XLI CILAMCE
XLI Ibero-Latin American Congress on Computational Methods in Engineering
16-19 November, 2020 FOZ DO IGUAÇU PARANÁ - BRAZIL

Shape optimization of cold-formed steel columns using generalized beam theory and genetic algorithms

M. Neves[1], C. Baságlia[1]

[1]*Dept. of Civil Engineering, Architecture and Urban Design, University of Campinas*
Rua Saturnino de Brito 224, 13083-889, Campinas, Brasil
marcos@neves.eng.br, cbasaglia@fec.unicamp.br

Abstract. The search for lighter and more efficient design has put thin walled steel structures on the center of the attention from civil engineers. Furthermore, with the necessity to fight its slenderness and improve its structural worth we have a need to find its best optimal cross section. The newest way to achieve such is to wed both Generalized Beam Theory (GBT) and Genetic Algorithms (GA) for an improved analysis that takes short periods of processing times. Enhancing structural elements to endure local and distortional failures with longitudinal stiffeners is not something new to engineers although could be even more efficient for a computer to do it. The pursuit for the best stiffener geometry and its location based on the knowledge of the local and distortional responses from multiple elements could save an abundance of resources and time. The goal of this work is to implement a computational calculation using a genetic algorithm to find the most suitable solution within a limit range of parameters for an optimal cross section design for channel and zed compressed columns. Genetic Algorithms are a heuristic search that mimics natural evolution events. Learning by evolving generations populated with random elements and combinations of the best cross sections the algorithm sets its goal to find the optimal solutions for distortional and local strengths separately. After its goals are met is its job to try to cross both solutions to turn into an optimal cross section design. With the local and distortional critical loads, the element could be analyzed using the Direct Strength Method (DSM) that has been widely used to design Cold-Formed Steel (CFS) elements. This implementation will be used in the future to accomplish the same on different structural elements composed of CFS and improve the way these elements are fabricated thus resulting in better and lighter overall structures.

Keywords: Cold-formed steel columns, Generalized Beam Theory, Genetic Algorithms, Optimization.

1 Introduction

Cold-formed steel sections are vastly chosen for its efficiency between weight and structural strength. As its uses grow, between residential and commercial structures, new solutions have been found to improve its slenderness' resistance. The most usual one is to bend the section's sheeting in ways to improve its local and distortional critical loads, creating longitudinal stiffeners in a way that its weight and cross section area are slightly affected and at the same time not having high impact changes in its manufacturing's costs. Where and how to apply this solution is the target of this article and will be exemplified in future items. The design of CFS elements is usually approached by "Effective Width" or "Direct Strength" methods as mentioned by Martins (e.g. [1]). At this time, the Direct Strength Method (DSM, e.g. [2]) was considered the most effective approach for its analysis of the local and distortional resistances on separate design curves, thus given the authors the possibility to achieve different results for the same problem. Using the Generalized Beam Theory (GBT) to get both critical loads we could get a structural analysis of the cross-section and categorize it. The simplest way to proceed toward a solution is brute-force methods although it computational coast is time consuming therefore will not be used.

The approach taken by the authors was to implement a Genetic Algorithm (GA) that could approximate to the best solution for the problem within a reasonable elapsed time. This type of algorithm was shown by A. M. Turing on his paper "Computing machinery and intelligence" (e.g. [3]) and this is consider by most to be the first time of its implementation. Currently because of our society's computation power is being used in association with neural networks for machine learning tasks. Other implementations were made to analyze beams and columns using this type of solution (e.g. [4], [5], [6]) some organic approaches and others more fabrication oriented. The solution opted is to get the best result overall for fully braced Lipped Channel and Zed sections within some fabrication limitations.

2 Genetic Algorithm - an overview

Genetic algorithms are inspired by natural evolutionary events. Those are mostly known by Darwin's theory of natural selection. Firstly is "Heredity" that implies that an offspring carries characteristics from its parents. Then we have "Variation" that says a population that is not suffering mutation will not evolve. Finally, "Selection" which suggests that every population have rules governing which of its members are apt for reproduction.

This work implemented those main characteristics on its code. The algorithm has a loop of generations of sections' populations that passes through their best element's features to the next (e.g. Figure 1). Every element gets evaluated going through a fitness function. Then the future parents are chosen based on its fitness. Upheld by Soons' work (e.g. [7]) an analysis of the best crossover implementation was made and the uniform crossover operator was chosen over the others because of its performance.

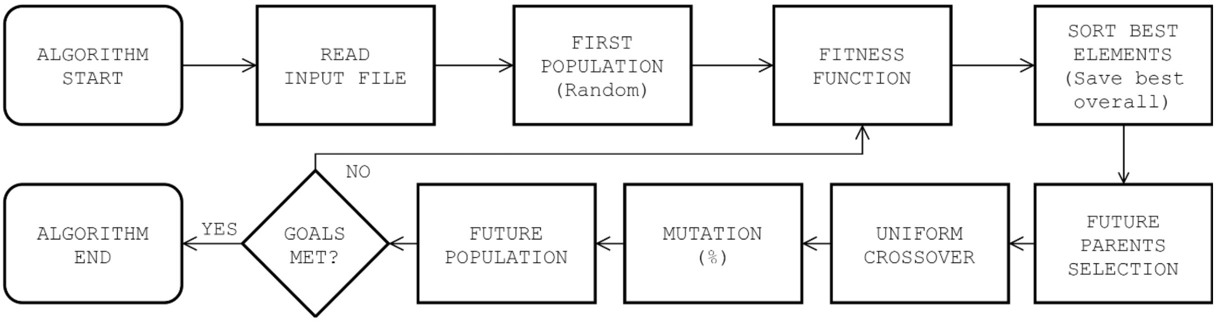

Figure 1. Genetic Algorithm Diagram

The population's members have distinct genotypes that are used to generate phenotypes in which are used to evaluate its fitness. The main geometry genotypes of each element are determined by: (i) Flange length; (ii) Web length; (iii) Lip length and (iv) Thickness (e.g. Figure 2). Those set of values are fluctuated or fixed depending on the input choices. The other genotypes are determined by the list of heights, widths and density of the stiffeners.

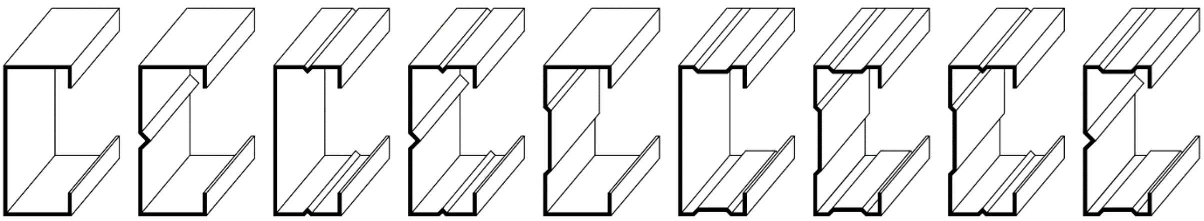

Figure 2. Section possibilities examples

Stiffeners can be applied on the web or the flange of the elements. Both can be of different heights and widths. A simple analysis of one element can take a short amount of time, but having millions and sometimes billions of possibilities, in which even on fast computers could take us months to brute-force a result from it.

2.1 Fitness function

The element's fitness is measured by three different factors: (i) Highest critical local load; (ii) Highest critical distortional load and (iii) Highest DSM resistance. At first it was four, one extra for when the local and distortional load would be the most approximate as possible, but this would generate local-distortional failures (e.g. [8] [9]) and seeing that would not be an viable solution it was discarded. Seeing that this could affect our DSM results it was implemented the local-distortional interaction on the DSM analysis thus resulting in most current solutions.

After getting the results from the DSM and GBT analysis it was needed to stablish a ranking model. Not always the highest resistance section is the best one. On a practical level filling every section of its perimeter with stiffeners would be impossible to fabricate it. So, it was chosen an approach that involves analyzing the cross-section area in set with its load and number of stiffeners. Using a three dimensional coordinate system with: (i) Cross-section area; (ii) Inverse of the critical or resistance load and (iii) Total number of stiffeners, it was set that the best sections were the ones with the shorter distance of its position to the origin.

2.2 Selection

After all sections got its fitness score, it was time to have an automated selection for future parents. This is made using the fitness score as a probability that the section will generate future proles. If your fitness score is high, it results in a greater probability of becoming a parent. Thus, resulting in proles with dominant characteristics that gets higher fitness' scores.

2.3 Crossover

As mentioned before, we used uniform crossover operator as our reproduction method. This method uses an equal probability of the parents' properties to be passed to its children (e.g. Figure 3).

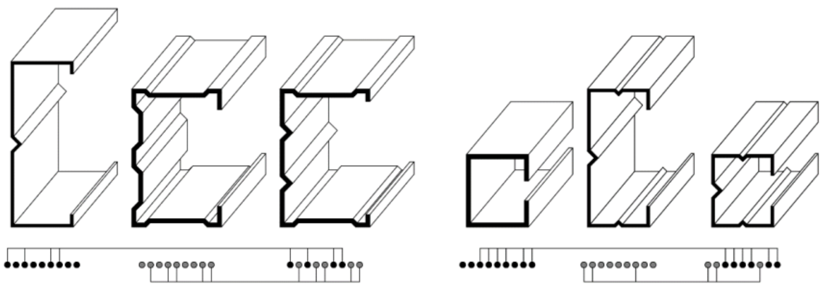

Figure 3. Crossover Examples

2.4 Mutation

To introduce new properties on the pool of elements it is needed random ones at different times. Is visible that populations with lower to no mutation ratio will not evolve. Although, populations with high mutation rates will take too long to converge on a solution. Every algorithm and analysis have its own optimal number. This work's algorithm stayed between twenty and forty percent depending on the number of inputted properties.

3 Generalized Beam Theory - motivations

As GBT is the linear combination of deformation modes (e.g. [10]) we can split each analysis by its mode type (e.g. Figure 4). Setting different goals for the same algorithm and resulting in multiple results. It was used the analytical solution based on the work from N. Silvestre (e.g. [11]) with multiple length analysis to get the critical loads for distortional and local modes.

As shown by H. Françoso Jr. on his work with stiffened cross-sections (e.g. [12]), always that is set a stiffener on the cross-section's web we get distortional modes as a best overall result. But it was found that some distortional modes, that by the default GBT's definitions are considered distortional, act like local modes of non-stiffened sections. This was mentioned by A. Landesmann (e.g. [13]) as he treated them separately and used the DSM's local curves for its analysis. This could be seeing on our firsts results that had shown almost in every situation the curves of best distortional elements were the same as the DSM's results. After that it was possible to assert this little modification on the algorithm, that now treats those modes as local and with its referred DSM's curve.

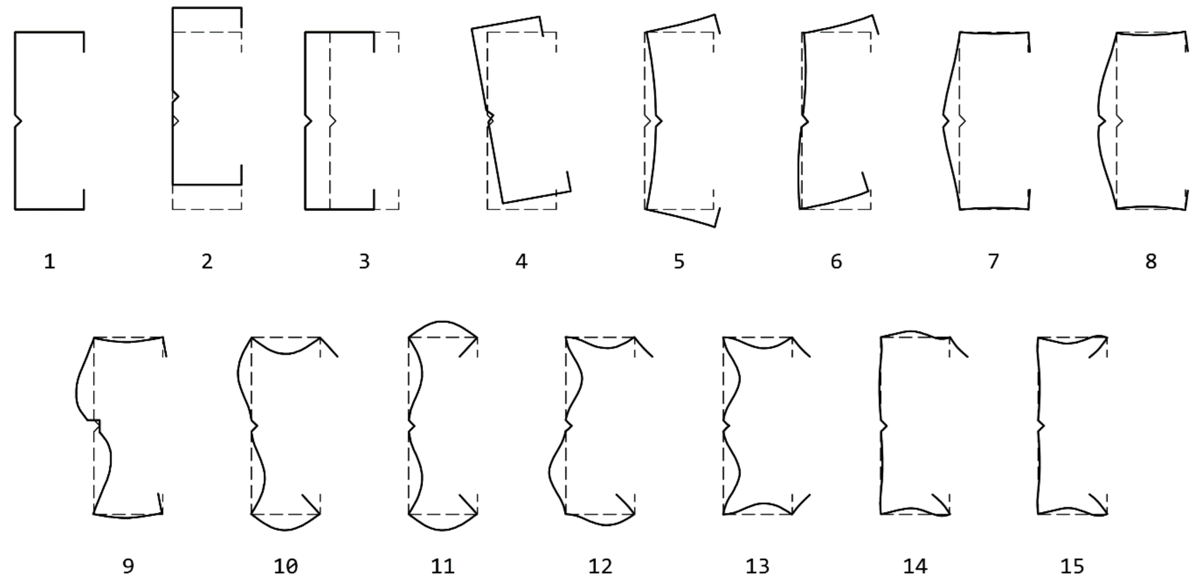

Figure 4. Stiffened lipped channel modes

4 Direct Strength Method (DSM) - an overview

The DSM method is based on different strength curves for local and distortional modes (e.g. [14]). With newer researches we have an additional verification for local-distortional interactions (e.g. [15], [16], [17]). Assuming fully braced elements we can set an analysis for the local and distortional curves and for a combination of both. Always setting probable elements that respect the method's geometric limitations. The curves were divided as shown on eq. (1 and 2) of reference [14] and equation (3) of reference [1].

$$P_{nL} = \begin{cases} P_{ne}, & \lambda_L \leq 0.776 \\ \left[1 - 0.15 * \left(\frac{P_{crL}}{P_{ne}}\right)^{0.4}\right] * \left(\frac{P_{crL}}{P_{ne}}\right)^{0.4} * P_{ne}, & \lambda_L > 0.776 \end{cases} \tag{1}$$

$$P_{nD} = \begin{cases} P_{ne}, & \lambda_D \leq 0.561 \\ \left[1 - 0.25 * \left(\frac{P_{crD}}{P_{ne}}\right)^{0.6}\right] * \left(\frac{P_{crD}}{P_{ne}}\right)^{0.6} * P_{ne}, & \lambda_D > 0.561 \end{cases} \tag{2}$$

$$P_{nLD} = \begin{cases} 0.80 \leq \frac{P_{crD}}{P_{crL}} \leq 1.30 \begin{cases} P_{nL}, & \lambda_{DL} \leq 0.561 \\ P_{nL} * \lambda_{DL}^{-1.2} * (1 - 0.25 * \lambda_{DL}^{-1.2}), & \lambda_{DL} > 0.561 \end{cases} \\ \frac{P_{crD}}{P_{crL}} > 1.30 \begin{cases} P_{nL} \ \boldsymbol{if} \ \lambda_L \leq 0.85 * \frac{P_{crD}}{P_{crL}} \\ P_1 + \frac{P_2 - P_1}{0.25} * \left(\lambda_L - 0.85 * \frac{P_{crD}}{P_{crL}}\right) \ \boldsymbol{if} \ 0.85 * \frac{P_{crD}}{P_{crL}} < \lambda_L < 0.85 * \frac{P_{crD}}{P_{crL}} + 0.25 \\ P_y * \lambda_L^{-1.2} * (1 - 0.15 * \lambda_L^{-1.2}) \ \boldsymbol{if} \ \lambda_L > 0.85 * \frac{P_{crD}}{P_{crL}} + 0.25 \end{cases} \end{cases} \tag{3}$$

With those equations the algorithm was set to achieve the best results from each curve. So, it tries to enhance the minimal points from local, distortional and for the combination of the three design curves (e.g. Figure 5).

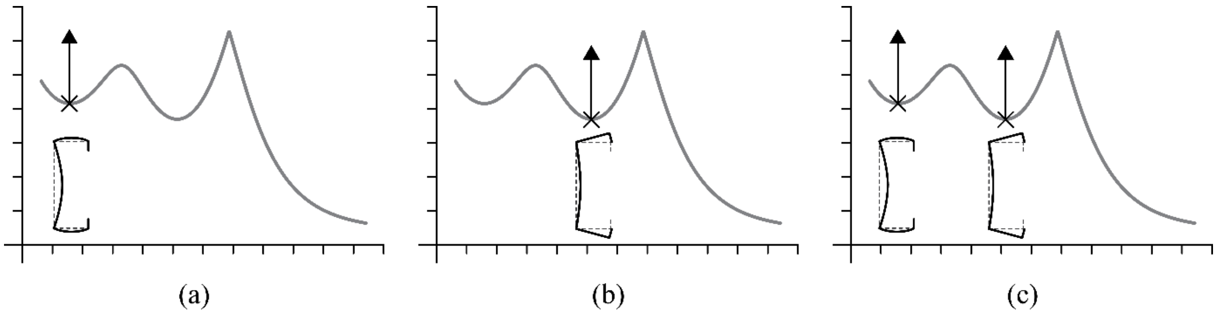

Figure 5. Algorithm goals: **(a)** Local Load **(b)** Dist. Lode **(c)** DSM results

5 Illustrative Analysis

In this work it was chosen four main analysis: (i) Unchanging web; (ii) Unchanging flange; (iii) Unchanging thickness and (iv) No unchanging geometry (e.g. Table 1). All of them are composed of a simple supported compressed column. The stiffener's height was set to: {3, 4, 5, 6, 7, 8}[mm]; Its width to: {2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15}[times height] and the density from zero to one hundred percent, to every analysis.

Table 1. Properties for analysis

Analysis	Web (mm)	Flange (mm)	Thickness (mm)	Lip (mm)	Young Modulus (kN/cm²)	Poisson Ratio	Yield Strength (kN/cm²)	Section Type
01	150	50 to 150	0.50 to 1.00	5 to 15	21 000	0.30	30	C
02	75 to 150	75	0.50 to 1.00	5 to 15	21 000	0.30	30	C
03	75 to 150	50 to 75	1.00	5 to 15	21 000	0.30	30	C
04	75 to 150	50 to 75	0.50 to 1.00	5 to 15	21 000	0.30	30	C

All analysis resulted in similar shapes showing a tendency depending on the type of goal (e.g. Figure 6). For this problem, the stiffener most used was trapezoidal and in most cases in the web. The curves are showing an approximation from the DSM results to the Distortional ones (e.g. Figure 7). One conclusion is that because of the impact of the number of stiffeners on the fitness from each element, it resulted in the use of one long trapezoidal stiffener instead of multiple triangular ones to achieve the same results.

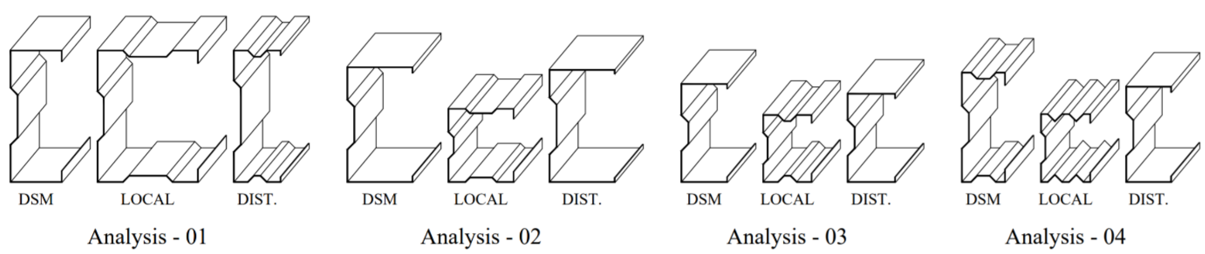

Figure 6. Results' shapes

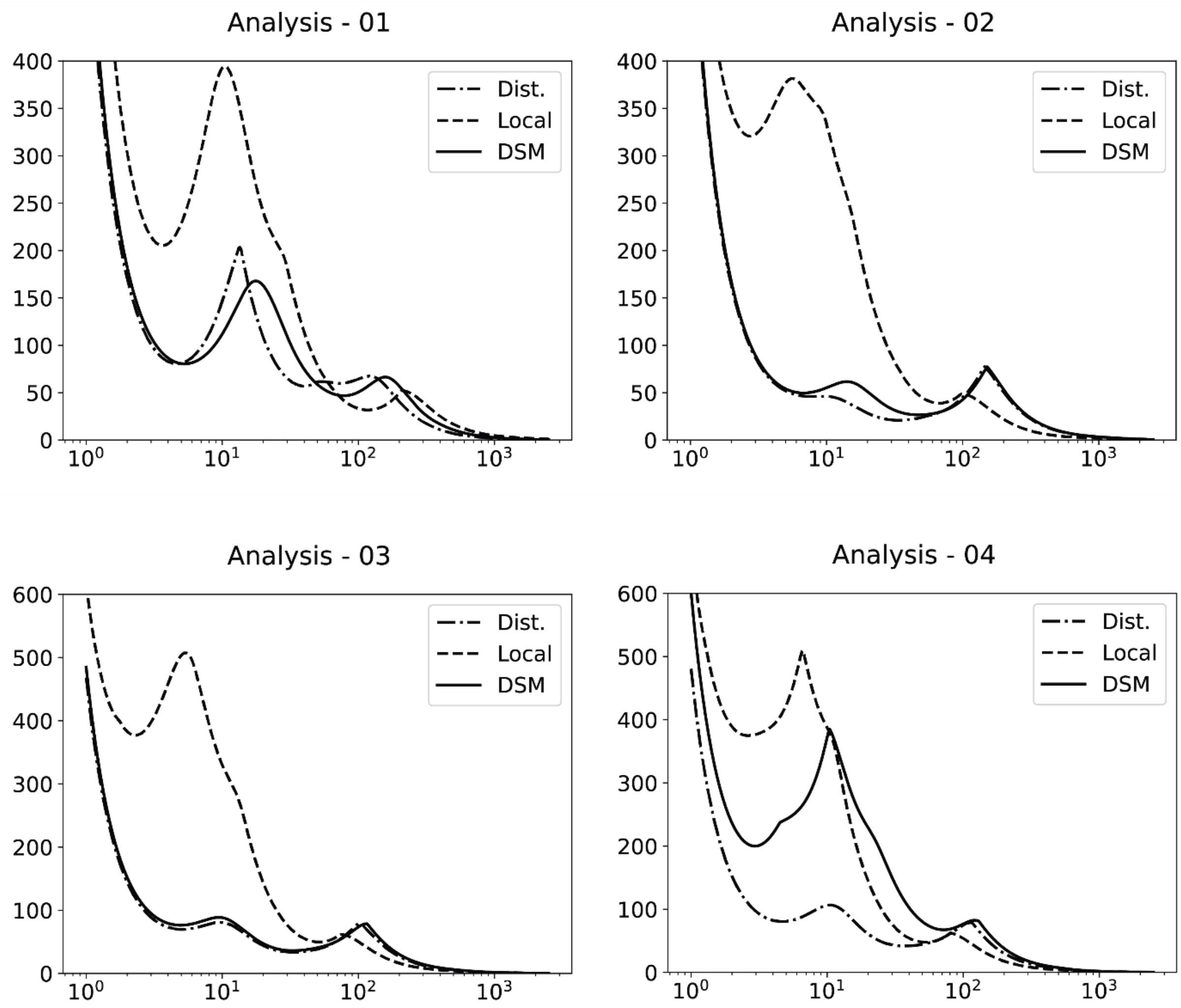

Figure 7. Analysis' results - Curves: Critical load [kN] x Length [mm]

It is visible that the results with no restrictions achieve better nominal critical load with lower cross-section area (e.g. Figure 8). It is not worth to analyze separately local or distortional modes, since the analysis that takes in consideration both achieves better results overall. Compared to the default channel sections without stiffeners is noticeable a great improvement in its resistance with few stiffeners' additions.

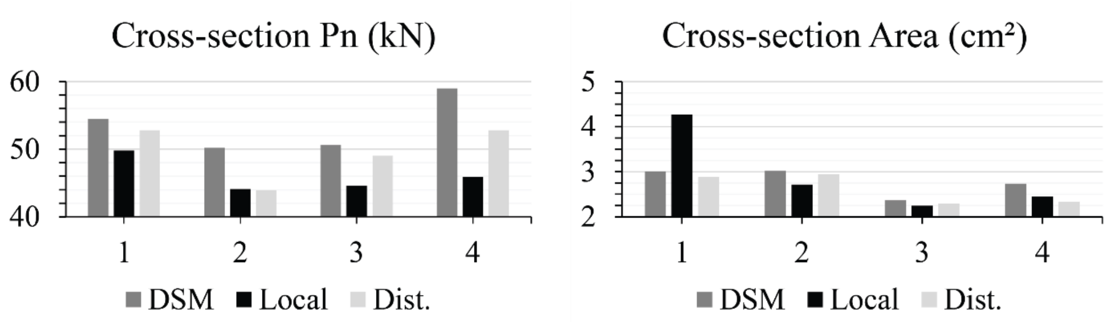

Figure 8. Properties' results

6 Conclusions

In every test better cross-section with improved structural worth were achieved compared to the default lipped channel without stiffeners. It is visible that this algorithm could be used in other bar elements. In the future it could be improved to function as a starting point for structural elements' design. The distortional mode was the master influencer in the DSM results, showing that the local resistance is enhanced with only few stiffeners. Something that stand out is that the local-distortional failure is a significant influencer on the DSM analysis, showing that when the local and distortional loads approximate it significantly lowers its resistance.

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

[2] AISI, "North American Specification for the Design of Cold-Formed Steel Structural Members". *American Iron and Steel Institute*, Washington D.C., 2016.

[3] A. M. Turing, "Computing machinery and intelligence". *Mind*, vol. 59, no. 236, pp. 60-433, 1950.

[4] J. Ye, I. Hajirasouliha, J. Becque, A. Eslami, "Optimum design of cold-formed steel beams using Particle Swarm Optimisation method". *Journal of Constructional Steel Research*, vol. 122, pp. 80-93, 2016.

[5] J. Lee, S. Kim, H. S. Park, "Optimum design of cold-formed steel columns by using micro genetic algorithms". *Thin-Walled Structures*, vol. 44, pp. 952-960, 2006.

[6] J. Leng, J. K. Guest, B. W. Schafer, "Shape optimization of cold-formed steel columns". *Thin-Walled Structures*, vol. 49, pp. 1492-1503, 2011.

[7] G. K. Soon, T. T. Guan, C. K. On , R. Alfred and P. Anthony, "A comparison on the performance of crossover techniques in video game". *2013 IEEE International Conference on Control System, Computing and Engineering*, pp. 493-498, 2013.

[8] A. D. Martins, D. Camotim, P. B. Dinis, "Behaviour and DSM design of stiffened lipped channel columns undergoing local-distortional interaction". *Journal of Constructional Steel Research*, vol. 128, pp. 99-118, 2017.

[9] 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*, vol. 73, pp. 12-30, 2012.

[10] C. Baságlia, D. Camotim, N. Silvestre, "GBT-based local, distortional and global buckling analysis of thin-walled steel frames". *Thin-Walled Structures*, vol. 47, pp. 1246-1264, 2009.

[11] N. Silvestre, "Generalised Beam Theory: New Formulations, Numerical Implementation and Applications". *Technical University of Lisbon*, 2005.

[12] H. Françozo Jr, "Non-linear analysis of cold formed steel compression members with stiffened cross-sections". Masc. Dissertation, University of Campinas, 2016.

[13] A. Landesmann, D. Camotim and R. Garcia, "On the strength and DSM design of cold-formed steel web/flange-stiffened lipped channel columns buckling and failing in distortional modes". *Thin-Walled Structures*, vol. 105, pp. 248-265, 2016.

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

[15] M. Chen, B. 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*, vol. 150, 2020.

[16] M. Chen, B. Young, A. D. Martins, D. Camotim, P. B. Dinis, "Uniformly bent CFS lipped channel beams experiencing local-distortional interaction: Experimental investigation". *Journal of Construction Steel Research*, vol. 170, 106098, 2020.

[17] E. S. dos Santos, E. M. Batista, D. Camotim, "Experimental investigation concerning lipped channel columns undergoing local-distortional-global buckling mode interaction". *Thin-Walled Structures*, vol. 54, pp. 19-34, 2012.