Structural Design of Cold-Formed Steel Columns: buckling interaction all-in-one method

Gustavo Yoshio Matsubara[1], Eduardo de Miranda Batista[2]

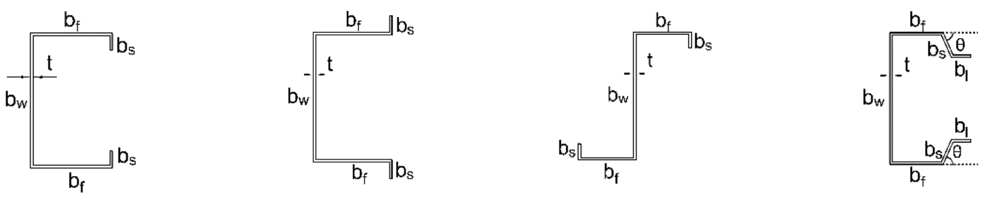
[1]*PCV, Civil Engineering Program, State University of Maringá*
Avenida Colombo, 5790, Bloco C67, Sala 2, 87020-900, Maringá/PR, Brazil
gustavoyoshio@coc.ufrj.br
[2]*COPPE, Civil Engineering Program, Federal University of Rio de Janeiro. Brazil*
Centro de Tecnologia, Bloco I, Sala I216, Ilha do Fundão, 21945-909, Rio de Janeiro/RJ, Brazil
batista@coc.ufrj.br

Abstract. Cold-formed steel members are lightweight structures that provide a good weight-to-strength ratio. For columns and beams, design procedures in standards such as the Brazilian, Australian-New Zealand, and American codes consider only local, distortional, and global buckling modes, as well as the interaction between local and global buckling modes (LG). The present research has focused on investigating the buckling interactions: local-distortional (LD), distortional-global (DG) and local-distortional-global (LDG). To develop a design approach for the interaction between buckling modes, the finite element method using ANSYS software was employed. A parametric study was conducted by varying the slenderness parameter (λ), in order to cover the usual geometric parameters of the steel thin-walled columns. The study resulted in the proposition of a new design approach, described as the Generalized Direct Strength Method (GDSM).

Keywords: Direct Strength Method, cold-formed steel column, buckling modes interaction, structural design.

1. Introduction

Cold-formed steel (CFS) profiles are very versatile due to their excellent weight-to-strength ratio, achieved through the application of folds in thin steel sheets, with the increase of its structural stiffeness for regular applications. Figure 1 shows the most commonly used cross-sections, including: (a) Lipped channel, (b) Hat, (c) Zed, and (d) Rack.



(a) (b) (c) (d)

Figure 1. Cold-formed steel sections (CFS): (a) lipped channel, (b) hat, (c) Zed, (d) rack.

The use of cold-formed steel profiles has been widely adopted in the light steel framing construction system, where these elements are primarily subjected to compression and bending, referred to as columns and beams, respectively. Figure 2 shows a two floors residence with a structural system employing cold-formed steel members.

Figure 2. Cold-formed steel structure system of a residence employing a light steel framing system (LSF) [1].

The Direct Strength Method (DSM) [2] is widely accepted for the design of CFS strutures, which takes advantage of computational software to obtain the critical buckling loads, such as GBTUL [3], CUFSM [4], THIN-WALL-2 [5], and FStr [6]. This method is incorporated into the design codes for cold-formed steel structures, as the North American [7], the Australian-New Zealand [8] and the Brazilian ABNT [9]. The DSM specifies procedures for designing columns and beams under local (L), distortional (D), and global (G) buckling modes, as well as the interaction between local and global buckling modes (LG).
However, it remains a need to establish design procedures that address the interactions between local-distortional (LD), distortional-global (DG) and local-distortional-global (LDG) buckling modes. Therefore, this study aims to propose design methodologies to address this gap, based on the DSM principles and current equations.

2. Direct Strength Method (DSM) for the Column Design

The Direct Strength Method (DSM) provides a straightforward approach for designing CFS columns subjected to local, distortional, global, and local-global buckling mode interactions. Equation 1 describes a Winter-type curve used for the structural design of columns under local and global buckling modes, as well as for local-global buckling mode interactions. The local and global buckling loads are denoted by P_L and P_G , respectively, while the squash load is represented by $P_y=Af_y$, with A as the cross section area and f_y as the steel yielding stress.

$$P_{nLG}=\begin{cases} P_{nG} & \lambda_{LG}\leq 0.776 \\ \left(1-\frac{0.15}{\lambda_{LG}^{0.8}}\right)\frac{P_{nG}}{\lambda_{LG}^{0.8}} & \lambda_{LG}>0.776 \end{cases} \quad \text{with} \quad \lambda_{LG}=\sqrt{\frac{P_{nG}}{P_L}} \tag{1.a}$$

$$\chi_n=\begin{cases} \left(0.658^{\lambda_G^2}\right) & \lambda_G\leq 1.50 \\ \left(\frac{0.877}{\lambda_G^2}\right) & \lambda_G>1.50 \end{cases} \quad \text{with } \lambda_G=\sqrt{\frac{P_y}{P_G}} \tag{1.b}$$

$$P_{nG}=\chi_n P_y \tag{1.c}$$

Equation 2 is the Winter-type curve used for designing columns under the distortional buckling mode. The design strength provided by DSM is the minimum value of Equations 1 and 2, $P_n=\min\{P_{nLG}, P_{nD}\}$.

$$P_{nD}=\begin{cases} P_y & \lambda_D\leq 0.561 \\ \left(1-\frac{0.25}{\lambda_D^{1.2}}\right)\frac{P_y}{\lambda_D^{1.2}} & \lambda_D>0.561 \end{cases} \quad \text{with } \lambda_D=\sqrt{\frac{P_y}{P_D}} \tag{2}$$

3. Generalized Direct Strength Method applied to CFS column

The Generalized Direct Strength Method based on research presented by Matsubara, Batista, and Salles [10]. More recently, Matsubara and Batista [11] proposed an original approach based on a parametric study using both experimental and finite element method (via ANSYS software) results. This new equation, described by Equation 3 (P_{nLDG}), considers lipped channel columns under isolated buckling modes (L, D, and G) as well as the interactions between buckling modes (LD, DG, and LDG), resulting in an "all-in-one" solution. This solution resulted in a Winter-type curve that incorporates the slenderness ratio between distortional and local slenderness, $R_{\lambda DL}=\lambda_D/\lambda_L$ as the main variable of the problem, together with the parameter $\lambda_{maxLD}=\max(\lambda_L;\lambda_D)$.

$$P_{nLDG} = \begin{cases} P_{nG} = \chi_n P_y & \text{for } \lambda_{LDG} \leq \lambda_{limLDG} \\ \left(1 - \frac{A}{\lambda_{LDG}{}^{B}}\right) \frac{\chi_m P_y}{\lambda_{LDG}{}^{B}} & \text{for } \lambda_{LDG} > \lambda_{limLDG} \end{cases} \quad \text{and} \quad \lambda_{limitLDG} = \sqrt[B]{0.5\mu + \sqrt{0.25\mu^2 - A\mu}} \tag{3.a}$$

$$\mu = \frac{\chi_m}{\chi_n} \geq 1.0 \quad \text{and} \quad \lambda_{LDG} = \lambda_{maxLD}\sqrt{\chi_m} \tag{3.b}$$

$$\chi_m = \begin{cases} \left(C^{\lambda_G{}^{D}}\right) & \lambda_G \leq 1.50 \\ \left(\frac{E}{\lambda_G{}^{F}}\right) & \lambda_G > 1.50 \end{cases} \tag{3.c}$$

$$A = \begin{cases} 0.15 & R_{\lambda DL} < 0.80 \\ 0.40\, R_{\lambda DL} - 0.17 & 0.80 \leq R_{\lambda DL} \leq 1.05 \\ 0.25 & R_{\lambda DL} > 1.05 \end{cases} \tag{3.d}$$

$$B = \begin{cases} 0.80 & R_{\lambda DL} < 0.45 \\ -2.26 R_{\lambda DL}{}^{2} + 4.06 R_{\lambda DL} - 0.57 & 0.45 \leq R_{\lambda DL} \leq 1.05 \\ 1.20 & R_{\lambda DL} > 1.05 \end{cases} \tag{3.e}$$

$$C = \begin{cases} 0.66 & R_{\lambda DL} < 0.45 \\ 0.20 R_{\lambda DL} + 0.57 & 0.45 \leq R_{\lambda DL} \leq 1.65 \\ 0.90 & R_{\lambda DL} > 1.65 \end{cases} \tag{3.f}$$

$$D = \begin{cases} 2.00 & R_{\lambda DL} < 0.45 \\ 0.20 R_{\lambda DL} + 1.91 & 0.45 \leq R_{\lambda DL} \leq 1.65 \\ 2.24 & R_{\lambda DL} > 1.65 \end{cases} \tag{3.g}$$

$$E = \begin{cases} 0.88 & R_{\lambda DL} < 0.45 \\ 0.35 R_{\lambda DL} + 0.72 & 0.45 \leq R_{\lambda DL} \leq 1.65 \\ 1.30 & R_{\lambda DL} > 1.65 \end{cases} \tag{3.h}$$

$$F = \begin{cases} 2.00 & R_{\lambda DL} < 0.55 \\ -0.59 R_{\lambda DL} + 2.32 & 0.55 \leq R_{\lambda DL} \leq 1.65 \\ 1.35 & R_{\lambda DL} > 1.65 \end{cases} \tag{3.i}$$

Equations 3 represents the column strength surface for the particular case of $R_{\lambda DL}$=1.0. It is noteworthy that this methodology generates multiple Winter-type curves, integrating the current formulation established by the original Direct Strength Method (DSM).

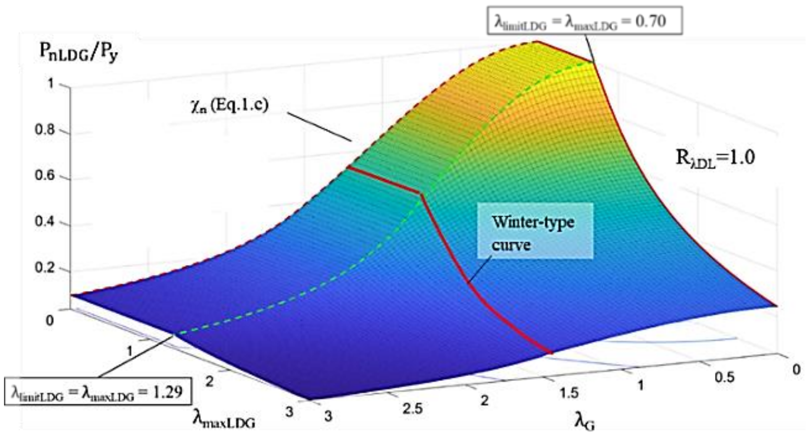


Figure 3. The proposed column strength surface P_{nLDG} defined by Equation 3, for the particular case of $R_{\lambda DL}$=1.0.

4. Assessment of the Generalized Direct Strength Method (GDSM)

The methodology of the Generalized Direct Strength Approach is comprehensively detailed in the flowchart provided in Figure 4.

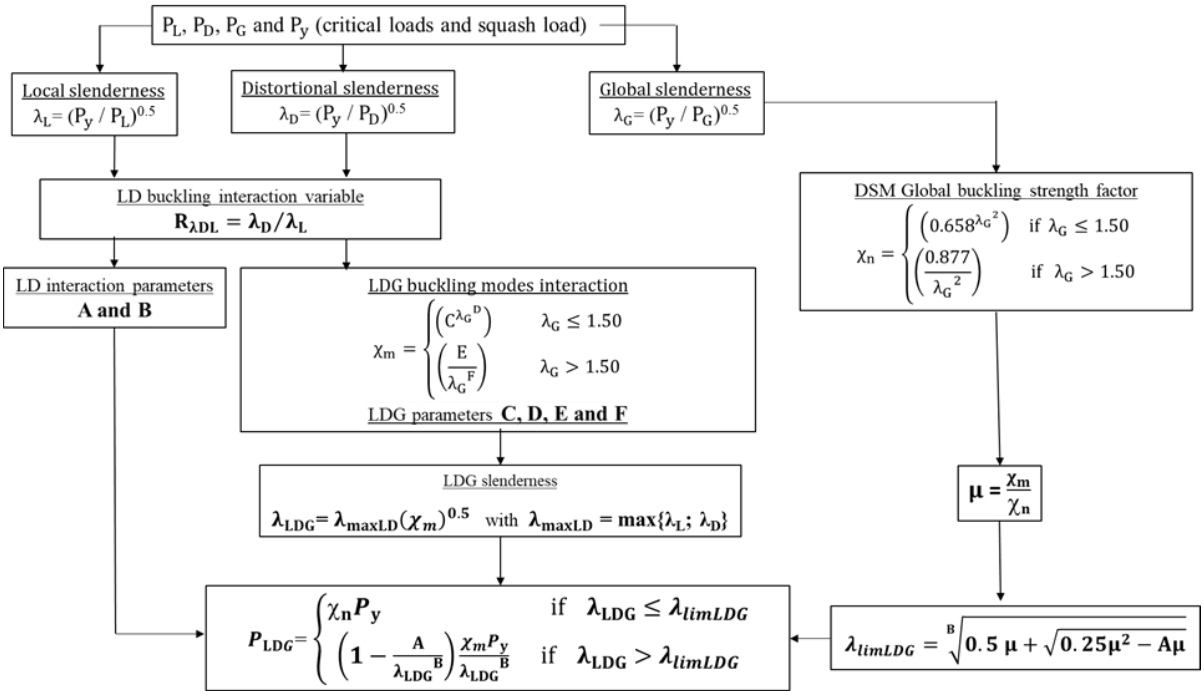


Figure 4. GDSM flowchart for the computation of CFS column strength, P_{nLDG}.

4.1 Comparison between Direct Strength Method and Generalized Direct Strength Method

An example of structural design is presented to illustrate the differences between DSM and GDSM. The column analyzed is considered simply supported, with a length of 4.6 meters and a lipped channel cross-section of 250x150x30x1.50 mm. The critical loads were obtained using FStr [6] , as shown in Figure 5. The steel mechanical properties are: Young's modulus is E=200 GPa, Poisson's ratio is ν = 0.3 and the yielding strees is f_y=350MPa.

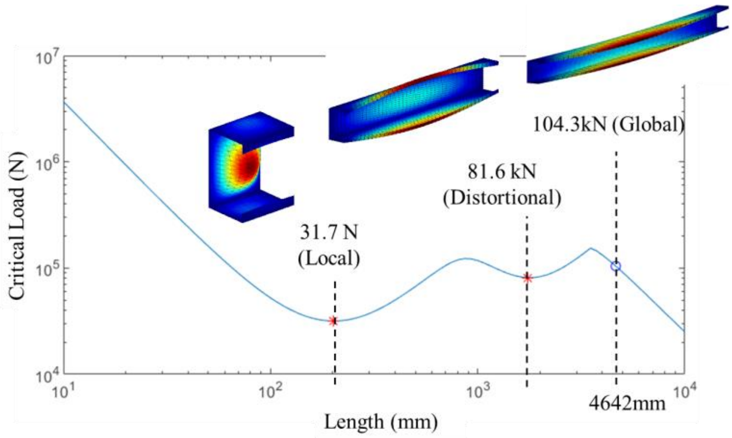


Figure 5. Signature curve of a lipped channel profile with dimensions 250x150x30x1.50 mm.

The ultimate strength obtained estimated using the DSM is 53.4 kN, while that obtained using the GDSM is 49.5 kN. It is notable that the difference between the two methods, amounting to 9%.

4.2 Load and Resistance Factor Design reliability analysis

The reliability of the GDSM was evaluated according to the LRFD (Load and Resistance Factor Design), included in both the North American and the Brazilian codes [7,9], described by Equation 4 and represented by γ. The safety factor γ incorporated the following parameters: (i) $C\phi$ = 1.52 as the LRFD correction factor, (ii) M_m=1.10 as the mean material factor, (iii) F_m=1.00 as the mean fabrication factor, (iv) V_M=0.10 as the coefficient of variation for the material factor, (v) V_F=0.05 as the coefficient of variation for the fabrication factor, (vi) C_p as the correction factor related to the number of test results, (vii) β_0=2.50 as the target reliability value for structural members, (viii) V_Q=0.21 as the load effect coefficient of variation, and (ix) P_m and V_p as the average and the coefficient of variation of the exact-to-predicted failure load ratios, respectively. It is worth mentioning that the γ value specified for DSM in the Brazilian standard is 1.20.

$$\gamma = \frac{1}{C_\phi M_m F_m P_m e^{-\beta_0\sqrt{V_M^2+V_F^2+C_p V_p^2+V_Q^2}}} \tag{4}$$

The present reliability analysis pertains to the LRFD provisions for a dead-to-live loads ratio of D/L=0.20D/L = 0.20D/L=0.20, as well as the load combination 1.2D+1.6L1.2D + 1.6L1.2D+1.6L. This combination is specified in the Brazilian code (NBR 14762:2010) [9].

4.3 Verification of the GDSM for experimental column results

Experimental results for columns are generally obtained under fixed-end conditions. For this reason, the analyzed experimental results were also under this condition. Experimental and numerical validations have already been performed for lipped channel columns [11,12]. Moreover, this paper includes experimental results for Hat, Zed, and Rack columns, as depicted in Figure 1. Figure 6 illustrates the comparison between experimental results (P_{EXP}) and GDSM, P_{nLDG}.

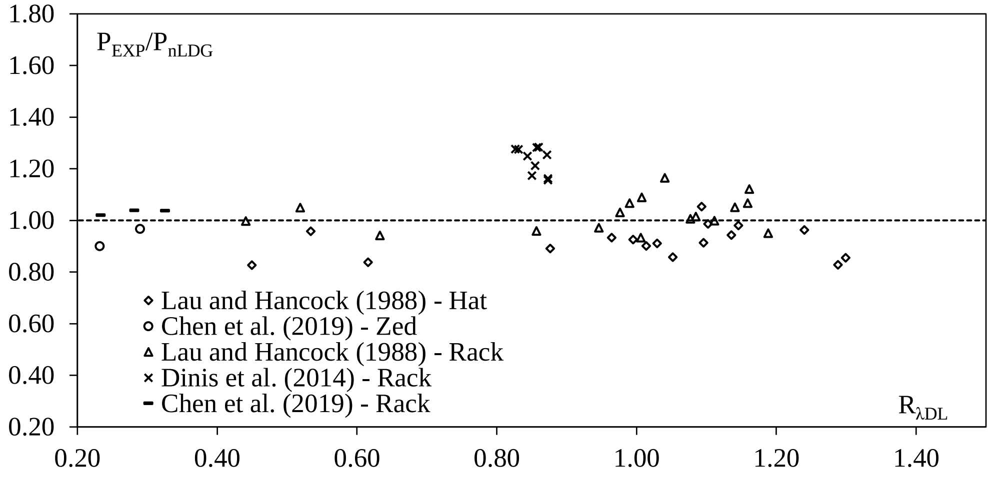


Figure 6. Comparison between experimental results (P_{EXP}) [13–15] and GDSM, P_{EXP}/P_{nLDG}.

Table 1 compares the experimental ultimate strength results under fixed-end conditions with ultimate strength estimates using the Generalized Direct Strength Method (GDSM), P_{nLDG}, for Lipped Channel, Hat, Zed, and Rack sections. The analysis were limited $\lambda_G < 2.5$, as this is more commonly used.

It is important to note that in Table 2, no mode interaction was observed in the Hat section, and only three experimental results were recorded for the Zed section, which are insufficient for a reliable analysis. Furthermore, no interaction involving the global mode was reported in the Rack section. The Lipped Channel section is the only one that shows a significant number of experimental results for columns exhibiting interaction between local-

distortional (LD) buckling modes and interaction involving global buckling modes (DG, LDG). Therefore, this article aims to assess the GDSM for the axial compression strength design of columns with Hat, Zed, and Rack cross-sections in a unified manner. For cases of interaction between buckling modes not listed in Table 2, additional experimental studies are needed to validate the method.
The LRFD values obtained for lipped channel and rack sections indicate that safe resistance factors are γ = 1.14 and γ = 1.05, respectively, which are lower than the 1.20 stipulated by the Brazilian code [9]. However, for Hat sections, based on the analyzed experimental results, the resistance factor γ was found to be slightly higher (less than 1%) than the specified value of 1.20 in the Brazilian code.

Table 1. Comparison between experimental results (P_{EXP}) [13–15] and GDSM, P_{EXP}/P_{nLDG} for different cross sections.

	P_{EXP}/P_{nLDG}			
Section	Lipped Channel	Hat	Zed	Rack
N	144	17	3	30
Average	1.02	0.92	0.92	1.09
St. Dev.	0.12	0.06	0.04	0.11
Coef.Var	0.12	0.07	0.04	0.10
Max.	1.31	1.05	0.97	1.28
Min.	0.81	0.83	0.90	0.93
γ	1.14	1.21	-	1.05

Table 2. Failure modes reported for the experiments presented in Table 1.

	Experimental Reported Failure Modes	References
Lipped Channel	L, D, FT, L+D, L+D+FT, L+D+F, D+FT	[13,14,16–25]
Hat	L, D, AD, FT	[13]
Zed	L+D, L	[14]
Rack	L, D, FT, L+D	[13–15]

Buckling Modes: Local (L), Distortional (D), Global Flexural-torsional (FT), Asymmetric distortional (AD), Local-Distortional (L+D), Distortional-Global Flexural torsional (D+FT), Local- Distortional-Global Flexural torsional (L+D+FT), Local- Distortional-Global Flexural (L+D+F)

5. Conclusions

The DSM is already incorporated into the North American, Australian-New Zealand, and Brazilian standards for the design of cold-formed steel sections. However, it does not yet provide a methodology to address the interaction between local-distortional (LD), distortional-global (DG), and local-distortional-global (LDG) modes. To address this gap, the Generalized Direct Strength Method (GDSM) has been developed. This method proposes an equation that incorporates solutions for cases of LD, DG, and LDG interaction, providing a unified approach to the cases already addressed by the DSM, as well as for the interactions between DG and LDG modes.
Despite the advantages presented by GDSM, it is important to note that experimental validations are lacking results for interactions between LD buckling modes for Hat sections, as well as DG and LDG interactions for Hat, Zed, and Rack sections.
Additionally, a more sophisticated structural reliability analysis to validate the GDSM is underway. This analysis employs the First Order Reliability Method (FORM), the First Order Second Moment (FOSM) method, and the Monte Carlo Simulation method (MCS).

References

[1] Associação Brasileira de Drywall, Steel frame, Drywall (n.d.). https://drywall.org.br/steel-frame/.
[2] B.W. Schafer, T. Peköz, Direct strength prediction of cold-formed steel members using numerical elastic buckling solutions, in: Department of Civil Engineering Center for Cold-formed Steel Structures University of Missouri, St. Louis, Missouri, 1998: pp. 1–8.

[3] R. Bebiano, Stability and dynamics of thin-walled members: application of generalised beam theory, Tese (Doutorado em Engenharia Civil), Instituto Superior Técnico, 2010.
[4] Z. Li, B.W. Schafer, Buckling analysis of cold-formed steel members with general boundary conditions using CUFSM: Conventional and constrained finite strip methods., in: Cold-Formed Steel Design and Construction, Roger A. LaBoube e Wei-Wen Yu, Saint Louis, Missouri, 2010.
[5] J.P. Papangelis, G.J. Hancock, Computer analysis of thin-walled structural members, Computers & Structures 56 (1995) 157–176. https://doi.org/10.1016/0045-7949(94)00545-E.
[6] J.A. de Lazzari, E. de M. Batista, Finite strip method computer application for buckling analysis of thin-walled structures with arbitrary cross-sections, REM, Int. Eng. J. 74 (2021) 337–344. https://doi.org/10.1590/0370-44672020740065.
[7] American Iron and Steel Institute, AISI S100-16: North American Specification for the Design of Cold-Formed Steel Structural Members, AISI, Washington, DC, 2016.
[8] Australian/New Zealand Standard, AS/NZS 4600:2018: Cold-formed steel structures, Australian/New Zealand Standard, Wellington, 2018.
[9] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, NBR 14762: Dimensionamento de estruturas de aço constituídas por perfis formados a frio, ABNT, Rio de Janeiro, 2010.
[10] G.Y. Matsubara, E. de M. Batista, G.C. Salles, Lipped channel cold-formed steel columns under local-distortional buckling mode interaction, Thin-Walled Structures 137 (2019) 251–270. https://doi.org/10.1016/j.tws.2018.12.041.
[11] G.Y. Matsubara, E.D.M. Batista, Local-Distortional-Global Buckling Interaction of Steel Cold-Formed Columns, in: ICSAS 2024, Luciano Lima and Eduardo Batista, Rio de Janeiro, RJ, 5-7 June: pp. 417–426.
[12] G.Y. Matsubara, E.D.M. Batista, Generalized direct strength design approach: steel cold-formed columns under buckling mode interaction, in: XLIV Ibero-Latin American Congress on Computational Methods in Engineering, Porto, PT, 2023.
[13] S.C.W. Lau, G.J. Hancock, Distortional buckling tests of cold-formed channel sections, in: Specialty Conference on Cold-Formed Steel Structures, Mssouri, 1988: pp. 45–73.
[14] J. Chen, M.-T. Chen, B. Young, Compression Tests of Cold-Formed Steel C- and Z-Sections with Different Stiffeners, J. Struct. Eng. 145 (2019) 04019022. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002305.
[15] P.B. Dinis, B. Young, D. Camotim, Local–distortional interaction in cold-formed steel rack-section columns, Thin-Walled Structures 81 (2014) 185–194. https://doi.org/10.1016/j.tws.2013.09.010.
[16] B. Young, N. Silvestre, D. Camotim, Cold-Formed Steel Lipped Channel Columns Influenced by Local-Distortional Interaction: Strength and DSM Design, J. Struct. Eng. 139 (2013) 1059–1074. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000694.
[17] B. Young, K.J.R. Rasmussen, Tests of Cold-formed Channel Columns, in: Missouri University of Science and Technology, St. Louis, Missouri, 1998: pp. 239–264.
[18] G.Y. Matsubara, E.D.M. Batista, Cold-Formed Steel Lipped Channel columns under Local-Distortional-Global buckling mode interaction, in: Proceedings of the Ibero-Latin-American Congress on Computational Methods in Engineering, Natal, RN, Brasil, 2019: pp. 1–15.
[19] Y.B. Kwon, G.J. Hancock, Tests of Cold-Formed Channels with Local and Distortional Buckling, J. Struct. Eng. 118 (1992) 1786–1803. https://doi.org/10.1061/(ASCE)0733-9445(1992)118:7(1786).
[20] 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 61 (2012) 14–21. https://doi.org/10.1016/j.tws.2012.03.025.
[21] B. Young, P.B. Dinis, D. Camotim, CFS lipped channel columns affected by L-D-G interaction. Part I: Experimental investigation, Computers & Structures 207 (2018) 219–232. https://doi.org/10.1016/j.compstruc.2017.03.016.
[22] 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, Ph.D. thesis in Civil Engineering, Federal University of Rio de Janeiro, 2014.
[23] L. Huang, W. Yang, T. Shi, J. Qu, Local and Distortional Interaction Buckling of Cold-formed Thin-Walled High Strength Lipped Channel Columns, Int J Steel Struct 21 (2021) 244–259. https://doi.org/10.1007/s13296-020-00436-z.
[24] Y.B. Heva, M. Mahendran, Flexural-torsional buckling tests of cold-formed steel compression members at elevated temperatures, Steel and Composite Structures 14 (2013) 205–227. https://doi.org/10.12989/SCS.2013.14.3.205.
[25] A.K. Jayasidhan, M.V. Anil Kumar, K.C.K. Aswathy, Experimental investigation on post-flexural–torsional buckling strength of CFS compression members, Thin-Walled Structures 185 (2023) 110638. https://doi.org/10.1016/j.tws.2023.110638.