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OPTIMIZATION OF COLD-FORMED STEEL CHANNEL USING THE DIRECT STRENGHT METHOD AND FINITE STRIP METHOD

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Abstract. *The use of cold-formed steel members has great application at the present time, such as in standard civil buildings (residential and industrial buildings) and in mechanical structures (structures of vehicles like: trucks, bus, wagons, etc.). A high structural performance for profiles is a required economic demand in present days. In this sense, the present work intends to explore the possibilities of parametric optimization of cold-formed steel channel and lipped channel members when submitted to compression, with the objective of getting optimum structural performance of the same. The tools used to accomplish such objective are the method of the Constrained Finite Strip Method and the Direct Strength Method. An optimization methodology based in genetic algorithms is incorporated in this form of analysis. Examples considering this methodology show the improvement that could be obtained. Some conclusions about the potentiality of the used methodology are also presented.*

1 INTRODUCTION

Cold-formed steel (CFS) members have a cross section composed of elements with very thin walls, i.e., the width/thickness ratio of the element is high. This feature makes these profiles be prone to the phenomenon of structural instability, such as local, distortional and global buckling, as well as the interaction between them.

Because of this, the determination of the resistance load of this type of profile is directly related to its stability analysis. Therefore, it is essential identify the critical buckling modes and determine their respective critical loads.

Project methods, such as Direct Strength Method (DSM) [1, 2], become highly efficient when the elastic stability analysis is made by any numerical method like: Finite Element Method (FEM), Finite Strip Method (FSM) or Generalized Beam Theory (GBT), they give a better understanding of the structural behavior of the CFS members.

The formulation of the DSM with experimental and theoretical researches in constant evolution arises as a promising method making part, inclusively, since 2004, of AISI [4], as an alternative method to the Effective Width Method, from which it derives.

An important characteristic of this method is to allow and stimulate the optimization of the cross-section, because it is applied to any cross-section geometries.

It is common to use FSM [5] as an alternative for the analysis made by FEM.

To help the user identify the pure buckling modes (i.e. modes that don't have any kind of interaction among them), some software try to solve this problem determining automatically the critical buckling stress in relation to the half-wavelengths buckling, as it is the case in CUFSM [6]. Despite this we often find cross-sections where this identification in not obvious [7].

In this context, and with the objective to improve the analysis made by the conventional FSM, Ádány and Schafer [7-9], incorporated to the FSM method a modal decomposition, which allows the elastic stability solutions be directed to only one pure buckling mode, and the modal identification, which allows the elastic stability solution obtained by the conventional FSM be classified as one of the fundamental buckling modes, being then called Constrained Finite Strip Method (cFSM).

Defining the cross-section shape of a cold-formed steel member is interesting from a structural viewpoint, and due to the different geometric possibilities in this choice, the problem becomes challenging in terms of optimization, a subject that has attracted the attention of researchers in this field [10-14].

The high nonlinear level of the mechanical behavior of the CFS, common optimization schemes based on gradient (gradient methods), using the deterministic design specifications for the nonlinear objective function, are highly inefficient and limited in its ability to search the solution space the cross-section shape, since this type of problem is characterized by having around the optimal solution (global minimum) several local optimal solutions (local minimum) [13].

It is necessary to use some stochastic optimization method to get around this problem, among others are include the genetic algorithms (GAs). The GAs use a set of actions that search for global optimum solution combining deterministic and probabilistic rules with any varying proportion without to require any other additional information about the behavior of problem (such as derives).

Since the GAs are heuristic techniques, a way to improve its performance is the inclusion of other optimization methods that are more efficient in the search for local minimum solution, a technique known as hybridization [15]. This alternative has the capability of global exploration of the feasible region allied with efficiency in local searches.

In this context, the present paper aims to propose a methodology to optimize the section of the CFS cross section subjected to compression using GAs.

The tool used in combination with GAs was the cFSM to perform the analysis of elastic stability. The great advantage of cFSM is that eliminates the problems of modal identification found in conventional FSM.

2 THEORETICAL FUNDAMENTATION

2.1 Design of cold-formed steel columns using the DSM

The value of axial strength of column is performed using the Direct Strength Method (DSM), which is part of Appendix 1 of the North American Specification for Design of Cold-Formed Steel Structural Members [4].

2.1.1 Determination of axial strength for columns

The axial strength is: $\phi_c P_n$ where, ϕ_c is the resistance factor and P_n is the nominal axial strength, being the minimum among P_{ne}, P_{nl} and P_{nd} values calculated as follows.

Flexural, torsional, or torsional-flexural buckling: The nominal axial strength, P_{ne}, for flexural, torsional or torsional-flexural buckling is determined using the following formulation:

$$P_{ne} = \left(0{,}658^{\lambda_c^2}\right) P_y \quad \text{for } \lambda_c \leq 1{,}5 \text{ and } P_{ne} = \left(\frac{0{,}877}{\lambda_c^2}\right) P_y \quad \text{for } \lambda_c > 1{,}5 \tag{1}$$

where $\lambda_c = \sqrt{P_y / P_{cre}}$, $P_y = A_g$ F_y, $P_{cre} = A_g$ F_e , in this expressions F_e is a critical elastic overall buckling stress the minimum among the Flexural, Torsional, or Torsional-Flexural Buckling, determined using analytical solutions given in sections C4.1.1 to C4.1.4 of the AISI [4].

Local buckling: The nominal axial strength, P_{nl}, for local buckling is

$$P_{nl} = P_{ne} \quad \text{for} \quad \lambda_l \leq 0{,}776 \quad \text{or} \quad P_{nl} = \left[1 - 0{,}15\,(\frac{P_{crl}}{P_{ne}})^{0,4}\right](\frac{P_{crl}}{P_{ne}})^{0,4}\, P_{ne} \quad \text{for} \quad \lambda_l > 0{,}776 \tag{2}$$

where $\lambda_l = \sqrt{P_{ne} / P_{crl}}$, P_{crl} is a local buckling load in a column and P_{ne} is the nominal axial strength determined in accordance with equations (1).

Distortional buckling: The nominal axial strength, P_{nd}, for distortional buckling in a column is

$$P_{nd} = P_y \quad \text{for} \quad \lambda_d \leq 0{,}561 \quad \text{or} \quad P_{nd} = \left[1 - 0{,}25(\frac{P_{crd}}{P_y})^{0,6}\right](\frac{P_{crd}}{P_y})^{0,6}\, P_y \quad \text{for} \quad \lambda_d > 0{,}561 \tag{3}$$

where $\lambda_d = \sqrt{P_y / P_{crd}}$, P_{crd} is a distortional buckling load critical elastic distortional in a column and P_y as defined previously.

2.1.2 Determination of critical elastic local and distortional column buckling load

Although the DSM comes in order to provide to designers a simple and reliable method to determine the ultimate strength of CFS, its which is based mainly on results provided by analysis of elastic stability, there are still many situations where the existing methodology presents some limitations.

One of such limitations is the situation where the elastic stability analysis carried out by conventional FSM is used to accomplish the classification of buckling modes: global (G), distortional (D) or local (L).

One way to do this classification is to analyze the minima values of the graph generated by mean of the FSM. However, although convenient, this approach is not general and depends on the cross section and loading specifications. Sometimes the minimum might be not to exist, or more than one minimum exists [16]. Qualitative definitions of modes are also presented in the "Commentary to the Direct Strength Method" [17], but up today such classifications are not general.

2.2 Using the modal analysis of the constrained Finite Strip Method (cFSM)

The DSM requires that the buckling modes are properly identified so that their equations can be used in an appropriate manner.

The development of cFSM [7-9] provided a way to separate the buckling modes (modal decomposition) and to perform its classification (modal identification). These characteristics make the DSM win in consistency, since that eliminates uncertainty in identifying the modes of buckling. In other hand, lets to incorporate the DSM and the cFSM in the optimization scheme of cold-formed steel profiles.

The constrained finite strip method (cFSM) is implemented in the computer program CUFSM - "Finite Strip Method - Cornell University, version 3.12, developed by Schafer [6], for analysis of elastic buckling. This program is freeware and can be freely copied to site address: www.ce.jhu.edu/bschafer/cufsm/.

This software is open source and was development in the Matlab language (Matlab7.6 [18]). These characteristics let us adequate the CUFSM to carried out the structural elements optimization considering the CUFSM algorithm to determine in automatic way the critical loads and the MRD to determine the collapse load.

How have the critical elastic loads chosen?

The current design specifications of CFS are calibrated to use solutions of elastic stability (critical elastic loads or stress) provided by conventional FSM or FEM, solutions which include the interaction between all modes of buckling.

For this reason up to have the MRD strength curves calibrated with the solution of pure modes of buckling obtained by cFSM Schafer [16] recommends that:

- the critical half wave length will be determined using MFFr.
- the critical values of force or moment that corresponds with the critical half-wavelength previously computed with cFSM will be determined with the conventional MFF.

Following this recommendation, is presented below the steps used for calculating the elastic critical forces:

(i) we determined via cFSM, the half-wavelengths for the minimum of pure buckling modes (Global, Local, Distortion and Other Modes);

(ii) with the values of half-wavelengths obtained previously, we withdrew from the graphic factor of load × half-wavelength (generated by conventional FSM, where the modes element interacting) the factors of load corresponding and consequently the critical stress and;

(iii) finally, we performed the modal classification following the criteria of cFSM. For more details of this methodology see Grigoletti [19].

3 FORMULATION OF OPTIMIZATION PROBLEM

Taking into account the previous considerations, the aim of this work is to optimize the cross-section of channel profiles (with or without lips) that resist the axial compression load, F, with the lowest consumption of material (less weight of steel or, equivalently, the smallest gross section, A_g), for fixed parameters.

Thus, for the channel sections without lips, hereafter denominated C-section, the design variables are the dimensions are b_w, b_f and t (as indicate in figure 1 (a)) and for channel sections with lips, hereafter simply denominated C_{lip}-section, the design variables are the dimensions designated by b_w, b_f, D and t (as in figure 1 (b)). Now we can represent the problem of minimizing the cross-section as:

$$\text{Minimize: } f(x_1, x_2, ..., x_n) = A_g \tag{4}$$

where:

$x_1 = b_w$, $x_2 = b_f$, $x_3 = t$ for C-section and $x_1 = b_w$, $x_2 = b_f$, $x_3 = D$, $x_4 = t$ for C_{lip}-section.

Subject to the following behavioral inequality constraints:

- $F \leq \phi_c P_n$, $b_w / t \leq 472$, $b_f / t \leq 159$, $4 \leq D / t \leq 33$, $0{,}7 \leq b_w / b_f \leq 5$, $0{,}05 \leq D / b_f \leq 0{,}41$, $\lambda \leq 200$ and the following side constraints:

$30 \text{ mm} \leq b_w \leq 1000 \text{ mm}$, $30 \text{ mm} \leq b_f \leq 1000 \text{ mm}$, $30 \text{ mm} \leq D \leq 1000 \text{ mm}$ and $0{,}614 \text{ mm} \leq t \leq 6{,}3$ mm.

Some explanations of the constraints used are presented below.

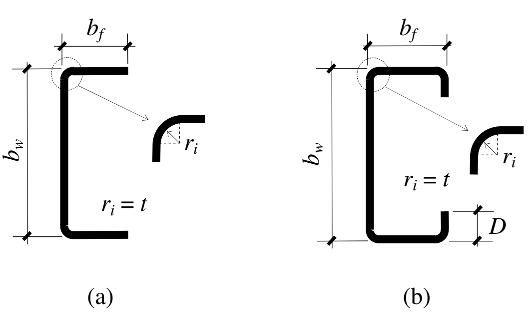

Figure 1: Cross-section of columns to be optimized: a) C-section without lips; b) C-section with lips

The behavioral inequality constraints were here with the goal that the optimized geometry does not fall bound outside of the “pre-qualified” columns of table 1.1.1-1 of Appendix 1 of the North American Specification for Design of Cold-Formed Steel Structural Members [4].

In figure 1 r_i is the inner radius of folding.

The side constraints were used for that the dimensions b_w, b_f, D and t with the goal that to use commercial acceptable limits and in this way reduce the search space used by the genetic algorithm.

The computational process of optimization of C-sections and C_{lip}-sections employed in the present study used source codes implemented in Matlab 7.6 [18] and the toolbox "Genetic Algorithm and Direct Search Toolbox" [20], which uses the method of Genetic Algorithms.

This toolbox, as well as, the CUFSM are open source codes and allow the implementation of new functions.

4 VALIDATION OF THE PROPOSED METHODOLOGY

We consider as reference the results of eight profiles tested by Chodraui [21], to validate the propose implementation.

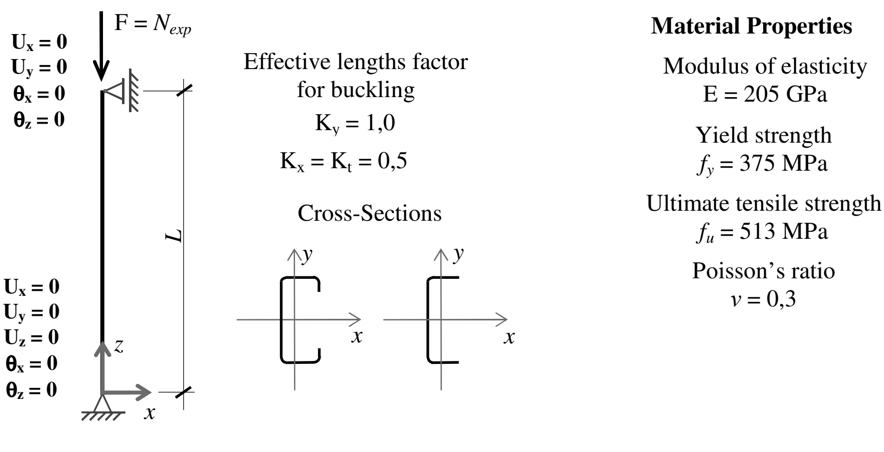

Figure 2: Reference system and boundary conditions of the columns optimized

In the optimization of each profile we fixated the load capacity obtained experimentally (N_{exp}). The boundary conditions, length, type C-section (either with or without lips) and mechanical properties adopted are shown in figure 2. We consider as variables in the optimization process b_f, b_w and t for both types of section and also D to the C_{lip}-section. The cross-sectional area of the profile is a variable dependent on the dimensions presented here, i.e., $A_g = f(b_f , b_w, t, D)$.

In Grigoletti [19] was performed the numerical modeling of the tests performed by Chodraui [21] using finite elements considering its mechanical and geometric non-linearities as well as geometric imperfections.

The comparison between the experimental and theoretical results obtained by FEM is shown in column 10 of table 1. This table also presents the results of the optimization in terms of the ratio between the area of optimized profile and the area of reference profile (A_{opt}/A_{ref}).

Thus, in the column 5 of table 1 values smaller than unity indicate that the section obtained shows better performance than the reference section. In column 6 of table 1 the percentage reduction of the area obtained in the optimization is also presented optimization.

Table 1: Comparison of results for profiles under pure axial compression

Reference sections				Optimum profiles						
Cross-sections	L (mm)	N^{ref}_{MEF*} (kN)	N^{ref}_{exp} (kN)	A_{opt} (mm^2)	$\frac{A_{opt}}{A_{ref}}$	Red. (%)	N_{NAS} (kN)	N^{opt}_{MEF} (kN)	$\frac{N^{ref}_{exp}}{N^{opt}_{MEF}}$	$\frac{N^{ref}_{MEF*}}{N^{opt}_{MEF}}$
C_{lip}-sections	1,015	141	168	507	0.82	17.79	168	140	1.20	1.01
	1,575	129	132	446	0.72	27.69	117	111	1.19	1.16
	2,130	92	75	318	0.52	48.46	60	70	1.07	1.31
	2,700	60	63	316	0.51	48.78	47	53	1.19	1.13
C-sections	850	101	119	392	0.86	14.30	100	98	1.21	1.03
	1,320	106	89	362	0.79	20.76	70	78	1.14	1.36
	1,800	66	55	298	0.65	34.78	40	37	1.49	1.78
	2,270	42	44	296	0.65	35.24	30	24	1.83	1.75

N^{ref}_{MEF*} - load capacity obtained by ANSYS to reference sections

N^{ref}_{exp} - load capacity obtained experimentally [21] to reference sections

N_{NAS} - load capacity obtained according with American standard [22] to the optimum profiles

N^{opt}_{MEF} - load capacity obtained by ANSYS to optimized sections

C_{lip} 125 × 50 × 25 × 2,38 A_{ref} = 617 mm^2 and C 100 × 50 × 2,38 A_{ref} = 457 mm^2

5 DISCUSSION OF RESULTS5

Of the results presented in Table 1, we can make the following observations:

- Since the boundary conditions of the reference profile respect to x-axis are fixed and with respect to the y-axis is hinged, the slenderness ratio in relation to the y-axis (λ_y) is greater than (λ_x), for this reason was consistent that the optimization searched a section with minor λ_y, and this tendency was confirmed.

-Table 1 also shows that when we determine the load capacity (strength) of the profiles Clip-section, optimized by FEM, the relationship $N^{ref}_{exp} / N^{opt}_{MEF}$ is between 1.07 and 1.20 (column 9 of table 1, which are acceptable, since this dispersion also happened in calibration of the finite element model (see Grigoletti [19]).

But when we determine the load capacity (strength) of the profiles C-section, optimized by FEM, we verified that the relationship $N^{ref}_{exp} / N^{opt}_{MEF}$ is between 1.21 and 1.83 (column 9 column of table 1).

In this case the values are acceptable only for the lengths of 850 and 1320 mm, not worth it for the profiles C-sections of lengths 1800 and 2270.

The explanation for this sensible difference (49 and 83%), for profiles with lengths of 1800 and 2270 mm, can be explained for: (i) the curves of DSM are not calibrated for the pure modes (buckling modes that have neither kind of interaction); (ii) the C-sections are not yet, pre-qualified sections by DSM (this would to require a coefficient of resistance more conservative. In the present work the comparisons were made with a nominal resistances) and; (iii) depending on the relationships between the dimensions of the section, the C-section can have the critical elastic buckling mode ranked by cFSM how distortional mode, i.e., in disagreement with the classification given by standards design, where the C-sections without lips admit only local buckling. This it implies that instead of using the resistance curve of the local buckling the curve of distortional buckling is used, that in this case overestimates the load capacity (strength) of the optimized profiles by DSM.

- The table 1 also is presented the strength nominal values obtained by mean of the American standard [22], that confirm the values obtained through MEF ($N_{\mathrm{MEF}}^{\mathrm{opt}}$), and in this case also appear the same phenomenon observed when comparing the experimental reference value with ($N_{\mathrm{MEF}}^{\mathrm{opt}}$).

- It is important point out that in the case of a perfectly correlation between the results the ratio $N_{\mathrm{exp}}^{\mathrm{ref}} / N_{\mathrm{MEF}}^{\mathrm{opt}} = 1$ will be expected, but values differences between 14 to 21% are waited as discussed in [19] and [21].

- In the comparison between the optimized profiles and the references profiles, we can to observe a great area reduction, (14% a 48%), as is appreciated in column 6 of the table 1, without considering the length 1800 and 2270 of the profiles C-section.

As a final commentary, it is important to say that the problems founded in the profiles C-section analysis could be avoided simply admitting that the classified buckling mode as distortional for cFSM, will be considered as local and then to use the strength curve corresponding to this mode, but this way is against the cFSM philosophy.

6 CONCLUSION

In this paper we proposed a methodology to optimize cold-formed steel members, via GAs, using the direct strength method (DSM) working with the constrained finite strip method (cFSM). From the obtained results, in different steps of this paper, we conclude that:

- *Regarding the methodology used for the elastic stability solution:* (i) the utilization of cFSM has demonstrated to be a useful tool to help the DSM, because it solves modal identification problems that are present when we use the conventional FSM or FEM; (ii) although the cFSM doesn't give necessarily the same results obtained via conventional FSM (which considers all modes interacting), it can be used together with the DSM, once the methodology explained by Grigoletti [19] is used to determine the critical loads; (iii) a difficulty of philosophical character in the utilization of cFSM is the fact that the mechanical definitions used to classify the buckling modes are not always in accordance with the classical concepts used for these modes, causing sometimes some confusion;

- *Regarding the methodology used for the column load capacity (strength) determination:* (i) the DSM has demonstrated to be an adequate tool to optimize profiles, as it incorporates naturally every form of collapse that the CFS are submitted to; (ii) although we only optimized C-section and C_{lip}-section profiles, the implemented methodology is general, so that it can also be used for other kinds of profiles;

- *Regarding the methodology used to optimize the cross-section form:* (i) during the simulation, the utilization of the hybrid function demonstrated to be an excellent tool to refine the search for optimum solution. This affirmation was proved through several optimization runs, coming from different points and looking for the best result. In practically all the runs the hybrid function, using the solution given by the GAs converged to the same value of the global minimum; (ii) a difficulty found was the processing time spent in the optimization as the cFSM passes the several half-wavelengths (50 at least to have an accurate result), executing to each half-wavelength an eigenvectors stability analysis.

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