Search for Improved Steel Cold-Formed Lipped Channel Beams

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Abstract. Cold-formed steel (CFS) members are light-weight structural elements with high strength-weight ratio, usually applied in many industrial applications. The CFS sections are frequently classified as thin-walled structures, which means high sensitivity to buckling behavior associated to the buckling modes: local, distortional and global. In order to improve the structural capacity of the CFS members, one may design thin-walled sections including intermediate stiffeners, providing quite improved structural behavior. The main purpose of the investigation is the development of a search procedure for stiffened lipped channel beams, performing the highest critical buckling moment and flexural strength. For this, the point of departure is a 600 mm width and 1.0 mm thick steel sheet, originated from a steel coil, which will be designed to produce lipped channel CFS with the following possibilities of intermediate stiffeners: (i) type of stiffener; (ii) number of stiffeners in a single element; (iii) stiffeners distribution in the flanges and the web; (iv) stiffener dimensions. As all the CFS's candidates will be created from the same initial coil (600 x1.0 mm), all will have the same cross-section area and weight. In this condition, the search process is restricted to the geometric organization of the cross-section dimensions and choice of the stiffeners geometry, dimensions and distribution, in order to display the most efficient section for simple bending loading (in the major axis). After the generation of the possible CFS's, the corresponding beam members were submitted to elastic buckling analysis with the help of the finite strip method computational program CUFSM, for the determination of the critical buckling bending moment. The obtained results are applied for the calculation of the flexural strength of the beams, on the basis of the Direct Strength Method (DSM) rules included in the Brazilian standard NBR 14762:2010. A shell FEM model was implemented via Ansys computational package, in order to confirm the accuracy of the DSM results in terms of the beam strength. Finally, it was concluded that (i) the presence of intermediate stiffeners may bring remarkable structural performance improvement (up to 60% in some cases) and (ii) that the combination of the FSM and the DSM proved to be an optimal tool for determining the most efficient geometry for a CFS cross section from any steel coil indicated as input data.

Keywords: Cold-formed steel beam, Thin walled lipped channel, Intermediate stiffeners, Finite strip method, Finite element method.

1 Introduction

According with Yu and Laboube [1] structural steel sections are divided into two main categories. The first and most common category is hot rolled sections. The second, of growing importance and already widespread, including in Brazil, is the Cold-Formed Sections, CFS, manufactured from the bending of steel plates, usually sold in coils of constant width up to 12000 mm. As highlighted by Ma *et al*. [2] this type of profile appears as an alternative for different types of structures, as it is a lightweight, economical constructive solution, with a with almost ilimited geometry variety, easy to manufacture, transport and assemble.

It is known that the performance of the structural element is closely related to the shape of the profile cross section. Therefore, it is of interest of the industry the search of more efficient solutions among several geometric possibilities, including intermediate stiffeners. Different cross-sectional geometries for CFS with intermediate stiffeners in a lipped channel are already found in the market, as indicated by Bruneau *et al.* [3].

At this point, it is worth mentioning some of the main works that approach the search for alternative geometries with the addition of intermediate stiffeners in cold-formed profiles, for example, Castellucci *et al.* [4] suggested the conception and analysis of a new geometry from the inclusion of two intermediate stiffeners in the web of a lipped channel section submitted to bending. Bending tests and flexural strength calculation were performed applying the effective section method that point to an increase in the ultimate load of about 15% related to an area increase of 5%.

In the work of Ye *et al*. [5] an optimization method was applied to define the most efficient cross-sectional geometry, from folds in a stiffened lipped channel section, with the search for the most resistant moment according to the effective width method present in Eurocode 3. The bending strengths of the optimized sections were compared by means of numerical models based on Finite Element Method (FEM), through nonlinear analysis considering initial geometric imperfections. Among a large number of cross-sectional geometries, with the same amount of material and constraints indicated as standard, a solution was obtained with a flexural strength 50% higher than the initial lipped channel.

2 Objectives and Methodology

The objective of this work is to investigate the influence of intermediate stiffeners on the buckling modes of cold-formed steel profiles when submitted to bending, as well as to look for the dimensions and positions of the intermediate stiffeners that define the sections with the highest critical moments and, in this way, the determination of stiffened lipped channel with more stable and flexural strength.

This work adopts a procedure of variation of the parameters that define the geometry of the cross section, in order to define the candidate sections. The procedure adopted also considers restrictions, with the objective of analyzing only sections with real practical applications and with manufacturing possibilities, among which will be identified those with greater structural strength.

The methodology consists of searching the initial section, i.e., determining the dimensions of the lipped channel profile that results in the highest distortional critical buckling moment, M_{dist}. Intermediate stiffeners will then be considered to improve local buckling behavior. From the initial defined lipped channel will be generated the stiffened sections: where the parameters are type, quantity, dimensions (height, bending angle and length) and position of the stiffeners. Twelve initial section types will be analyzed, schematized in scale in Figure 1.

The various variations in geometry will not change the area of the section, so that the creation of a stiffener decreases the height of the section and the other dimensions remain constant, that is, all the sections have the same area and different heights, with a difference in the number and angles of bending (Fig. 1).

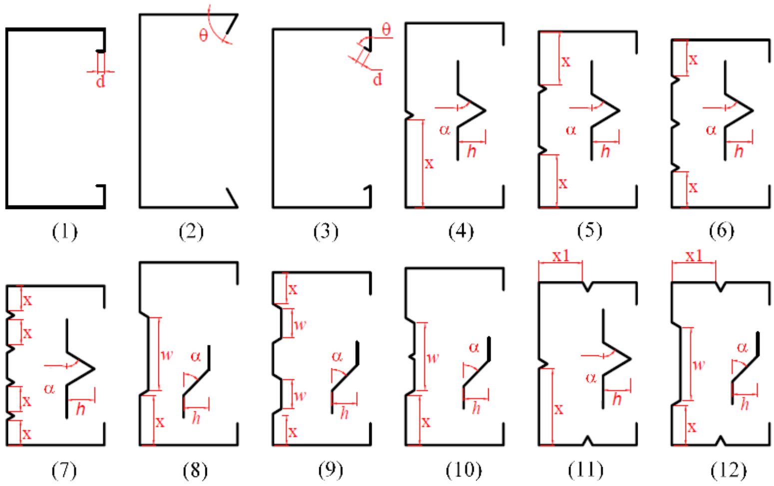


Figure 1. Types of analyzed sections and parameters that define the stiffeners of the candidate sections

The CUFSM program (Li and Schafer [6]) will be adopted for the calculation of the critical buckling moment of the profiles under study. The strengths of the optimal sections will be calculated with numerical analysis with the Finite Element Method (FEM) to be then compared with the flexural strength obtained with the Direct Strength Method (DSM) indicated in the Brazilian standard ABNT NBR 14762 [7] in lipped channel.

For the finite element model, the program ANSYS will be used, with shell element, SHELL181 in the mesh discretization and to simulate the bending of beams, end conditions as simply supported at both ends where pure bending loading is also applied, with nodal loads of variable intensity with height, where the resultant is a moment that generates a bending moment at each end, as indicated by Dangi [8]. To reduce the computational expenditure, symmetry boundary conditions were applied to half the length of the beam, so that only half of the beam is modeled. The condition of simply supported beam was modeled by a flexible sheet, thinner than the thickness of the profile analyzed (Fig. 2), at both ends of the beam, this sheet is supported by a rigid frame so that when applying the load at both ends the sheet has free movement and only supports the profile, thus representing a simple support.

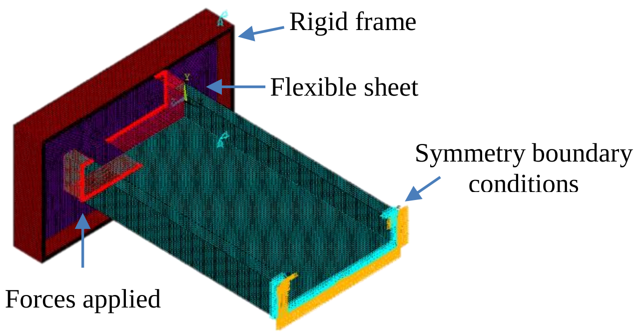


Figure 2. Boundary conditions adopted for the model of a simply supported beam

The validation of the end conditions adopted for the model of a beam simply supported on finite elements, for the analysis of elastic stability, occurred with the comparison of models with different lengths, obtained from multiples of the number of half-waves (L_{cr}) that indicated an increase of the critical bending moment (M_{cr}) practically the same model analyzed with the GBTUL tool (Bebiano *et al*. [9]). This guarantees that the model and the boundary conditions adopted in finite elements are able to represent the simple supported beam system.

The non-linear analysis in finite elements is performed with the application of load increments and with the adoption of the arc length technique, as an iteration strategy, in the search for responses beyond the critical points. The nonlinearity of the material is also considered, with the use of a bilinear stress-strain curve. In this model, until the yield stress (f_y) the material is in the elastic regime, with slope in the stress-strain graph equal to the modulus of elasticity (E). Once the yield stress is reached, the material passes to the plastic deformation regime with a slope smaller and equal to 0.1*E.

3 Results

Parametric analysis of the dimensions of the lipped channel, such as web (b_w), flange (b_f) and the final stiffener (b_l) resulted in Fig. 3, where it can be seen that an increase in the size of the b_l, results in greater distortional critical moments, and that the maximum value occurs in values of $b_f/b_w = 0.23$ in all cases.

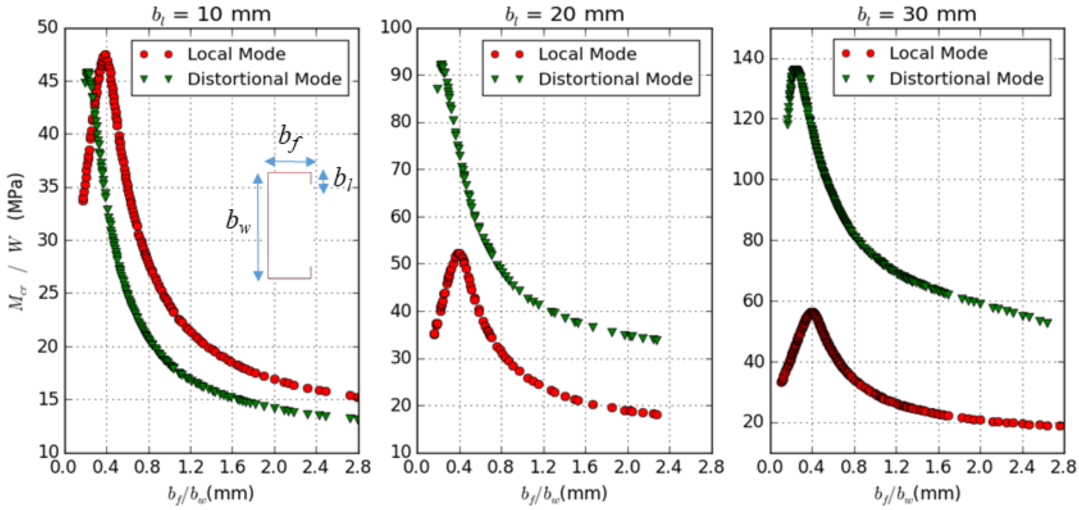


Figure 3. Critical moments for different dimensions of the stiffened U-section

Thus, the procedure to determine the section lipped channel with maximum distortional critical moment, when submitted to bending, follows the following system of equations in eq. (1).

$$\begin{cases} b_w + 2b_f + 2b_l = \text{Coil width} \\ \frac{b_f}{b_w} \cong 0.23 \\ b_l \text{ maximal}, \ 10 \leq b_l \leq 30 \end{cases} \tag{1}$$

In the case of a coil 600 mm wide and 1 mm thickness, the section with the maximum distortional buckling moment, has as dimensions b_w = 368 mm, b_f = 86 mm and b_l = 30 mm and will be adopted as an initial section in the following analyses, in the process of creating intermediate stiffeners, in order to raise the critical moment of local buckling. It is also observed that the local mode is maximum in b_f/b_w = 0.4. It can be stated that (i) the variation of b_l has little influence on the value of the local mode, however (ii) in the distortional mode the value of b_l is decisive, but that (iii) there is no guarantee that the distortional mode will be dominant for high values of b_f/b_w .

After defining the initial lipped channel with which it guarantees the highest distortional critical buckling moment, the next step is the variation of all the geometric parameters of the stiffeners. The stability analyses of the candidate sections have determined the sections with the maximum local critical bending moment, these "optimal" sections for each type of section are indicated in Fig. 4 with the sections presented in the same scale, allowing comparison of the geometries. It is observed that sections with intermediate stiffeners in the web (section type 4 to 10) have a local critical bending moment about 3.0 times larger than section lipped channel of the same area. In addition, sections with stiffeners in the web and in the flange (section type 11 and 12) the local critical bending moment is about 6.0 times higher than the lipped channel of the same area, and the increase of the local critical moment is so evident that only in these cases the local mode ceases to be the critical mode.

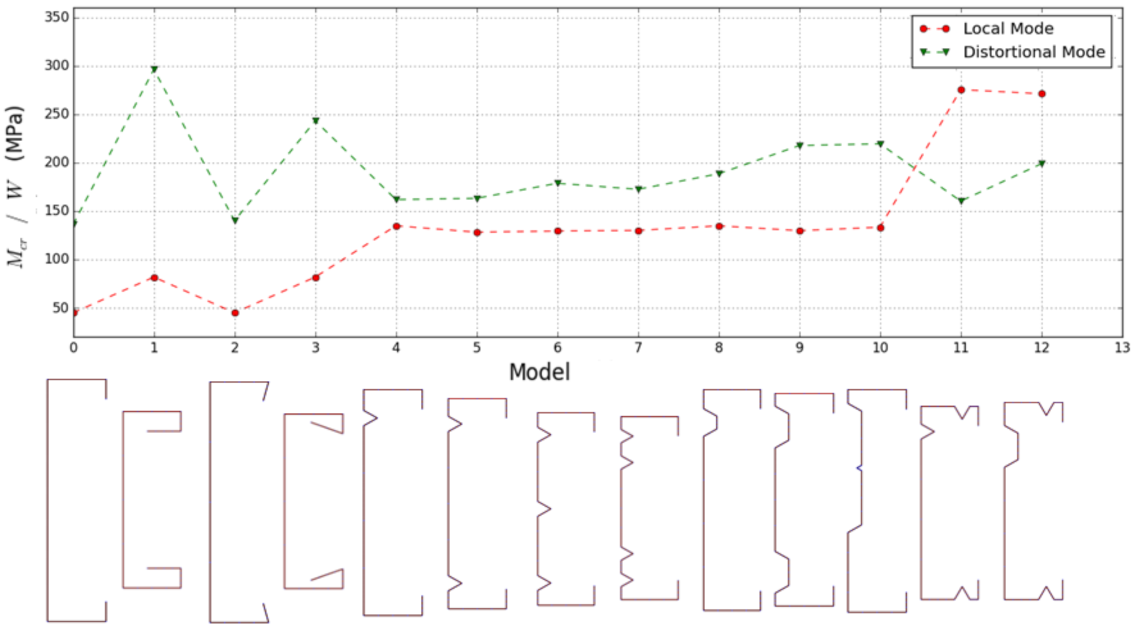


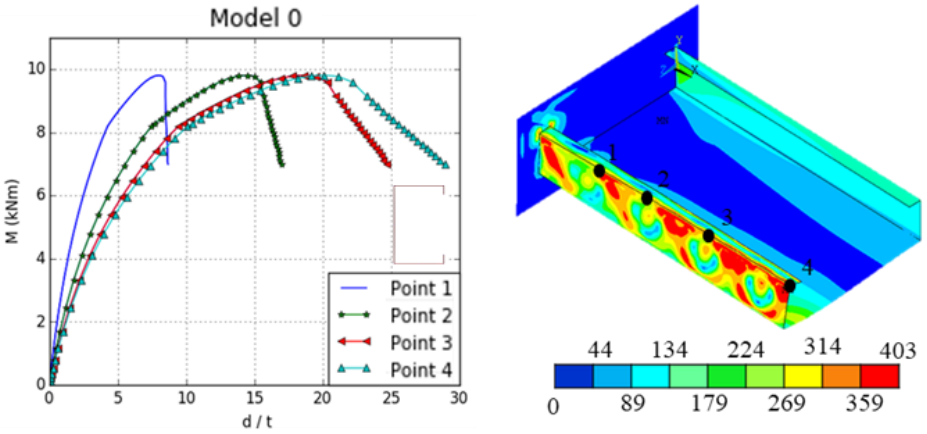
Figure 4. Critical buckling moments of the "optimal" sections in each section type

The elastic stability analyses of the optimal sections were compared with the finite element models with a beam length of 7*L_{cr}, a procedure that eliminates the influence of the boundary conditions and is widely used in numerical models in the literature. Table 1 presents the comparison of the results of critical buckling moments adopting models with FSM and FEM, for all the sections defined as "optimal" for each type of optimal section. The maximum difference between the results is less than 4%, which guarantees the validity of the model. Also in Tab. 1 is presented the comparison of the flexural strength results obtained with DSM and FEM nonlinear analyses, of the "optimal" sections. The steel properties adopted for all sections under analysis are: modulus of elasticity E = 210000 MPa, Poisson coefficient ν = 0.3 and yield stress f_y = 350 MPa.

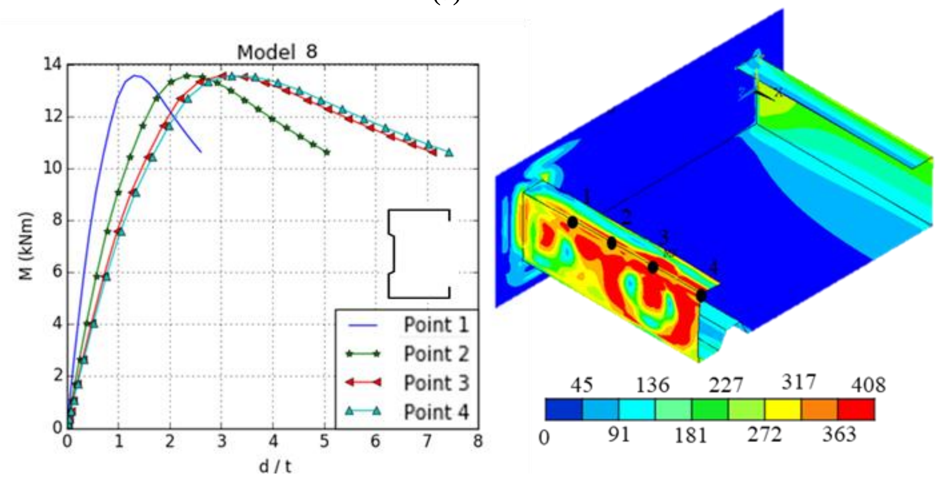
Table 1. Comparison between FEM and FSM for critical loads and FEM and DSM for ultimate load

Section type	Length (mm)		M_{cr} (kNm)				Flexural strength (kNm)		
	L_{cr} (Local)	7*L_{cr}	FSM Local	FSM Dist.	Ansys	FSM/ FEM	FEM	DSM	DSM/ FEM
0	187.38	1311.66	2.86	8.65	2.87	1.00	9.60	9.14	0.95
1	148.50	1039.50	4.05	13.85	4.01	1.01	8.27	8.87	1.07
2	187.38	1311.66	2.86	8.90	2.84	1.01	8.82	9.15	1.04
3	148.50	1039.50	4.16	12.38	4.21	0.99	7.25	9.12	1.26
4	83.02	581.14	8.37	10.05	8.33	1.00	12.88	13.31	1.03
5	73.91	517.37	7.33	9.33	7.12	1.03	12.28	12.05	0.98
6	73.91	517.37	6.72	9.28	6.48	1.04	10.95	10.98	1.00
7	73.91	517.37	6.51	8.63	6.39	1.02	10.48	10.60	1.01
8	73.91	517.37	8.32	11.64	8.18	1.02	13.56	13.24	1.00
9	73.91	517.37	7.34	12.31	7.30	1.01	11.99	11.97	1.00
10	73.91	517.37	7.84	12.90	7.86	1.00	12.50	12.56	1.00
11	58.60	410.20	15.54	9.04	15.83	0.98	18.50	15.49	0.84
12	58.60	410.20	14.99	10.99	15.26	0.98	17.97	15.10	0.84

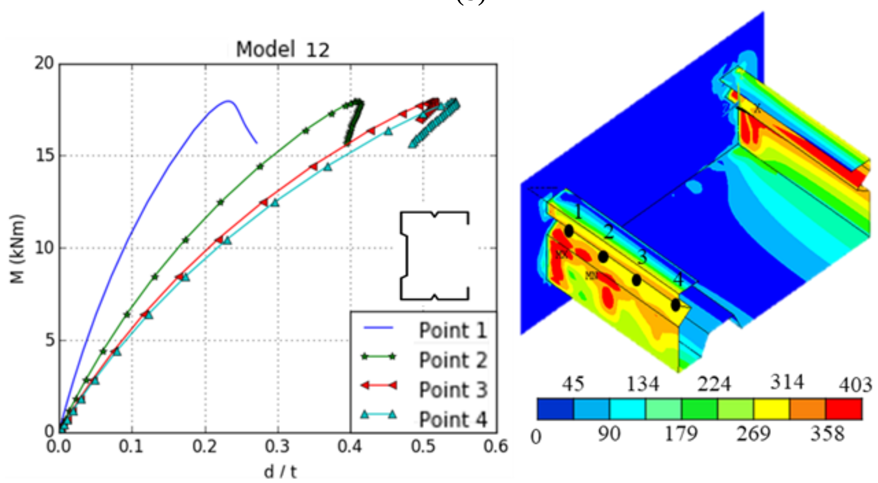
The ultimate load, or limit load, identified from the FEM analyses is identified in the graphs Load vs. Displacement included in Fig. 5, corresponding to section types 0, 8 and 12, according with Tab. 1. In this case, the equilibrium trajectories of four displacements points (1 to 4) were recorded along the length of the beams and one may observe the contribution of the distortional buckling mode. Moreover, Fig. 5 displays the Von Mises stress distribution at the limit load step.



(a)



(b)



(c)

Figure 1. FEM results of (i) the applied bending moment vs. displacements at points 1 to 4 for the optimal section types 0, 8 and 12 (see Tab. 1) and (ii) stress distribution at the limit loading step

4 Conclusions

In this work, a search for cold-formed steel cross sections was proposed, in order to guarantee the maximum critical load of local buckling and strength when subjected to bending. After varying all geometric parameters of intermediate stiffeners in predefined sections of the same area, it was observed that the degree of complexity of the stiffened cross-section does not necessarily result in larger critical bending moment. For example, sections with a single trapezoidal stiffener in the web may present larger local buckling critical bending moment than section with four web stiffeners of the same geometry.

The inclusion of intermediate stiffeners, in all cases, brought benefits. The results point to a critical load, of the section with intermediate stiffener, as six times greater. The optimal sections found with intermediate stiffeners in the web and in the flange showed an increase of the flexural strength of about 69% in relation to the section of the same area without intermediate stiffeners.

Therefore, it is concluded that the combination of FSM and DSM for the determination of member strength proved to be an optimal tool for determining the most efficient geometry for a CFS cross section from any coil width indicated as input data. The obtained results of the structural improvement of the steel cold-formed stiffened lipped channel beams were based on a methodology that included the possibility of programing in the CUFSM source computational program. This procedure allowed automation of the generation of the stiffened sections, together with the finite strip method-based computation of the stability analysis.

Acknowledgements. The authors are grateful to CNPq, National Council for the Scientific and Technological Development, for its financial support of the first author (concession procedure number 131044/2018-4) and Agência Nacional do Petróleo, Gás Natural e Biocombustíveis –ANP – , da Financiadora de Estudos e Projetos – FINEP – e do Ministério da Ciência, Tecnologia e Inovação – MCTI through the Human Resources Program of ANP for the Oil and Gas Sector – PRH-ANP/MCTI.

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