Nonlinear Analysis on the Distortional-Global Couple Phenomenon in Cold-Formed Steel Lipped Channel Columns

Joao Alfredo De Lazzari[1], Eduardo de Miranda Batista[1]

[1]*COPPE, Civil Engineering Program, Federal University of Rio de Janeiro*
Centro de Tecnologia–Bloco I–Sala I216, Ilha do Fundão, CEP 21945-970, Rio de Janeiro/RJ, Brazil.
joaoadelazzari@outlook.com.br, batista@coc.ufrj.br

Abstract. The objective of this work is to understand the distortional-global (DG) buckling interaction of cold-formed steel (CFS) lipped channel (LC) columns in its post buckling structural behavior and strength. There are a few studies conducted on this topic in the literature, and the present study can be a motivation to encourage new design procedures for CFS structures. The research program included the development of a FEM model, which allowed detailed study of the DG buckling interaction and the comparison of the obtained results with usual design procedures. In order to perform elastic buckling analysis, a software entitled FStr Computer Application was developed, based on the finite strip method. The developed computational program is able to generates the buckling mode geometry to be inserted as the initial geometric imperfection (IGI) in the shell finite element model. Furthermore, the nonlinear analysis carried out stability paths for different combination of IGI of global and distortional buckling modes. This IGI combination helps to understand the DG buckling interaction in a wide range of cases. A parametric study varying the column's length has demonstrated that the nominal column strength equation for global buckling, presented in ABNT NBR 14762:2010, is enough to cover the DG interaction.

Keywords: Cold-Formed Steel, Lipped Channel Column, Distortional-Global Buckling Interaction, Finite Strip Method Computational Program, Finite Element Method Nonlinear Analysis.

1 Introduction

Cold-formed steel (CFS) structures are composed of thin-walled cross-sections, forming very slender structural systems easily susceptible to buckling. Therefore, structural designers are obligated to deal with the complexity of the phenomenon, which requires research development to allow structural solution with simple design equations. In terms of design procedures, these structural design equations are still under constant adjustments.

The current codes, Brazilian standard ABNT NBR 14762:2010 [1], Australian/New Zealand code AS/NZS 4600 [2], North-American standard AISI S100-16 [3] and European code EN 3 1-3 [4], have been changing their designing approaches over the past decades. The need of constant modifications on the design procedures, due to the semi-empirical procedures, obliges laboratory experimental campaigns combined with accurate numerical solutions to calibrate the equations and procedures. Nowadays, the most accepted design method presented in the current codes is the Direct Strength Method, DSM (originally proposed by Schafer and Peköz [5], based on an idea from Hancock *et al.* [6]), which offers a general formulation for the design of structural members affected by the buckling modes (see Figure 1) L (local), D (distortional) and G (global), isolated and LG interaction.

The buckling coupled phenomena must be considered for the structural design, since the modal interaction may conduct to reduction of the strength capacity, usually recognized as erosion of the limit load, as reported by Batista [7]. Therefore, many research efforts have been developed since the early investigations devoted to the buckling modes interaction. Since then, the design prescriptions in the codes have been revised and, by now, the rules for local-global interaction, LG, for both columns and beams are widely recognized and conduct to safe and economic solutions, *e.g.* Batista [8]. Recently, other buckling mode interaction have been under investigation these last decades: local-distortional, LD (*e.g.* Chen *et al.* [9] and Matsubara *et al.* [10]), distortional-global, DG (*e.g.*

Dinis and Camotim [11] and Martins *et al.* [12]) and local-distortional-global, LDG (*e.g.* Santos *et al.* [13] and Matsubara and Batista [14]). One may find recent results indicating robust conclusions and design propositions to handle these particular coupled phenomena cases. Anyway, the challenge is to define as simple as possible rules with clear physical meaningful and avoiding intricate blank box solution.

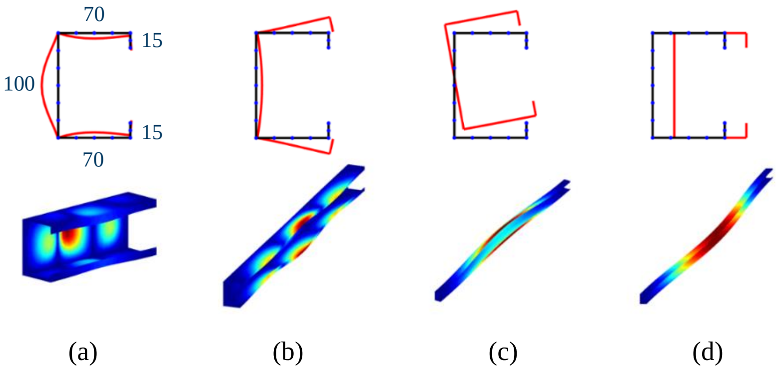

Figure 1. CFS lipped channel 100x70x15x2.70 mm column (fixed-fixed end) and its buckling modes: (a) local L; (b) distortional D; (c) global G or FT (flexural-torsional); (d) global G or F (flexural).

The purpose of this work is to investigate the DG coupled phenomenon in CFS lipped channel (LC) columns. More specifically, it is focused on the phenomenon behavior and column strength under different types of initial imperfections and the column slenderness, which can be achieved with appropriate variations of the columns' length and steel yield stress. Additionally, the obtained results of the strength of columns under DG buckling interaction are compared with design procedures found in the literature.

2 Numerical model

For a numerical investigation of DG buckling interaction, a Finite Element Method (FEM) is performed in order to understand the structural behavior. Also, the FEM is employed with assistance of ANSYS Mechanical APDL [15]. The analysis using the FEM is addressed to capture and observe nonlinear equilibrium paths and detect strength of a structural element.

The adopted model is described in six different groups: (i) discretization, (ii) end boundary condition, (iii) loading, (iv) material model, (v) initial geometric imperfections and (vi) analysis method. For each group, the model is summarized in Table 1, according to the ANSYS Mechanical APDL Theory Reference [15] and considerations retrieved from the literature.

Table 1. Numerical model description summary

i.	Discretization	*6-node triangular and 8-node quadrilateral SHELL281 element (size 5x5)*
ii.	End boundary conditions	*Fixed-Fixed Column*
iii.	Loading	*Compressive load to both ends*
iv.	Material model	*Bilinear isotropic hardening*
v.	IGI*	*L/1000 for global imperfection and 0.94t for distortional imperfection*
vi.	Analysis method	*Arc-length method with displacement control*

* The initial geometric imperfection (IGI) was generated using the FStr computer application, by Lazzari [16], and the imperfection amplitudes were given from Martins *et al.* [12].

Since there is an absence of laboratory testing experiencing the DG interaction, the finite element model is validated for columns that demonstrated only global buckling mode and distortional buckling mode, before collapsing. For the validation, the experimental results from Heva [17] and Salles [18] are taken. The complete validation is described in detail in Lazzari [16] and Lazzari and Batista [19]. According to Lazzari [16], the available experimental results allowed calibration of the FEM model, which proved to be accurate to accomplish the equilibrium path of the columns under DG interaction.

3 Parametric analysis on DG buckling coupled phenomenon

A parametric study is addressed to a lipped channel cold-formed steel column (LC 100x70x15x2.70 mm, see Figure 1-a) under different DG buckling interaction nature. According to Martins *et al.* [12], the DG buckling interaction can be classified in 3 types of interaction natures: secondary-global bifurcation DG interaction (SGI), true DG interaction (TI) and secondary-distortional bifurcation DG interaction (SDI). Basically, adopting $R_{\lambda GD} = \lambda_G/\lambda_D = \sqrt{P_{crD}/P_{crG}}$ (where P_{crD} is the elastic critical distortional buckling load and P_{crG} elastic critical global buckling load) one can be classified as: (*i*) TI when $0.95 < R_{\lambda GD} < 1.05$; (*ii*) SDI when $R_{\lambda GD} \geq 1.05$; (*iii*) SGI when $R_{\lambda GD} \leq 0.95$. In order to illustrate the slenderness ratio $R_{\lambda GD}$ with the buckling interaction nature concepts, Figure 2 is displaying the signature curve of the LC 100x70x15x2.70 mm (out-to-out dimensions), in a length range of 1000 to 3000 mm, *i.e.* $0.60 < R_{\lambda GD} < 1.50$.

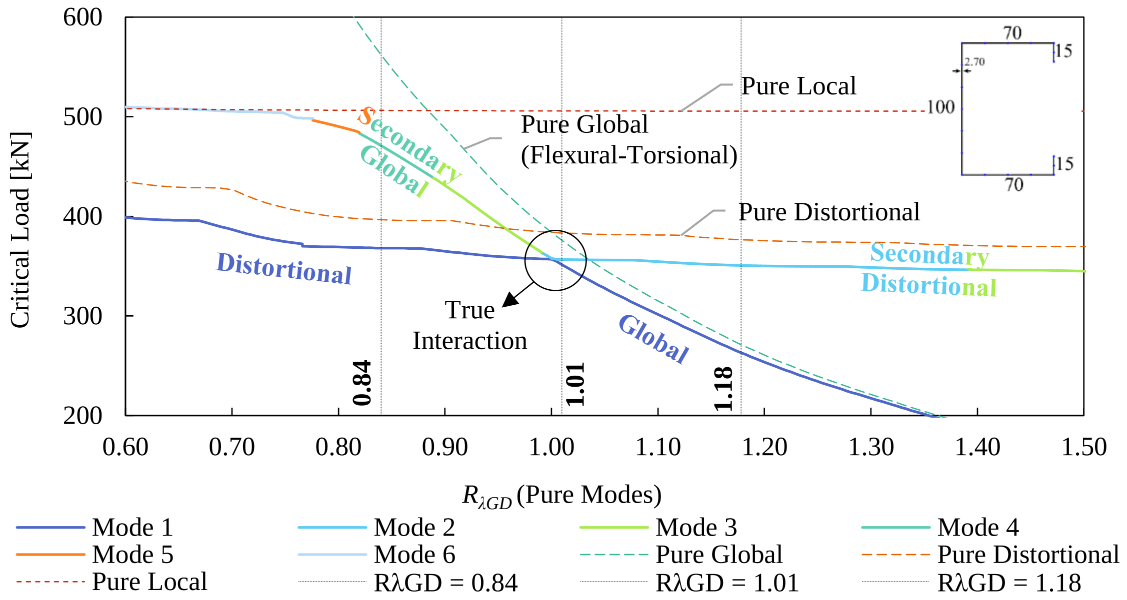

Figure 2. Critical load vs. $R_{\lambda GD}$ for LC 100x70x15x2.70 mm, illustrating SGI, TI, and SDI regions in all mode analysis (critical mode curve) and pure mode analysis.

The first parametric study is conducted with different combinations of initial geometric imperfections (IGIs) and yield stress only in TI nature (*i.e.* L=1850 mm), graphically displayed in Figure 2, for $R_{\lambda GD} = 1.01$. The main idea of this study, is to understand the structural behavior and strength influence of the IGI in the DG couple phenomenon, from low to high slenderness columns.

The second parametric study includes a variation of the column's length and yield stress in TI, SGI and SDI nature (*i.e.* column's length from 1500 to 2200 mm), displayed in Figure 2, for $0.84 < R_{\lambda GD} < 1.18$. The purpose of the study is to understand the nature behavior and strength of DG interaction in a slenderness range, including SGI, TI and SDI nature, from low to high slenderness columns.

3.1 Initial geometric imperfection combination from low to high slenderness columns

The analysis is performed for yield stress of 345 MPa, 508 MPa, 1016 MPa and 1523 MPa, for a lipped channel geometry with a gross area of 699.84 mm2 and critical buckling load of 354.5 kN. The goal of this study is to identify the column's strength and behavior sensibility and possible relevance to IGIs using "impure" modal combination. The geometry is determined for a column experiencing true DG interaction.

The IGI combination is managed combining the first elastic critical buckling mode with the second superior elastic buckling mode (known as global and distortional buckling modes, respectively). With assistance of an elastic buckling analysis software, called FStr (Finite Strip Computer Application, by Lazzari [16]), the buckling mode combination was capable to be achieved. The buckling mode combination is well described in Lazzari [16].

Comparing the strength of these columns with different IGI combination and different yield strength, it is possible to notice which IGI has more influence in the column's load capacity. Figure 3 shows the column strength vs. squash load, normalized with critical load in both axes. Seven types of IGI combination is chosen, *i.e.* $\theta = 0^o, 15^o, 30^o, 45^o, 60^o, 75^o$, and 90^o, due to a cyclic and symmetric behavior, according to Lazzari and Batista [19] (where θ is an initial geometric imperfection parameter, which it is a useful parameter for combining the first critical buckling mode with the second superior mode in all possible cases).

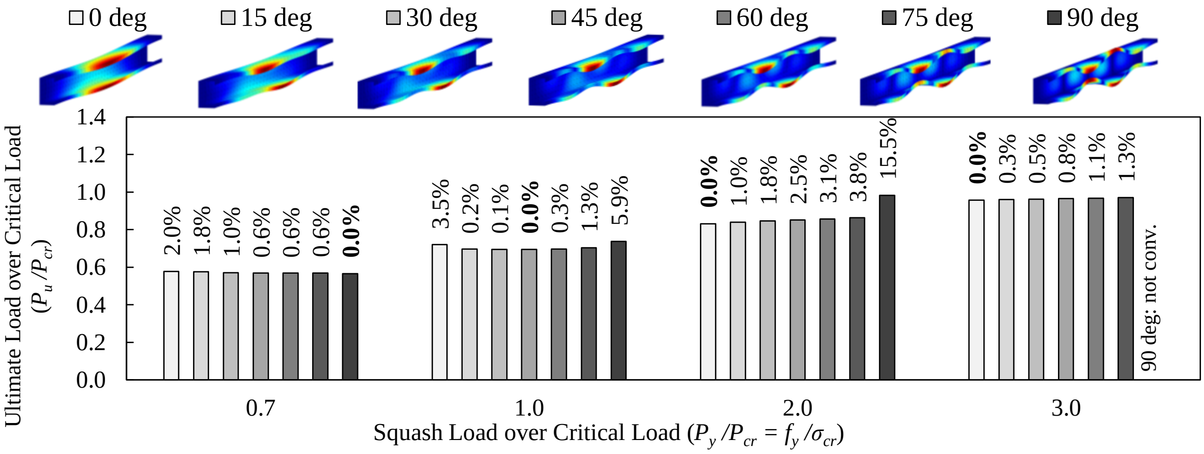

Figure 3. P_u/P_{cr} vs. P_y/P_{cr} of columns under different initial geometric imperfection combination, $\theta = [0^o, 90^o]$ and with yield strength of 345 MPa, 508 MPa, 1016 MPa and 1523 MPa.

As expected, in Figure 3, for more elastic columns, the ultimate load increases. For $P_y/P_{cr} = 0.7$, the lower ultimate load occurs with only distortional initial imperfection ($\theta = 90^o$ or in other symbology, 0G+1D). However, for $P_y/P_{cr} = 1.0$, the most detrimental load takes place with 50% of global and 50% of distortional buckling mode contribution ($\theta = 45^o$ or in other symbology, 0.5G+0.5D) of IGI. Moreover, for high slenderness columns, the lower ultimate load is affected only by global IGI ($\theta = 0^o$ or in other symbology, 1G+0D).

Basically, the proposed study of IGI combination allowed a deep understanding of the complex behavior of the True DG buckling interaction (TI). It has shown that the different IGI combination affects the ultimate load and structural behavior for a column under the TI DG buckling interaction nature. Now, it is important to study the behavior of the DG buckling interaction with different type of their nature, *i.e.* under SDI and SGI regions.

3.2 Study of DG coupled phenomenon nature

This study consists of investigating columns with different slenderness factors, to understand the influence of the interaction nature in the column's strength. For this study the same geometry employed in the IGI combination analysis is treated, however, only two types of IGI is used: 1G+0D and 0.5G+0.5D. The lengths of the column are reshaped, from 1500 to 2200 mm, with an increment step of 50 mm (total of 15 lengths). This column's length changing permits a modification of the global and distortional slenderness ratios and its contribution on the column behavior. Additionally, in order to reach from low to high slender columns, the yield stress of the CFS is changed. For this study, 3 types of yielding are employed: 345 MPa, 508 MPa and 1016 MPa.

More specifically, the study consists of compare the ultimate load with the nominal axial strength given in the codes and literature. The design approaches used in this study are: (*i*) nominal axial strength for the global buckling, P_{nG} [1], [2], [3] and [4]; (*ii*) nominal axial strength for the distortional buckling, P_{nD} [1], [2], [3] and [4]; (*iii*) nominal axial strength for the distortional-global interactive buckling, P_{nDG}, proposed by Schafer [20]; (*iv*) nominal axial strength for the global-distortional interactive buckling, P_{nGD}, suggested by Martins et al. [12].

The results are illustrated in two different graphs in Figure 4. First, Figure 4-a shows the numerical strength results comparing with the design approaches P_{nG} [1], P_{nD} [1], P_{nDG} [20], and P_{nGD} [12]. Secondly, Figure 21-b shows all the 90 columns strength over squash load ratio (P_u/P_y) versus the global buckling slenderness factor (λ_G), in addition with the global buckling DSM equation (ABNT NBR 14762 [1]) and the Euler column curve

$(1/\lambda_G{}^2)$ for reference.

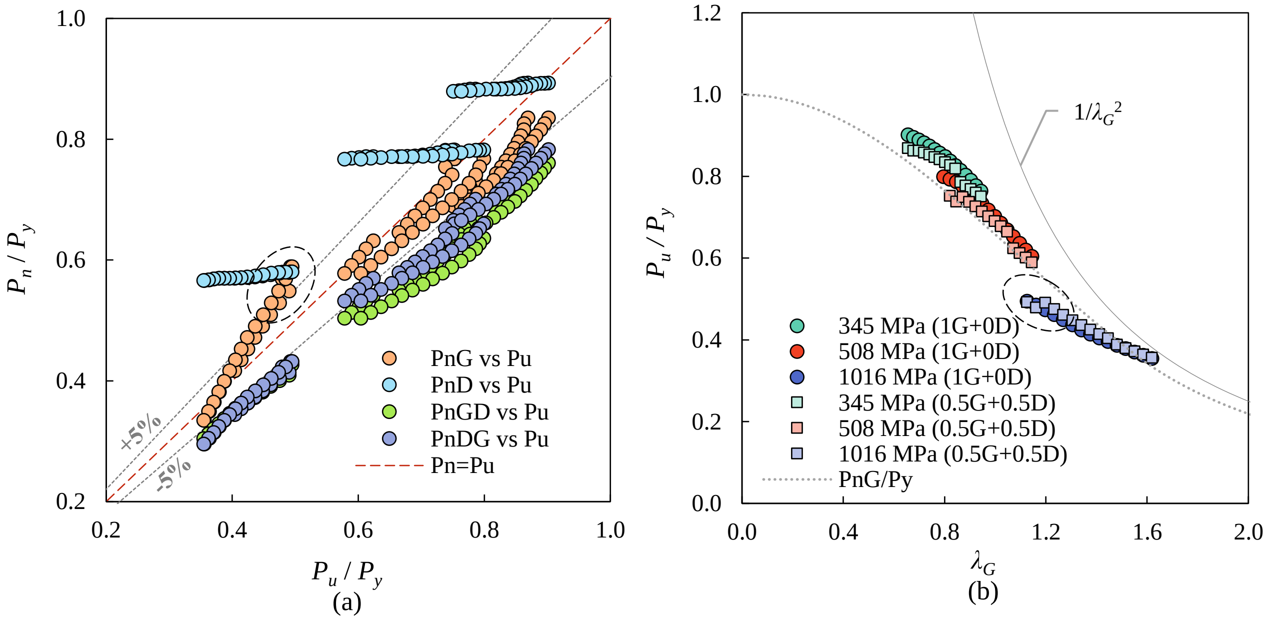

Figure 4. Column strength over Squash Load (P_u/P_y) results, with different yield stress and IGI, compared with: (a) the DSM equations (P_{nG}, P_{nD}, P_{nGD}, and P_{nDG}); (b) the global DSM equation Eq. (1) and Euler $1/\lambda_G{}^2$ curve.

In Figure 4-a is shown how disperse the ultimate load (P_u) are from the DSM equations (P_n). Notice that the P_{nD} procedure is clearly not corresponding to the column's strength. Furthermore, the P_{nG}, P_{nGD}, and P_{nDG} appears to be more stable approaches, even though the P_{nGD} and P_{nDG} procedures have shown to be quite conservative (points along the line -5% of $P_n = P_u$).

Notice in Figure 4-b, that the difference of the 1G+0D and 0.5G+0.5D IGI in the global DSM equation is negligible. Additionally, one important observation in Figure 4-b is the influence of the yielding stress. For yielding of 345 MPa and 508 MPa, the P_u/P_y ratios are above the P_{nG} equation, while for yielding of 1016 MPa, the P_u/P_y ratios are mostly below the P_{nG} equation (see dashed circle in Figure 4-b). These results indicate that the global DSM equation manage well the columns under different DG types of buckling interaction nature (*i.e.* TI, SDI and SGI).

One important observation can be retrieved from the data inside the dashed circles in Figure 4, related to the data from 1016 MPa compared to the P_{nG} equation. The data with P_u/P_y in the range of $R_{\lambda GD} < 0.87$ (*i.e.* $\lambda_G \approx 1.20$) seems to be far from the nominal axial strength for global buckling (see data inside dashed circles in Figure 4-a and Figure 4-b). However, these values of nominal axial strength are close to the distortional equation (see dashed circle in Figure 4-a). These results are an interesting finding, instigating that these columns are probably in a region of distortional failure, or perhaps in a weak DG coupled phenomenon failure, under secondary-global bifurcation DG interaction nature.

4 Closing remarks

The present research mainly provided an improvement of the comprehension of the distortional-global buckling coupled phenomenon. With respect to the parametric analysis on this coupled phenomenon, the following remarks must be pointed out:

Remark 1: The DSM equation addressed to global buckling can manage well the columns under the different DG nature studied in this research. However, the limits of the present investigation must be pointed, addressed only to lipped channel columns. Additional results of columns with different cross-section shapes and a wider range of slenderness factors are needed to strengthen this assumption as a rule;

Remark 2: The authors believe that the new calibrated equations for global buckling, *i.e.* Dinis *et al.* [21], might be a good proposal for consider the DG buckling interaction for high slenderness columns. Additionally, for different class of end boundary condition, the DG buckling coupled phenomenon design procedure, might be considered combining the new calibrated equations (*i.e.* Dinis *et al.* [21] for global buckling and Liu *et al.* [22] for distortional buckling). The conception is based on an idea from Schafer [20], *i.e.* replace the squash load from the distortional equation given by Liu *et al.* [22], by the global buckling equation presented by Dinis *et al.* [21];

Remark 3: The final remarks obtained from the DG buckling coupled phenomenon behavior are basically lined up with the ones found in Martins *et al.* [12]. However, more investigations on this topic are still needed, to better understand the phenomenon, since there is a lack of experimental tests of columns experiencing the distortional-global buckling interaction, in different types of nature.

To sum up, this work was mainly responsible for a deeper understanding of cold-formed lipped-channel columns under DG buckling interaction, with assistance of an elastic buckling analysis by the finite strip method, complimented by nonlinear FEM analysis. As initially proposed, the goal of this study has been achieved, with possible open topics that may be investigate in future research activities.

Acknowledgements. This research was financially supported by CNPq (Proc. 131199/2018-8) and FAPERJ grant E-26/200.825/2019 (242580).

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS and ABNT, *NBR 14762 - Dimensionamento de estruturas de aço constituídas por perfis formados a frio*, Segunda. Rio de Janeiro, RJ, Brazil, Brasil: ABNT, 2010.

[2] AS/NZS 4600, *Cold-formed steel structures, Standards Australia & Standard New Zealand*. Australian/New Zealand Standard™, 2018.

[3] AISI S100-16, *North American Specification for the Design of Cold-Formed Steel Structural Members*. American Iron and Steel Institute, 2016.

[4] E. Standard, "Eurocode 3 - Design of steel structures - Part 1-3: General rules - Suplementary rules for cold-formed members and sheeting," *Design*, 2005.

[5] B. W. Schafer and T. Peköz, "Direct strength prediction of cold-formed steel members using numerical elastic buckling solutions," in *Proceedings of 14th International Specialty Conference on Cold-Formed Steel Structures: Recent Research and Developments in Cold-Formed Steel Design and Construction*, 1998, pp. 69–76.

[6] G. J. Hancock, Y. B. Kwon, and E. S. Bernard, "Strength design curves for thin-walled sections undergoing distortional buckling," *J. Constr. Steel Res.*, vol. 31, no. 2–3, pp. 169–186, Jan. 1994, doi: 10.1016/0143-974X(94)90009-4.

[7] E. de M. Batista, "Modelling Buckling Interaction," in *Phenomenological and Mathematical Modelling of Structural Instabilities*, vol. 470, M. Pignataro and V. Gioncu, Eds. Vienna: Springer Vienna, 2005, pp. 135–194.

[8] E. de M. Batista, "Effective section method: A general direct method for the design of steel cold-formed members under local-global buckling interaction," *Thin-Walled Struct.*, vol. 48, no. 4–5, pp. 345–356, 2010, doi: 10.1016/j.tws.2009.11.003.

[9] M.-T. Chen, B. Young, A. D. Martins, D. Camotim, and P. B. Dinis, "Experimental investigation on cold-formed steel stiffened lipped channel columns undergoing local-distortional interaction," *Thin-Walled Struct.*, vol. 150, no. November 2019, p. 106682, May 2020, doi: 10.1016/j.tws.2020.106682.

[10] G. Y. Matsubara, E. de M. Batista, and G. C. Salles, "Lipped channel cold-formed steel columns under local-distortional buckling mode interaction," *Thin-Walled Struct.*, vol. 137, pp. 251–270, Apr. 2019, doi: 10.1016/j.tws.2018.12.041.

[11] P. B. Dinis and D. Camotim, "Post-buckling behaviour and strength of cold-formed steel lipped channel columns experiencing distortional/global interaction," *Comput. Struct.*, vol. 89, no. 3–4, pp. 422–434, 2011, doi: 10.1016/j.compstruc.2010.11.015.

[12] A. D. Martins, D. Camotim, and P. B. Dinis, "On the distortional-global interaction in cold-formed steel columns: Relevance, post-buckling behaviour, strength and DSM design," *J. Constr. Steel Res.*, vol. 145, pp. 449–470, Jun. 2018, doi: 10.1016/j.jcsr.2018.02.031.

[13] E. S. dos Santos, E. de Miranda Batista, and D. Camotim, "Cold-formed steel columns under L-D-G interaction," *Steel*

Constr., vol. 7, no. 3, pp. 193–198, Sep. 2014, doi: 10.1002/stco.201410034.

[14] G. Y. Matsubara and E. de M. Batista, "Cold-Formed Steel Columns Under Local-Distortional-Global Buckling Mode Interaction," in *Proceedings of the XL Ibero-Latin-American Congress on Computational Methods in Engineering, ABMEC, Natal, RN, Brazil*, 2019.

[15] ANSYS, *ANSYS Mechanical APDL Theory Reference Release 17.0*, vol. Release 17, no. January 2016. Canonsburg, PA: ANSYS, Inc., 2016.

[16] J. A. de Lazzari, "Distortional-Global Interaction In Cold-Formed Steel Lipped Channel Columns: Buckling Analysis, Structural Behavior And Strength," Master's Thesis, Civil Engineering Program, Federal University of Rio de Janeiro, COPPE, 2020.

[17] Y. B. Heva, "Behaviour and design of cold- formed steel compression members at elevated temperatures," Thesis, School of Urban Developments Queensland University of Technology, 2009.

[18] G. C. de Salles, "Investigação Analítica, Numérica e Experimental do Modo de Flambagem Distorcional em Perfis Formados a Frio," Dissertação de Mestrado, Universidade Federal do Rio de Janeiro, COPPE, 2017.

[19] J. A. de Lazzari and E. D. M. Batista, "Behavior and Strength of Distortional-Global Interaction in Cold Formed Steel Lipped Channel Columns," in *Proceedings of the XL Ibero-Latin-American Congress on Computational Methods in Engineering, ABMEC*, 2019, pp. 1–20.

[20] B. W. Schafer, "Local, Distortional, and Euler Buckling of Thin-Walled Columns," *Journal of Structural Engineering*, vol. 128. pp. 289–299, 2002.

[21] P. B. Dinis, D. Camotim, A. Landesmann, and A. D. Martins, "Improving the Direct Strength Method prediction of column flexural-torsional failure loads," *Thin-Walled Struct.*, vol. 148, no. October 2019, Mar. 2020, doi: 10.1016/j.tws.2019.106461.

[22] Z. Liu, Y. Yang, X. Zhou, and Z. He, "Unified formulae for critical load and unified DSM expressions for pinned-end and fixed-end columns exhibiting pure distortional buckling," *Thin-Walled Struct.*, vol. 151, Jun. 2020, doi: 10.1016/j.tws.2020.106746.