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Determination of the critical length of elastic buckling by distortion in Z-profiles stiffened under centered compression using artificial neural networks

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Abstract: NBR 14762 (ABNT, 2010) does not have a defined method to determine the critical distortional buckling stress, making it difficult for designers to verify the PFF strength. Because of this, researches were developed in order to solve this problem. However, there are difficulties in the methods developed in the literature. An alternative to overcome such difficulties is the use of the critical length associated with the distortional mode in order to help in the determination of the distortionary critical elastic stress. In this sense, this article aimed to determine an equation for the critical length associated with the distortional mode of cold-formed profiles with Z section stiffened under centered compression and with bi-articulated support with free warping. For this, Artificial Neural Networks (ANNs) were trained. Such ANNs were validated using experimental and numerical results available in the literature and some equations were generated. The equations obtained through the adopted ANN obtained good correlations with the literature.

Keywords: Artificial Neural Networks, cold formed profiles, critical length.

1 Introduction

As new materials are developed and new techniques are used in civil construction, especially in the area of structures, studies are necessary that can contemplate phenomena that influence structural behavior, which have not been detected so far [1]. The use of structures composed of cold-formed profiles is an example of an application that needs research. As they consist of profiles with open sections and thin walls, cold-formed steel profiles become susceptible to problems of local, distortional and global instabilities. In addition, the interaction between the modes occurs, considerably reducing the resistant capacity of the structure. According to Andrade [2] the advantages of using cold-formed profiles include optimizing the structure and reducing the use of material. These factors, which further encouraged the dissemination of use in civil construction. A new tool that has been used in engineering as a solution to complex and non-linear problems is the use of artificial neural networks (ANN). The computational techniques known as ANN have a mathematical learning model that is based on the behavior of the neural network of the human brain, being able to recognize, generalize and associate patterns [3]. Several authors have published works in order to develop a method to describe distortional buckling. or critical length associated with the distortional mode in cold formed profiles. It can be highlighted: Santos et al.[4], Pala [5], Pinto Neto [3], Andrade [2], El-Kassas et al. [6] and ALI [7] using Artificial Neural Networks (ANN).

Santos et al.[4], Pala [5] and Pinto Neto [3] obtained an equation that predicted the critical elastic distortional stress in stiffened U-profiles subjected to centered compression, whose output data used for training were obtained according to the finite range method. El-Kassas et al. [6] applied Artificial Neural Networks to provide a fast and practical method for fault load prediction. Andrade [2], in turn, obtained the critical length associated with the distortional mode of profiles with cross-section C stiffened under centered compression and simple bending with bi-articulated support with free warping. Finally, ALI [7] aimed to provide a fast and accurate technique to estimate the bearing capacity of C and Z section purlins due to local buckling using Artificial Neural Networks. All these published works had good results comparing with results with the literature. NBR 14762, in its first version in

2001, proposed a calculation procedure for the distortional buckling stress, which had as reference the work of Lau and Hancock [8] via the Finite Range Method. However, in 2010, with a new update, this calculation method was removed, no longer providing a procedure to obtain the critical distortional buckling stress, stating only that it must be calculated through elastic stability analysis. An alternative to overcome such difficulties is the use of the critical length associated with the distortional mode in order to help in the determination of the distortionary critical elastic stress. In this sense, this article aims to provide an equation so that it is possible to obtain the critical length associated with the distortional mode for profiles with stiffened Z cross section.

2 Methodology

This work was developed based on the methodology applied by Pinto Neto [9] for distortional stress in stiffened Z-type (Ze) profiles and on the methodology applied by Andrade [2] for critical length in stiffened C-type profiles.

In this work, Ze-type profiles subjected to centered compression were studied, seeking to obtain an equation capable of determining the critical length of distortional buckling. The analyzes were carried out considering that the ends of the profiles are bi-articulated with free warping, a more unfavorable situation with regard to buckling resistance [3,9]. In addition, the modulus of elasticity and Poisson's ratio adopted were 200GPa and 0.3 respectively.

As an output, the critical lengths of distortional buckling of the studied profiles obtained from a program based on the formulation of the Generalized Beam Theory, GBT, [10] were used. Chosen because it provides the value of distortional voltage and critical length in isolated mode, that is, without coupling with the other modes.

As input parameters, the geometric dimensions of the Ze profiles were used, such as web (bw), flanges (bf), stiffener (D) and wall thickness (t), and the maximum and minimum values were determined according to Pinto Neto [1], shown in Table 1.

Table 1: Limit values of the parameters of the cross section

Parameters	Value Range (mm)	Pitch (mm)
$\boldsymbol{bw}$	50 a 400	5
$\boldsymbol{bf}$	25 a 100	5
$\boldsymbol{D}$	10 a 30	5
$\boldsymbol{t}$	1 a 5	0,25

96,560 cross sections were generated and then restrictions were applied according to international and national standards as indicated in Table 2.

Table 2: Geometric and mechanical specifications of the studied profiles

	Limit	Standard applied
(i)	$\frac{\boldsymbol{bf}}{\boldsymbol{t}} \leq \mathbf{60}$	NBR 14762 EUROCODE 3, part 1:3 AISI-100
(ii)	$\frac{\boldsymbol{bw}}{\boldsymbol{t}} \leq \mathbf{260}$	NBR 14762 AISI-100
(iii)	$\mathbf{5} \leq \frac{\boldsymbol{D}}{\boldsymbol{t}} \leq \mathbf{50}$	NBR 6355 EUROCODE 3, part 1:3
(iv)	$\mathbf{0,2} \leq \frac{\boldsymbol{D}}{\boldsymbol{bf}} \leq \mathbf{0,6}$	EUROCODE 3, part 1:3
(v)	$\boldsymbol{fu} \leq \mathbf{570}\boldsymbol{MPa}$	AS/NZS 4600
(vi)	$\mathbf{0,1} \leq \frac{\boldsymbol{D}}{\boldsymbol{bw}} \leq \mathbf{0,3}$	NBR 6355
(vii)	$\mathbf{0,3} \leq \frac{\boldsymbol{bf}}{\boldsymbol{bw}} \leq \mathbf{1}$	Restriction imposed

Constraint (vii), called shape constraint, although not normative, was imposed seeking to eliminate cross sections that would not be used in the construction industry. After applying the restrictions, 9,876 sections remained subjected to centered compression.

Several studies on the stability of cold formed profiles, such as Pinto Neto [3], Andrade [2], Pala [5], Santos et al. [4] and El-Kassas [6] show that ANN with feedforward connection pattern with backpropagation learning algorithm present good responses. Therefore, the ANNs were trained using MATLAB®'s Neural Network Toolbox, and the connection pattern used was feedforward with a backpropagation learning algorithm associated with the Levenberg-Marquardt update rule, which optimizes the back propagation of errors, making training faster.

Based on the results of Pinto Neto [9] and Andrade [2] it was observed that an intermediate layer provides satisfactory results and that the hyperbolic tangent activation function with respect to logarithmic presented better performance, in addition, with three neurons in the intermediate layer were errors up to 10% were obtained. The percentage of errors was stipulated as acceptable up to 10%, due to the sensitivity of the ANNs to error and based on the errors obtained in the works on the determination of the conventional stress of elastic buckling by distortion: Hancock (1997), who presented maximum errors of 8%; Silvestre and Camotim (2004b), with errors smaller than 7%; Pala [5] with errors on the order of 11%; Pinto Neto [9] with errors less than 7%; Pinto Neto et al. [3] with errors of up to 6%; Andrade [2], with errors less than 8%; and Pinto Neto et. al [16], with errors smaller than 2%. In this way, three RNAs were trained with 1 (RNA 1), 2 (RNA 2) and 3 (RNA 3) neurons in the intermediate layer, and the activation function was hyperbolic tangent.

After training, based on correlation coefficients (R²) and error histograms, the ANNs were analyzed and the one that presented errors smaller than 10% [2,9,7] and the smallest number of neurons in the intermediate layer was chosen. Once the network was chosen, the equation that provides the critical distortional length for Ze-type profiles under centered compression was then set up.

Validation was performed by comparing the results obtained, for a new group of profiles that did not participate in the training, with the results obtained in GBT and INSLOD. INSLOD is a computer program based on the Finite Range Method for elastic stability analysis. [1]

3 Analysis of Artificial Neural Networks

The efficiency of neural networks was analyzed based on correlation coefficients (R²) and error histograms, with errors smaller than 10% [2,9,7] and the smallest number of neurons in the intermediate layer as a criterion for choosing the smaller the number of neurons, the smaller the resulting equation, which facilitates its application.

Table 3 presents the results of R² and of greater negative and positive errors for the trained ANNs.

Table 3: Summary of ANN results

Number of neurons in the middle layer	R²	biggest negative error	biggest positive error
1	0,987	21%	18%
2	0,998	8,7%	5,8%
3	0,999	6,2%	6,2%

ANN 1 presented errors greater than 10%, which ruled out its use as it did not meet the first choice criterion. ANN 2 and ANN 3 presented maximum absolute error values of 8.7% and 6.2% respectively, that is, both met the initial criterion. Before the application of the second criterion, a lower number of neurons in the intermediate layer, the performance of the ANNs was analyzed based on the distribution of errors. Figure 1 presents the error histogram of the 3 trained ANNs. It can be observed that although ANN 3 presents a lower absolute error, the performance along the histogram is significantly similar to ANN 2, not justifying the change in the selection criteria.

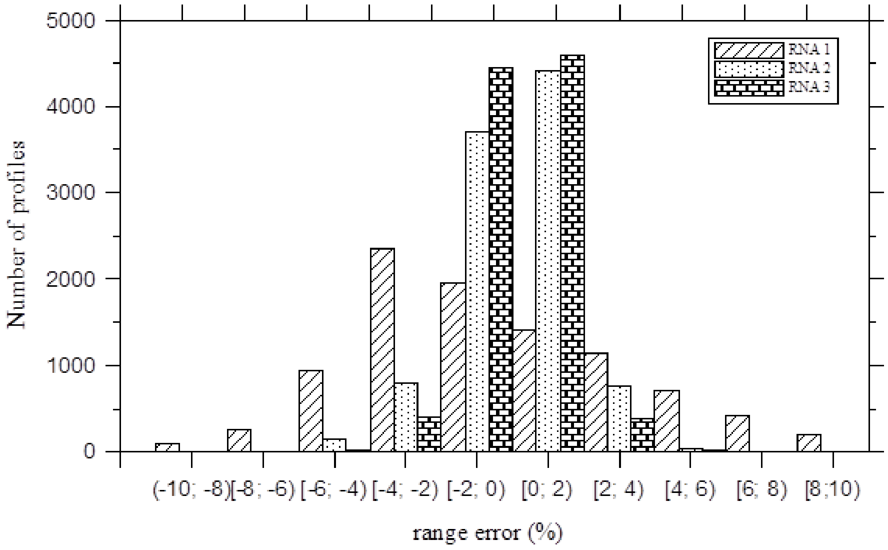

Figure 1: Error Histogram

Figure 2 shows the regression graph (R²) for the network with two neurons in the middle layer and with a hyperbolic tangent transfer function, the ANN 2. From the graph it can be seen that the ANN model presents a good fit to the set of Dice.

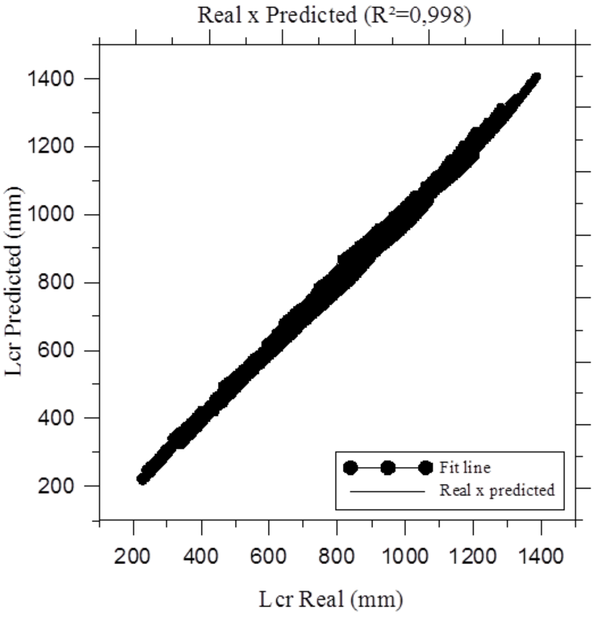

Figure 2: Coefficient of determination (R²) of ANN

3.1 Equation for calculating Lcr

The equation obtained from the ANN with two neurons in the intermediate layer and with a hyperbolic tangent transfer function, capable of determining the critical length associated with the elastic distortional buckling stress of cold-formed steel profiles, type Z, subjected to centered compression, is presented. in Equation 1.

$$Lcr = \frac{599679}{2012} tanh\,(a) + \frac{926831}{569} tanh\,(b) + \frac{567638}{563} \tag{1.a}$$

$$a = \frac{527}{253493}bw + \frac{2377}{180999}bf + \frac{4982}{144927}D - \frac{15383}{16187}t - \frac{36079}{29245} \quad (1.b)$$

$$b = \frac{821}{1514162}bw + \frac{7606}{2396889}bf + \frac{391}{37327}D - \frac{6077}{117967}t - \frac{12286}{26339} \quad (1.c)$$

where bw, bf, D, t, Lcr are web, flanges and stiffeners widths, wall thickness and member critical distortional buckling length respectively, for Z-profiles stiffened under centered compression, with all units are in millimeters.

3.2 Validation

Validation is a fundamental step because it allows to verify the applicability and adjustment to sections not used during training, however the chosen sections must meet the geometric relationships established in the range of Table 2. Validation was performed using GBT and INSLOD. Table 3 presents the results obtained in the validation.

Table 3: Comparison of results obtained from ANN 2

Profile	Cross section parameters (mm)				Lcr (mm)			Erro (%)	
	bw	*bf*	*D*	*t*	RNA	GBT	INSLOD	RNA/ GBT	RNA/ INSLOD
a	67,18	34,98	15,82	1,63	352	346	360	1,02	0,98
b	77,9	41,38	18,16	2,44	351	356	368	0,99	0,95
c	80,06	41,86	17,93	3,02	301	322	332	0,94	0,91
d	76,45	41,53	15,37	2,18	329	338	344	0,97	0,95
e	41,28	20,65	9,53	1,91	129	148	153	0,87	0,84

The map elaborated by [17] (Figure 3) shows the influence of geometric relations on the interaction between local-distortional and distortional-global buckling modes. The map is divided into three areas, where each area is divided by curves that represent a mode or the interaction between modes as a function of the geometry of the profile under analysis. The region delimited by D+L represents the interaction between the distortional and local plate modes, the D+G region indicates the interaction of the distortional and global modes and D represents the area of the distortional mode.

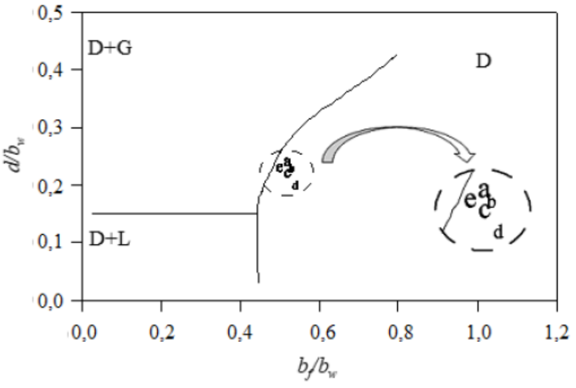

Figure 3: Graph representing the critical stress relationship with buckling modes

The profiles used in the validation present buckling behavior close to the threshold between the “pure” distortional mode and the distortional-global modal interaction, which presents a certain difficulty in determining the critical length that can be observed by the error presented in the profile and , where errors were greater than

10% of 13% and 16% in relation to GBT and INSLOD respectively.

This can be explained by the fact that the profile (e) 41.28x20.65x9.53x1.91, presents the geometric relationships at the threshold between the behavior of the “pure” distortional mode and the coupling between the global and distortional modes (bf/bw) = 0.50, which can be seen in Figure 3.

4 Conclusions

This work presented an equation for the determination of the critical length associated with the distortional mode of stiffened Z profiles submitted to centered compression with conditions that simulate joints and free warping, using Artificial Neural Networks (ANN).

With the help of the GBT program, the critical lengths associated with the distortional mode of 9876 cross-sections were obtained, after applying the geometric and shape constraints present in national and international standards. The equation obtained for the critical length associated with the distortional mode in Ze profile under centered compression with bi-articulated supports with free warping, obtained errors smaller than 10% for networks trained with two and three neurons. To validate the results, it was applied to profiles a,b,c,d and e in the GBT[10] and INSLOD [1] programs. The results obtained had satisfactory errors, since the profiles a,b,c and d had errors less than 10%, however the profile e presented an error greater than 10%, because the profile is on the threshold of the “pure” distortional mode and the distortional-global modal interaction.

Complementary studies are needed to consider the influence of couplings between the buckling modes and the consideration of different support conditions. The determination of an equation, for this purpose, makes the process of dimensioning cold-formed profiles much more practical, and can be implemented in structural calculation software or in electronic spreadsheets.

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Authorship statement.

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References

[1]. Nagahama K de J. Análise de estabilidade local de seção aberta em aço e em resina reforçada com fibra de vidro. Universidade Federal do Rio de Janeiro; 2003.

[2]. Andrade PDS. influência do comprimento na capacidade resistente de perfis de chapa dobrada a frio sob flambagem distorcional. Universidade Estadual de Feira de Santana, Feira de Santana; 2020.

[3]. Pinto Neto DDO, Nagahama KDJ, Gadéa ADSM. Determinação da tensão elástica de flambagem distorcional em perfis Z enrijecidos. Rev Sul-americana Eng Estrutural. 2017;14(3).

[4] Santos, F.; Nagahama, K.; Gádea, A. (2013). Formulação para tensão de flambagem distorcional em colunas com seção U enrijecido de chapa de aço dobrada a frio. Revista da Escola de Minas – REM, Ouro Preto, 66(1), p. 19-24.

[5]. Pala M. A new formulation for distortional buckling stress in cold-formed steel members. J Constr Steel Res. 2006;62(7):716–22.

[6] EL-kassas, E.M.A; Mackie, R.I; EL-sheikh, A.I. Using neural networks to predict the design load of cold-formed steel compression members. Advances In Engineering Software, [S.L.], v. 33, n. 7-10, p. 713-719, jul. 2002. Elsevier BV. http://dx.doi.org/10.1016/s0965-9978(02)00051-0.

[7] ALI, Dr. Ahmed Ajel. neural network modeling for rotational capacity of cold-formed purlin steel sections. International Journal Of Civil Engineering And Technology (Ijciet), An-Najaf, p. 362-372, 12 dez. 2017.

[8] Lau, S. C. W.; Hancock, G. J. Distortional buckling formulas for channel columns. Journal of Structural Engineering, v. 113, n. 5, p. 1063-1078, 1987.

[9]. Neto DDOP. Formulação para determinação da tensão de flambagem distorcional em perfis de aço formados a frio utilizando redes neurais artificiais . Universidade Estadual de Feira de Santana, Feira de Santana; 2017.

[10]. Silvestre N, Camotim D. Distortional buckling formulae for cold-formed steel C and Z-section members: Part I - Derivation. Thin-Walled Struct. 2004 Nov;42(11):1567–97.

[11] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 14762: Dimensionamento de estruturas de aço constituídas de perfis formados a frio. Rio de Janeiro, 2010.
[12] ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 6355: Perfis estruturais de aço formados a frio – Padronização. Rio de Janeiro, 2012.
[13]. ABNT. NBR 14762:2010 - Dimensionamento de estruturas de aço construidas por perfis formados a frio. Associação Brasileira de Normas Técnicas. 2010. 93 p.
[14]HANCOCK, G. J. Design for distortional buckling of flexural members. Thin-Walled Structures, v. 27, p. 3–12, 1997.
[15]SILVESTRE, N.; CAMOTIM, D. Distortional buckling formulae for cold-formed steel C- and Zsection members: Part II — Validation and application. Thin-Walled Structures, v. 42, p. 1599– 1629, 2004b.
[16]Pinto Neto DDO, Andrade, P. dos S., Nagahama KDJ, Gadéa ADSM, Leite, M. B. Determinação da tensão convencional de flambagem elástica por distorção em perfis cartola usando Redes Neurais Artificiais. Revista da Estrutura de Aço, v. 10, p. 161-180, 2020.
[17] D. C. T. Cardoso, G. C. De Salles, E. de M. Batista, and P. B. Gonçalves, "Thin- Walled Structures Explicit equations for distortional buckling of cold-formed steel lipped channel columns," Thin Walled Struct., vol. 119, no. April, pp. 925‑933, 2017, doi: 10.1016/j.tws.2017.08.014.