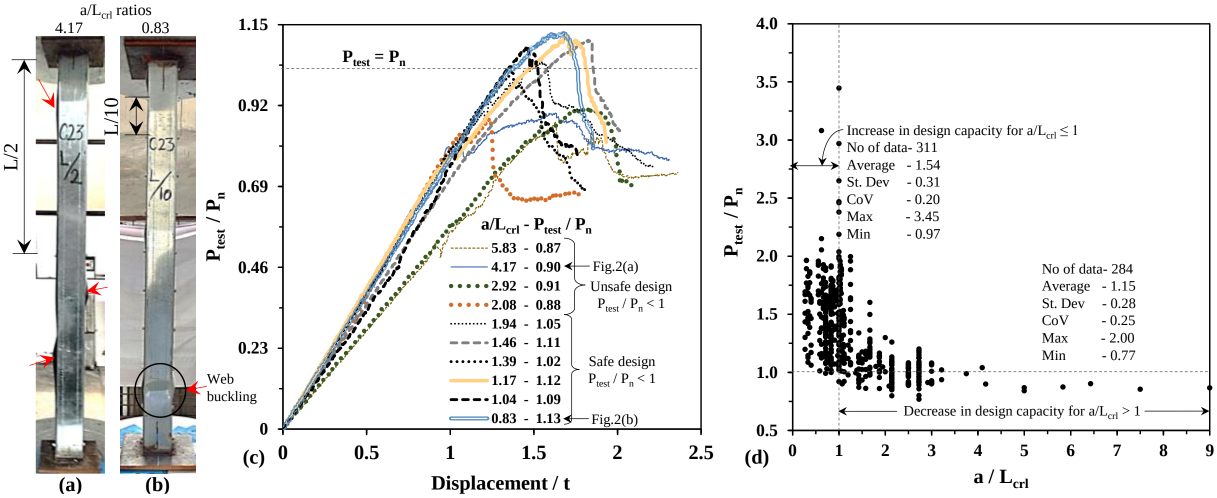

Fig. 2. Representation of built-up column test results for analyzing the influence of intermediate fastener spacing: (a) failure mode of column with a/Lcrl ratio of 4.17; (b) failure mode of column with a/Lcrl ratio of 0.83; (c) load displacement response with a design results for built-up columns of various a/Lcrl ratios; (d) collective data: comparison of column test and design results with a/Lcrl ratios

To provide an overview of relevant behavioral features exhibited by cold-formed steel built-up closed cross-section columns, a representative sample of experimental results reported by Selvaraj and Madhavan (2022) is presented in this section followed by a comprehensive design analysis with 595 compiled test data. A perfect example of an overlapping local buckling feature can be explained by comparing the columns with an a/L_{crl} ratio of 4.17 (Fig. 2a - column with only one fastener connection at the middle length) and 0.83 (Fig. 2b - column with intermediate fastener connection spacing of L/10). It can be observed that when the a/L_{crl} ratio is 4.17, the local bucking occurred freely on the flanges (Fig. 2a - indicated by arrows) while the local buckling was restrained on the flanges with the column of a/L_{crl} ratio 0.83 (Fig. 2b). The reduced a/L_{crl} ratio led to copious overlapping effect at the flanges (partial double thickness effect in the unstiffened element) and let the web to buckle (stiffened element - indicated by the circle in Fig. 2b). This is because the flanges of the column are stiffened with overlapping with double thickness effect and let the adjacent web (single thickness) to buckle, indicating that the overlapping effect with a/L_{crl} ratio of 0.83 is significantly high. A similar effect of intermediate fastener spacing in behavioral features on built-up columns was also presented in Craveiro et al. (2022).

The axial compression load response (load versus displacement) of the built-up closed cross-section columns (P_{test}) were compared with the AISI design strength predictions (P_n according to section E2 of AISI S100 2020) in Fig. 2c. The P_{test} vs P_n comparison indicates that the columns with higher a/L_{crl} ratio ($a/L_{crl} > 2$) failed at less than the predicted design strength (P_{test}/P_n <1) also with less stiffness (Fig. 2c) compared to the column with a/L_{crl} ratio less than 2. This indicates that when the a/L_{crl} ratio is higher than 2, the fastener connected unstiffened flange elements of the closed cross-section columns fail in local buckling without overlapping effect and leads to interactive local-global failure (simultaneous occurrence of local and global buckling) thereby making the current AISI design predictions unconservative ($P_{test}/P_n < 1$). In reality, the local buckling of unstiffened elements erodes the built-up column's strength significantly. Though it is comparatively clear that the a/L_{crl} ratio is playing a key role in built-up closed cross-section column local-global interactive buckling mechanics, the limiting value for the a/L_{crl} ratio at which local-global interaction is occurring or restraining is not clear at this stage.

To determine the a/L_{crl} ratio limit that inhibits the local-global interactive buckling and improve the current DSM design approach for the built-up closed cross-section columns (similar to the ones shown in Fig. 1), the database of 595 test results with vast parameters was compared with the design predictions using current AISI in Fig. 2d (P_{test}/P_n versus a/L_{crl}). The analysis of 595 P_{test}/P_n results further endorsed the findings of Selvaraj and Madhavan (2022) and Craveiro (2022) that the column with an a/L_{crl} ratio less than one has higher strength ($P_{test} > P_n$ when $a/L_{crl} < 1$ - see Fig. 2d) while the column with an a/L_{crl} ratio higher than one has a lesser strength ($P_{test} < P_n$ when $a/L_{crl} > 1$ - see Fig. 2d) compared to the AISI predictions. It is now evidently clear from Fig. 2d (average P_{test} / P_n is 1.54 for $a/L_{crl} < 1$) that the local-global interaction buckling in built-up closed cross-section columns can be inhibited by providing intermediate fastener spacing less than or equal to the local buckling half-wavelength. Therewithal, some columns with an a/L_{crl} ratio more than unity up to 4 also had higher axial loading capacity ($P_{test} > P_n$) which indicates little overlapping effect or decreased effect of local-global interaction buckling. However, all columns with an a/L_{crl} ratio higher than 4 had less strength than the predicted design capacity ($P_{test}/P_n < 1$) indicating higher interaction between local-global buckling as shown in Fig 2d. The higher axial loading capacity in some columns with $1< a/L_{crl}<4$ perhaps may be attributed to the following reasons; (1) some local imperfection patterns compensate for each other (Crisan et al 2012), so if the overlapping flanges had opposite imperfections (flare versus overbent) or buckling (translating) in opposite directions they may act together and will not buckle locally; (2) various local buckling pattern possibilities according to the cross-section shape and plate slenderness resulting in overlapping effect as explained in Selvaraj and Madhavan (2023a).

4. Incorporating the Influence of Intermediate Fastener Spacing in the Direct Strength Method for Accurate Design Predictions

Based on the above interpretations pertaining to the influence of intermediate fastener spacing, the current DSM expressions require the following necessary changes;

1. First, the a/L_{crl} limit for allowing interaction buckling should be set or the a/L_{crl} limit should be specified strictly for avoiding the interaction buckling in built-up closed cross-section columns.
2. Erosion of strength due to the arrant local-global interaction buckling in columns with a/L_{crl} more than 4 should be incorporated; currently, the DSM is unconservative by a maximum of 33% for columns with a/L_{crl} ratio more than 1 (minimum value of P_{test}/P_n for $a/L_{crl} > 1$ is 0.77) as shown in Fig. 2d.
3. The overlapping local buckling effect on the members with an a/L_{crl} limit less than 1 should be incorporated to increase the design strength of the member, currently, the DSM expressions are conservative by an average of 54% and a maximum of 245% (as shown in Fig. 2d.

4.1 Limit for local-global interaction buckling

This may be a straightforward approach as it is for inhibiting or allowing the interaction buckling in the built-up closed section column; the experimental results and the corresponding interpretations categorically indicated that the columns with an a/L_{crl} ratio higher than one failed in interaction buckling. Therefore, the main DSM design approach can be classified with failure modes as Eq. (1). The individual global and local buckling curves to be used or interaction buckling with overlapping effect (with λ_{lem} in Eq. 4a) when the a/L_{crl} ratio is less than or equal to one {min [P_{ne} and max (P_{nl} and P_{nle})]} and the local-global interactive equation to be used (with λ_{lem} in Eq. 4b) when the a/L_{crl} ratio is higher than one (P_{nle} when $a/L_{crl} > 1$).

4.2 Improving the local-global interaction buckling curve

Further to be noted that the effect of local-global interaction buckling increases (strength erosion) with an increase in a/L_{crl} ratio, and the interaction becomes arrant beyond the a/L_{crl} value of 4. This clearly indicates that the strength is influenced by the external parameters but no error in the codification of the existing AISI's local-global interaction curve. Therefore, this gradual (decrease or increase) interaction effect can be addressed by altering the inputs for local-global interaction buckling curve (Eq. 4). Therefore, the local-global interaction slenderness (λ_{le}) is reformed for incorporating the a/L_{crl} effect, i.e., the slenderness is increased (Eq. 4b) when the a/L_{crl} value is higher than one to decrease the design load, the slenderness is decreased (Eq. 4a) when the a/L_{crl} value is less than one to increase the design load. The local-global interaction slenderness (λ_{le}) is modified by multiplying the a/L_{crl} ratio with an exponent of 0.2. This modified slenderness approach is similar to the ones proposed by Wang and Young (2018) and Selvaraj and Madhavan (2022) for incorporating the intermediate fastener spacing connection effect in built-up members.

4.3 Overlapping local buckling effect

Finally, the increase in strength due to the overlapping elements of the column with an a/L_{crl} ratio less than one is incorporated into the design equations by decreasing the modified local-global interactive slenderness of the members by 15% for an a/L_{crl} ratio less than one. i.e. the λ_{le} is multiped by 0.85 (Eq. 4a). This decrease in slenderness value will increase the design strength of the member gradually with respect to the a/L_{crl} ratio. Such an empirical approach is successfully used by various researchers for improving the DSM design method (Dinar and Camotim 2019, Wang and Young 2018, and Li and Young 2022b). Finally, in the newly improved design for cold-formed steel built-up closed cross-section columns, Eqs. 1-4 with $f_{crl\text{-}s}$ (single section model for local buckling), $F_{cre\text{-}b}$ (built-up model for global buckling), and modified local slenderness (Eqs. 4a and 4b) is used. The comparison between the 595 test results and the corresponding design results (P_{test} versus P_n) shown in Fig. 3c indicates that the improved design approach is safely predicting the axial loading capacity of the built-up closed cross-section columns.

$$P_n = \begin{cases} \min\,[P_{ne} \text{ and} \max\ (P_{nl} \text{ and } P_{nle})] & if\ a/L_{crl} \leq 1 \\ P_{nle} & if\ a/L_{crl} > 1 \end{cases} \tag{1}$$

$$P_{ne} = \begin{cases} \left(0.658^{\lambda_c^{\,2}}\right) P_y & if\ \lambda_c \leq 1.5 \\ \left(\frac{0.877}{\lambda_c^{\,2}}\right) P_y & if\ \lambda_c > 1.5 \end{cases} \quad \text{with } \lambda_c = \sqrt{P_y/P_{cre}} \tag{2}$$

$$P_{nl} = \begin{cases} P_y & if\ \lambda_l \leq 0.776 \\ \left[1 - 0.15\left(\frac{P_{crl}}{P_y}\right)^{0.4}\right]\left(\frac{P_{crl}}{P_y}\right)^{0.4} P_y & if\ \lambda_l > 0.776 \end{cases} \quad \text{with} \quad \lambda_l = \sqrt{P_y/P_{crl}} \tag{3}$$

$$P_{nle} = \begin{cases} P_{ne} & if\ \lambda_{\text{lem}} \leq 0.776 \\ \left[1 - 0.15\left(\frac{1}{\lambda_{\text{lem}}{}^2}\right)^{0.4}\right]\left(\frac{1}{\lambda_{\text{lem}}{}^2}\right)^{0.4} P_y & if\ \lambda_{\text{lem}} > 0.776 \end{cases} \tag{3}$$

$$\lambda_{\text{lem}} = 0.85\sqrt{\frac{P_{ne}}{P_{crl}}}\left(\frac{a}{L_{crl}}\right)^{0.2}\ when\ a/L_{crl} \leq 1 \tag{4a}$$

$$\lambda_{\text{lem}} = \sqrt{\frac{P_{ne}}{P_{crl}}}\left(\frac{a}{L_{crl}}\right)^{0.2}\ when\ a/L_{crl} > 1 \tag{4b}$$

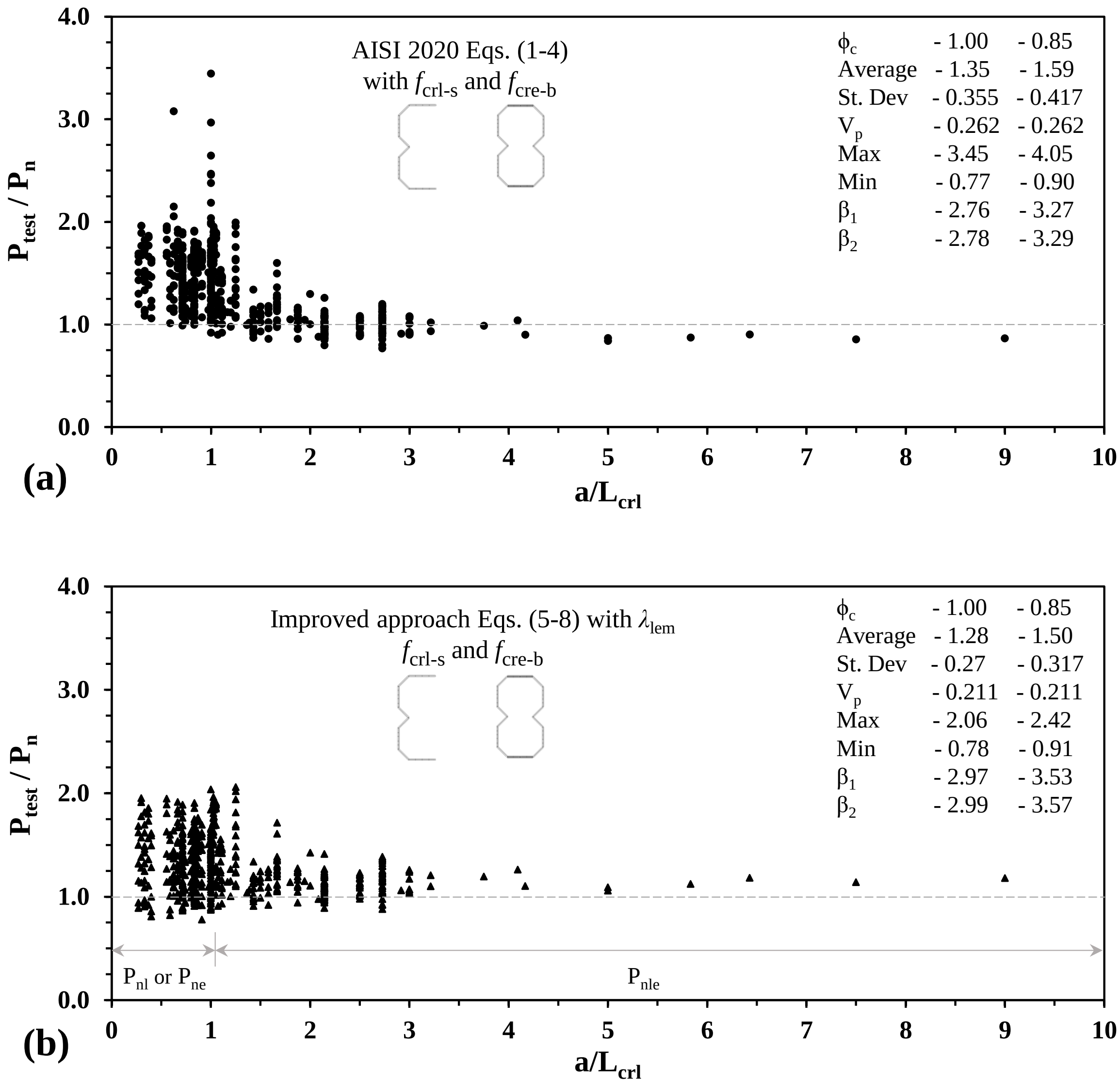

Fig. 3. Distribution of design predictions using various approach with respect to a/L_{crl} ratio: (a) original DSM (current version) from AISI (2020); (b) Improved DSM approach (Eqs. 1-4 - with $f_{\text{crl-s}}$ and $f_{\text{cre-b}}$)

5. Conclusions

The improved DSM based design approach for axially loaded CFS built-up closed cross-section columns exhibiting local, global and local-global interactive buckling is presented. The authors' test results and data from the various researchers were collected, consisting of 595 test results with vast parameters, including six types of built-up closed cross-sections, various lengths, slenderness, intermediate fastener spacing, local buckling half-wavelength, and material properties. It is shown that the current DSM curves for local-global interaction failure need improvement for accounting the effect of the ratio to the intermediate fastener spacing (a) and local buckling half-wavelength (L_{crl}). The influence of the a/L_{crl} ratio is comprehensively presented, including the mechanics reasoning behind the failure modes and increase in strength. The suggested improvements to the current DSM approach are (i) limiting the buckling mode by classifying the individual and local-global interactive failure; (ii) modifying the local-global slenderness expression for accurate local-global interactive failure load prediction; (iii) incorporating the increase in strength due to overlapping effect.

References

Abbasi, M., Khezri, M., Rasmussen, K.J.R. and Schafer, B.W., (2018). Elastic buckling analysis of cold-formed steel built-up sections with discrete fasteners using the compound strip method. Thin-Walled Structures, 124, pp.58-71.

AISI (2020). North American Specification for the Design of Cold-formed Steel Structural Members, 2016 Edition (Reaffirmed 2020) with Supplement 2, 2020 Edition.

Anbarasu M (2016). Local-distortional buckling interaction on cold-formed steel lipped channel beams, Thin-Walled Structures, 98B, 351-359.

Bai, L., & Wadee, M. A. (2015). Imperfection sensitivity of thin-walled I-section struts susceptible to cellular buckling. International Journal of Mechanical Sciences, 104, 162-173.

Basaglia, C., and Camotim, D. (2012). Buckling, post buckling, strength, and DSM design of cold-formed steel continuous lipped channel beams. Journal of Structural Engineering, 139(5), 657-668.

Camotim, D., Martins, A.D., Dinis, P.B., Young, B., Chen, M.T. and Landesmann, A., (2020a). Mode interaction in cold‐formed steel members: state‐of‐art report: Part 1: Fundamentals and local‐distortional coupling. Steel Construction, 13(3), pp.165-185.

Camotim, D., Martins, A.D., Dinis, P.B., Young, B., Chen, M.T. and Landesmann, A., (2020b). Mode interaction in cold‐formed steel members: state‐of‐art report: Part 2: Couplings involving global buckling. Steel Construction, 13(3), pp.186-207.

Camotim, D., and Basaglia, C. (2014). On the behaviour, failure and direct strength design of thin-walled steel structural systems. Thin-Walled Structures, 81, 50-66.

Craveiro, H.D., Rahnavard, R., Laím, L., Simões, R.A. and Santiago, A., (2022). Buckling behavior of closed built-up cold-formed steel columns under compression. Thin-Walled Structures, 179, p.109493.

Crisan, A., Ungureanu, V. and Dubina, D., 2012. Behaviour of cold-formed steel perforated sections in compression: Part 2—numerical investigations and design considerations. Thin-Walled Structures, 61, pp.97-105.

Dar, M.A., Sahoo, D.R., Pulikkal, S. and Jain, A.K., 2018. Behaviour of laced built-up cold-formed steel columns: Experimental investigation and numerical validation. Thin-Walled Structures, 132, pp.398-409.

Dinis, P.B. and Camotim, D., (2004). Local-plate and distortional post-buckling behavior of cold-formed steel columns: elastic and elastic–plastic FEM analysis. In Proceedings of SSRC Annual Stability Conference (pp. 24-27).

Dinis PB, Young B, Camotim D (2014). Local-distortional interaction in cold-formed steel rack-section columns, Thin-Walled Structures, 81, 185-194.

Dinis, P. B., and Camotim, D. (2019). Proposal to Improve the DSM Design of Cold-Formed Steel Angle Columns: Need, Background, Quality Assessment, and Illustration. Journal of Structural Engineering, 145(8), 04019071.

Dinis PB, Camotim D, Martins AD, Landesmann A (2020). Global-global interaction in cold-formed steel channel columns: relevance, post-buckling behavior, strength and DSM design, Website Proceedings of SSRC 2020 Annual Stability Conference (Atlanta 21-24/4), paper 14.

Dinis, P.B., Camotim, D., Landesmann, A., Martins, A.D. and Cerqueira, E., (2022). Global–global interaction in cold-formed steel plain and lipped channel columns. Thin-Walled Structures, 172, p.108872.

Dubina, D. (2001). The ECBL approach for interactive buckling of thin-walled steel members. Steel and Composite Structures, 1(1), 75-96.

Dubina, D., & Ungureanu, V. (2002). Effect of imperfections on numerical simulation of instability behaviour of cold-formed steel members. Thin-walled structures, 40(3), 239-262.

Dubina, D., Ungureanu, V. and Crisan, A., (2013). Experimental evidence of erosion of critical load in interactive buckling. Journal of Structural Engineering, 139(5), pp.705-716.

Dubina, D., and Ungureanu, V. (2014). Instability mode interaction: from Van Der Neut model to ECBL approach. Thin-Walled Structures, 81, 39-49.

Dundu, M. and Kemp, A.R., (2006). Plastic and lateral-torsional buckling behavior of single cold-formed channels connected back-to-back. Journal of Structural Engineering, 132(8), pp.1223-1233.

Kumar MVA, Kalyanaraman V (2018). Interaction of local, distortional, and global buckling in CFS lipped channel compression members, Journal of Structural Engineering, 144(2), paper 04017192.

Kwon YB, Kim BS, Hancock GJ (2009). Compression tests of high strength cold-formed steel channel with buckling interaction, Journal of Constructional Steel Research, 65(2), 278-289.

Li, Y., Li, Y., Wang, S. and Shen, Z., (2014). Ultimate load-carrying capacity of cold-formed thin-walled columns with built-up box and I section under axial compression. Thin-Walled Structures, 79, pp.202-217.

Li, Y., Zhou, T., Zhang, L., Ding, J. and Zhang, X., (2021). Distortional buckling behavior of cold-formed steel built-up closed section columns. Thin-Walled Structures, 166, p.108069.

Li, Q.Y. and Young, B., (2021). Tests of cold-formed steel built-up open section members under eccentric compressive load. Journal of Constructional Steel Research, 184, p.106775.

Li, Q.Y. and Young, B., (2022a). Experimental and numerical investigation on cold-formed steel built-up section pin-ended columns. Thin-Walled Structures, 170, p.108444.

Li, Q.Y. and Young, B., (2022b). Beam-column tests of cold-formed steel built-up closed sections. Journal of Structural Engineering, 148(4), p.04022020.

Li, L., and Boissonnade, N. (2022). Local/global coupled instabilities of slender I-sections under compression. Thin-Walled Structures, 172, 108842.

Martins AD, Camotim D, Dinis PB (2017). On the direct strength design of cold-formed steel columns failing in local-distortional interactive modes, Thin-Walled Structures, 120, 432-445.

Martins AD, Camotim D, Dinis PB (2018a). On the distortional-global interaction in cold-formed steel columns: relevance, post-buckling behaviour, strength and DSM design, Journal of Constructional Steel Research, 145, 449-470.

Martins AD, Camotim D, Dinis PB (2018b). Distortional-global interaction in lipped channel and zed-section beams: strength, relevance and DSM design, Thin-Walled Structures, 129, 289-308.

Martins AD, Camotim D, Gonçalves R, Dinis PB (2018c). GBT-based assessment of the mechanics of distortional-global interaction in thin-walled lipped channel beams, Thin-Walled Structures, 124, 32-47.

Mulligan, G.P. and Pekoz, T., (1987). Local buckling interaction in cold-formed columns. Journal of Structural Engineering, 113(3), pp.604-620.

Nie, S.F., Zhou, T.H., Zhang, Y. and Liu, B., (2020). Compressive behavior of built-up closed box section columns consisting of two cold-formed steel channels. Thin-Walled Structures, 151, p.106762.

Papangelis, J.P. and Hancock, G.J., 1995. Computer analysis of thin-walled structural members. Computers & Structures, 56(1), pp.157-176.

Rasmussen, K.J., Khezri, M., Schafer, B.W. and Zhang, H., (2020). The mechanics of built-up cold-formed steel members. Thin-Walled Structures, 154, p.106756.

Santos ES, Batista EM, Camotim D (2012). Experimental investigation concerning lipped channel columns undergoing local-distortional-global buckling mode interaction, Thin-Walled Structures, 54, 19-34.

Selvaraj, S. and Madhavan, M., (2014). Study on partially closed built-up sections using cold formed steel with geometric imperfection combinations under axial compression. In 7th international conference on thin-walled structures. South Korea.

Selvaraj, S. and Madhavan, M., (2018a). Cold-Formed Steel Built of Columns: Experimental Investigation. Proceedings of the ninth international conference on Advances in Steel Structures. Edited by Siu-Lai Chan, Tak-Ming Chan and Songye Zhu. The Hong Kong Institute of Steel Construction. DOI: 10.18057/ICASS2018.P.168.

Selvaraj, S. and Madhavan, M., (2018b). Behavior of Cold-Formed Steel Built-Up Beams: Experimental Investigation. In: 8 th International Conference on Thin-Walled Structures (ICTWS), 24-27 July 2018, Lisbon, Portugal.
Selvaraj, S. and Madhavan, M., (2019). Structural design of cold-formed steel face-to-face connected built-up beams using direct strength method. Journal of Constructional Steel Research, 160, pp.613-628.
Selvaraj, S. and Madhavan, M., (2021a). Design of cold-formed steel back-to-back connected built-up beams. Journal of Constructional Steel Research, 181, p.106623.
Selvaraj, S. and Madhavan, M., (2021b). Direct strength approach for local buckling of cold-formed steel built-up beams with slender unstiffened flange elements. Practice Periodical on Structural Design and Construction, 26(3), p.06021004.
Selvaraj, S. and Madhavan, M., (2021c). Design of cold-formed steel built-up columns subjected to local-global interactive buckling using direct strength method. Thin-Walled Structures, 159, p.107305.
Selvaraj, S. and Madhavan, M., (2022a). Design of cold-formed steel built-up closed section columns using direct strength method. Thin-Walled Structures, 171, p.108746.
Selvaraj, S. and Madhavan, M., (2022b). Experimental investigation and design considerations on cold-formed steel built-up I-section columns subjected to interactive buckling modes. Thin-Walled Structures, 175, p.109262.
Selvaraj, S., and Madhavan, M. (2023a) Proposal to Improve AISI S100 DSM Design Standards for Cold-Formed Steel Built-Up Closed Cross-Section Columns Subjected to Local–Global Interaction Buckling. J. Struct. Eng, https://doi.org/10.1061/JSENDH/STENG-11916.
Selvaraj, S. and Madhavan, M., (2023b). Splice Connections for Built-Up Column Assemblies in Cold-Formed Steel Construction. Journal of Structural Engineering, 149(3), p.04022250.
Shen, J., & Wadee, M. A. (2018a). Length effects on interactive buckling in thin-walled rectangular hollow section struts. Thin-Walled Structures, 128, 152-170.
Shen, J., & Wadee, M. A. (2018b). Imperfection sensitivity of thin-walled rectangular hollow section struts susceptible to interactive buckling. International Journal of Non-Linear Mechanics, 99, 112-130.
Shen, J., and Wadee, M. A. (2019). Local-global mode interaction in thin-walled inelastic rectangular hollow section struts part 2: Assessment of existing design guidance and new recommendations. Thin-Walled Structures, 145, 106184.
Van der Neut, A. (1969). The interaction of local buckling and column failure of thin-walled compression members. In Applied Mechanics (pp. 389-399). Springer, Berlin, Heidelberg.
Wang, L. and Young, B., (2018). Behaviour and design of cold-formed steel built-up section beams with different screw arrangements. Thin-Walled Structures, 131, pp.16-32.
Ye, J., Hajirasouliha, I. and Becque, J., 2018. Experimental investigation of local-flexural interactive buckling of cold-formed steel channel columns. Thin-walled structures, 125, pp.245-258.
Yang D, Hancock GJ (2004). Compression tests of high strength steel channel columns with interaction between local and distortional buckling, Journal of Structural Engineering (ASCE), 130(12), 1954-1963.
Young B, Rasmussen KJR (1998). Design of lipped channel columns, Journal of Structural Engineering (ASCE), 124(2), 140-148.
Young B, Yan J (2002). Channel columns undergoing local, distortional and overall buckling, Journal of Structural Engineering (ASCE), 128(6), 728-736
Young, B. and Chen, J., (2008). Design of cold-formed steel built-up closed sections with intermediate stiffeners. Journal of Structural Engineering, 134(5), pp.727-737.
Young B, Silvestre N, Camotim D (2013). Cold-formed steel lipped channel columns influenced by local-distortional interaction: strength and DSM design, Journal of Structural Engineering (ASCE), 139(6), 1059-1074.
Young B, Dinis PB, Camotim D (2018). CFS lipped channel columns affected by L-D-G interaction I: Experimental investigation, Computers & Structures, 207, 219-232.
Zhang, J.H. and Young, B., (2015). Numerical investigation and design of cold-formed steel built-up open section columns with longitudinal stiffeners. Thin-Walled Structures, 89, pp.178-191.
Zhang, J.H. and Young, B., (2018a). Experimental investigation of cold-formed steel built-up closed section columns with web stiffeners. Journal of constructional steel research, 147, pp.380-392.
Zhang, J.H. and Young, B., (2018b). Finite element analysis and design of cold-formed steel built-up closed section columns with web stiffeners. Thin-Walled Structures, 131, pp.223-237.
Zhou, X., Xiang, Y., Shi, Y., Xu, L. and Zou, Y., (2021). Simplified design method of cold-formed steel columns with built-up box sections. Engineering Structures, 228, p.111532.