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Lipped Channel, Hat, Zed and Rack Cold-Formed Steel Columns Under Local-Distortional Buckling Interaction

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Abstract.
Cold-Formed Steel (CFS) are usually thin-walled structural members, susceptible to several individual buckling phenomena, namely local (L), distortional (D), global (G) (flexural or flexural-torsional) or interaction buckling behavior, denominated local-distortional (LD), local-global (LG), distortional-global (DG) and local-distortional-global (LDG) interactive buckling modes. The currently codified design approaches are able to handle single local (L), distortional (D) and global (G) modes, as well as local-global (LG) interaction buckling failure. The buckling mode interaction may conduct to erosion of the column strength, if compared to isolated single modes, and must be taken into account in the structural design practice. The present work is aimed to propose a design approach for CFS columns undergoing LD interaction, condition not considered by the Brazilian code ABNT NBR14762:2010. The authors' developed equations for LD design approach for CFS lipped channel columns were tested for other CFS shapes, in order to expand its validity to usual CFS geometries, as zed, hat and rack. The obtained results and the validation of the proposed solution proved to be easy to apply and reliable in predicting the column strength of the most usual CFS.

Keywords: Cold-formed Steel Columns; Local-Distortional Buckling Interaction; Finite Element Method; Structural Design Approach.

1. Introduction

Cold-Formed Steel (CFS) is widely used in Light Steel Framing System because its favorable strength-to-weight ratio for structural applications. These members are currently applied in buildings, storage racks, bridges, sheds, roofs and many other applications. Despite the varied applications these members are susceptible to several individual buckling phenomena, namely local (L), distortional (D), global (G) (flexural or flexural-torsional) or interaction buckling behavior, denominated local-distortional (LD), local-global (LG), distortional-global (DG) and local-distortional-global (LDG) interactive buckling modes. Moreover, the currently codified design approaches are able to handle single local (L), distortional (D) and global (G) modes, as well as local-global (LG) interaction buckling failure. Hence, a large amount of research work was recently developed devoted to investigate mainly local-distortional (LD), distortional-global (DG), local-distortional-global (LDG) interaction failures modes. The buckling mode interaction may conduct to erosion of the column strength, if compared to isolated single modes, and must be taken into account in the structural design practice.

The strength erosion caused by the LD interaction was studied by Kwon e Hancock [1], Dinis *et al.* [2], Silvestre *et al.* [3], Loughlan *et al.* [4], Young *et al.* [5], Martins *et al.* [6], Martins *et al.* [7], Dinis and Camotim [8], Martins *et al.* [9], Matsubara *et al.* [10], Batista *et al.* [11], Chen *et al.* [12] e Campos *et al.* [13]. The mentioned works developed numerical and experimental researches to better understand the phenomenon.

In addition, important results related to DG and LDG interaction were carried out by Dinis *et al.* [14], Dinis *et al.* [15], Santos [16], Cava *et al.* [17], Young *et al.* [18], Dinis *et al.* [19], Martins *et al.* [20], Martins *et al.* [21] and Lazzari [22].

In this context, the present work is aimed to propose a design approach for CFS columns undergoing LD interaction, condition not considered by the Brazilian code ABNT NBR14762:2010 [23]. Moreover, the authors' developed equations are a good design approach for CFS lipped channel, zed, hat and rack columns under LD interaction.

2. LD design approach for columns under LD interaction

The cold-formed steel columns are susceptible to buckling phenomena and can develop buckling modes namely Local (L), Distortional (D) and Global (G), as illustrated in Figure 1.

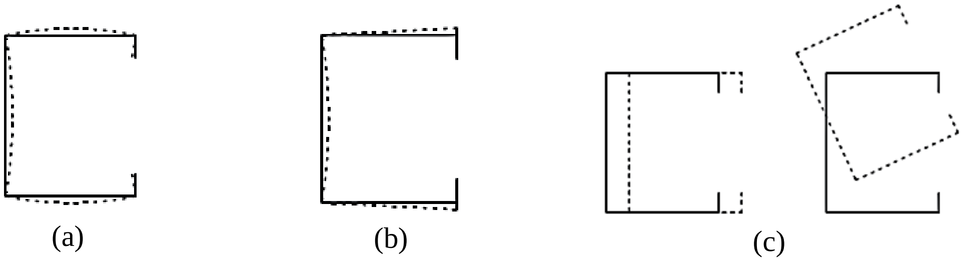


Figure1. Lipped channel column subjected to: (a) Local mode; (b) Distortional mode and (c) Global mode.

Moreover, L, D and G modes can interact with each other, resulting the Local-Distortional (LD), Local-Global (LG), Distortional-Global (DG) and Local-Distortional-Global (LDG) buckling interactions. In figure 2, it is possible to observe the LD interaction in CFS lipped channel column.

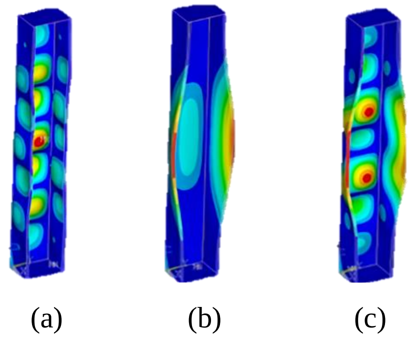


Figure 2. CFS Lipped channel column subjected to: (a) L mode; (b) D mode and (c) LD mode interaction [24].

The design approach for CFS columns undergoing LD interaction, DG and LDG condition are not considered Brazilian code ABNT NBR14762:2010 [25] and North American Specification [26]. However, interaction may conduct to erosion of the column strength, if compared to isolated single modes, and must be taken into account in the structural design practice. For LD interaction there are recent proposals to deal with LD interaction and can be accessed in Schafer [26], Martins *et al.* [9], Matsubara *et al.* [10] and Batista *et al*. [11].

Batista *et al.* [11] proposed a design approach, f_{nLD} – eq. (1), which was developed and calibrated for lipped channel columns under Local, Distortional and LD interaction. The methodology was similar to that described by Matsubara *et al.* [10] adding improvements for better practical application. The solution obtained is based on the ratio between distortional slenderness and local buckling slenderness factors, $R_{\lambda DL}=\lambda_D/\lambda_L$, with $\lambda_D=(f_y/f_{crD})^{0.5}$ and $\lambda_L=(f_y/f_{crL})^{0.5}$, f_y is the steel yielding stress, f_{crD} is the critical distortional buckling stress and f_{crL} is the critical local buckling stress. Moreover, the solution maintains the well-known Winter strength equation concept.

$$f_{nLD} = \left(1 - \frac{A}{\lambda_{maxLD}{}^{B}}\right)\frac{f_y}{\lambda_{maxLD}{}^{B}} \quad \text{for} \quad \lambda_{maxLD} = \text{máx}\,\{\lambda_L,\lambda_D\} \text{ e } \frac{f_{nLD}}{f_y} \leq 1 \tag{1}$$

$$A = \begin{cases} 0.15 & R_{\lambda DL} < 0.80 \\ 0.40\, R_{\lambda DL} - 0.17 & 0.80 \leq R_{\lambda DL} \leq 1.05 \\ 0.25 & R_{\lambda DL} > 1.05 \end{cases}$$

$$B = \begin{cases} 0.80 & R_{\lambda DL} < 0.45 \\ -2.26 R_{\lambda DL}{}^2 + 4.06\, R_{\lambda DL} - 0.57 & 0.45 \leq R_{\lambda DL} \leq 1.05 \\ 1.20 & R_{\lambda DL} > 1.05 \end{cases}$$

The good accuracy of f_{nLD} can be verified in numerical results shown in Figure 3. The ratio between numerical ultimate strength lipped channel columns, $f_{unumerical}$, and f_{nLD} approach presented mean and standard deviation equal to 1.04 and 0.08, respectively. The calculated LRFD (Load and Resistance Factor Design) resistance factor is ϕ= 0.89. According to North American Specification (NAS) [25] values of $\phi \geq 0.85$ are in accordance with the safety criteria.

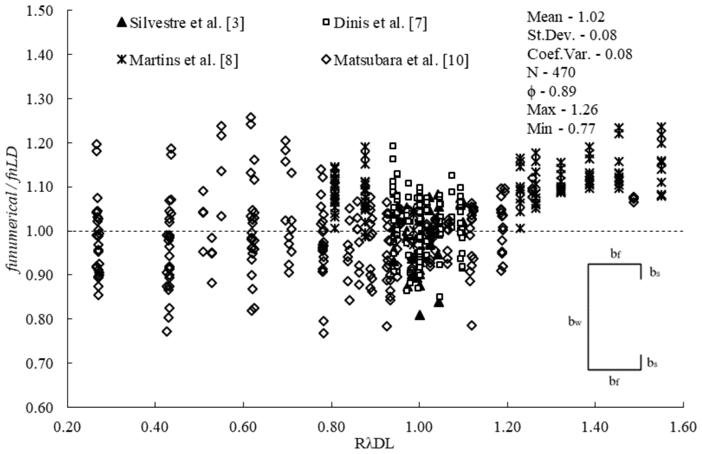


Figure 3. Numerical tests of lipped channel columns: $f_{unumerical}$ /f_{nLD} ratio vs $R_{\lambda DL}$ (λ_D/λ_L).

Furthermore, Figure 4 shows the good accuracy of f_{nLD} for experimental results of lipped channel columns. The mean and standard deviation of f_{uexp} /f_{nLD} (ratio between experimental ultimate strength, f_{uexp}, and proposed approach f_{nLD} for the strength of lipped channel columns), equal to 0.94 and 0.09, respectively. The calculated LRFD (Load and Resistance Factor Design) resistance factor is ϕ = 0.87.

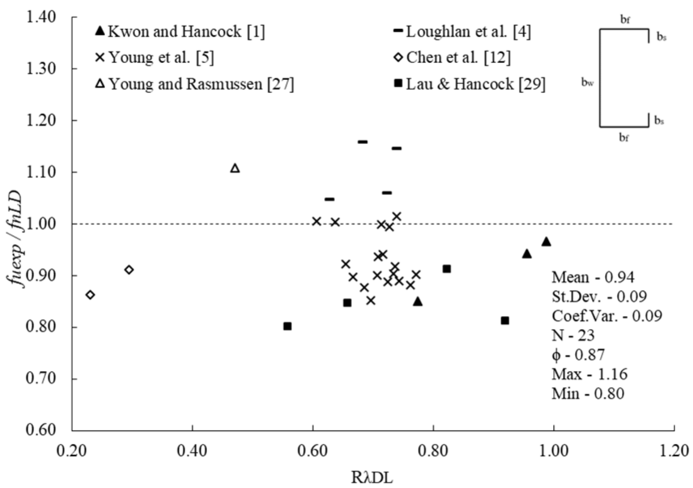


Figure 4. Experimental tests of lipped channel columns: f_{uexp} /f_{nLD} ratio vs $R_{\lambda DL}$ (λ_D/λ_L).

In addition, the present work proposes an adjustment of the eq. (1) to apply to hat, zed and rack sections. To achieve this goal, a section adjustment coefficient (S_n) is added to as shown in the eq. (2), f_{nLD*}. The S_n coefficient was obtained through adjustments of numerical results performed by Dinis *et al.* [7], Martins *et al.* [8] and Campos [13]. The results of these adjustments are summarized in Table 1 and one may observe eq. (2) reproduce eq. (1)

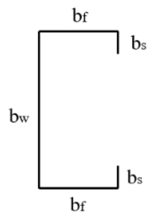
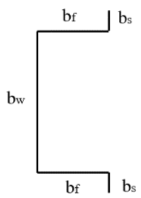
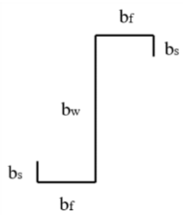
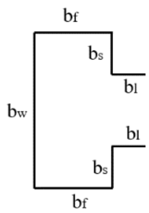
for lipped channel columns.

$$f_{nLD^*} = \left(1 - \frac{A}{\lambda_{maxLD}{}^{B}}\right)\frac{S_n \cdot f_y}{\lambda_{maxLD}{}^{B}} \quad \text{for} \quad \lambda_{maxLD} = \max\{\lambda_L, \lambda_D\} \text{ e } \frac{f_{nLD}}{f_y} \leq 1 \qquad (2)$$

$$A = \begin{cases} 0.15 & R_{\lambda DL} < 0.80 \\ 0.40\, R_{\lambda DL} - 0.17 & 0.80 \leq R_{\lambda DL} \leq 1.05 \\ 0.25 & R_{\lambda DL} > 1.05 \end{cases}$$

$$B = \begin{cases} 0.80 & R_{\lambda DL} < 0.45 \\ -2.26 R_{\lambda DL}{}^2 + 4.06\, R_{\lambda DL} - 0.57 & 0.45 \leq R_{\lambda DL} \leq 1.05 \\ 1.20 & R_{\lambda DL} > 1.05 \end{cases}$$

Table 1. Section coefficient of lipped channel, hat, zed and rack columns, S_n.

Section		S_n
Lipped channel		$S_n = 1$
Hat		$R_{\lambda DL} < 0.45$ $S_n = 1$ $0.45 \leq R_{\lambda DL} \leq 1.05$ $S_n = -0.98\, R_{\lambda DL}{}^2 + 1.47\, R_{\lambda DL} + 0.54$ $R_{\lambda DL} > 1.05$ $S_n = 1$
Zed		$R_{\lambda DL} < 0.45$ $S_n = 1$ $0.45 \leq R_{\lambda DL} \leq 1.00$ $S_n = -1.34\, R_{\lambda DL}{}^2 + 1.95\, R_{\lambda DL} + 0.39$ $R_{\lambda DL} > 1.00$ $S_n = 1$
Rack		$R_{\lambda DL} < 0.45$ $S_n = 1$ $0.45 \leq R_{\lambda DL} \leq 0.95$ $S_n = -1.12\, R_{\lambda DL}{}^2 + 1.57\, R_{\lambda DL} + 0.52$ $R_{\lambda DL} > 0.95$ $S_n = 1$

In figures 5, 6 and 7 it is possible to verify the good performance of f_{nLD^*} for designing zed, hat and rack numerical columns. These figures show the relationship between numerical ultimate strength, $f_{unumerical}$, and proposed approach f_{nLD^*} with the variation of $R_{\lambda DL}$. The LRFD values of all columns are in accordance with the safety criteria, $\phi \geq 0.85$. Furthermore, it is possible to notice more conservative results for values of $R_{\lambda DL} > 1.20$ for all analyzed columns. The reason for this unexpected behavior is under study. In this region, the eqs. (1) and (2) result in pure distortional formulation, reproducing the usual procedure found in Brazilian code ABNT NBR14762:2010 [23] and North American Specification [25].

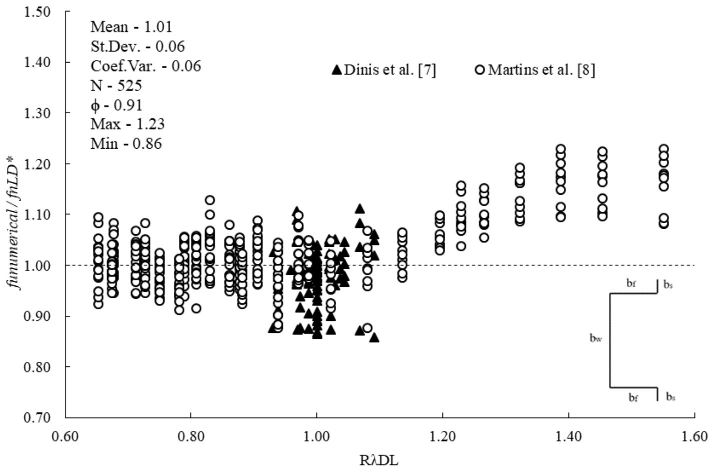


Figure 5. Numerical Hat columns tests: $f_{unumerical}$ /f_{nLD*} ratio vs R$_{\lambda DL}$ (λ_D/λ_L).

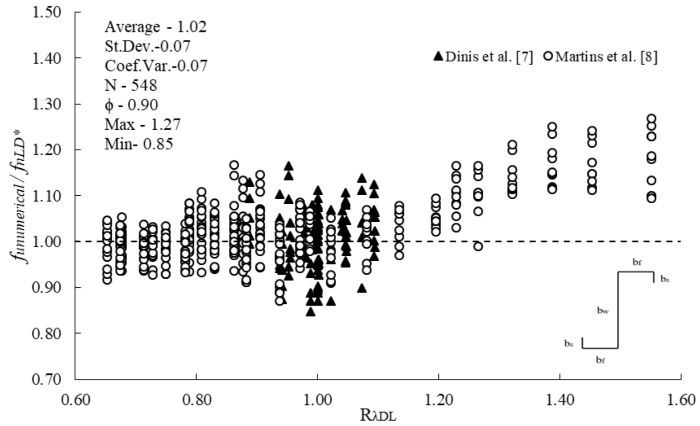


Figure 6. Numerical Zed columns tests: $f_{unumerical}$ /f_{nLD*} ratio vs R$_{\lambda DL}$ (λ_D/λ_L).

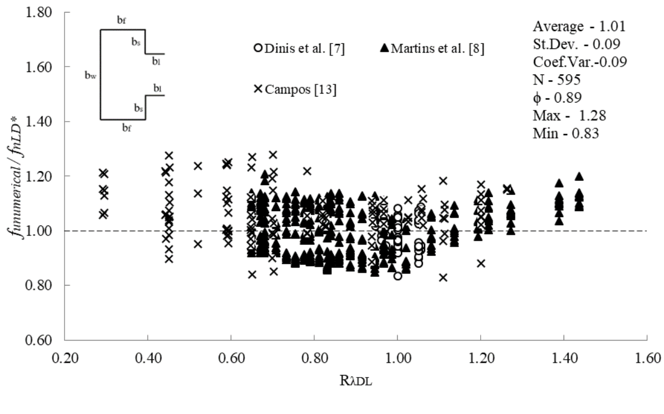


Figure 7. Numerical Rack columns tests: $f_{unumerical}$ /f_{nLD*} ratio vs R$_{\lambda DL}$ (λ_D/λ_L).

Finally, eq. (2) proved to be an accurate procedure for designing columns subjected to L, D and LD mode in CFS lipped channel, hat, zed and rack columns. The f_{nLD*} proposal is easy to apply and further studies are underway involving global mode.

Conclusions

This work was intended to continue the research reported by Batista *et al.* [11] in order to expand the eq. (1), f_{nLD}, for zed, hat and rack columns. For this purpose, the shape coefficient (S_n) was added, resulting in eq. (2), f_{nLD*}.

The solution presented by f_{nLD*} proved to be very effective and easy to apply for designing usual practical sections columns. For such validation, 23 experimental columns and 470 lipped channel numerical columns were used. In addition, 525 hat, 548 zed and 595 rack additional numerical columns were validated. All columns presented LRFD (Load and Resistance Factor Design) resistance factor in accordance with the safety criteria defined by North American Specification (NAS) [25]. The results are summarized in Table 2.

Table 2. Summary of results.

Column	N	ϕ
Lipped Channel	23 experimental	0.87
	470 numerical	0.89
Hat	525 numerical	0.91
Zed	548 numerical	0.90
Rack	595 numerical	0.89

Finally, studies related to interaction involving the global mode are ongoing, being possible to disclose new results in the near future.

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References

[1] Y. B. Kwon and G. J. Hancock. "Tests of cold-formed channels with local and distortional buckling". *Journal of Structural Engineering*, v. 118, p. 1786–1803, 1992.

[2] P. B. Dinis; D. Camotim; N. Silvestre. "FEM-based analysis of the local-plate/distortional mode interaction in cold-formed steel lipped channel columns". *Computers and Structures*, v. 85, n. 19–20, p. 1461–1474, 2007.

[3] N. Silvestre; D. Camotim; P. B. Dinis. "Post-buckling behaviour and direct strength design of lipped channel columns experiencing local/distortional interaction". *Journal of Constructional Steel Research*, v. 73, p. 12-30, 2012.

[4] J. Loughlan; N. Yidris; K. Jones. "The failure of thin-walled lipped channel compression members due to coupled local-distortional interactions and material yielding". *Thin-Walled Structures*, v. 61, p. 14-21, 2012.

[5] B. Young; N. Silvestre; D. Camotim. "Cold-Formed Steel Lipped Channel Columns Influenced by Local-Distortional Interaction: Strength and DSM Design". *Journal of Structural Engineering*, v. 139, p. 1059-1074, 2013.

[6] A. D. Martins; D. Camotim; P. B. Dinis. "Local-Distortional Interaction in Cold-formed Steel Columns: Mechanics, Testing, Numerical Simulation and Design". *Structures*, v. 4, p. 38-57, 2015.

[7] P. B. Dinis and D. Camotim. "Cold-formed steel columns undergoing local–distortional coupling: Behaviour and direct strength prediction against interactive failure". *Computers and Structures*, v. 147, p. 181-208, 2015.

[8] A. D. Martins; P. B. Dinis; D. Camotim. "On the relevance of local-distortional interaction effects in the behaviour and design of cold-formed steel columns". *Computers and Structures*, v. 160, p. 57-89, 2015.

[9] A. D. Martins; D. Camotim; P. B. Dinis. "On the direct strength design of cold-formed steel columns failing in local-distortional interactive modes". *Thin-Walled Structures*, v. 120, p. 432-445, 2017.

[10] G. Y. Matsubara; E. M. Batista; G. C. Salles. "Lipped Channel cold-formed steeel columns under local-distortional buckling mode interaction". *Thin-Walled Structures*, v. 137, p. 251-270, 2019.

[11] E. M. Batista; G. Y. Matsubara; J. M. S. Franco. "Local-distortional buckling interaction of cold-formed steel columns

design approach". In: Prague: International Colloquia on Stability and Ductility of Steel Structures (2019), pp. 1-8.

[12] M. T. Chen; B. Y. Young; A. D. Martins; D. Camotim; P. B. Dinis. "Experimental investigation on cold-formed steel stiffened lipped channel columns undergoing local-distortional interaction". *Thin-Walled Structures*, v. 150, p. 1-20, 2020.

[13] R. G. A. Campos. Análise da interação entre os modos de flambagem local e distorcional em perfis de aço formados a frio com seção rack sob compressão axial. Master's Dissertation, University of Rio de Janeiro, 2020.

[14] P.B. Dinis; D. Camotim; E. M. Batista; E. S. Santos. "Local/distortional/global mode coupling in fixed lipped channel columns: behaviour and strength". *Advanced Steel Construction*, v. 7, p. 113-130, 2011.

[15] P.B. Dinis; D. Camotim; E. M. Batista; D. Camotim; E. S. Santos. "Local/distortional/global mode coupling in fixed lipped channel columns: behaviour and strength". *Thin-Walled Structures*, v. 61, p. 2-13, 2012.

[16] E. S. Santos. Interação entre os modos de flambagem local-distorcional-global em perfis de aço formados a frio com seção u enrijecido na compressão axial. PhD thesis, University of Rio de Janeiro, 2014.

[17] D. Cava; D. Camotim; P. B. Dinis; A. Madeo. "Numerical investigation and direct strength design of cold-formed steel lipped channel columns experiencing local-distortional-global interaction". *Thin-Walled Structures*, v. 105 p. 231-247, 2016.

[18] B. Young; P. B. Dinis; D. Camotim. "CFS lipped channel columns affected by L-D-G interaction. Part I: Experimental Investigation". *Computer and Structures*, v. 207, p. 219-232, 2017.

[19] P. B. Dinis; D. Camotim; B. Young; E. M. Batista. "CFS lipped channel columns affected by L-D-G interaction. Part II: Numerical simulations and design considerations". *Computer and Structures,* v. 207, p. 200-218, 2018.

[20] A. D. Martins; D. Camotim; P. B. Dinis. "On the distortional-global interaction in cold-formed steeel columns: Relevance, post-buckling behaviour, strength and DSM design". *Journal of Constructional Steel Research,* v. 145, p. 449-470, 2018.

[21] A.D. Martins; D. Camotim; R. Gonçalves; P. B. Dinis. "On the mechanics of distortional-global interaction in fixed-ended columns". *Thin-Walled Structures*, v. 123, p. 162-184, 2018.

[22] J. A. Lazzari. Distortional-global interaction in cold-formed steel lipped channel columns: buckling analysis, structural behavior and strength. Master's Dissertation, University of Rio de Janeiro, 2020.

[23] Brazilian Association of Standards (ABNT) 2010, Brazilian standard on design of cold-formed steel structures (NBR 14762:2010), Rio de Janeiro, Brazil (Portuguese).

[24] G. Y. Matsubara. Interação entre modos de flambagem local-distorcional em perfis de aço formado a frio com seção u enrijecido sob compressão axial. Master's Dissertation, University of Rio de Janeiro, 2018.

[25] American Iron and Steel Institute (AISC), North American Specification (NAS) for the Design of Cold-Formed Steel Structural Members (AISC-S100-16), Washington DC, 2016.

[26] B.W. Schafer. "Local, Distortional, and Euler Buckling of Thin-Walled Columns". *Journal of Structural Engineering*, v. 121, p. 289-299, 2002.

[27] B. Young; K. J. R. Rasmussen. "Design of lipped channel columns". *Journal of Structural Engineering*, v. 124, p. 140-148, 1998.

[28] G. C. Salles. Investigação analítica, numérica e experimental do modo de flambagem distorcional em perfis formados a frio. Master's Dissertation, University of Rio de Janeiro, 2018.

[29] S. C. W. Lau; G. J. Hancock. "Distortional buckling tests of cold-formed channel sections". St. Louis: Ninth International Specialty Conference of Cold-Formed Steel Structures (1988), pp. 45-73.